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Natural Resource Stewardship and Science

An Evaluation of Temperature and Precipitation Data for Parks of the Mojave Desert Network

Natural Resource Report NPS/MOJN/NRR—2016/1339

ON THE COVER

Photograph of Badwater Basin (elevation -86 m) taken from Rogers Peak (elevation 3046 meters). Both of these locations are in Death Valley National Park, but they have very different climates.

Photograph courtesy of the National Park Service

An Evaluation of Temperature and Precipitation Data for Parks of the Mojave Desert Network

Natural Resource Report NPS/MOJN/NRR—2016/1339

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Abstract

We evaluated meteorological records from 23 sites in and near seven park units of the Mojave Desert Network (MOJN) to provide managers and planners with information on how climate is changing in their parks. We summarized monthly temperature and precipitation variables, including total precipitation during the monsoon season. We tested for monotonic trends in each time series using Mann-Kendall and Seasonal Mann-Kendall tests. Many locations had missing daily observations within months and we evaluated the rigor of test results to missing data by serially excluding mean monthly values from test iterations that had varying numbers of days missing from them. We used the metadata to determine when climate stations were relocated and we evaluated whether any observed temperature or precipitation trends may have been attributable to known station movements.

Our findings were consistent with observations of regional warming and showed that most stations recorded warming during their periods of record. We found statistically significant warming trends in mean monthly temperature at 16 (~70%) of the 23 sites we evaluated. The proportion of sites with statistically significant ($\alpha \leq 0.05$) warming trends in monthly mean minimum temperature (78%), monthly mean maximum temperature (61%), and minimum monthly temperature (74%) were similar. The evidence for significant warming in maximum monthly temperatures was less compelling, with only 8 (35%) of the 23 sites having positive trends. Only two sites associated with Joshua Tree NP and one site at Great Basin NP showed trends (increasing) in monsoonal precipitation. Evidence of trends in monthly precipitation data was also scant.

Based on our changepoint analyses, station relocations appeared to have little effect on temperature results. In contrast, we found statistical evidence that some station relocations may have contributed to our failing to find any significant precipitation trends for those stations. Our sensitivity analysis suggested that the reported trends were insensitive to the number of days used to generate monthly climate values.

Acknowledgments

We wish to extend our gratitude to David Gundlach, NPS, for creating the maps used in this report and to Charles Erdman, U. Idaho, for assisting with statistical analyses. Work by the University of Idaho was supported by Great Basin Cooperative Ecosystem Studies Unit agreement number P12AC15064 with administrative support from Cheryl Chambers (UI). We are also indebted to Laura Edwards, acting State Climatologist for South Dakota, and Patrick Gonzales, National Park Service Principal Climate Change Scientist, for their reviews of this report.

Introduction

The Mojave Desert Inventory and Monitoring Network (MOJN) is comprised of eight national park units located in southern Nevada, Arizona, and California (Figure 1). Multiple ecosystems are represented across MOJN parks including desert, lakes, springs, and montane habitats. The physical infrastructure, natural and cultural resources, visitor experience, and intrinsic values of national parks are at risk from the effects of climate change (NPS 2010) and the U.S. National Park Service (NPS) is challenged to protect park resources under rapidly shifting environmental conditions at broad spatial scales (Hansen et al. 2014, Monahan and Fisichelli 2014). The goal of this report was to examine temperature and precipitation data from stations in and around the MOJN parks and evaluate how any trends may have been manifested. This report compliments the work of Monahan and Fisichelli (2014), who examined climate trends in national parks using gridded climate data sets.

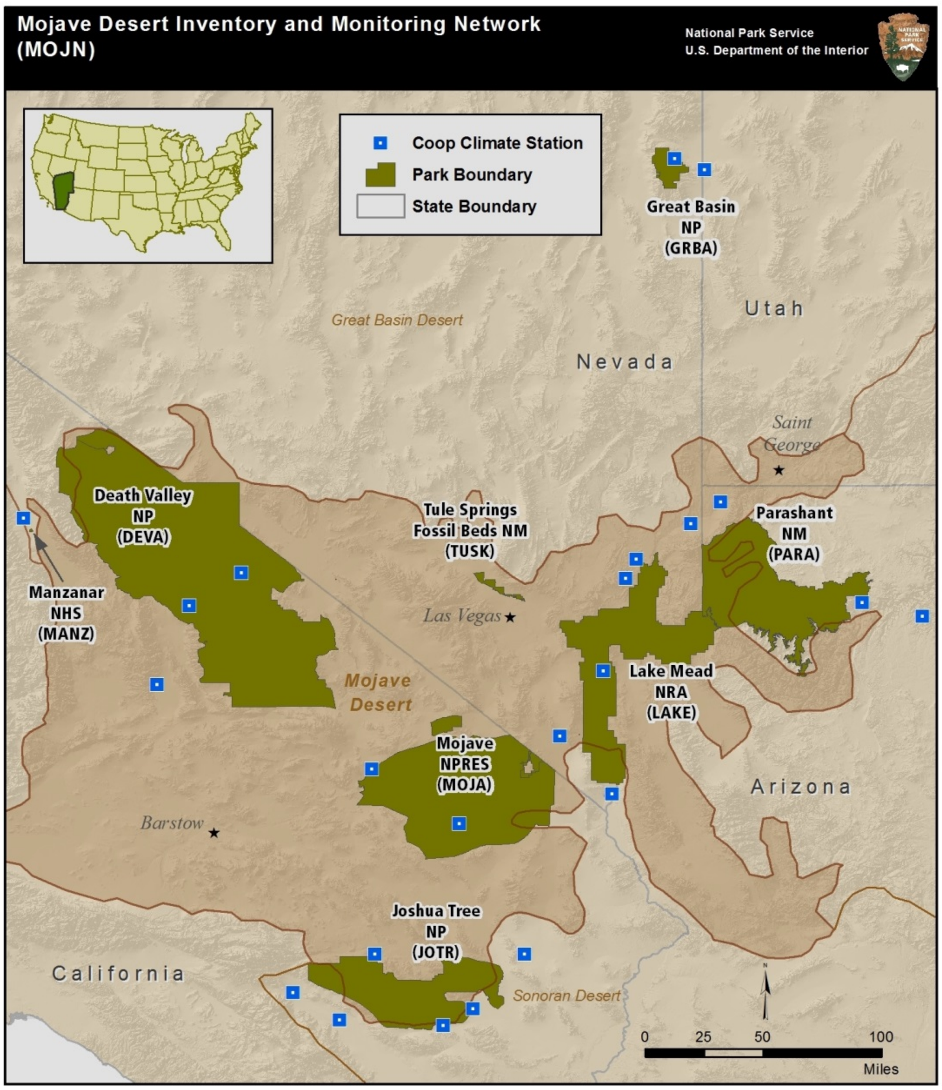

Figure 1. Map of the Mojave Desert Inventory and Monitoring Network with eight national park units in Nevada, Arizona, and California.

Methods

We obtained metadata and monthly data for six variables (monthly mean temperature, monthly mean minimum temperature, monthly mean maximum temperature, minimum temperature within month, maximum temperature within month, and total monthly precipitation) from the Western Regional Climate Center (http://www.wrcc.dri.edu/) for 23 sites within and near seven of the eight MOJN parks (Tule Springs Fossil Beds National Monument was established after this project was initiated). When available, we also obtained daily precipitation data and generated a seventh variable for total precipitation within each year's monsoon season (15 June – 30 September). We restricted analysis to the selected sites using two criteria determined by NPS: 1) station proximity to parks, defined as < 40 km from a boundary and not separated from the park by a major physiographic boundary (e.g., a mountain range or the Grand Canyon), and 2) a minimum time series of approximately 30 years (*actual minimum* = 355 months). All sites were maintained by the National Weather Service Cooperative Observer Program (COOP).

Trend Tests

We tested for the presence of monotonic (single-direction) trends in each time series using analyses based on the Kendall rank correlation. Kendall tests are non-parametric tests of independence between two variables. Mann (1945) first suggested using Kendall's correlation coefficient tau (τ) to test for trends and the Mann-Kendall test can be stated most generally as a test for whether values of metric Y tend to increase or decrease with time (Helsel and Frans 2006).

A weakness of many types of trend tests, including Kendall tests, is that they are affected by autocorrelation (also referred to as serial correlation). Specifically, the chance of finding significant answers increases for sites with autocorrelated time series, even in the absence of a trend (Cox and Stuart 1955, Hamed and Rao 1998). We tested for the presence of first order serial correlations in each time series using Durbin-Watson Tests (Durbin and Watson 1951) in the SAS software package (Proc Reg, SAS Institute, Cary, NC) and found that the six monthly climate metrics were positively serially-correlated at most or all sites, thus breaking a key assumption of the Kendall test.

For the six monthly parameters, we used Seasonal Mann-Kendall Tests, or SKT (Hirsch et al. 1982, Helsel and Frans 2006). With SKT, the data are "blocked" into seasons (in this case, into months), and the data from within each season are compared only to each other for the purposes of trend testing. The elimination of the effects of seasonal patterns from trend testing eliminates one source of autocorrelation, but the time-series' can still be autocorrelated due to lower-frequency patterns such as strong multi-year climate cycles (Hirsch and Slack 1984). We used SKT to test for the presence of trends for each metric at each station. We performed the tests in the R software environment (R Development Core Team 2016). Using the 'rkt' package (Marchetto 2015), we blocked by month and used the 'correct=True' option, which adjusted 2-sided p-values for any autocorrelation between blocks (Hirsch and Slack 1984).

The Seasonal Mann-Kendall Tests could not be applied to the monsoonal precipitation data, which were annual totals. Therefore, we used the standard Mann-Kendall Test, or MKT (i.e., no blocking by month) to test for the presence of trends in the monsoon precipitation records. We tested for the presence of first order autocorrelations in each time series using Durbin-Watson Tests (Durbin and Watson 1951) in the SAS software package (Proc Reg, SAS Institute, Cary, NC) and found that six of the 23 sites we evaluated had annual monsoon data that were significantly autocorrelated (Death Valley, Searchlight, Bullhead City, Willow Beach, Independence, and Beaver Dam). For these six sites, we adjusted p-values to account for autocorrelation (Butler 2015). We used the 'mkTrend' function in the 'Fume' package (Santander Meteorology Group 2012) in R to run the Mann-Kendall Tests on the monsoon precipitation records, which performed both adjusted and unadjusted Mann-Kendall Tests. The Death Valley monsoon data produced a negative value of the correction factor during the Mann-Kendall test and therefore, could not generate an adjusted p-value.

Slope Estimates

The rate of change for each climate metric at each station was estimated using a Theil-Sen-type slope estimate. The Theil-Sen slope is a non-parametric statistic that fits a line to a set of points based on the median slope among all lines through pairs of l-sample points. For the records where SKT was used, we used Seasonal Kendall Slope, a generalization of Theil-Sen slope where only pairs of data points from the same seasonal block (in this case, month) were compared. The method is a form of robust regression, which is designed to be not overly affected by violations of assumptions and outliers (Li 1985, Verardi and Croux 2009). Theil-Sen slope and Seasonal Kendall slope were calculated using the 'fume' package and the 'rkt' package, respectively.

For some sites, the SKT showed significant trends in monthly precipitation data but slope estimates were equal to zero. This can occur when there are a disproportionate number of ties (in this case, months with zero precipitation), which causes the median slope to be zero (McBride 2000). The reported slope of zero in these cases should be viewed as a mathematical artifact, and not a true estimate of the slope.

Sensitivity Analyses

The climate records used in this study had many months with one or more missing daily observations. Systematic blocks of missing daily data, particularly at the beginning or end of the month could produce spurious trends in the time series. We evaluated the sensitivity of the observed trend tests to the presence of months with large numbers of missing daily data by serially excluding mean monthly values from test iterations that had varying numbers of days missing from them. The original time series had already excluded months that had 26 or more days missing for any monthly estimate and we ran three additional sets of trials excluding months that were missing ≥15 d, >10 d, and >5 d.

Changepoint Analyses

We used the metadata to determine when climate stations were relocated and we evaluated whether any observed temperature or precipitation trends may have been attributable to reported station movements rather than climate. Specifically, we applied linear regression models in SAS to monthly values across any two periods that bracketed a known station move. We excluded the value for the month when the station was moved and used a Mann-Whitney U Test to compare ranked values of the regression residuals from before and after the potential changepoint (Bates et al. 2012, Rodionov 2005). Significant results ($p < 0.05$) from Mann-Whitney tests suggested that climate metrics may not have been the sole drivers of SKT results when significant, whereas non-significant outcomes could have resulted because a) station movements may have masked any real changes in climate metrics when SKT or b) the station movement introduced no bias or trend to the time series.

Site Descriptions and Results from Statistical Analyses

Joshua Tree National Park

Summary of Sites Analyzed

We analyzed data from six sites near Joshua Tree National Park, none of which were in the park (Table 1). All sites were within 40 km of a park boundary and maintained by the National Weather Service Cooperative Observer Program (COOP) (Figure 2). The elevation of the sites ranged from 6 m below sea level to 602 m above sea level. Two large desert ecosystems, primarily determined by elevation, come together in the park. The eastern portion of the park is in the Colorado Desert, which is part of the Sonoran Desert and is dominated by the abundant creosote bush. The slightly cooler and wetter Mojave Desert contains habitat for Joshua trees, which occur in extensive stands throughout the western portion of the park (NPS 2015b).

Weather and Climate

Days are typically clear with less than 25% humidity. Temperatures are most moderate in the spring and fall, with an average high/low of 85 and 50°F (29 and 10°C), respectively (Figure 3). Winter brings cooler days, around 60°F (15°C), and freezing nights. It occasionally snows at higher elevations. Summers are hot, over 100°F (38°C) during the day, and there is little cooling below 75°F (24°C) until the early hours of the morning (NPS 2015a). Total monthly precipitation is typically less than an inch (Figure 4). Mean annual monsoonal precipitation ranged from 0.6 – 1.7 inches among sites (Figure 5).

Table 1. Station names, periods of record, and elevations of monitoring sites adjacent to Joshua Tree National Park.

Station	In park?	Period of Record	Elev. (m)
Palm Springs	No	Jan 1922 to Oct 2015	130
Indio Fire Station	No	Jan 1894 to Oct 2015	-6
Iron Mountain	No	Jan 1935 to Oct 2015	281
Twentynine Palms	No	Jan 1935 to Oct 2015	602
Hayfield Reservoir	No	Jul 1933 to Oct 2015	418
Eagle Mountain	No	Sep 1933 to Oct 2015	297

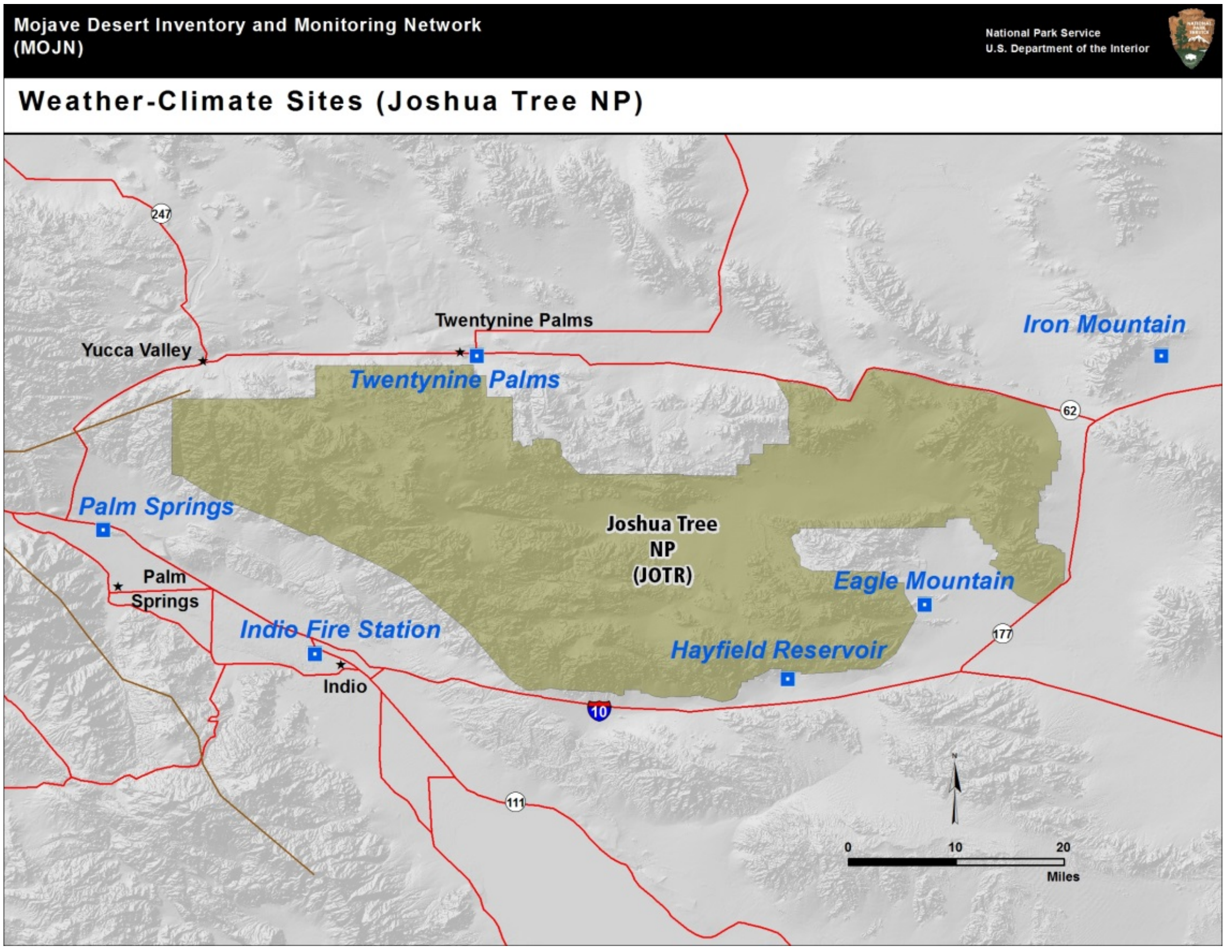

Figure 2. Map of the six climate monitoring sites near Joshua Tree National Park.

