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# Long-Term Trend Analysis in Annual and Seasonal Precipitation, Maximum and Minimum Temperatures in the Southwest United States

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Received: 15 September 2020; Accepted: 28 November 2020; Published: 2 December 2020

**Abstract:** The objective of this study is to perform trend analysis in the historic data sets of annual and crop season [May–September] precipitation and daily maximum and minimum temperatures across the southwest United States. Eighteen ground-based weather stations were considered across the southwest United States for a total period from 1902 to 2017. The non-parametric Mann–Kendall test method was used for the significance of the trend analysis and the Sen's slope estimator was used to derive the long-term average rates of change in the parameters. The results showed a decreasing trend in annual precipitation at 44.4% of the stations with the Sen's slopes varying from −1.35 to −0.02 mm/year while the other stations showed an increasing trend. Crop season total precipitation showed non-significant variation at most of the stations except two stations in Arizona. Seventy-five percent of the stations showed increasing trend in annual maximum temperature at the rates that varied from 0.6 to 3.1 °C per century. Air cooling varied from 0.2 to 1.0 °C per century with dominant warming phenomenon at the regional scale of the southwest United States. Average annual minimum temperature had increased at 69% of the stations at the rates that varied from 0.1 to 8 °C over the last century, while the annual temperature amplitude showed a decreasing trend at 63% of stations. Crop season maximum temperature had significant increasing trend at 68.8% of the stations at the rates varying from 0.7 to 3.5 °C per century, while the season minimum temperature had increased at 75% of the stations.

**Keywords:** climate change; crop growing season; precipitation; temperature; southwest United States

## 1. Introduction

Food production is governed by different factors, of which climate is the most important, that causes inter-annual variability in precipitation, air temperature, relative humidity and affects the socioeconomic and environmental systems related to surface and groundwater resources management and planning. Change in average weather conditions or long-term variation in climate variables is referred as climate change. Global warming due to an increase in greenhouse emissions implies an increase in temperature. Global warming is revealed as evident and demonstrated through numerous studies. The global combined ocean and air average annual temperature has increased by 0.65–1.06 °C during the 1880–2012 period [1]. Average air temperature has increased by 1.52 °C in Eastern China over the past century [2]. Ceppi et al. [3] found that seasonal air temperature in Sweden has increased by 0.30–0.62 °C/decade in summer and 0.02–0.38 °C/decade in autumn during the 1959–2008 period in Sweden. A significant warming trend in annual minimum temperature and mean temperature was observed in different irrigation zones in Pakistan, while the maximum temperature showed significant variation elsewhere except at high altitudes [4]. An increasing trend in air temperature was reported across the United States except for Pennsylvania and Maine [5,6]. The global mean surface temperature might increase in the range of 0.3 to 0.7 °C during the 2016–2035 period compared to the 1986–2005 period under different Representative Concentration Pathways [7]. Sing et al. [8] reported evidence of accelerated warming and wetting over northern Canada, while strong evidence of hot and dry conditions was found in the Prairies provinces as reported by Bonsal et al. [9]. Djaman et al. [10] reported a significant increase in average annual maximum and minimum air temperature and significant decrease in annual precipitation across the Senegal River valley. Men et al. [11] reported that air temperature had significantly increased over the Beijing-Tianjin-Hebei region in China during the 1960–2013 period and the temperature and precipitation showed strong correlation in change.