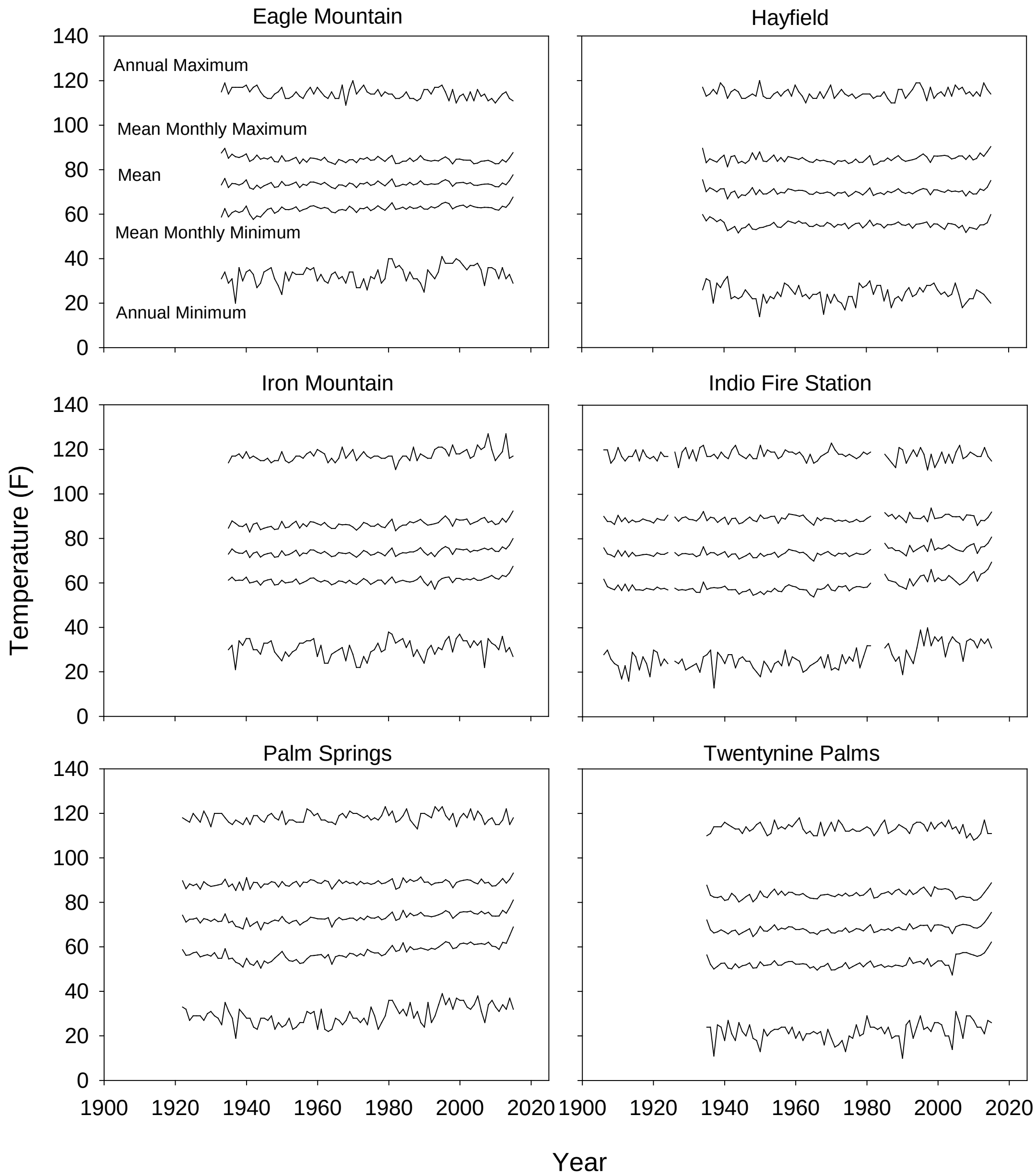

Figure 3. Annual minima and maxima, mean monthly minima and maxima, and mean monthly air temperatures recorded at sites associated with Joshua Tree National Park. Note: annual temperature metrics displayed here are for illustration purposes only. With the exception of the monsoon precipitation metric, all analyzed data were monthly values.

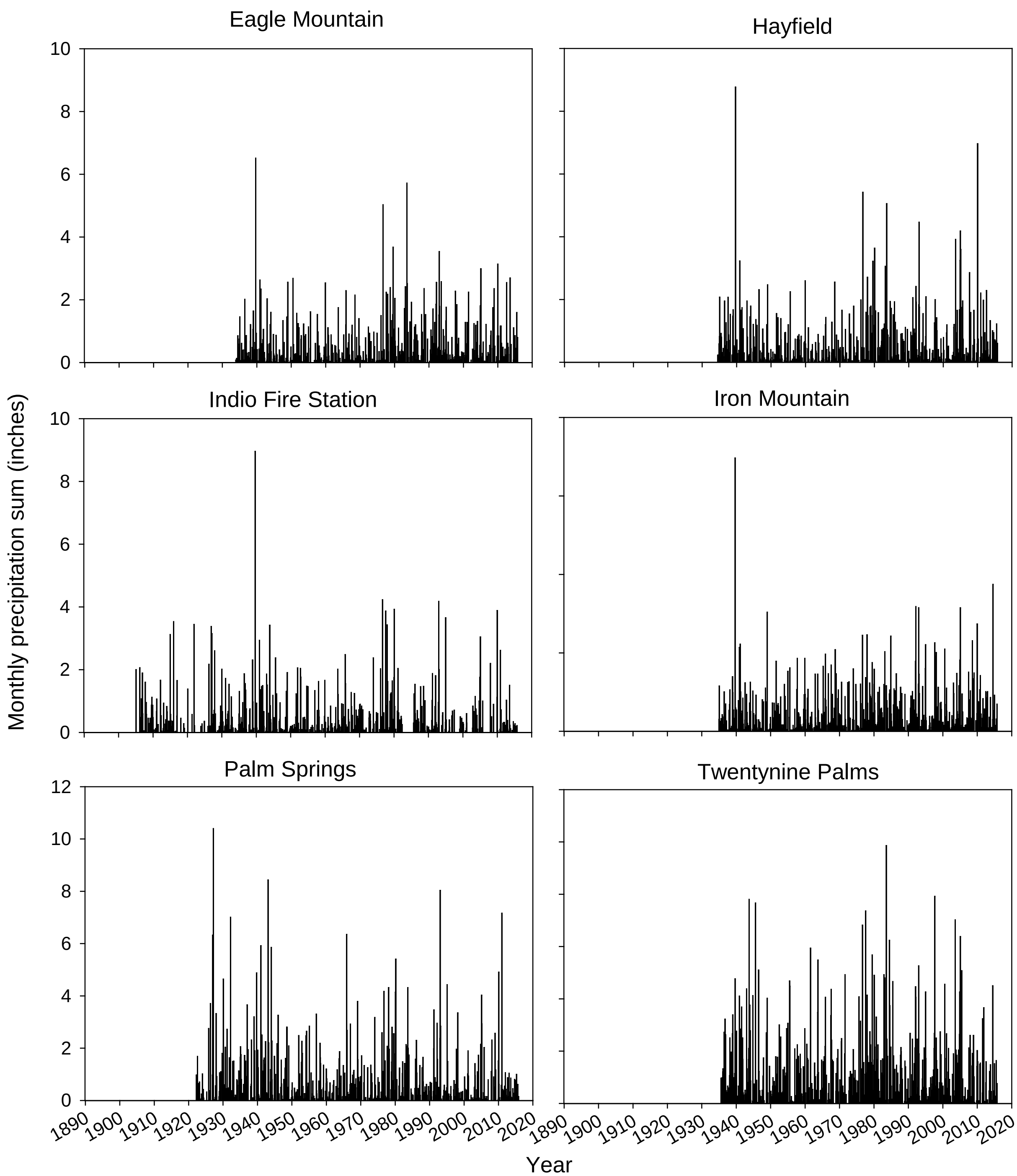

Figure 4. Total monthly precipitation recorded at sites near Joshua Tree National Park.

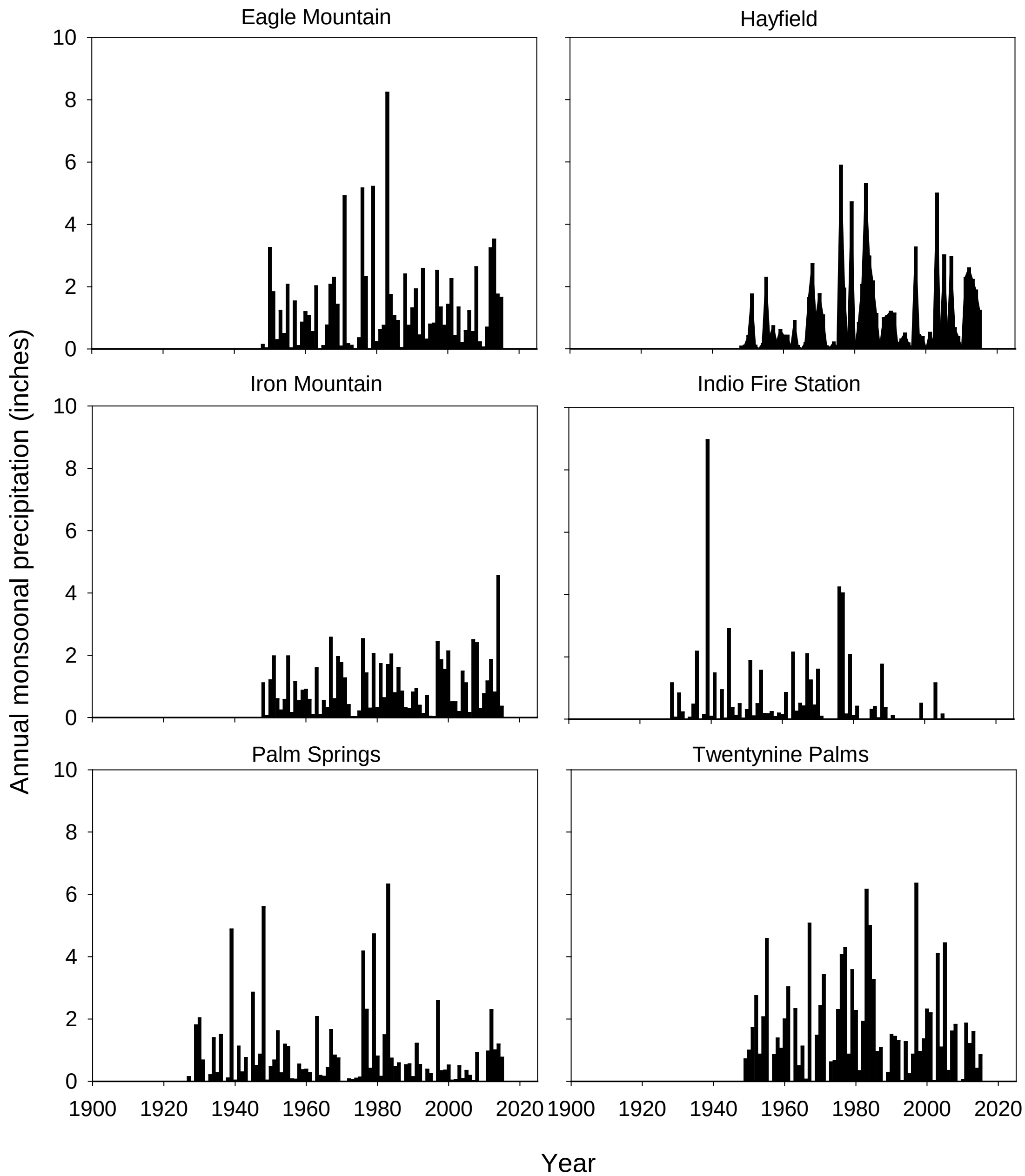

Figure 5. Annual monsoonal precipitation recorded at sites near Joshua Tree National Park. For some sites, monthly data were available but daily data were not, which precluded our generating estimates of annual monsoonal precipitation for some years.

Tests for Trends

We found positive trends in temperature metrics for most sites near Joshua Tree National Park. Four of the six sites had four of five metrics exhibiting positive trends (Table 2). Hayfield Reservoir was an exception in that only the mean maximum temperature had a positive trend. Among the four trends found at Eagle Mountain, two were positive (i.e., minimum temperature metrics) and two were negative (i.e., maximum temperature metrics). All other temperature trends were positive. We found trends in monthly precipitation at Palm Springs and Indio Fire Station but could not determine the direction of the trends because of ties among ranks. Trends in monsoonal precipitation were negative at Indio Fire Station but positive at Hayfield Reservoir.

For all temperature metrics, we found no evidence that relocation was associated with a significant change in temperature. We therefore concluded that results from Seasonal Mann-Kendall Tests were not affected by station relocations (Table 3). We did find evidence that test results may have been affected for the monthly precipitation metric at four sites with known station relocations. Specifically, the significant Mann-Whitney results for the Palm Springs and Indio Fire Station precipitation data would have diminished support for the significant trends we found but this was inconsequential because we could not determine the slope of the trends. In contrast, significant Mann-Whitney results for the station relocations at the Iron Mountain and Twentynine Palms sites may have contributed to our failing to find any significant precipitation trends in the Seasonal Mann-Kendall Tests.

Table 2. Probabilities and slope estimates from Seasonal Mann-Kendall tests for monotonic changes in climate metrics at COOP stations near Joshua Tree National Park. Bold font indicates significant results (*P*<0.05). Slope is reported in °F per year, total inches precipitation per year or total inches of monsoonal precipitation per year. See Appendix for samples sizes of all site × metric combinations.

	Palm Springs		Indio Fire Station		Iron Mtn		Twentynine Palms		Hayfield Reservoir		Eagle Mtn.	
Climate metric	***P***	**Slope**	***P***	**Slope**	***P***	**Slope**	***P***	**Slope**	***P***	**Slope**	***P***	**Slope**
Mean temp	**<0.001**	0.052	**<0.001**	0.029	**<0.001**	0.028	**<0.001**	0.035	0.432	0.004	0.456	0.003
Mean min temp	**<0.001**	0.090	**<0.001**	0.047	**0.001**	0.021	**<0.001**	0.047	0.218	-0.008	**<0.001**	0.033
Mean max temp	**<0.001**	0.016	**0.007**	0.010	**<0.001**	0.036	**0.004**	0.019	**0.007**	0.017	**<0.001**	-0.026
Min temp in month	**<0.001**	0.100	**<0.001**	0.067	**0.003**	0.020	**<0.001**	0.048	0.395	0.000	**<0.001**	0.045
Max temp in month	0.592	0.000	0.784	0.000	**<0.001**	0.029	0.927	0.000	0.059	0.000	**<0.001**	-0.029
Total monthly precip	**0.047**	*0.000	**<0.001**	*0.000	0.093	0.000	0.821	0.000	0.486	0.000	0.528	0.000
Monsoonal precipitation	0.655	-0.001	**0.021**	-0.001	0.424	0.004	0.958	0.000	**0.039**	0.008	0.180	0.008

*Direction of slope could not be determined by the method used in this report (McBride 2000)

Table 3. Hyperlinks to station metadata and Mann-Whitney Test results expressed as probabilities for known station relocations at sites near Joshua Tree National Park. Significant results (*P*<0.05) are presented in bold.

Site	Metadata Link and Known Station Relocations	Avg. Temp.	Avg. Max.	Avg. Min.	Max. Temp.	Min. Temp.	Precip.
Palm Springs	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca6635						
	Jul. 1948 – moved south and raised 30 ft. in elevation	0.202	0.366	0.105	0.276	0.201	**0.022**
	Dec. 1948 – moved east w/ no change in elevation	0.323	0.210	0.416	0.227	0.553	0.232
	Feb. 1952 – moved west and raised 20 ft. in elevation	0.973	0.601	0.567	0.914	0.812	0.070
	Jul. 1974 – moved northeast and raised 10 ft. in elevation	0.992	0.996	0.897	0.747	0.657	**< 0.0001**
Indio Fire Station	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca4259						
	Jun. 1985 - moved west and lowered 30 ft. in elevation	0.783	0.663	0.361	0.194	0.127	**< 0.0001**
Iron Mountain	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca4297						
	Jul. 1948 – move southeast and lowered 20 ft. in elevation	0.651	0.824	0.537	0.833	0.350	**< 0.0001**
Twentynine Palms	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca9099						
	Nov. 1958 – moved east and lowered 10 ft. in elevation	0.389	0.767	0.116	0.449	0.109	**< 0.0001**
Hayfield Reservoir	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca3855						
	No known station moves.	-	-	-	-	-	-
Eagle Mountain	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca2598						
	No known station moves.	-	-	-	-	-	-

Great Basin National Park

Summary of Sites Analyzed

We analyzed data from two sites for Great Basin National Park; one was in the park and the Garrison site was east of the park in Utah (Table 4; Figure 6). Both sites were maintained by the NWS COOP. The elevation of the sites ranged from 1594-2070 m above sea level. The park hosts a wide variety of ecotypes, including sagebrush, pinyon-juniper, montane, and alpine communities, and is home to the long-lived Bristlecone pine (NPS 2016a). The Great Basin site is representative of lower elevation habitats within the park; no monitoring data were available for higher elevation habitats.

Table 4. Station names, periods of record, and elevations of monitoring sites in and adjacent to Great Basin National Park.

Station	In park?	Period of Record	Elev. (m)
Great Basin National Park	Yes	Oct 1937 to Oct 2015	2070
Garrison, UT	No	Jan 1903 to Aug 1917, May 1951 to Jul 1990	1594 - 1600

Weather and Climate

Weather conditions in the park are the coolest and wettest of the MOJN parks and climate varies considerably with elevation, which varies by ~8000 feet from the top of Wheeler Peak to the valley floor. In late spring and early summer, days in the valley may be hot, yet the snow pack may not have melted in the higher elevations. The Great Basin is a desert, with low relative humidity and sharp drops in temperature at night. In the summer, fierce afternoon thunderstorms are common. It can snow any time of the year at high elevations (NPS 2016a). Temperatures at the Great Basin monitoring site varied annually from near 100 °F to below freezing (Figure 7). Mean monthly precipitation at the Garrison and Great Basin sites for the period of record was ~0.6 and 1.1 inches per month, respectively (Figure 8). Mean annual monsoonal precipitation was 3.6 inches for the Great Basin site and 2.1 inches for the Garrison site (Figure 9).

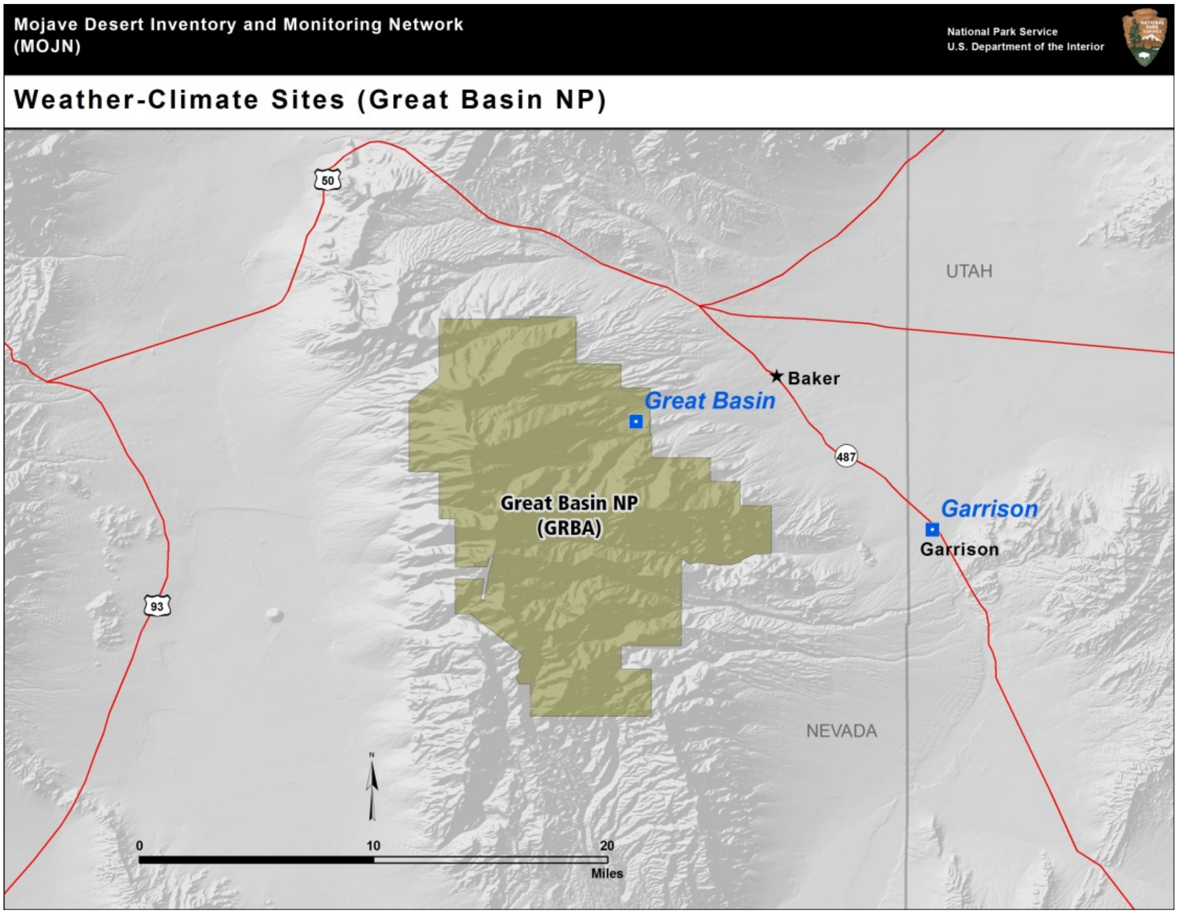

Figure 6. Map of the two climate monitoring sites in and near Great Basin National Park.

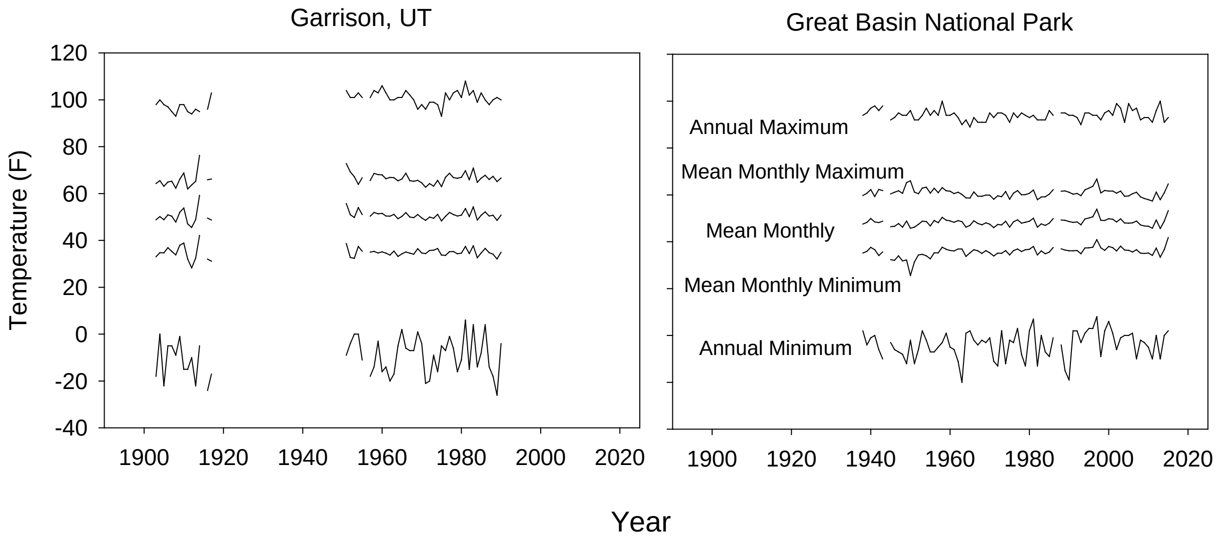

Figure 7. Annual minima and maxima, mean monthly minima and maxima, and mean monthly air temperatures recorded at Garrison and Great Basin National Park. Note: annual temperature metrics displayed here are for illustration purposes only. With the exception of the monsoon precipitation metric, all analyzed data were monthly values.

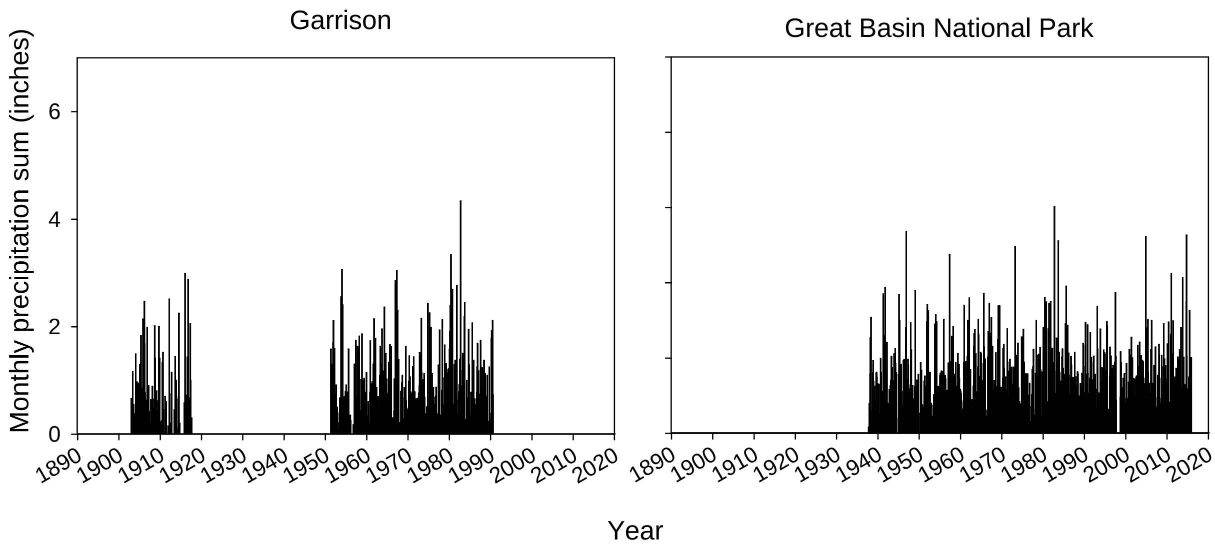

Figure 8. Total monthly precipitation recorded at Garrison and Great Basin National Park.

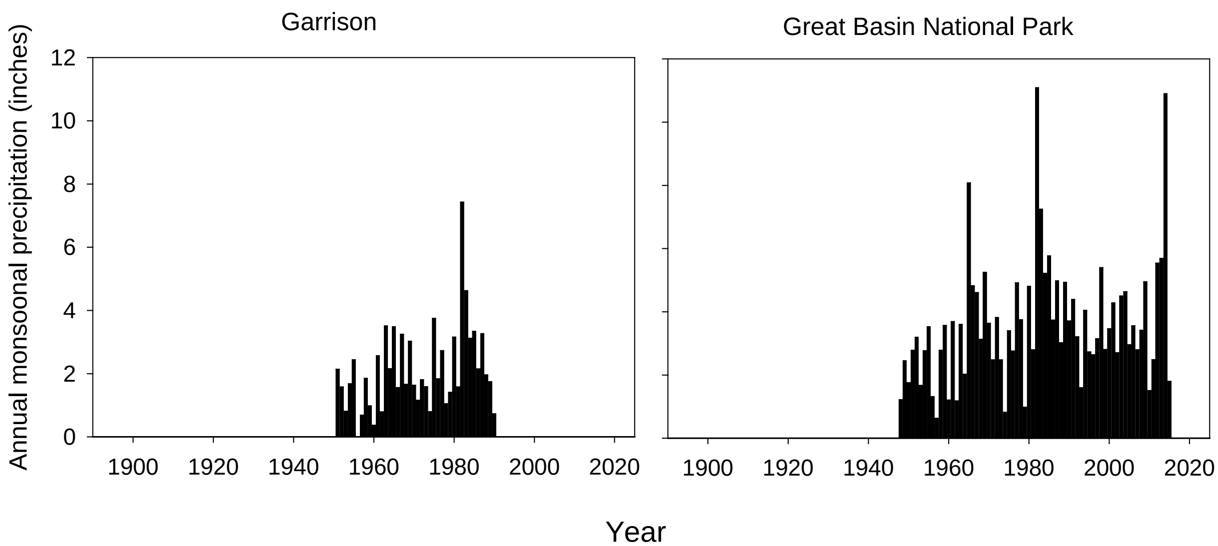

Figure 9. Annual monsoonal precipitation recorded at Garrison and Great Basin National Park. For some sites, monthly data were available but daily data were not, which precluded our generating estimates of annual monsoonal precipitation for some years.

Tests for trends

We found positive trends in all temperature metrics at the Garrison site whereas we found them in only the two minimum temperature metrics at Great Basin National Park (Table 5). We found positive trends in monthly precipitation at both sites and one trend in monsoonal precipitation at Great Basin. The relocations of the Garrison site in 1951 and 1989 did not affect Seasonal Mann-Kendall Test results for any climate metrics based on Mann-Whitney U Test results (Table 6).

Table 5. Probabilities and slope estimates from Seasonal Mann-Kendall tests for monotonic changes in climate metrics at COOP stations in and near Great Basin National Park. Bold font indicates significant results (*P*<0.05). Slope is reported in °F per year, total inches precipitation per year or total inches of monsoonal precipitation per year. See Appendix for samples sizes of all site × metric combinations..

	Great Basin		Garrison	
Climate metric	***P***	**Slope**	***P***	**Slope**
Mean temp	0.119	0.011	**0.003**	0.023
Mean min temp	**<0.001**	0.033	**0.027**	0.018
Mean max temp	0.083	-0.013	**0.005**	0.031
Min temp in month	**<0.001**	0.039	**0.002**	0.025
Max temp in month	0.918	0.000	**0.005**	0.026
Total monthly precip	**0.042**	0.002	**0.039**	0.001
Monsoonal precipitation	**0.014**	0.024	0.077	0.030

Table 6. Hyperlinks to station metadata and Mann-Whitney Test results expressed as probabilities for known station relocations at sites in and near Great Basin National Park.

Site	Metadata Link and Known Station Relocations	Avg. Temp.	Avg. Max.	Avg. Min.	Max. Temp.	Min. Temp.	Precip.
Garrison	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ut3138						
	Nov. 1951 – raised 10 ft. in elevation near same location	0.932	0.915	0.816	0.960	0.705	0.183
	Jul. 1989 – lowered 20 ft. in elevation near same location	0.923	0.833	0.975	0.855	0.809	0.776
Great Basin Nat'l Park	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nv3340						
	No known changes in location.	-	-	-	-	-	-

Death Valley National Park

Summary of Sites Analyzed

Two of the three sites used to evaluate climactic trends in/near Death Valley National Park were in the park and one was not (Table 7; Figure 10). The elevation of the sites ranged from 58 m below sea level to 1242 m above sea level. The park includes all of Death Valley, a 156-mile-long north/south-trending trough that formed between two major block-faulted mountain ranges: the Amargosa Range on the east and the Panamint Range on the west. Telescope Peak, the highest peak in the Park and in the Panamint Mountains, rises 11,049 feet above sea level and lies only 15 miles from the lowest point in the United States in the Badwater Basin, 282 feet below sea level (NPS 2016c).

Table 7. Station names, periods of record, and elevations of monitoring sites in and adjacent to Death Valley National Park.

Station	In park?	Period of Record	Elev. (m)
Trona	No	Jan 1920 to Oct 2015	512 - 515
Death Valley National Park	Yes	Jun 1911 to Oct 2015	-58 - -52
Wildrose Ranger Station	Yes	Jan 1969 to Jan 2000	1242

Weather and Climate

Death Valley is known as the hottest place on earth and the driest place in North America. The world record highest air temperature of 134°F was recorded at Furnace Creek on July 10, 1913. Summer temperatures often top 120°F in the shade with overnight lows dipping into the 90s°F (Figure 11). Average rainfall is less than 2 inches, a fraction of what most deserts receive (Figures 12 and 13). Occasional thunderstorms, especially in late summer, can cause flash floods. In contrast to the extremes of summertime, winter and spring are very pleasant. Winter daytime temperatures are mild in the low elevations, with cool nights that only occasionally reach freezing. Higher elevations are cooler than the low valley. Temperatures drop 3 to 5°F with every thousand vertical feet (approx. 300m). Sunny skies are the norm in Death Valley, but winter storms and summer monsoons can bring cloud cover and rain. Wind is common in the desert, especially in the spring. Dust storms can suddenly blow up with approaching cold fronts (NPS 2016b).

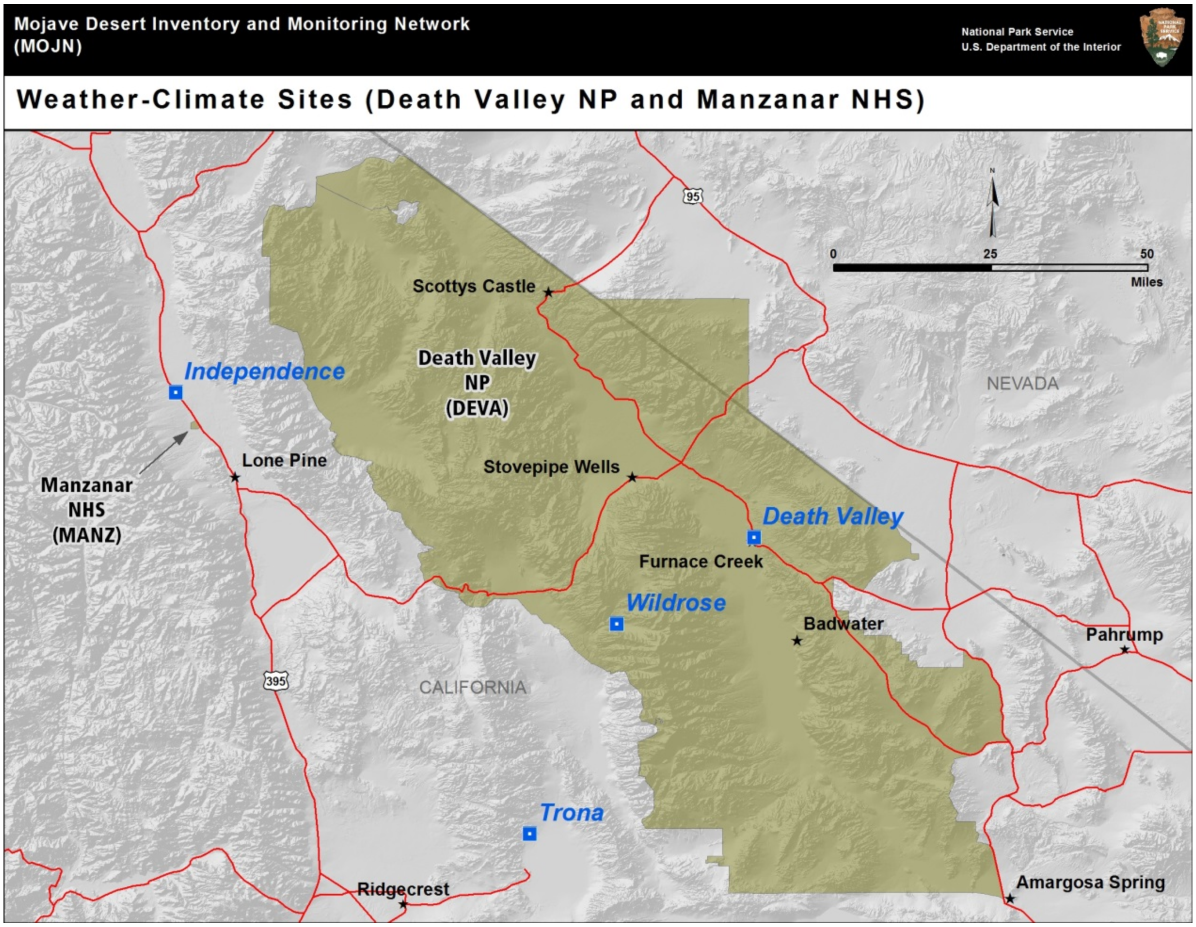

Figure 10. Map of the three climate monitoring sites in or near Death Valley National Park and the location of Independence climate monitoring site near Manzanar Historical Site.

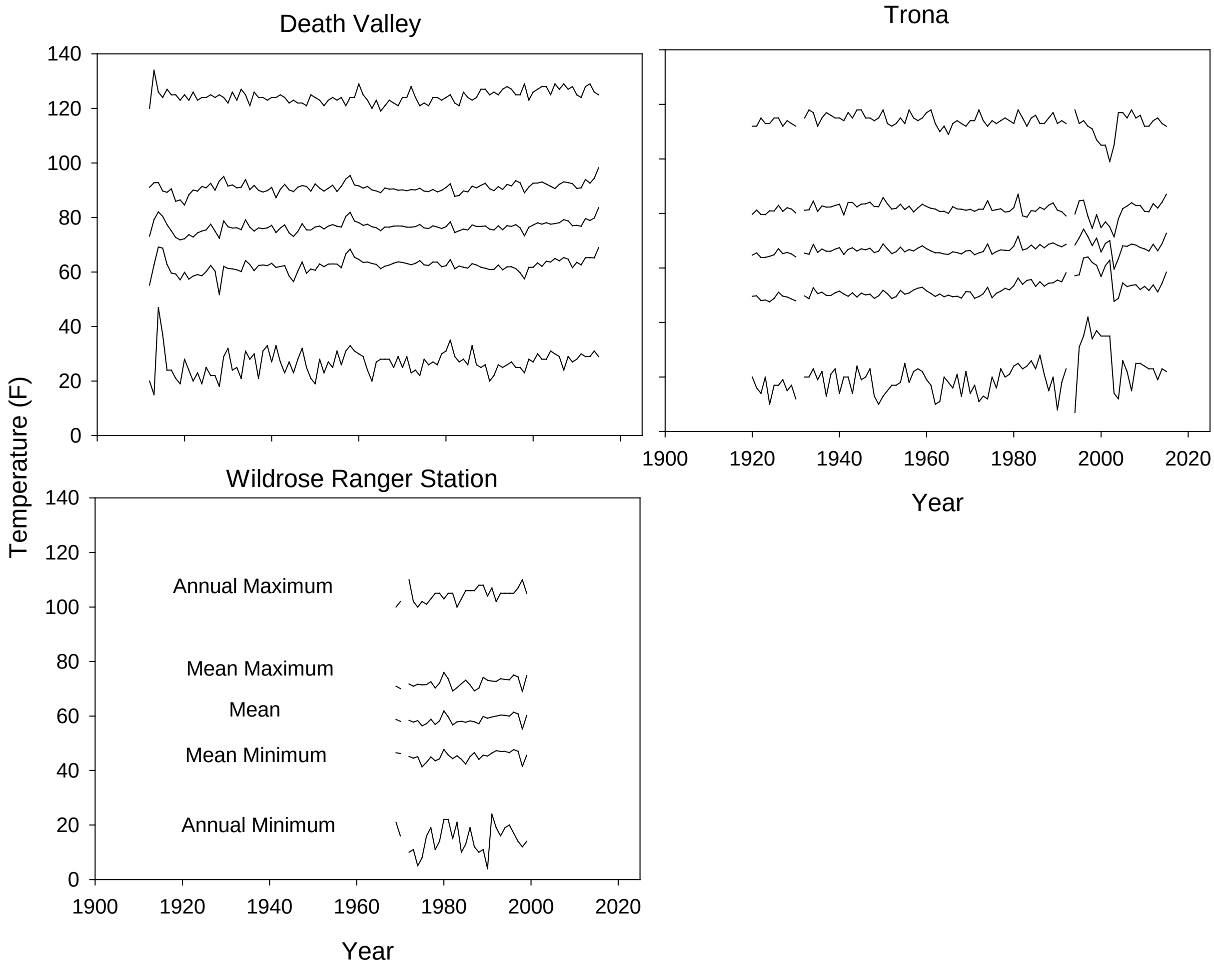

Figure 11. Annual minima and maxima, mean monthly minima and maxima, and mean monthly air temperatures recorded at sites associated with Death Valley National Park. Note: annual temperature metrics displayed here are for illustration purposes only. With the exception of the monsoon precipitation metric, all analyzed data were monthly values.