Different patterns of change in annual and seasonal precipitation are presented at the global scale with increase in zonal and regional precipitation at some locations, while a decrease is observed at other locations with intensification of the extreme events. Sibanda et al. [12] found that the 1950–2015 period annual mean precipitation may not have changed from the 1886–1906 period in Zimbabwe but there is 34% decrease in the number of rainy days with increase in the intensity of precipitation. Gajbhiye et al. [13] reported an increasing trend in annual and seasonal rainfall across the Indian River basin for the 1901–2002 period. A similar trend was reported by Kumar et al. [14] at the half of their study sites across the Haryana and coastal Karnataka areas of India. A non-significant decreasing trend in annual precipitation was observed in the Pieria region in Greece for the period of 1974–2007 [15]. Wang et al. [16] showed significant decrease in the overall drought index, while there was an increase in spring drought index for the 1960–2018 period in the northern Shaanxi region of China. Gao et al. [17] projected an increase in annual precipitation across the Loess Plateau in China up to the year 2050. Nawaz et al. [4] reported an increase in annual precipitation at zonal and regional levels in Pakistan with a decrease in annual precipitation at elevation greater than 1000 m above sea level. Valdés-Pineda et al. [18] reported that along the pacific coast of South America, non-significant positive trends in annual precipitation were found for the region between 36° and 44° S, at least during the 1930–2006 period and a significant decreasing trend in annual precipitation between 44° and 49° S during the same period.

The southwest United States is a huge agricultural region with a large diversity of crops. The unpredictable climate puts crops under drought and heat stress conditions which jeopardize crop yield mostly under rainfed production. Crop producers, researchers, policy makers, crop consultants, tourists, recreation managers, and other agricultural actors should be aware of the long-term variability of the local climate variables for planning and management of water resources, crops, and livestock to avoid the incidence of extreme temperatures on the crops and livestock. Ground-based climatic datasets analysis offers insights of changes in the hydro-meteorological and climatic systems with the diagnosis of the consistency or abrupt break in time and space and constitutes a historical baseline for future climate projections [19]. Despite the broad studies across the western United States on the spatial and temporal trend analysis and variability patterns in climate parameters such as air temperatures and precipitation, most of the studies did not use a long-term record about a century of climate data. Thus, a limited information is available on paleoclimate of the southwest United States, the objective of this study is to investigate the change in annual and crop season precipitation, and the annual and crop season average maximum and minimum air temperature across the southwest United States to help crop producers, environmental engineers, crop consultants, and hydrologists and other water use entities in water resources planning.

## 2. Materials and Methods

### *2.1. Study Sites, Precipitation, and Temperature Data Collected*

This study is concentrated in the southwest United States including the states of Texas, New Mexico, Arizona, California, Nevada, Utah and Colorado. Ground-based weather station measurements of the daily precipitation and maximum and minimum air temperatures were collected at day time step. The data used in this study were downloaded from the National Oceanic and Atmospheric Administration (NOAA) website (https://www.ncdc.noaa.gov/data-access). While there are hundreds of NOAA stations across the southwest United States, the first criterion used for station selection was ground-based stations with a minimum of 100-year data and the second criterion was the least missing data (less than 5%). These criteria yielded only 18 stations. Three stations in Texas, New Mexico, Arizona, and two stations in Utah, Nevada, and Colorado were considered for the precipitation analysis (Figure 1, Table 1), while three stations in New Mexico and California and two stations in Texas, Arizona, Colorado, Utah, and Nevada were considered for the analysis of the maximum and minimum air temperatures (Figure 1, Table 1). The study period is variable with weather stations due to the availability of the data and covers the period from 1930 to 2017 for precipitation and from 1902 to 2017 for air temperature (Table 1). Crop growing season duration may vary across the study area but the period from 1 May to 30 September of each year is considered as the crop growing season across the study area. Annual and growing season temperature amplitudes were computed as the difference between the annual or the growing season maximum temperature and the annual or the growing season minimum temperature. Linear regression plotting was first used to check data time series fitting. All data were also checked for normality using the Shapiro–Wilk test and for homogeneity of variances using the Bartlett test.