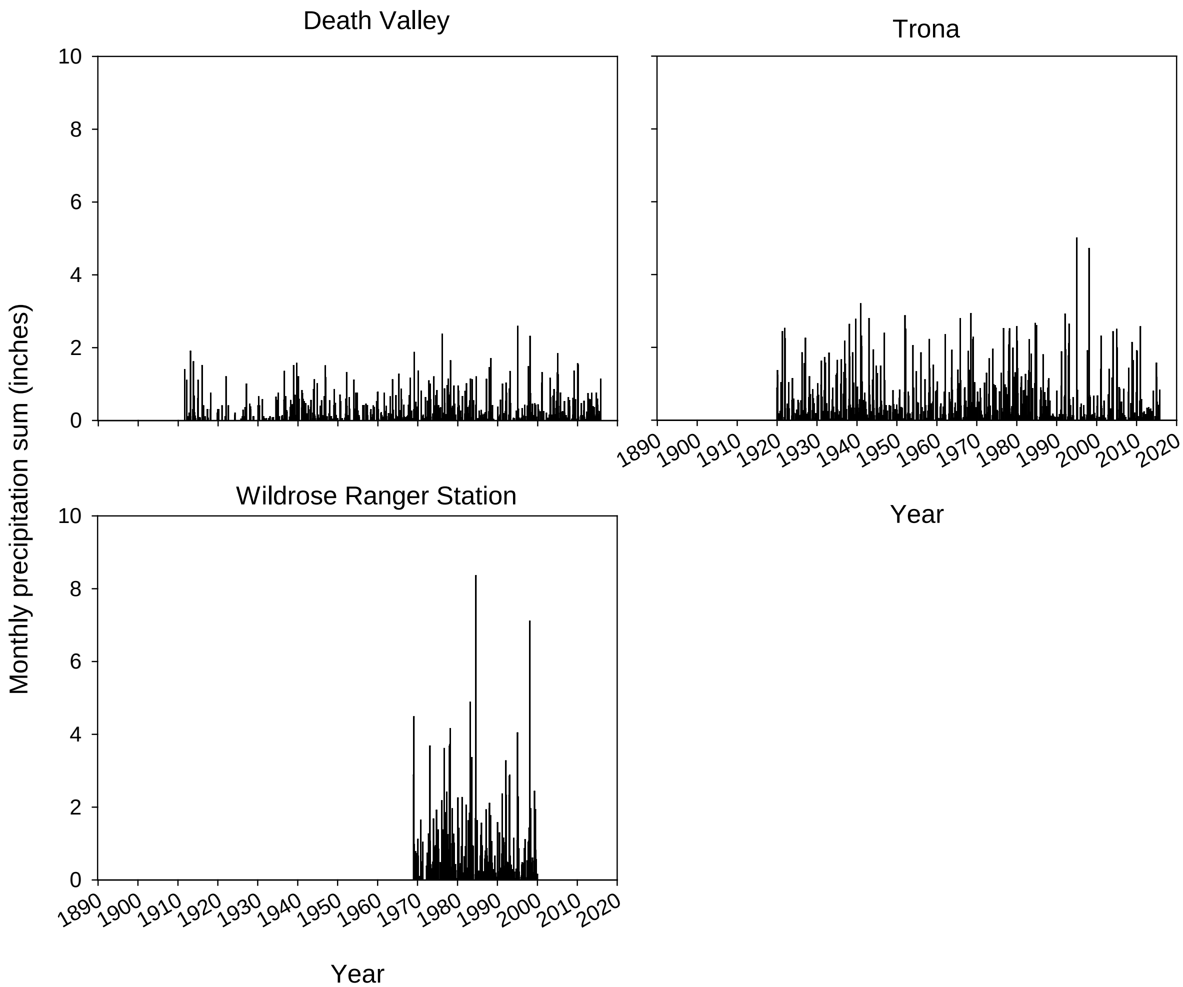

Figure 12. Total monthly precipitation recorded at sites associated with Death Valley National Park.

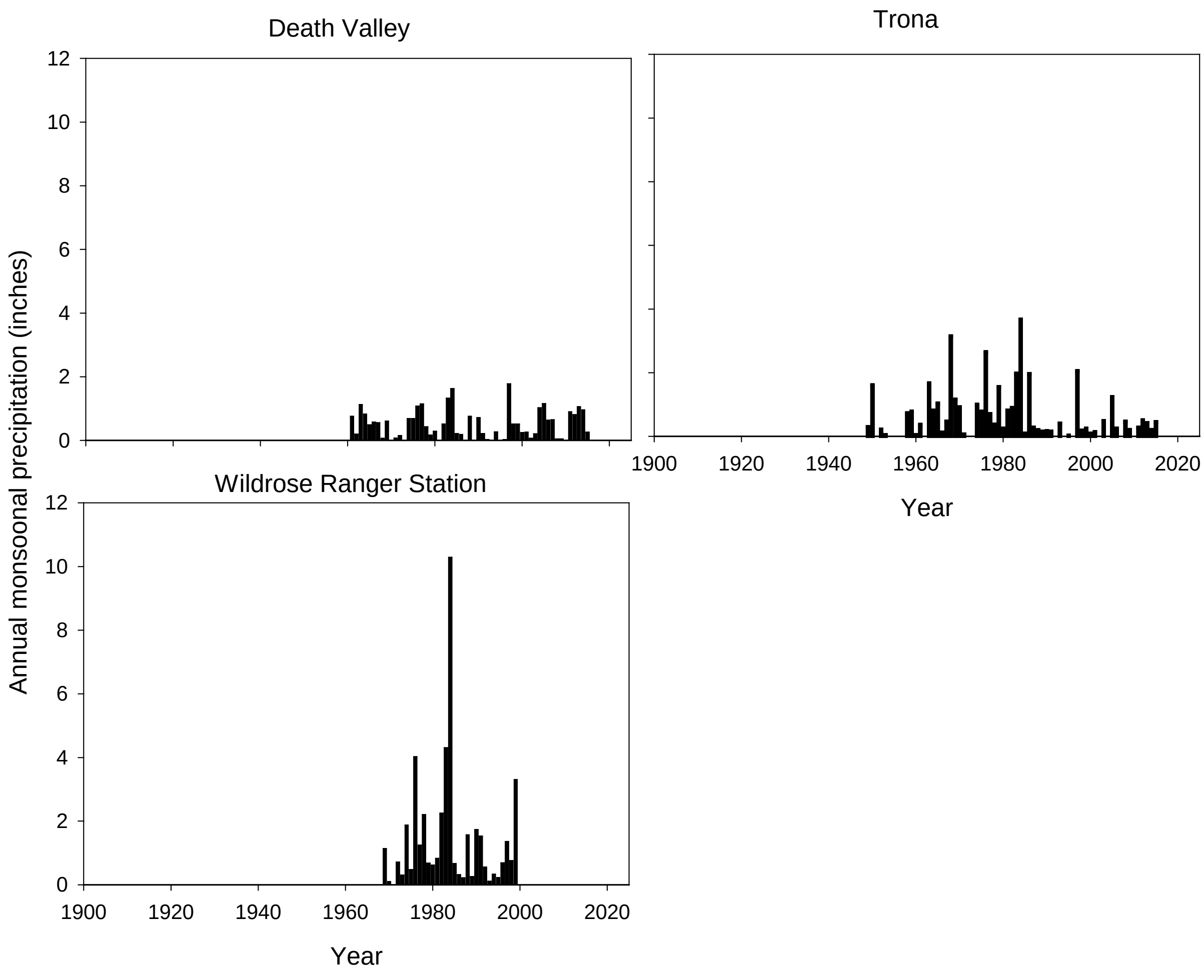

Figure 13. Annual monsoonal precipitation recorded at sites associated with Death Valley National Park. For some sites, monthly data were available but daily data were not, which precluded our generating estimates of annual monsoonal precipitation for some years.

Tests for trends

We found positive trends for at least three of the five temperature metrics from all three monitoring sites associated with Death Valley National Park (Table 8). We found trends in monthly precipitation values for the Trona and Death Valley sites but we could not determine their slope (see McBride 2000). We found no monsoonal precipitation trends for any of the three sites.

For all temperature metrics, we found no evidence that Seasonal Mann-Kendall Test results were affected by known station relocations (Table 9). We did find evidence that test results may have been affected for the monthly precipitation metric at two sites with known station relocations. Specifically, the significant Mann-Whitney results for the Trona and Death Valley precipitation data indicated that the significant trend may have been attributable, at least in part, to station relocations.

Table 8. Probabilities and slope estimates from Seasonal Mann-Kendall tests for monotonic changes in climate metrics at COOP stations in and near Death Valley National Park. Bold font indicates significant results (*P*<0.05). Slope is reported in °F per year, total inches precipitation per year or total inches of monsoonal precipitation per year. See Appendix for samples sizes of all site × metric combinations.

	Trona		Death Valley		Wildrose	
Climate metric	***P***	**Slope**	***P***	**Slope**	***P***	**Slope**
Mean temp	**<0.001**	0.034	**<0.001**	0.027	**0.005**	0.077
Mean min temp	**<0.001**	0.074	**<0.001**	0.034	**0.044**	0.058
Mean max temp	0.111	-0.011	**0.003**	0.015	**0.005**	0.090
Min temp in month	**<0.001**	0.091	**<0.001**	0.033	0.053	0.077
Max temp in month	0.077	0.000	**<0.001**	0.018	**0.001**	0.111
Total monthly precip	**0.012**	*0.000	**<0.001**	*0.000	0.888	0.000
Monsoonal precipitation	1.000	0.000	**NA	0.000	0.812	0.002

*Direction of slope could not be determined (McBride 2000).

**Unable to produce corrected p value – see Methods.

Table 9. Hyperlinks to station metadata and Mann-Whitney Test results expressed as probabilities for known station relocations at sites near Death Valley National Park. Significant results (*P*<0.05) are presented in bold.

Site	Metadata Link and Known Station Relocations	Avg. Temp.	Avg. Max.	Avg. Min.	Max. Temp.	Min. Temp.	Precip.
Death Valley	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca2319						
	Jan. 1982 – lowered 20 ft. in elevation near same location	0.655	0.855	0.341	0.595	0.450	**< 0.0001**
Trona	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca9035						
	Jan. 1959 – moved south w/ no elevation change	0.222	0.231	0.252	0.171	0.296	**< 0.0001**
	Oct. 1988 – lowered 10 ft. in elevation near same location	0.931	0.457	0.639	0.305	0.516	**< 0.0001**
Wildrose RS	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca9671						
	No known changes in location.	-	-	-	-	-	**-**

Manzanar National Historical Site

Summary of Site Analyzed

Independence, California, is located approximately six miles north of Manzanar National Historical Site. The weather station has ranged in elevation from 1185-1197 m above sea level (Table 10; Figure 10).

Table 10. Station name, period of record, and elevations of the monitoring site associated with Manzanar National Historical Site.

Station	In park?	Period of Record	Elev. (m)
Independence	No	Jan 1893 to Nov 1894, Dec 1916 to Dec 1917, Dec 1924 to Oct 2015	1185-1197

Weather and Climate

Manzanar is one of ten camps where more than 110,000 Japanese American were incarcerated during World War II. It is located in the Owens Valley at 4,000 feet elevation, at the eastern base of the Sierra Nevada. Summer temperatures can soar over 100 °F whereas winter highs are usually in the 40's (Figure 14). Nighttime temperatures year round are 30 to 40 degrees less than daytime highs and high winds are common in any season (NPS 2016d). There is relatively little precipitation (Figures 15 and 16) but there are four distinct seasons.

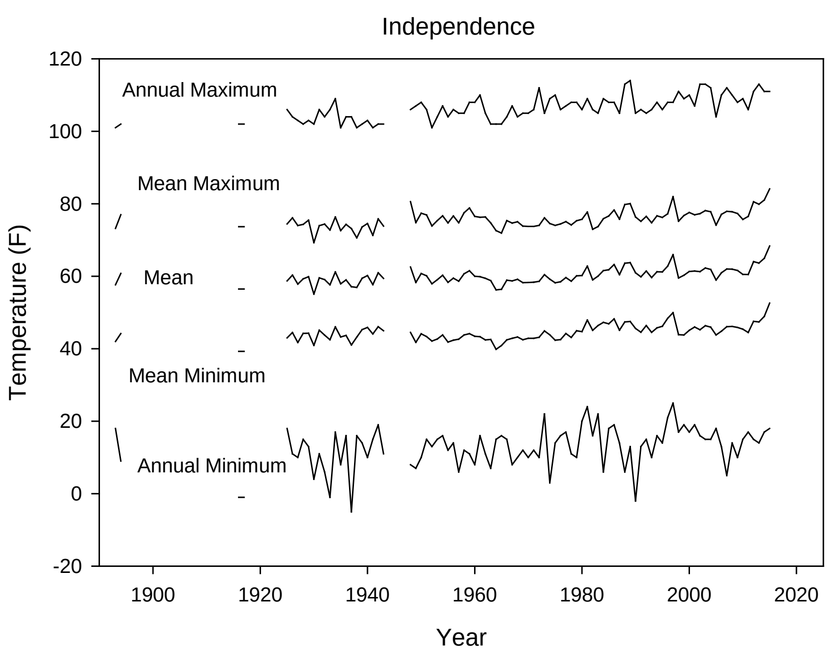

Figure 14. Annual minima and maxima, mean monthly minima and maxima, and mean monthly air temperatures recorded at the site associated with Manzanar National Historical Site. Note: annual temperature metrics displayed here are for illustration purposes only. With the exception of the monsoon precipitation metric, all analyzed data were monthly values.

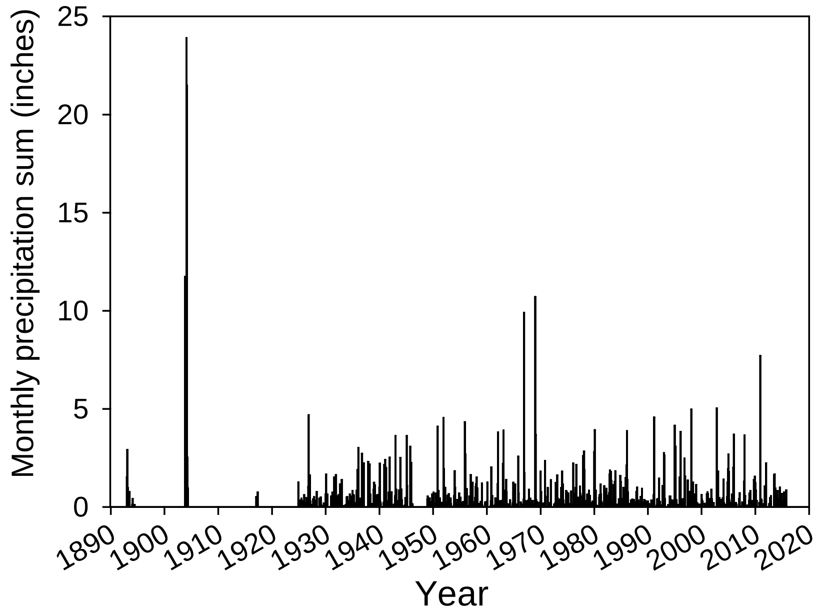

Figure 15. Total monthly precipitation recorded at Independence, the site associated with Manzanar National Historical Site.

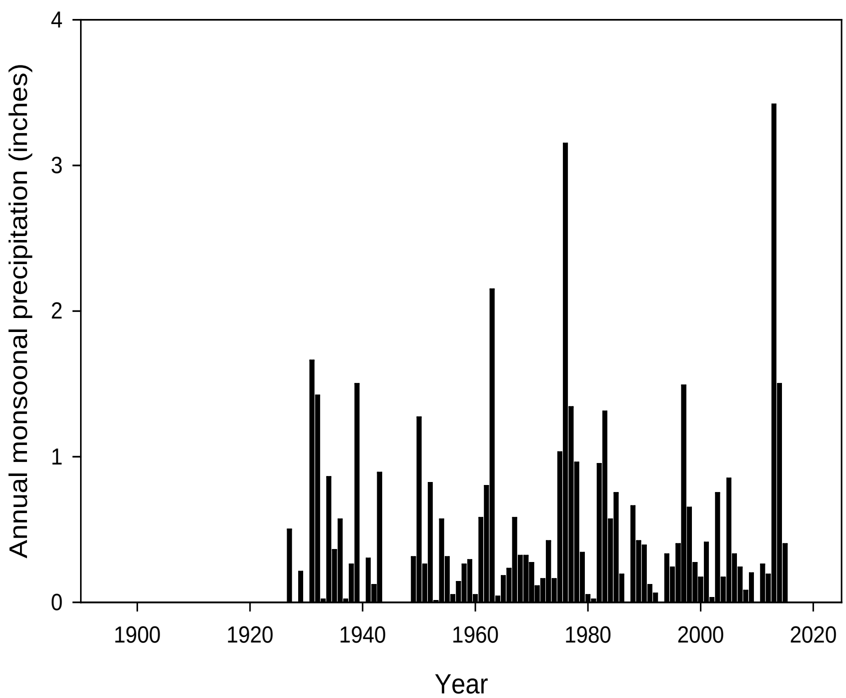

Figure 16. Annual monsoonal precipitation recorded at Independence, the site associated with Manzanar National Historical Site. For some sites, monthly data were available but daily data were not, which precluded our generating estimates of annual monsoonal precipitation for some years.

Tests for Trends

We found positive trends in all temperature metrics at Independence but in neither precipitation metric (Table 11). Theil-Sen slope estimates for the temperature metrics ranged from 0.040 to 0.061 ºF per month. Mann-Whitney results suggested that the station relocations at Independence in 1933 and 1982 may have reduced power to detect precipitation trends in the Seasonal Mann-Kendall Tests (Table 12).

Table 11. Probabilities and slope estimates from Seasonal Mann-Kendall tests for monotonic changes in climate metrics at a COOP station near Manzanar National Historic Site. Bold font indicates significant results (*P*<0.05). Slope is reported in °F per year, total inches precipitation per year or total inches of monsoonal precipitation per year. See Appendix for samples sizes for each metric.

	Independence	
Climate metric	***P***	**Slope**
Mean temp	**<0.001**	0.044
Mean min temp	**<0.001**	0.043
Mean max temp	**<0.001**	0.047
Min temp in month	**<0.001**	0.040
Max temp in month	**<0.001**	0.061
Total monthly precip	0.823	0.000
Monsoonal precipitation	0.354	0.001

Table 12. Hyperlinks to station metadata and Mann-Whitney Test results expressed as probabilities for known station relocations at sites near Manzanar National Historical Site. Significant results (*P*<0.05) are presented in bold.

Site	Metadata Link and Known Station Relocations	Avg. Temp.	Avg. Max.	Avg. Min.	Max. Temp.	Min. Temp.	Precip.
Independence	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca4232						
	Jan. 1933 – raised 30 ft. in elevation near same location	0.932	0.942	0.845	0.606	0.689	**< 0.0001**
	Jan. 1982 – raised 10 ft. in elevation near same location	0.771	0.993	0.461	0.983	0.652	**0.0002**

Lake Mead National Recreation Area

Summary of Sites Analyzed

Of the five sites used for our evaluations, Willow Beach was the only one located in Lake Mead National Recreation Area. The elevation of sites ranged from 230-1073 m above sea level (Table 13; Figure 17).

Table 13. Station name, periods of record, and elevations of monitoring sites associated with Lake Mead National Recreation Area.

Station	In park?	Period of Record	Elev. (m)
Valley of Fire State Park	No	Dec 1972 to Oct 2015	606
Overton	No	May 1939 to Jan1968, Feb 1992 to Oct 2015	370-391
Searchlight	No	Dec 1913 to Oct 2015	1073
Bullhead City	No	Nov 1977 to Oct 2015	164-176
Willow Beach	Yes	Oct 1967 to Sep 2007	230-242

Weather and Climate

Many visitors journey to Lake Mead to enjoy the 110º F plus air temperatures (Figure 18). The area generally has less than five inches of annual rainfall (Figures 19 and 20) and water temperatures may range from 45- 85° F during winter and summer, respectively (NPS 2016e).

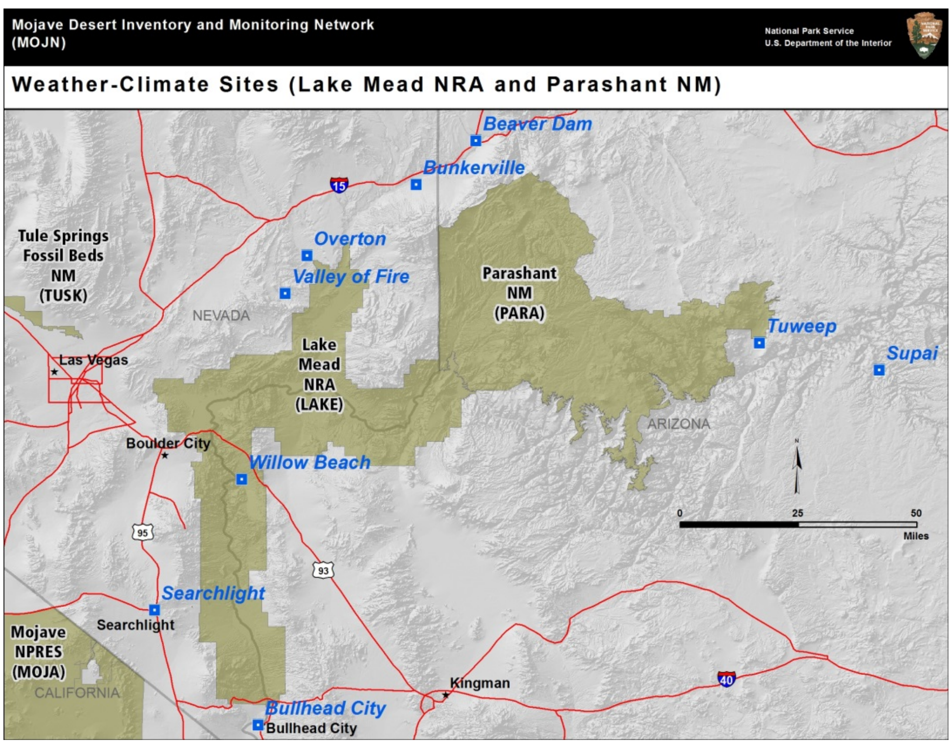

Figure 17. Map of the climate monitoring sites in and near Lake Mead National Recreation Area and the Grand Canyon-Parashant National Monument.

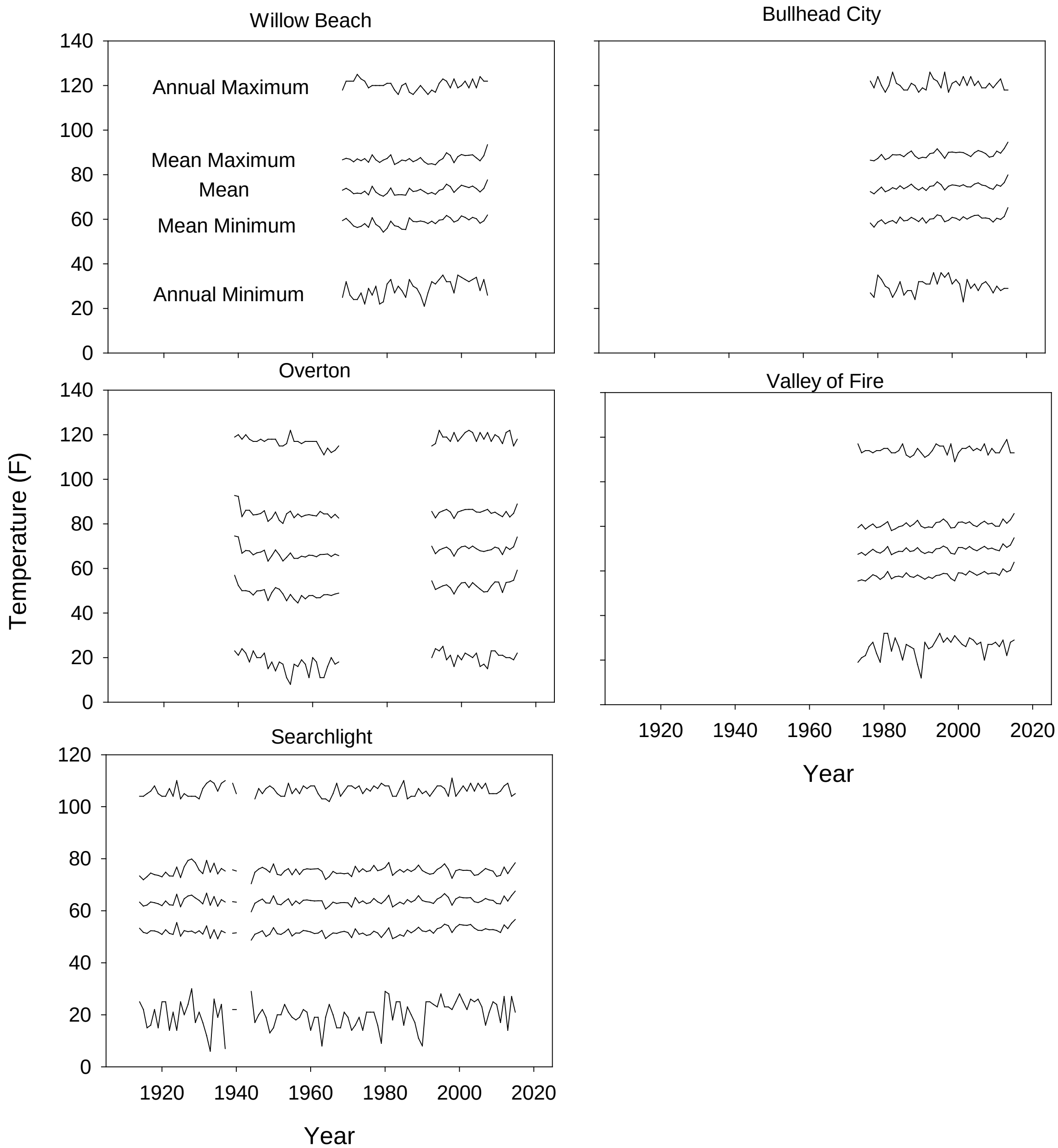

Figure 18. Annual minima and maxima, mean monthly minima and maxima, and mean monthly air temperatures recorded at sites associated with Lake Mead National Recreation Area. Note: annual temperature metrics displayed here are for illustration purposes only. With the exception of the monsoon precipitation metric, all analyzed data were monthly values.

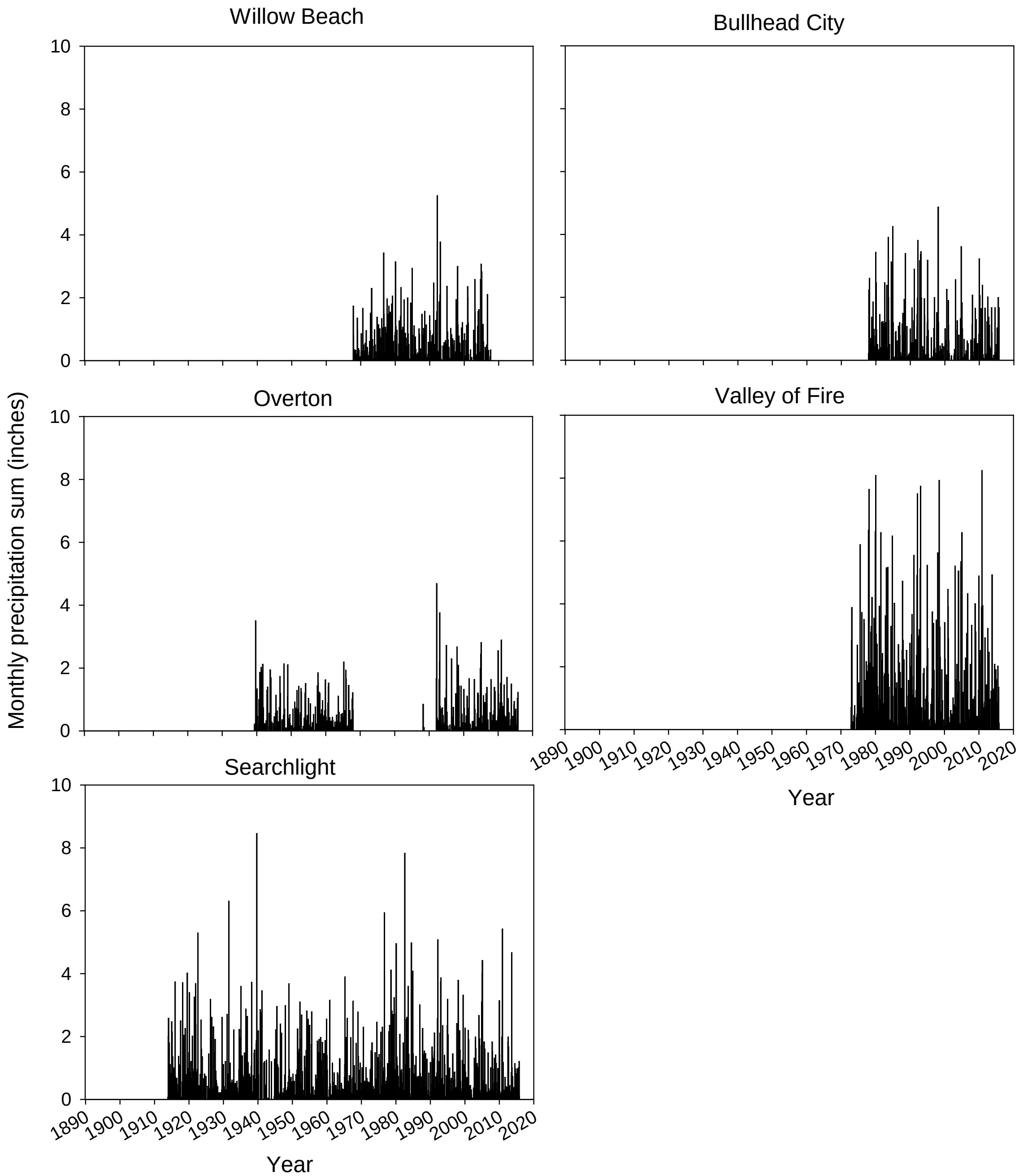

Figure 19. Total monthly precipitation recorded at sites associated with Lake Mead National Recreation Area.

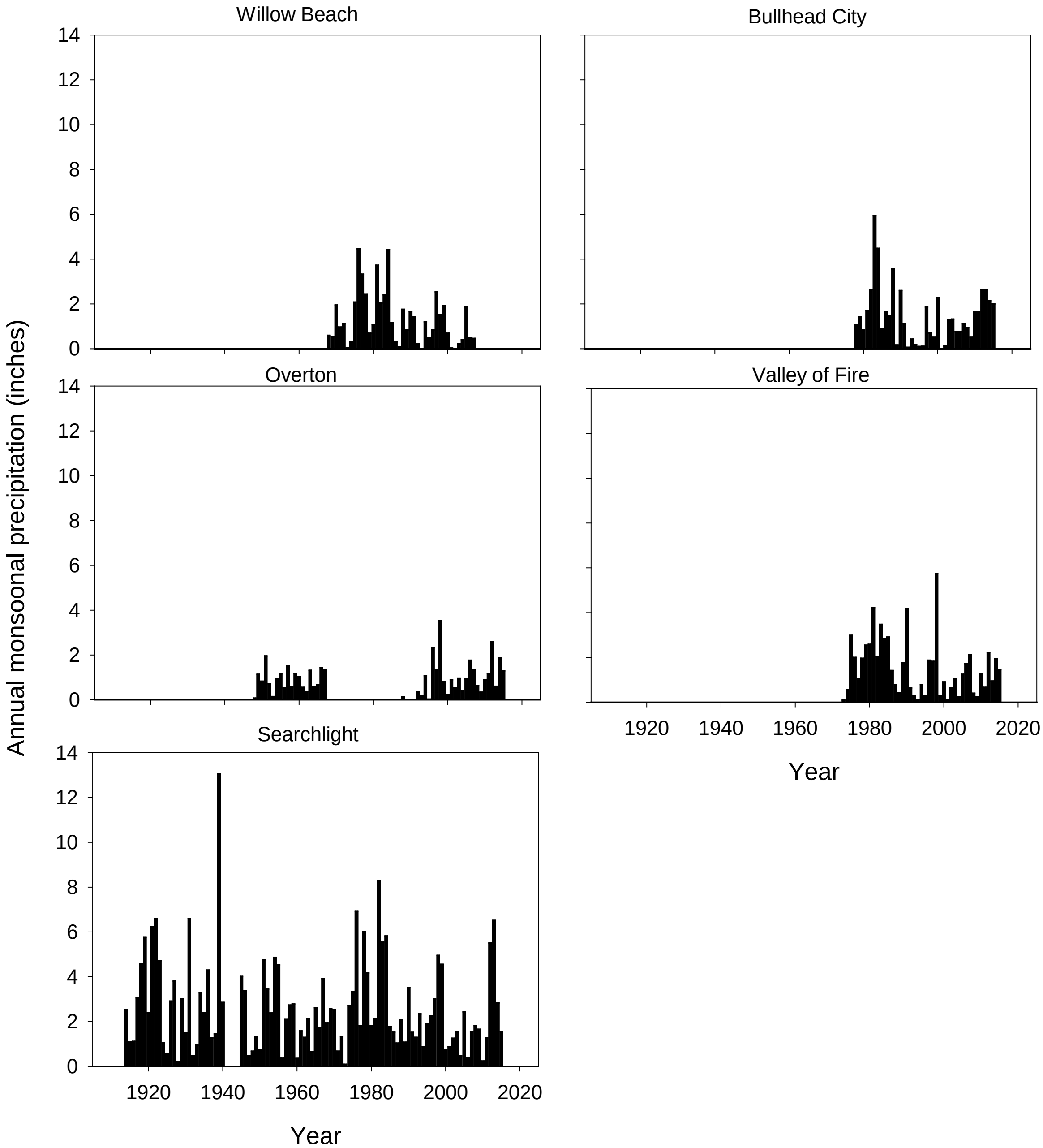

Figure 20. Annual monsoonal precipitation recorded at sites associated with Lake Mead National Recreation Area. For some sites, monthly data were available but daily data were not, which precluded our generating estimates of annual monsoonal precipitation for some years.

Tests for Trends

We found positive trends in at least three of the five temperature metrics for all five monitoring sites associated with the Lake Mead National Recreation Area (Table 14). All sites had positive trends in mean monthly temperature and the two minimum temperature metrics. Bullhead City was the only site that had a statistically significant trend in monthly precipitation but we could not determine the direction of the trend. We found no trends in monsoonal precipitation among all sites associated with the recreation area. For all temperature metrics, we found no evidence that Seasonal Mann-Kendall

Test results were affected by known station relocations (Table 15). Significant Mann-Whitney test results for the Overton and Willow Beach sites suggest that station relocations may have reduced statistical power to detect precipitation trends there.

Table 14. Probabilities and slope estimates from Seasonal Mann-Kendall tests for monotonic changes in climate metrics at COOP stations in and near Lake Mead National Recreation Area. Bold font indicates significant results (*P*<0.05). Slope is reported in °F per year, total inches precipitation per year or total inches of monsoonal precipitation per year. See Appendix for samples sizes of all site × metric combinations

	Valley of Fire State Park		Overton		Searchlight		Bullhead City		Willow Beach	
Climate metric	***P***	**Slope**	***P***	**Slope**	***P***	**Slope**	***P***	**Slope**	***P***	**Slope**
Mean temp	**<0.001**	0.073	**0.001**	0.032	**0.002**	0.012	**<0.001**	0.069	**0.001**	0.065
Mean min temp	**<0.001**	0.084	**<0.001**	0.054	**<0.001**	0.020	**0.001**	0.065	**0.001**	0.087
Mean max temp	**0.001**	0.052	0.346	0.007	0.339	0.004	**0.001**	0.068	**0.013**	0.050
Min temp in month	**<0.001**	0.100	**<0.001**	0.067	**0.001**	0.019	**0.001**	0.071	**<0.001**	0.125
Max temp in month	**0.017**	0.029	0.055	0.014	0.391	0.000	0.122	0.000	0.316	0.000
Total monthly precip	0.116	0.000	0.780	0.000	0.218	0.000	**0.001**	*0.000	0.244	0.000
Monsoonal precipitation	0.205	-0.019	0.280	0.005	0.453	-0.004	0.960	0.000	0.092	-0.024

*Direction of slope could not be determined (McBride 2000)

Table 15. Hyperlinks to station metadata and Mann-Whitney Test results expressed as probabilities for known station relocations at sites in and near Lake Mead National Recreation Area. Significant results ($P<0.05$) are presented in bold.