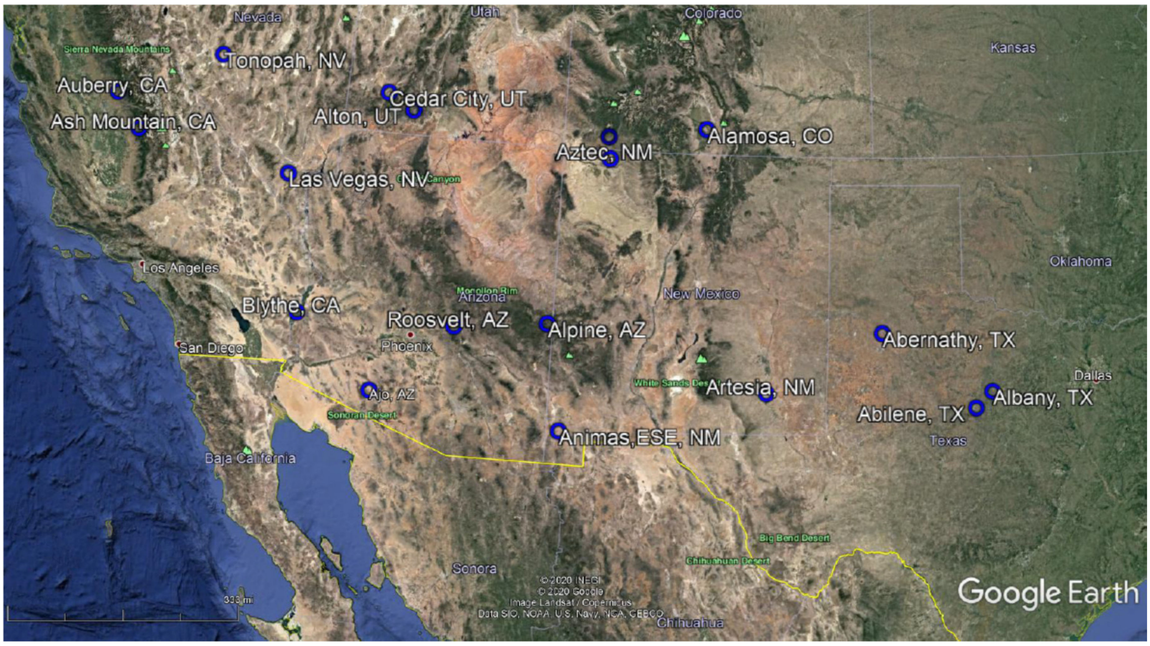



**Figure 1.** Presentation of the study sites in southwest United States (white dots) (downloaded from Google earth on 28 October 2020). The study sites are marked with the blue circles and the scale is 535.91 km (333 miles).

**Table 1.** Weather station geographic coordinates with the data collection periods for daily precipitation and air temperature.

| Locations | Latitude (degrees) | Longitude (degrees) | Elevation (m) | Precipitation | | Air Temperature | |
|---|---|---|---|---|---|---|---|
| | | | | First Year | Last Year | First Year | Last Year |
| Abernathy, TX | 33.83 | −101.84 | 1026.6 | 1944 | 2017 | - | - |
| Abilene R.A., TX | 32.41 | −99.68 | 545.6 | 1948 | 2017 | 1948 | 2017 |
| Albany, TX | 32.70 | −99.30 | 439.2 | 1930 | 2017 | 1902 | 2017 |
| Animas ESE, NM | 31.94 | −108.77 | 1371.9 | 1930 | 2017 | 1930 | 2017 |
| Artesia S, NM | 32.75 | −104.38 | 1026 | 1930 | 2015 | 1910 | 2017 |
| Aztec R.N.M., NM | 36.84 | −108.00 | 1720.3 | 1930 | 2010 | 1930 | 2010 |
| Ajo, AZ | 32.37 | −112.86 | 533.7 | 1930 | 2017 | 1915 | 2017 |
| Alpine, AZ | 33.85 | −109.15 | 2453.6 | 1930 | 2012 | - | - |
| Roosevelt W.N.W, AZ | 33.67 | −111.15 | 672.1 | 1930 | 2017 | 1906 | 2017 |
| Ash Mountain, CA | 36.49 | −118.83 | 520.6 | 1930 | 2017 | 1927 | 2017 |
| Auberry NW, CA | 37.09 | −119.51 | 637 | 1930 | 2017 | 1913 | 2017 |
| Blythe, CA | 33.61 | −114.60 | 81.7 | 1930 | 2016 | 1913 | 2017 |
| Alton, UT | 37.44 | −112.48 | 2163.5 | 1930 | 2017 | 1917 | 2017 |
| Cedar City M.A., UT | 37.71 | −113.09 | 1702.6 | 1949 | 2017 | 1949 | 2017 |
| Alamosa S.L.V.R.A.,CO | 37.44 | −105.86 | 2296.1 | 1948 | 2017 | 1948 | 2017 |
| Fort Lewis, CO | 37.23 | −108.05 | 2320.7 | 1930 | 2010 | 1917 | 2017 |
| Las Vegas M.I.A., NV | 36.07 | −115.16 | 664.5 | 1949 | 2017 | 1949 | 2017 |
| Tonopah Airport, NV | 38.05 | −117.09 | 1644.4 | 1955 | 2017 | 1955 | 2017 |