Site	Metadata Link and Known Station Relocations	Avg. Temp.	Avg. Max.	Avg. Min.	Max. Temp.	Min. Temp.	Precip.
Valley of Fire S.P.	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nv8588						
	No known changes in location.	-	-	-	-	-	-
Overton	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nv5846						
	Jul. 1952 – moved southeast & lowered 40 ft. in elevation.	0.535	0.223	0.895	0.367	0.769	0.893
	Sep. 1954 – moved north & lowered 20 ft. in elevation.	0.469	0.505	0.469	0.509	0.444	0.753
	Dec. 1961 – moved southeast w/ no change in elevation.	0.784	0.830	0.720	0.741	0.656	0.592
	Mar. 1988 – moved northwest and raised 70 ft. in elevation.	0.897	0.788	0.901	0.725	0.981	**0.007**
Searchlight	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nv7369						
	No known changes in location.	-	-	-	-	-	-
Bullhead City	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?az1050						
	Oct. 1986 – moved northeast & lowered 20 ft. in elevation.	0.690	0.759	0.639	0.979	0.547	0.245
Willow Beach	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?az9376						
	Mar. 1986 – lowered 40 ft. in elevation near same location.	0.883	0.767	0.473	0.708	0.563	**0.001**

Grand Canyon-Parashant National Monument

Summary of Sites Analyzed

We analyzed data from four sites near Grand Canyon-Parashant National Monument, one of which was in the park (Table 16; Figure 17). All sites were within 40 km of a park boundary. The elevation of the sites ranged from 461 - 973 m above sea level.

Table 16. Station names, periods of record, and elevations of monitoring sites associated with Grand Canyon-Parashant National Monument.

Station	In park?	Period of Record	Elev. (m)
Beaver Dam	No	Oct 1951 to Sep 1963, Sep 1966 to Oct 2015	558-588
Bunkerville	No	Dec 1979 to Jan 1993, Dec 1995 to Nov 2015	461-470
Tuweep	Yes	Jun 1941 to Nov 1985	1448
Supai	No	Sep 1899 to Sep 1901, Dec 1907 to Nov 1909, Mar 1911 to Jun 1934, Jul 1956 to Feb 1987	970-973

Weather and Climate

The Grand Canyon-Parashant National Monument is jointly managed by the Bureau of Land Management (BLM) and the NPS. Covering more than one million acres, it has deep canyons, mountains, and buttes that testify to the power of past geological forces. The monument is relatively under-formed and unobscured by vegetation, which offers a clear view for understanding the Colorado Plateau's geologic history. Geologic, geographic, and biological transitions give rise to the monument's astonishing ecological diversity. Two geologic provinces meet here, the Basin and Range and the Colorado Plateau, and two ecoregions also meet here, the Mojave Desert, where the Bunkerville COOP station is located, and Colorado Plateau, where the Beaver Dam, Tuweep, and Supai sites are located (BLM 2016).

The vast changes in elevation cause large gradients in temperature and precipitation. Many different microclimates are found throughout the canyon. In general, temperature increases 5.5°F with each 1,000 feet loss in elevation. The highest temperatures are found at the lowest elevations inside the canyon (Figure 21). Low relative humidity and generally clear skies mean that most of the sun's energy is available for daytime heating. These same conditions lead to rapid heat loss at night. Consequently, diurnal temperature fluctuations can be large. Winter precipitation usually falls as snow on the rims, but melts to rain before reaching the canyon floor (Figure 22). Late spring and early summer are the driest times of the year, with relative humidity often falling below 10% during the day. By mid-summer, strong ground-level heating creates updrafts of warm air, which climb tens of thousands of feet producing powerful thunderstorms whenever there is sufficient atmospheric moisture (NPS 2016f). Mean annual monsoonal precipitation ranged from 1.32 (Bunkerville) to 5.0 inches (Tuweep) among sites (Figure 23).

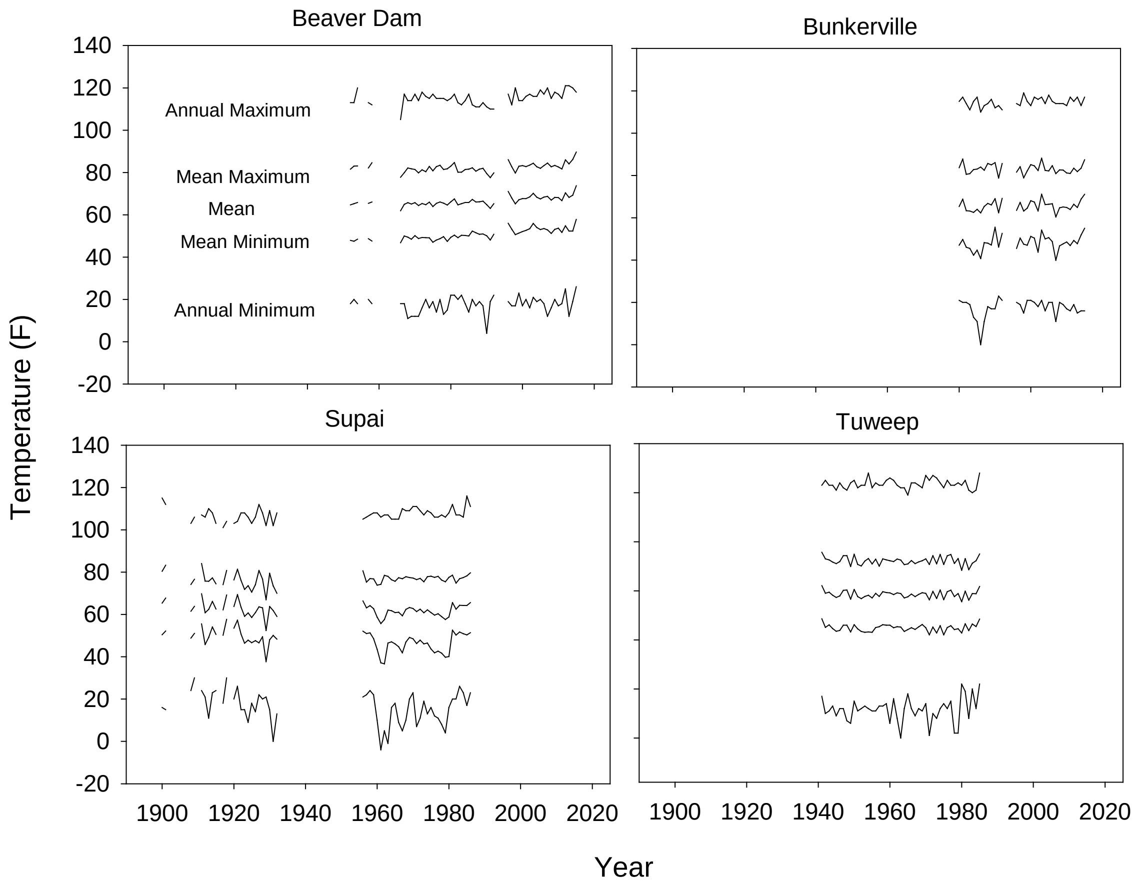

Figure 21. Annual minima and maxima, mean monthly minima and maxima, and mean monthly air temperatures recorded at sites associated with Grand Canyon-Parashant National Monument. Note: annual temperature metrics displayed here are for illustration purposes only. With the exception of the monsoon precipitation metric, all analyzed data were monthly values.

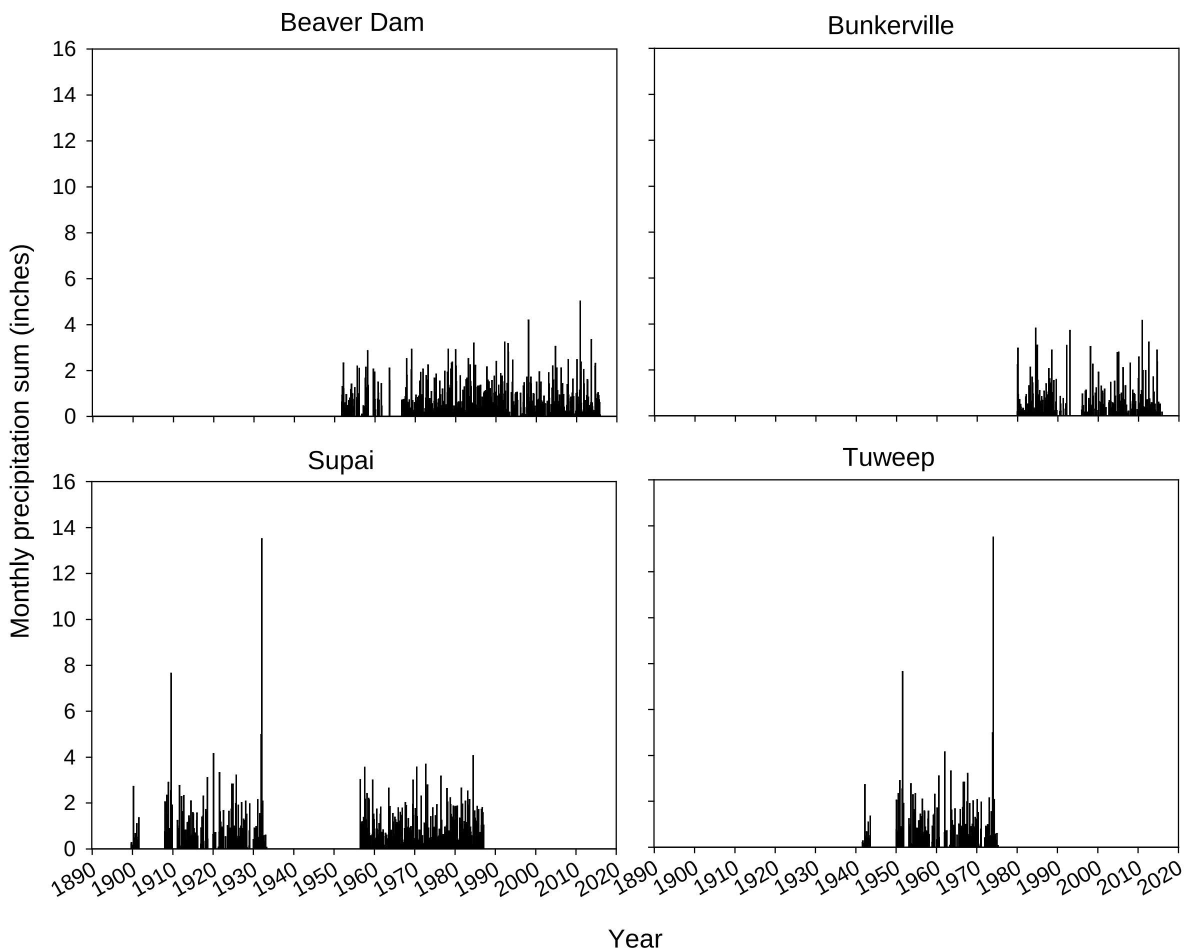

Figure 22. Total monthly precipitation recorded at sites associated with Grand Canyon-Parashant National Monument.

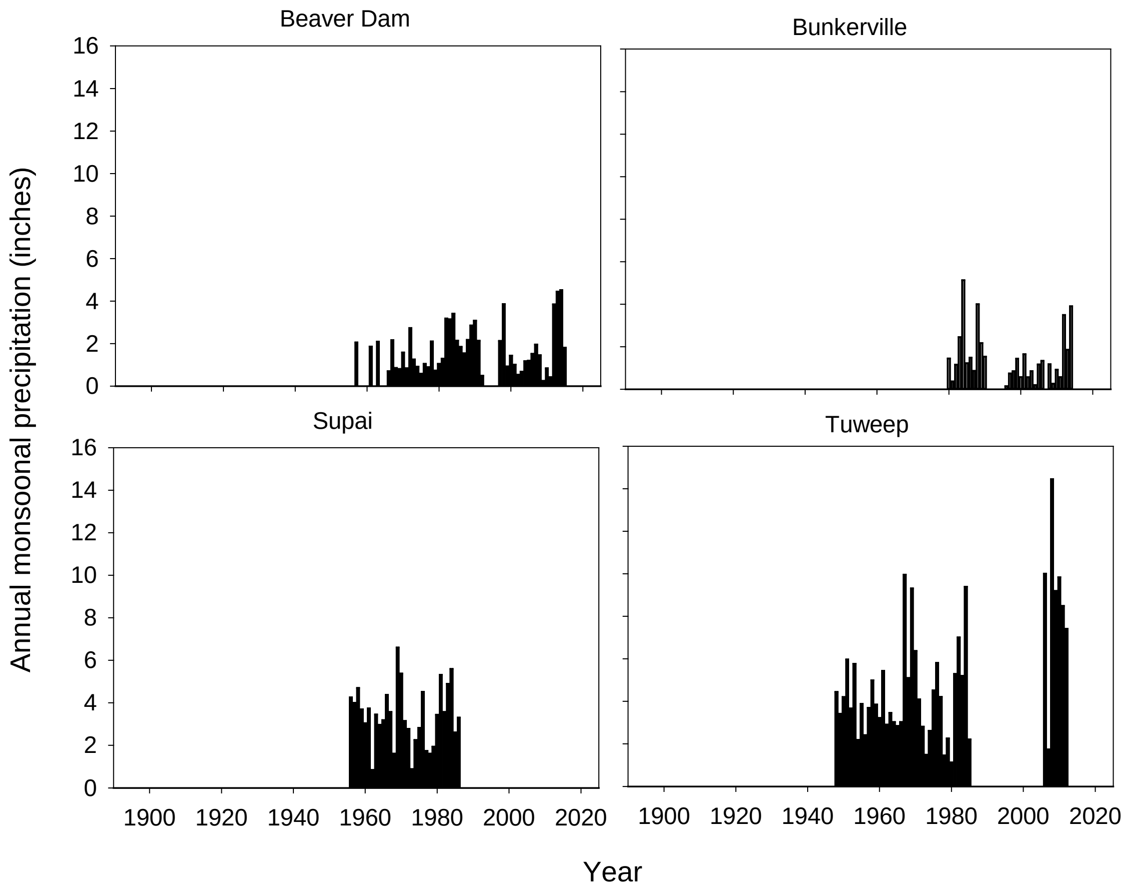

Figure 23. Annual monsoonal precipitation recorded at sites associated with Grand Canyon-Parashant National Monument. For some sites, monthly data were available but daily data were not, which precluded our generating estimates of annual monsoonal precipitation for some years.

Tests for Trends

The Beaver Dam site provided the most compelling evidence for increasing temperature trends among sites associated with the Grand Canyon-Parashant National Monument whereas the Tuweep site provided none, possibly because its record only extended to 1985 (Table 17). We found increasing thermal trends at the Bunkerville site, which had three significant, positive slopes among the five temperature metrics. Results for the Supai site were mixed in that the trends for the two maximum temperature metrics were positive and the two metrics minimum temperature metrics were negative. This suggested that while daytime temperatures were becoming warmer, nighttime temperatures were becoming cooler. The only trend in monthly precipitation data was at the Bunkerville site but we could not determine the slope. There were no trends in monsoonal precipitation at any site.

Relocations of the Supai site may have contributed to our finding mixed results there (Table 18). The significant Mann-Whitney results for all temperature metrics diminished support for the results being driven solely by climate. The station relocation may also have contributed to our failing to find any trends in the precipitation metrics.

Table 17. Probabilities and slope estimates from Seasonal Mann-Kendall tests for monotonic changes in climate metrics at COOP stations in and near Parashant National Monument. Bold font indicates significant results (*P*<0.05). Slope is reported in °F per year, total inches precipitation per year or total inches of monsoonal precipitation per year. See Appendix for samples sizes of all site × metric combinations.

	Beaver Dam		Bunkerville		Tuweep		Supai	
Climate metric	***P***	**Slope**	***P***	**Slope**	***P***	**Slope**	***P***	**Slope**
Mean temp	**<0.001**	0.074	**0.016**	0.052	0.733	-0.005	0.292	-0.012
Mean min temp	**<0.001**	0.109	**0.006**	0.101	0.800	0.004	**0.021**	-0.044
Mean max temp	**0.003**	0.039	0.979	0.000	0.260	-0.016	**0.036**	0.023
Min temp in month	**<0.001**	0.087	**0.001**	0.125	0.723	0.000	**0.001**	-0.067
Max temp in month	**0.001**	0.045	0.451	0.000	1.000	0.000	**0.029**	0.020
Total monthly precip	0.988	0.000	**0.011**	*0.000	0.063	0.004	0.484	0.000
Monsoonal precipitation	0.264	0.011	0.588	-0.008	0.159	0.051	0.610	-0.014

*Direction of slope could not be determined (McBride 2000)

Table 18. Hyperlinks to station metadata and Mann-Whitney Test results expressed as probabilities for known station relocations at sites near Grand Canyon-Parashant National Monument. Significant results (P<0.05) are presented in bold.

Site	Metadata Link and Known Station Relocations	Avg. Temp.	Avg. Max.	Avg. Min.	Max. Temp.	Min. Temp.	Precip.
Beaver Dam	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?az0672						
	Jul. 1961 – lowered 100 ft. in elevation near same location.	0.127	0.225	0.056	0.307	0.078	0.188
	Aug. 1966 – raised 10 ft. in elevation near same location.	0.227	0.220	0.228	0.324	0.176	0.800
	Feb. 1977 – raised 10 ft. in elevation near same location.						
Bunkerville	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nv1327						
	Mar. 1983 – moved northeast & raised 30 ft. in elevation.	0.895	0.989	0.860	0.967	0.640	0.960
Tuweep	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?az8895						
	No known changes in location.	-	-	-	-	-	-
Supai	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?az8343						
	Jan. 1982 – lowered 10 ft. in elevation near same location.	**0.038**	0.518	**0.001**	0.428	**0.001**	**0.136**
	Oct. 1986 – raised 10 ft. in elevation near same location.	**0.037**	**0.023**	0.060	**0.037**	0.068	0.917
	May 1987 – lowered 10 ft. in elevation near same location.	Too few data to analyze					

Mojave National Preserve

Summary of Sites Analyzed

We analyzed data from two sites associated with Mojave National Preserve. One was in the Preserve (i.e., Mitchell Caverns) and the Baker site was not. The elevation of sites ranged from 285-1318 m above sea level (Table 19; Figure 24).

Table 19. Station names, periods of record, and elevations of monitoring sites associated with Mojave National Preserve.

Station	In park?	Period of Record	Elev. (m)
Baker	No	Jan 1972 to May 1990 Sep 1996 to Aug 2013	285
Mitchell Caverns	Yes	Mar 1958 to Apr 2011	1306-1318

Weather and Climate

Temperatures vary greatly by elevation within the Preserve and temperatures over 100 ºF can begin as early as May (Figure 25). Annual precipitation ranges from 3.5 inches at lower elevations to nearly 10 inches in the mountains (Figure 26). Most rain falls between November and April, with occasional snow accumulations in the mountains. Summer thunderstorms may bring sudden, heavy rainfall and the driest months are May and June. Mean annual monsoonal precipitation averages 0.9 inches at Baker and 2.9 inches at Mitchell Caverns (Figure 27). Winds are a prominent feature of Mojave Desert weather and strong winds typically occur in the fall, late winter, and early spring months (NPS 2016g).

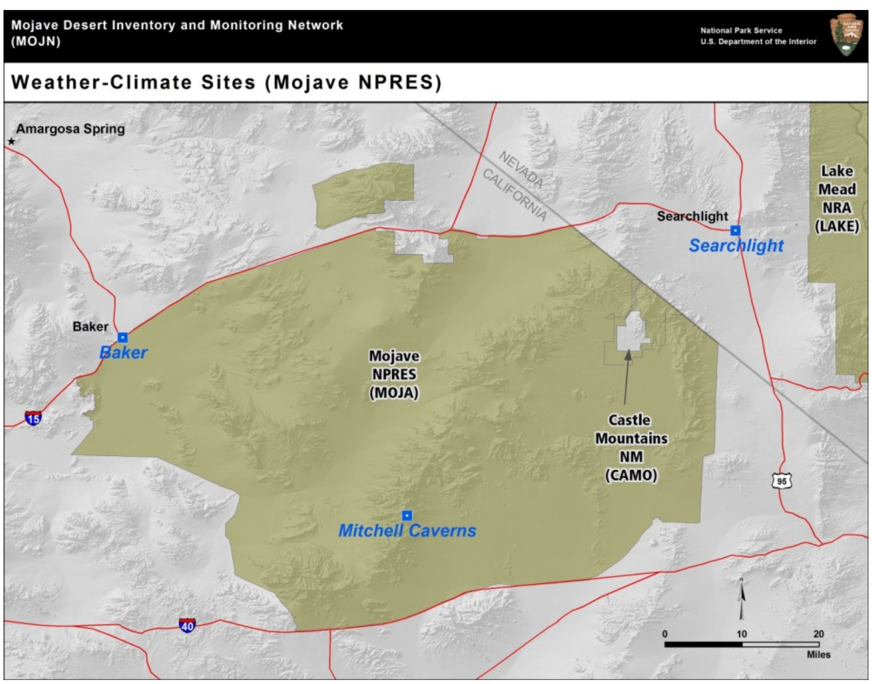

Figure 24. Map of the two climate monitoring sites in or near the Mojave National Preserve. The climate monitoring site at Searchlight is discussed in the Lake Mead section.

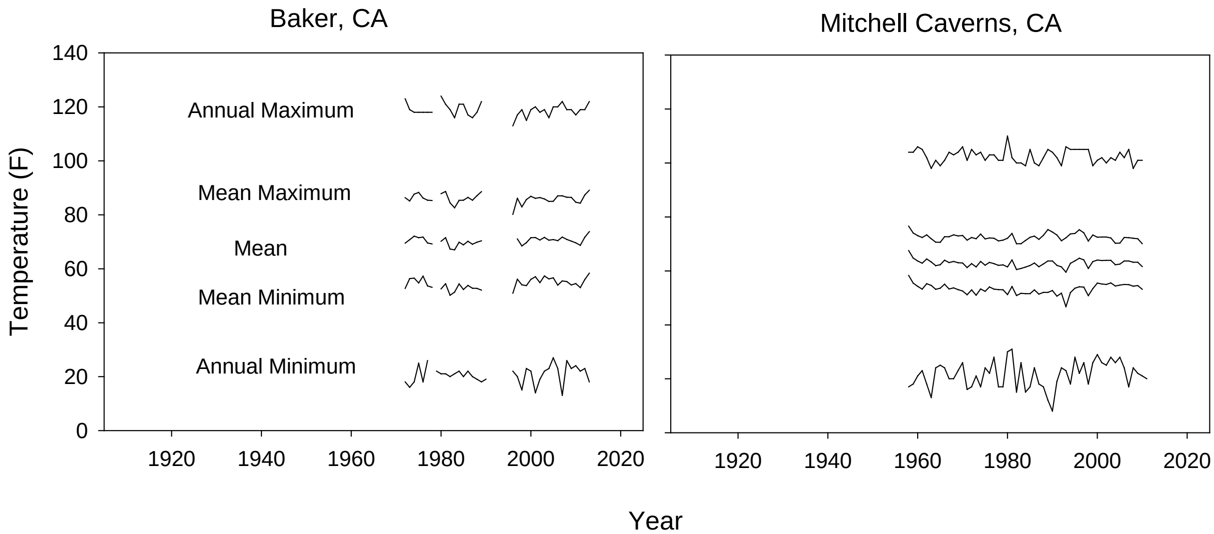

Figure 25. Annual minima and maxima, mean monthly minima and maxima, and mean monthly air temperatures recorded at sites associated with Mojave National Preserve. Note: annual temperature metrics displayed here are for illustration purposes only. With the exception of the monsoon precipitation metric, all analyzed data were monthly values.

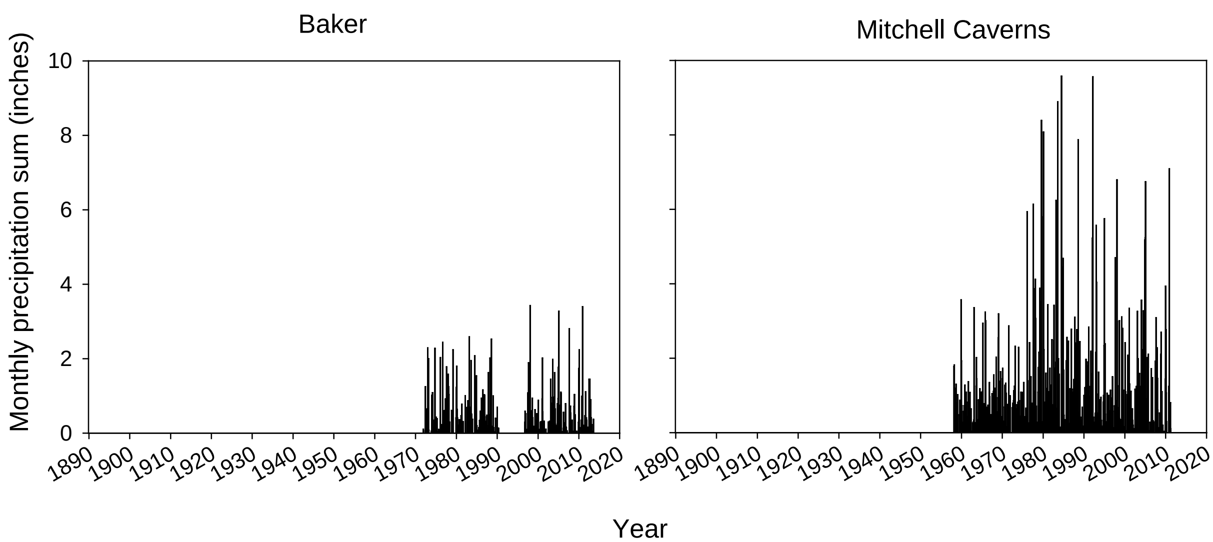

Figure 26. Total monthly precipitation recorded at sites associated with Mojave National Preserve.

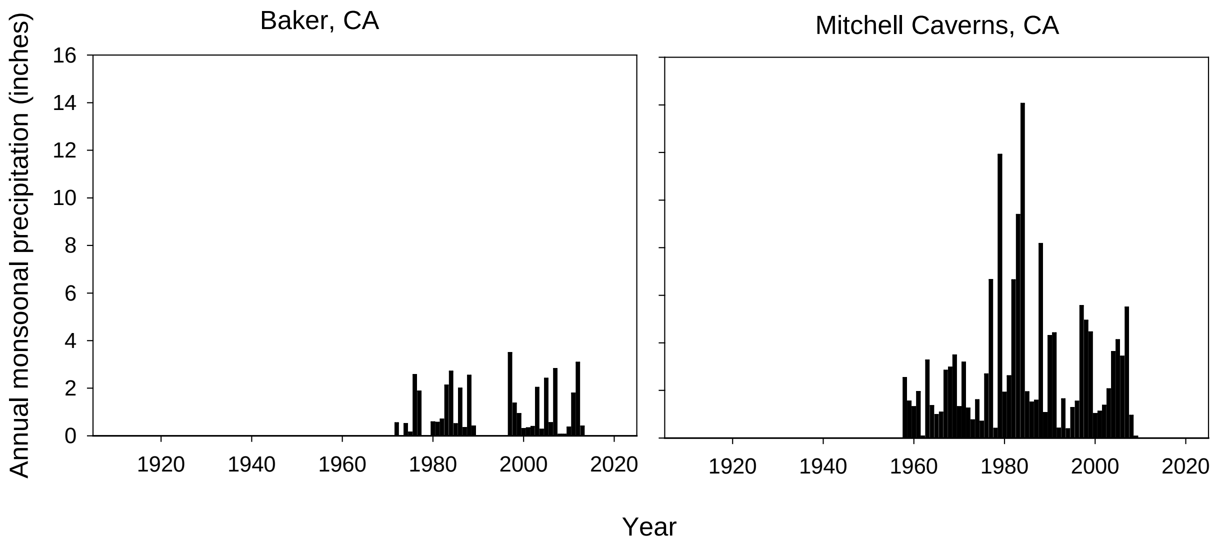

Figure 27. Annual monsoonal precipitation recorded at sites associated with Mojave National Preserve. For some sites, monthly data were available but daily data were not, which precluded our generating estimates of annual monsoonal precipitation for some years.

Tests for Trends

We found no trend in any climate metric at either of the two monitoring sites associated with Mojave National Preserve (Table 20). Results from the changepoint analysis suggested that the known station relocations at Mitchell Caverns had no effect on the Seasonal Mann-Kendall Test results (Table 21).

Table 20. Probabilities and slope estimates from Seasonal Mann-Kendall tests for monotonic changes in climate metrics at COOP stations in and near Mojave National Preserve. Bold font indicates significant results (*P*<0.05). Slope is reported in °F per year, total inches precipitation per year or total inches of monsoonal precipitation per year. See Appendix for samples sizes of all site × metric combinations

	Baker		**Mitchell Caverns**	
Climate metric	***P***	**Slope**	***P***	**Slope**
Mean temp	0.545	0.010	0.786	-0.003
Mean min temp	0.145	0.035	0.667	0.006
Mean max temp	0.445	-0.014	0.374	-0.010
Min temp in month	0.229	0.000	0.229	0.000
Max temp in month	0.773	0.000	0.278	0.000
Total monthly precip	0.770	0.000	0.969	0.000
Monsoonal precipitation	0.573	0.003	0.914	0.002

Table 21. Hyperlinks to station metadata and Mann-Whitney Test results expressed as probabilities for known station relocations at sites near Mojave National Preserve. Significant results (P<0.05) are presented in bold.

Site	Metadata Link and Known Station Relocations	Avg. Temp.	Avg. Max.	Avg. Min.	Max. Temp.	Min. Temp.	Precip.
Baker	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca0436						
	No known changes in location.	-	-	-	-	-	**-**
Mitchell Caverns	http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca5721						
	Dec. 1966 - raised 20 ft. in elevation near same location.	0.975	0.789	0.807	0.713	0.827	0.188
	Feb. 1977 – raised 20 ft. in elevation near same location.	0.833	0.940	0.604	0.823	0.814	0.815

Results of the Sensitivity Analysis

The sensitivity analysis was intended to evaluate how robust the SKT analysis of climate records was to missing data. The trend tests were repeated using four different cutoffs for the maximum number of days of missing data permitted before a month was excluded from the analysis (Appendix A). Of the 136 site × metric combinations (Table 22), we found five cases (<4%) in which using different cutoffs changed the *p* values from significant to insignificant or vice versa. We therefore find that the results from the Seasonal Mann-Kendall Tests were robust to the inclusion of monthly values with varying number of days missing from them.

Table 22. Summary of sensitivity analysis associated with results from Seasonal Mann-Kendall Tests that serially excluded mean monthly values from test iterations with varying numbers of days missing. Negative signs denote site × metric combinations that had either all significant ($P<0.05$) or non-significant results among treatments. Positive signs denote combinations that had both significant and non-significant results among treatments.

Park Unit	Site	Mean monthly temp.	Mean monthly min. temp.	Mean monthly max. temp.	Monthly min. temp.	Monthly max. temp.	Monthly precip.
Death Valley	Trona	-	-	-	-	-	-
	Death Valley	-	-	-	-	-	-
	Wildrose RS	-	-	-	-	-	-
Great Basin	Great Basin NP	-	-	-	-	-	-
	Garrison	-	+	-	-	-	-
Joshua Tree	Palm Springs	-	-	-	-	-	+
	Indio Fire Station	-	-	-	-	-	-
	Iron Mtn	-	-	-	-	-	-
	Twentynine Palms	-	-	-	-	-	-
	Hayfield Reservoir	-	-	-	-	-	-
	Eagle Mtn	-	-	-	-	-	-
Lake Mead	Valley of Fire SP	-	-	-	-	-	-
	Overton	-	-	-	-	-	-
	Searchlight	-	-	-	-	-	-
	Bullhead City	-	-	-	-	-	-
	Willow Beach	-	-	-	-	-	-
Manzanar	Independence	-	-	-	-	-	-
Mojave	Baker	-	-	-	-	-	-
	Mitchell Caverns	-	-	-	-	-	-
Parashant	Beaver Dam	-	-	-	-	-	-
	Bunkerville	+	-	-	+	-	-
	Tuweep	-	-	-	-	-	+
	Supai	-	-	-	-	-	-

Discussion

Our findings from meteorological sites in and near MOJN parks were consistent with regional observations of climate warming in the southwestern U.S. (Steenburgh et al. 2013). Broadly, we found the strongest evidence of warming in minimum temperatures (significant, increasing trends in mean monthly minimum temperature = 78% of the 23 sites across all parks; minimum monthly temperature = 74% of sites), followed by average temperatures (mean monthly temperature = 70% of sites). Evidence of increases in maximum temperatures was less consistent across park units (mean monthly maximum temperature = 61%; maximum monthly temperature = 35% of sites). Comparisons among parks showed clear evidence of warming in nearly all site × metric combinations at Manzanar, Joshua Tree, and Death Valley, whereas Lake Mead, Grand Canyon-Parashant, and Great Basin stations had greater evidence of increased minimum temperatures than average or maximum temperatures. Interestingly, we found no warming trends in the Mojave National Preserve, the most centrally-located site among the park units we evaluated, although that result may be due to the fact that only two climate records were tested. On balance, however, our results were in line with those of Monahan and Fisichelli (2014), who found that parks are at the warm end of their historic temperature distributions for several metrics.

Changing climate has multiple potential effects on park ecosystems through both physical and biological processes. Increased warming has been associated with changes in species distributions, phenology (season timing of life history events such as blooming), mortality rates and persistence of native plants due to direct effects of temperature (reviewed in Fleischman et al. 2013). Increased warming can also reduce snowpack and stream flows (Barnett et al. 2008; Hildago et al. 2009) and increase demand for water diversions (Tanaka et al. 2006). Drought and increased temperatures associated with climate change have caused many tree deaths across the Southwest (Breshears et al. 2005) and winter warming has also increased some insect outbreaks by allowing animals that might die in cold weather, to survive and reproduce (Raffa et al. 2008). These phenomena can contribute to increasing the intensity and frequency of wildfires (Hurteau et al. 2008). Populations of plants and animals can persist in changing conditions by altering behavior, movement within or across generations, or through genetic adaptation. However, the ability of species to adapt to changing conditions varies widely (Chen et al. 2011) and rapid change is almost certain to have impacts at the ecosystem level, with the potential for wholesale shifts in ecosystem state (Barnosky et al. 2012). Notably, variability in climate may be changing and can have important ecological effects on biota The quantification of variability through time and effects on biota are potentially valuable future avenues of research.

The impact of changing climate on individual parks will likely vary due to differences in the climate, biota, geography (i.e., size and elevation gradient present), and the landscape position of parks (i.e., potential for movement of biota in response to changing climate). For example, subalpine communities in the Great Basin National Park will have limited ability to adapt by vertical migration up elevation gradients because the community occupies the upper elevation limits.

Most of Arizona, western New Mexico, and portions of extreme southeast California, southern Nevada, southern Utah, and southwest Colorado observe a pronounced peak in precipitation in late summer due to the influence of the monsoon (Steenburgh et al. 2013). Since monsoon precipitation is produced primarily by thunderstorms covering less than 3% of the surface area at any one time (Barry and Chorley 2010), weather stations may record zero precipitation during major storms occurring a short distance away, making the records of monsoon precipitation inherently noisy. Among all sites, the Indio Fire Station and Hayfield Reservoir sites, both associated with Joshua Tree National Park, were the only ones showing increasing trends in monsoonal precipitation. Evidence of trends in monthly precipitation data was also scant in our evaluations. Two sites at Death Valley National Park and two at Joshua Tree National Park showed positive trends in monthly precipitation but for most park units, few or no trends were present. This is generally consistent with Monahan and Fisichelli (2014), who found precipitation patterns to be geographically heterogeneous across the MOJN parks.

We evaluated the potential for known station moves and missing data to introduce artifacts to the time series and found little evidence that any observed trends resulted from either potential source of error. Changepoints can substantially alter conclusions made from climatic series (Lund and Reeves 2002) and Lund et al. (2001) demonstrated that changepoint information is the single most important factor in obtaining accurate estimates of linear temperature change rates for a fixed U.S. station. Based on our analyses, station relocations (i.e., documented changepoints) appeared to have little effect on temperature results from Seasonal Mann-Kendall Tests. In contrast, significant Mann-Whitney results for some station relocations may have contributed to our failing to find any significant precipitation trends by introducing variance as sampling error into the time series. We did not attempt to identify undocumented changepoints for several reasons. First, testing for undocumented changepoints is technically challenging and results of analyses are further hampered by decisions about whether identified changepoints are valid environmental signals or result from methodological changes (Reeves et al. 2007, Beaulieu et al. 2012). Second, within this study, the lack of evidence for effects of known changepoints among the analyzed locations suggest changes in site location and protocol did not have a consistent effect on time series among these sites. Thus, by inference, undocumented changepoints were unlikely to explain the large number of positive trends in climate metrics across all sites assuming there were not systematic differences in the reporting of changes across all sites. Third, detection of undocumented changepoints requires changes of larger magnitude than for documented changepoints (Reeves et al. 2007) and we observed little qualitative evidence of large changepoints. These two points suggest few undocumented changepoints would be identified. Finally, such analyses were deemed beyond the available resources given the above considerations and higher prioritization of other analyses. We note tests for single or multiple undocumented changepoints may be appropriate for individual locations should greater confidence in time series trends be required and future analyses may use frequentist or Bayesian approaches (Lund and Reeves 2002, Reeves et al. 2007). Our sensitivity analysis of the effects of missing observations suggested that we could have reasonable confidence in results from Seasonal Mann-Kendall Tests with respect to variations in numbers of days used to generate monthly climate values.