### 2.2. *Temporal Trend Analysis*

The Mann–Kendall test [20–22], a nonparametric method for trend analysis, was used for the analysis of temporal trend in annual precipitation, crop growing season precipitation, annual average maximum and minimum temperatures, and the growing season average maximum and minimum temperatures. The Mann–Kendall test is a statistical test widely used for the analysis of trend in climatologic [23,24] and hydrologic time series [25,26]. There are two advantages of using this test: it is a nonparametric test and does not require the data to be normally distributed and the test has low sensitivity to abrupt breaks due to non-homogeneous time series [27]. According to this test, the null hypothesis ($H_0$) assumes that there is no trend (the data is independent and randomly ordered) and this is tested against the alternative hypothesis ($H_1$), which assumes that there is a trend. The Mann–Kendall test statistic S is given as follows:

$$S = \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \mathrm{sign}\,(xi - xj), \tag{1}$$

where xi and xj are the data values at time i and j, n is the length of the dataset, and sign( ) is the sign function which can be computed as:

$$\mathrm{sign}(xi - xj) = \begin{cases} 1 & \text{if } (xi - xj) > 0 \\ 0 & \text{if } (xi - xj) = 0 \\ -1 & \text{if } (xi - xj) < 0 \end{cases}. \tag{2}$$

For $n > 10$, the test statistic Z approximately follows a standard normal distribution:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S < 0 \end{cases}, \tag{3}$$

in which Var(S) is the variance of statistic S:

$$\mathrm{Var}(s) = 1/18\left[n, (n-1), (2n+5), -, \sum_{j=1}^{m} Tj\, j(j-1)(2j+5)\right], \tag{4}$$

where $T_j$ is the number of data in the tied group and m is the number of tied ranks.

A positive value of Z indicates that there is an increasing trend, and a negative value indicates a decreasing trend. The null hypothesis that there is no trend in the records is either accepted or rejected, depending on whether the computed Z statistic is less than or more than the critical Z value obtained from the normal distribution table at the 5% significance level [28]. If $|Z| > Z_{(1-\alpha/2)}$, the null hypothesis of no autocorrelation and trend in time series is rejected, in which $Z_{(1-\alpha/2)}$ is corresponding to the normal distribution with $\alpha$ being the significance level.

The Theil–Sen estimator (TSE) is an unbiased estimator of the true slope in simple linear regression [29]. The TSE is robust with a high breakdown point of 29.3%, has a bounded influence function, and possesses a high asymptotic efficiency. If there is a trend in the data, the magnitude of the change in any variable can be denoted by trend slope β [29,30]:

$$\beta = \mathrm{Median}\left(\frac{xi - xj}{i - j}\right) \quad \forall\, j < I\,, \tag{5}$$

where xi and xj are data values at the time ti and tj (i> j), respectively.