The outcome of future climate projections depend on emission scenarios but they consistently predict increases in temperature between 4.5-8 °F by the century's end (Garfin et al. 2013). Similar to our findings, predicted changes in precipitation patterns are less consistently directional and overall predictions suggest a slight (~4%) decrease in precipitation. Effects of changing climate will likely be many-fold and will likely exacerbate pressures on water supplies and landscapes via increasing human development in the Mojave and Great Basin deserts. Given these probable changes, systematic climate monitoring along elevation gradients within parks, coupled with vegetation monitoring, may be particularly useful for detecting the magnitude of climate shifts, predicting effects on biota and ecosystems, and for identifying management options.

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Appendix A-1. Probabilities and samples sizes (*n*) from Seasonal Mann-Kendall Tests for monotonic changes in mean monthly air temperature from sites in the southwestern United States.

Park	Site	*n*	Months w/ ≥26 d missing excluded	*n*	Months w/ ≥15 d missing excluded	*n*	Months w/ ≥10d missing excluded	*n*	Months w/ ≥5 d missing excluded
DEVA	Trona	1111	**<0.001**	1101	**<0.001**	1092	**<0.001**	1071	**<0.001**
DEVA	Death Valley	1236	**<0.001**	1227	**<0.001**	1212	**<0.001**	1186	**<0.001**
DEVA	Wildrose RS	361	**0.005**	359	**0.005**	350	**0.005**	330	**0.004**
GRBA	Great Basin NP	909	0.119	902	0.142	895	0.204	877	0.298
GRBA	Garrison	599	**0.003**	566	**0.007**	538	**0.007**	489	**0.013**
JOTR	Palm Springs	1100	**<0.001**	1094	**<0.001**	1066	**<0.001**	985	**<0.001**
JOTR	Indio Fire Station	1253	**<0.001**	1221	**<0.001**	1185	**<0.001**	1134	**<0.001**
JOTR	Iron Mtn	966	**<0.001**	963	**<0.001**	958	**<0.001**	914	**<0.001**
JOTR	Twentynine Palms	956	**<0.001**	953	**<0.001**	951	**<0.001**	923	**<0.001**
JOTR	Hayfield Reservoir	980	0.432	976	0.399	974	0.420	949	0.506
JOTR	Eagle Mtn	984	0.456	983	0.482	978	0.441	955	0.412
LAKE/TUSK	Valley of Fire SP	515	**<0.001**	511	**<0.001**	504	**<0.001**	413	**<0.001**
LAKE	Overton	620	**0.001**	615	**0.001**	595	**0.001**	551	**0.001**
LAKE	Searchlight	1180	**0.002**	1175	**0.002**	1157	**0.002**	1024	**0.010**
LAKE	Bullhead City	456	**<0.001**	449	**<0.001**	433	**<0.001**	385	**<0.001**
LAKE	Willow Beach	474	**0.001**	467	**0.001**	457	**0.002**	432	**0.005**
MANZ	Independence	1078	**<0.001**	1075	**<0.001**	911	**<0.001**	799	**<0.001**
MOJA	Baker	412	0.545	403	0.478	399	0.476	376	0.525
MOJA	Mitchell Caverns	633	0.786	631	0.787	626	0.721	603	0.829
PARA	Beaver Dam	666	**<0.001**	655	**<0.001**	642	**<0.001**	610	**<0.001**
PARA	Bunkerville	355	**0.016**	320	0.063	284	0.115	198	0.451
PARA	Tuweep	513	0.733	489	0.681	459	0.675	392	0.490
PARA	Supai	629	0.292	622	0.293	610	0.324	558	0.304

Sample sizes within site varied based on the number of days within months that had missing values. Bold font indicates significant results ($P < 0.05$).

Appendix A-2. Probabilities and samples sizes (*n*) from Seasonal Mann-Kendall Tests for monotonic changes in mean monthly minimum air temperature from sites in the southwestern United States.

Park	Site	*n*	Months w/ ≥26 d missing excluded	*n*	Months w/ ≥15 d missing excluded	*n*	Months w/ ≥10d missing excluded	*n*	Months w/ ≥5 d missing excluded
DEVA	Trona	1112	**<0.001**	1103	**<0.001**	1099	**<0.001**	1078	**<0.001**
DEVA	Death Valley	1236	**<0.001**	1229	**<0.001**	1218	**<0.001**	1197	**<0.001**
DEVA	Wildrose RS	361	**0.044**	359	**0.042**	350	**0.045**	333	**0.025**
GRBA	Great Basin NP	909	**<0.001**	902	**<0.001**	897	**<0.001**	882	**<0.001**
GRBA	Garrison	599	**0.027**	568	0.071	542	**0.040**	493	**0.040**
JOTR	Palm Springs	1101	**<0.001**	1097	**<0.001**	1074	**<0.001**	1024	**<0.001**
JOTR	Indio Fire Station	1253	**<0.001**	1225	**<0.001**	1192	**<0.001**	1147	**<0.001**
JOTR	Iron Mtn	966	**0.001**	966	**0.001**	963	**0.001**	931	0.001
JOTR	Twentynine Palms	957	**<0.001**	955	**<0.001**	955	**<0.001**	944	**<0.001**
JOTR	Hayfield Reservoir	983	0.218	981	0.226	980	0.235	857	0.195
JOTR	Eagle Mtn	984	**<0.001**	984	**<0.001**	980	**<0.001**	964	**<0.001**
LAKE/TUSK	Valley of Fire SP	515	**<0.001**	511	**<0.001**	504	**<0.001**	423	**<0.001**
LAKE	Overton	631	**<0.001**	627	**<0.001**	610	**<0.001**	567	**<0.001**
LAKE	Searchlight	1180	**<0.001**	1176	**<0.001**	1166	**<0.001**	1134	**<0.001**
LAKE	Bullhead City	456	**0.001**	450	**0.001**	434	**0.001**	400	**0.002**
LAKE	Willow Beach	474	**0.001**	467	**0.001**	458	**0.001**	434	**0.001**
MANZ	Independence	1078	**<0.001**	1078	**<0.001**	955	**<0.001**	801	**<0.001**
MOJA	Baker	414	0.145	404	0.118	401	0.117	379	0.133
MOJA	Mitchell Caverns	634	0.667	633	0.677	630	0.756	612	0.665
PARA	Beaver Dam	666	**<0.001**	657	**<0.001**	646	**<0.001**	614	**<0.001**
PARA	Bunkerville	356	**0.006**	323	**0.007**	291	**0.018**	210	0.107
PARA	Tuweep	513	0.800	491	0.875	461	0.961	405	0.318
PARA	Supai	630	**0.021**	623	**0.023**	615	**0.026**	580	**0.026**

Sample sizes within site varied based on the number of days within months that had missing values. Bold font indicates significant results ($P < 0.05$).

Appendix A-3. Probabilities and samples sizes (*n*) from Seasonal Mann-Kendall Tests for monotonic changes in mean monthly maximum air temperature from sites in the southwestern United States.

Park	Site	*n*	Months w/ ≥26 d missing excluded	*n*	Months w/ ≥15 d missing excluded	*n*	Months w/ ≥10d missing excluded	*n*	Months w/ ≥5 d missing excluded
DEVA	Trona	1114	0.111	1111	0.116	1104	0.165	1087	0.190
DEVA	Death Valley	1245	**0.003**	1242	**0.002**	1238	**0.003**	1227	**0.002**
DEVA	Wildrose RS	361	**0.005**	359	**0.005**	350	**0.005**	331	**0.006**
GRBA	Great Basin NP	910	0.083	905	0.078	900	0.068	884	0.052
GRBA	Garrison	602	**0.005**	571	**0.009**	544	**0.008**	498	**0.023**
JOTR	Palm Springs	1105	**<0.001**	1100	**<0.001**	1080	**<0.001**	1011	**<0.001**
JOTR	Indio Fire Station	1253	**0.007**	1223	**0.009**	1191	**0.012**	1139	**0.048**
JOTR	Iron Mtn	966	**<0.001**	964	**<0.001**	958	**<0.001**	940	**<0.001**
JOTR	Twentynine Palms	956	**0.004**	953	**0.006**	951	**0.006**	925	**0.004**
JOTR	Hayfield Reservoir	980	**0.007**	977	**0.006**	977	**0.006**	967	**0.008**
JOTR	Eagle Mtn	984	**0.000**	984	**<0.001**	979	**<0.001**	968	**<0.001**
LAKE/TUSK	Valley of Fire SP	515	**0.001**	513	**0.001**	507	**0.001**	438	**0.002**
LAKE	Overton	620	0.346	616	0.341	601	0.366	565	0.398
LAKE	Searchlight	1181	0.339	1176	0.387	1160	0.344	438	0.517
LAKE	Bullhead City	456	**0.001**	449	**0.001**	434	**0.002**	393	**0.003**
LAKE	Willow Beach	474	**0.013**	467	**0.017**	459	**0.027**	441	0.070
MANZ	Independence	1078	**<0.001**	1077	**<0.001**	951	**<0.001**	800	**<0.001**
MOJA	Baker	413	0.445	403	0.387	400	0.346	382	0.293
MOJA	Mitchell Caverns	633	0.374	632	0.391	628	0.328	611	0.476
PARA	Beaver Dam	666	**0.003**	656	**0.004**	646	**0.004**	624	**0.004**
PARA	Bunkerville	356	0.979	335	0.783	310	0.660	229	0.504
PARA	Tuweep	513	0.260	490	0.210	462	0.388	401	0.124
PARA	Supai	633	**0.036**	626	**0.038**	615	**0.035**	573	**0.026**

Sample sizes within site varied based on the number of days within months that had missing values. Bold font indicates significant results ($P < 0.05$).

Appendix A-4. Probabilities and samples sizes (*n*) from Seasonal Mann-Kendall Tests for monotonic changes in monthly minimum air temperature from sites in the southwestern United States.

Park	Site	*n*	Months w/ ≥26 d missing excluded	*n*	Months w/ ≥15 d missing excluded	*n*	Months w/ ≥10d missing excluded	*n*	Months w/ ≥5 d missing excluded
DEVA	Trona	1112	**<0.001**	1103	**<0.001**	1099	**<0.001**	1078	**<0.001**
DEVA	Death Valley	1236	**<0.001**	1229	**<0.001**	1218	**<0.001**	1197	**<0.001**
DEVA	Wildrose RS	361	0.053	359	0.051	350	0.051	333	**0.044**
GRBA	Great Basin NP	909	**<0.001**	902	**<0.001**	897	**<0.001**	882	**<0.001**
GRBA	Garrison	599	**0.002**	568	**0.004**	542	**0.001**	493	**0.002**
JOTR	Palm Springs	1101	**<0.001**	1097	**<0.001**	1074	**<0.001**	1024	**<0.001**
JOTR	Indio Fire Station	1253	**<0.001**	1225	**<0.001**	1192	**<0.001**	1147	**<0.001**
JOTR	Iron Mtn	966	**0.003**	966	**0.003**	963	**0.003**	931	**0.006**
JOTR	Twentynine Palms	957	**<0.001**	955	**<0.001**	955	**<0.001**	944	**<0.001**
JOTR	Hayfield Reservoir	983	0.395	981	0.402	980	0.418	957	0.447
JOTR	Eagle Mtn	984	**<0.001**	984	**<0.001**	980	**<0.001**	964	**<0.001**
LAKE/TUSK	Valley of Fire SP	515	**<0.001**	511	**<0.001**	504	**<0.001**	515	**<0.001**
LAKE	Overton	631	**<0.001**	627	**<0.001**	610	**<0.001**	567	**<0.001**
LAKE	Searchlight	1180	**0.001**	1176	**0.001**	1166	**0.001**	515	**0.001**
LAKE	Bullhead City	456	**0.001**	450	**0.001**	434	**0.001**	400	**<0.001**
LAKE	Willow Beach	474	**<0.001**	467	**<0.001**	458	**<0.001**	434	**<0.001**
MANZ	Independence	1078	**<0.001**	1078	**<0.001**	955	**<0.001**	801	**<0.001**
MOJA	Baker	414	0.229	404	0.225	401	0.238	379	0.239
MOJA	Mitchell Caverns	634	0.229	633	0.199	630	0.248	612	0.236
PARA	Beaver Dam	666	**<0.001**	657	**<0.001**	646	**<0.001**	614	**<0.001**
PARA	Bunkerville	356	**0.001**	323	**0.003**	291	**0.007**	210	0.063
PARA	Tuweep	513	0.723	491	0.838	461	0.931	405	0.405
PARA	Supai	630	**0.001**	623	**0.001**	615	**0.001**	580	**0.002**

Sample sizes within site varied based on the number of days within months that had missing values. Bold font indicates significant results ($P < 0.05$).

Appendix A-5. Probabilities and samples sizes (*n*) from Seasonal Mann-Kendall Tests for monotonic changes in monthly maximum air temperature from sites in the southwestern United States.

Park	Site	*n*	Months w/ ≥26 d missing excluded	*n*	Months w/ ≥15 d missing excluded	*n*	Months w/ ≥10d missing excluded	*n*	Months w/ ≥5 d missing excluded
DEVA	Trona	1114	0.077	1111	0.088	1104	0.107	1086	0.151
DEVA	Death Valley	1245	**<0.001**	1242	**<0.001**	1238	**<0.001**	1227	**<0.001**
DEVA	Wildrose RS	361	**0.001**	359	**0.001**	350	**0.001**	331	**0.001**
GRBA	Great Basin NP	910	0.918	905	0.748	900	0.667	884	0.563
GRBA	Garrison	602	**0.005**	571	**0.013**	544	**0.010**	498	**0.028**
JOTR	Palm Springs	1105	0.592	1100	0.637	1080	0.404	1011	0.156
JOTR	Indio Fire Station	1253	0.784	1223	0.924	1191	0.720	1139	0.485
JOTR	Iron Mtn	966	**<0.001**	964	**<0.001**	958	**<0.001**	940	**<0.001**
JOTR	Twentynine Palms	956	0.927	953	0.891	951	0.896	925	0.890
JOTR	Hayfield Reservoir	980	0.059	977	0.052	977	0.052	967	0.065
JOTR	Eagle Mtn	984	**<0.001**	984	**<0.001**	979	**<0.001**	968	**<0.001**
LAKE/TUSK	Valley of Fire SP	515	**0.017**	513	**0.017**	511	**0.019**	438	**0.009**
LAKE	Overton	620	0.055	616	0.058	601	0.060	565	**0.046**
LAKE	Searchlight	1181	0.391	1176	0.461	1160	0.407	438	0.661
LAKE	Bullhead City	456	0.122	449	0.117	434	0.091	393	0.184
LAKE	Willow Beach	474	0.316	467	0.260	459	0.310	441	0.349
MANZ	Independence	1078	**<0.001**	1077	**<0.001**	951	**<0.001**	801	**<0.001**
MOJA	Baker	413	0.773	403	0.788	400	0.706	382	0.663
MOJA	Mitchell Caverns	633	0.278	632	0.293	628	0.239	611	0.220
PARA	Beaver Dam	666	**0.001**	656	**0.001**	646	**0.001**	624	**0.003**
PARA	Bunkerville	356	0.451	335	0.414	310	0.335	229	0.475
PARA	Tuweep	513	1.000	490	0.751	462	0.737	401	0.541
PARA	Supai	633	**0.029**	626	**0.029**	615	**0.025**	573	**0.025**

Sample sizes within site varied based on the number of days within months that had missing values. Bold font indicates significant results ($P < 0.05$).

Appendix A-6. Probabilities and samples sizes (*n*) from Seasonal Mann-Kendall Tests for monotonic changes in monthly precipitation from sites in the southwestern United States.

Park	Site	*n*	Months w/ ≥26 d missing excluded	*n*	Months w/ ≥15 d missing excluded	*n*	Months w/ ≥10d missing excluded	*n*	Months w/ ≥5 d missing excluded
DEVA	Trona	1098	**0.012**	1093	**0.019**	1092	**0.019**	1087	**0.017**
DEVA	Death Valley	1204	**<0.001**	1201	**<0.001**	1201	**<0.001**	1199	**<0.001**
DEVA	Wildrose RS	360	0.888	360	0.888	358	0.874	357	0.855
GRBA	Great Basin NP	910	**0.042**	904	**0.035**	903	**0.040**	898	**0.048**
GRBA	Garrison	602	**0.039**	581	**0.032**	568	**0.020**	550	**0.028**
JOTR	Palm Springs	1105	**0.047**	1103	0.052	1092	0.062	1071	**0.043**
JOTR	Indio Fire Station	1148	**<0.001**	1130	**<0.001**	1115	**<0.001**	1106	**<0.001**
JOTR	Iron Mtn	966	0.093	966	0.093	965	0.078	954	0.062
JOTR	Twentynine Palms	957	0.821	956	0.865	956	0.865	950	0.829
JOTR	Hayfield Reservoir	980	0.486	980	0.486	980	0.486	979	0.503
JOTR	Eagle Mtn	980	0.528	980	0.528	979	0.525	973	0.554
LAKE/TUSK	Valley of Fire SP	512	0.116	504	0.131	503	0.134	501	0.143
LAKE	Overton	609	0.780	592	0.576	589	0.545	589	0.545
LAKE	Searchlight	1167	0.218	1157	0.290	1157	0.290	501	0.321
LAKE	Bullhead City	456	**0.001**	454	**0.001**	442	**0.002**	422	**0.002**
LAKE	Willow Beach	474	0.244	470	0.383	469	0.424	467	0.415
MANZ	Independence	1072	0.823	1071	0.817	1068	0.898	1067	0.928
MOJA	Baker	411	0.770	410	0.813	409	0.819	405	0.757
MOJA	Mitchell Caverns	633	0.969	633	0.969	632	0.922	630	0.914
PARA	Beaver Dam	664	0.988	656	0.978	653	0.868	649	0.777
PARA	Bunkerville	355	**0.011**	346	**0.017**	343	**0.013**	327	**0.032**
PARA	Tuweep	511	0.063	506	**0.048**	501	0.090	501	0.090
PARA	Supai	605	0.484	594	0.411	593	0.414	592	0.425

Sample sizes within site varied based on the number of days within months that had missing values. Bold font indicates significant results ($P < 0.05$).

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