Linear regression analysis was also applied for analyzing trends in the time series. The main statistical parameter drawn from the regression analysis is the slope which indicates the mean temporal change in the precipitation and temperature time series under study. A positive slope indicates an increasing trend, while a negative slope indicates a decreasing trend. Change in precipitation and maximum and minimum temperatures over a decade or century is estimated as the product of the Sen's slope time 10 or 100, as a decade is 10 years and a century is 100 years.

## 3. Results and Discussion

### *3.1. Trend Analysis in Annual and Crop Growing Season Precipitation*

The Mann–Kendall test showed variation in the trend of the long-term precipitation across the study area. There was a decreasing trend in long-term annual precipitation at eight stations out of eighteen (44.4%), while 55.6% of the stations showed increasing trend in the long-term annual precipitation. A significant decrease in long-term annual precipitation was observed at Ajo and Fort Lewis (Table 2), while a non-significant decreasing trend was observed at Albany, Roosevelt, Ash Mountain, Blythe, Las Vegas, and Tonopah. The Sen's slopes varied from −1.35 to −0.02 mm/year. A decrease in annual precipitation is the most intense at Ash Mountain followed by Ajo with Sen's slope with values of −1.35 and −1.27 mm/year, respectively. A significant increase in the annual precipitation was observed at Artesia, Alpine, and Cedar City with a Sen's slope of 0.87, 1.38, and 0.82 mm/year, respectively. Similar trends were also shown by the regression analysis presented in Figure 2. However, the slopes of the regression lines are slightly different in magnitude from the estimated Sen's slope but both slopes have similar sign. In Texas, one station showed a non-significant decreasing trend in annual precipitation, while the other two stations showed non-significant increasing trend. An increasing trend in the annual precipitation is observed at all three stations in New Mexico with only one significant trend. Two stations in Arizona showed a decreasing trend in annual precipitation similar to California, while both stations in Utah showed an increasing trend in the annual precipitation. A decreasing trend in annual precipitation was observed at both stations in Nevada. In Colorado, one out of two stations showed an increasing trend in annual precipitation. There was no correlation between the estimated Sen's slope and the geographical coordinates of the weather stations. The results of this study showed evidence of change in precipitation across the southwest United States, however, this change varied greatly in magnitude from one location to another, with some locations getting wetter while others are getting drier on annual basis.

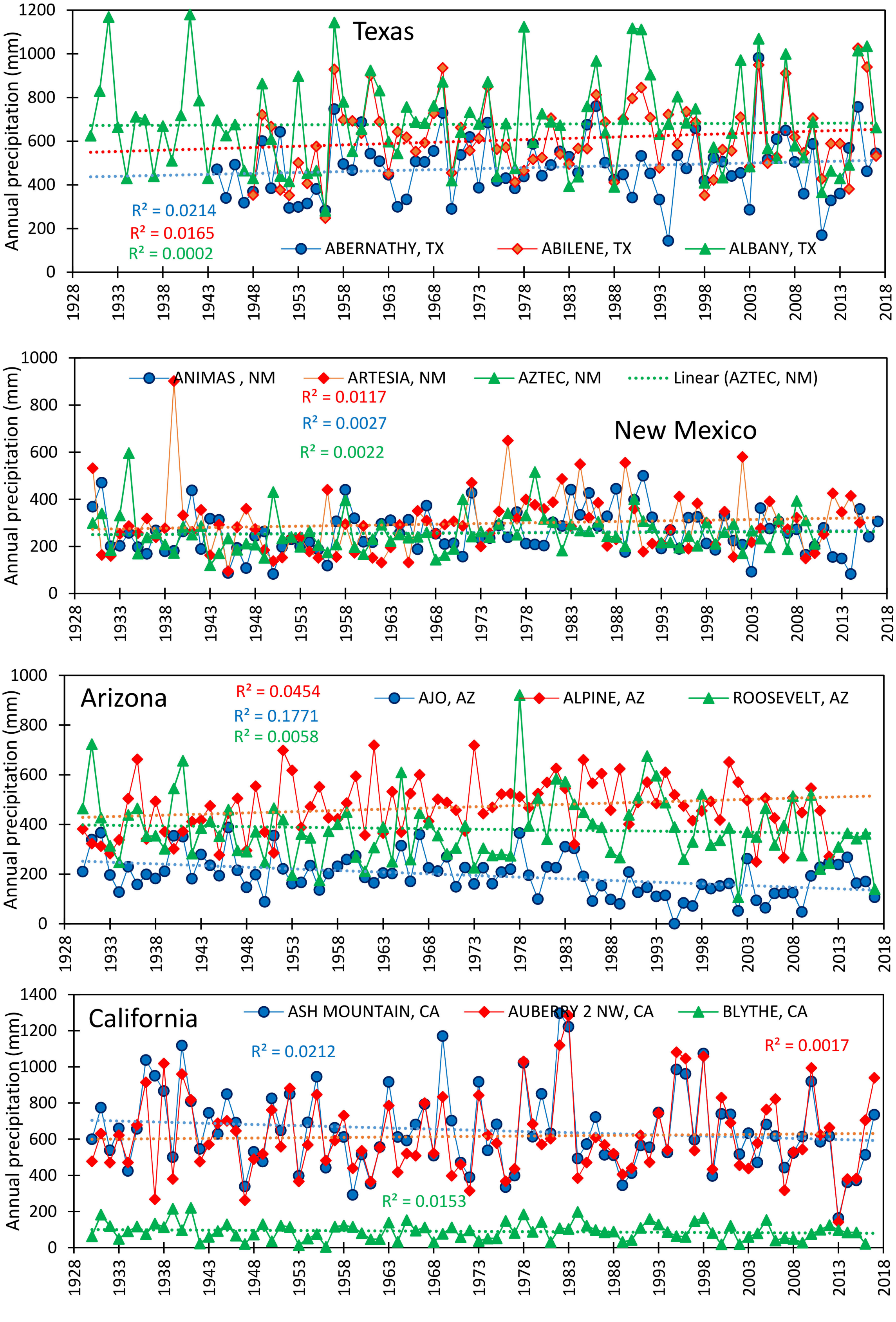



**Figure 2.** *Cont.*

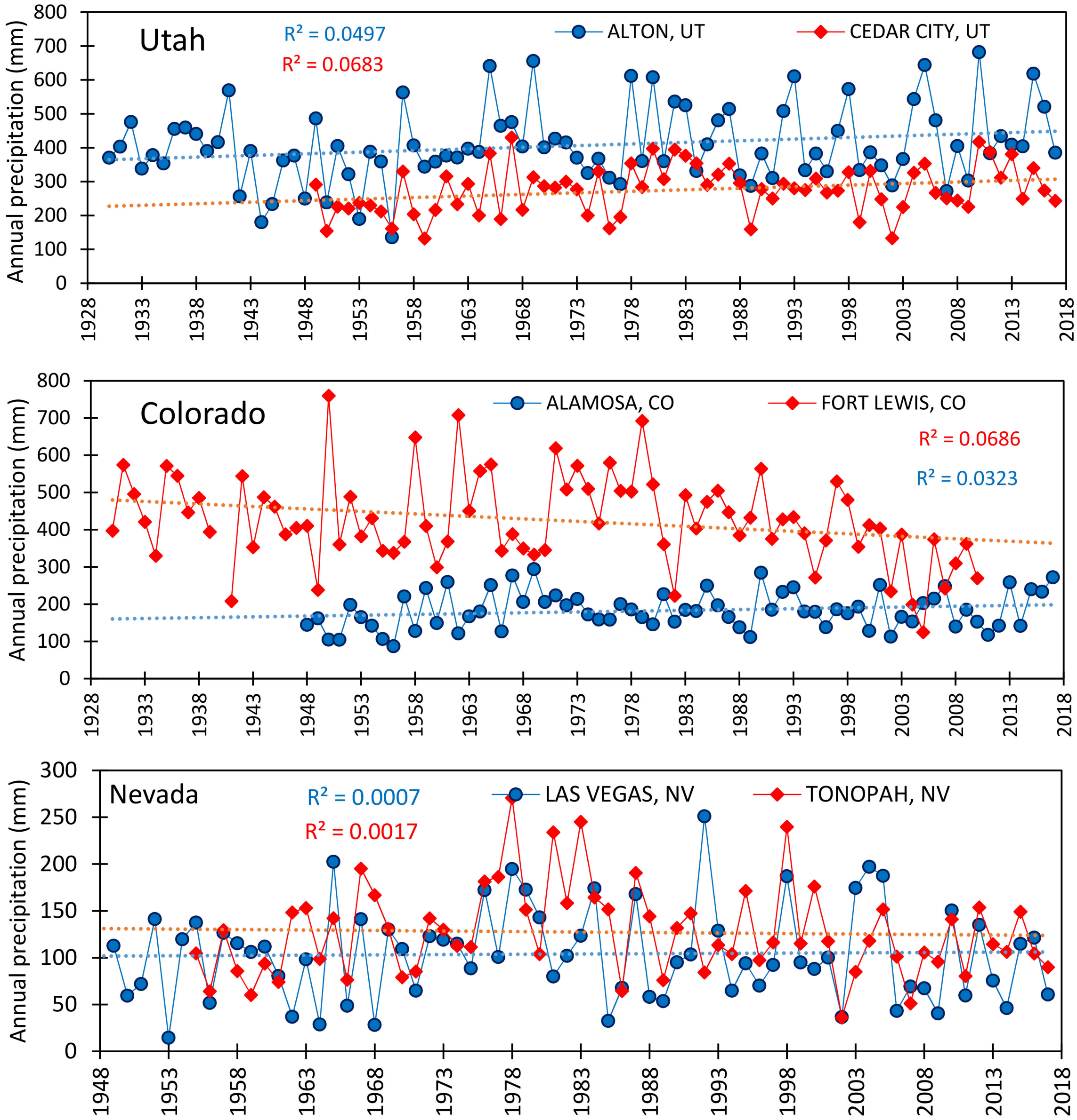


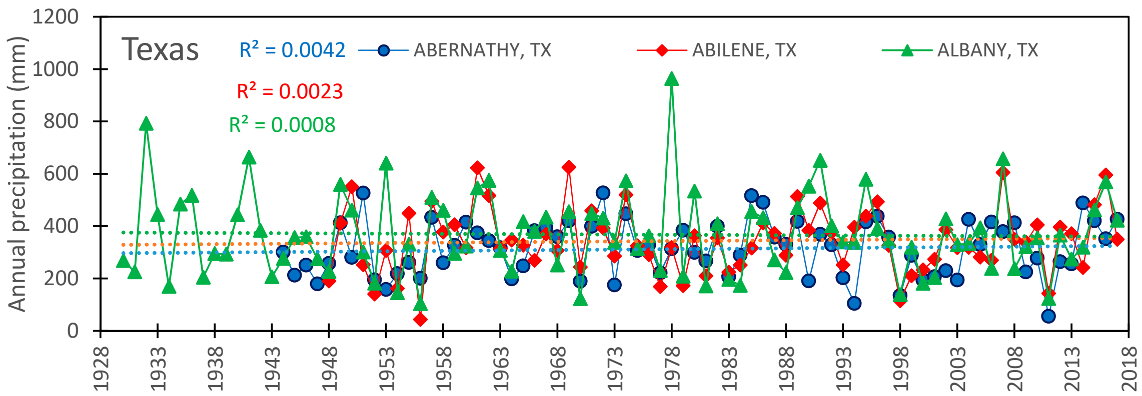

**Figure 2.** Temporal trend in annual precipitation in the states of Texas, New Mexico, Colorado, Arizona, Utah, Nevada, and California.

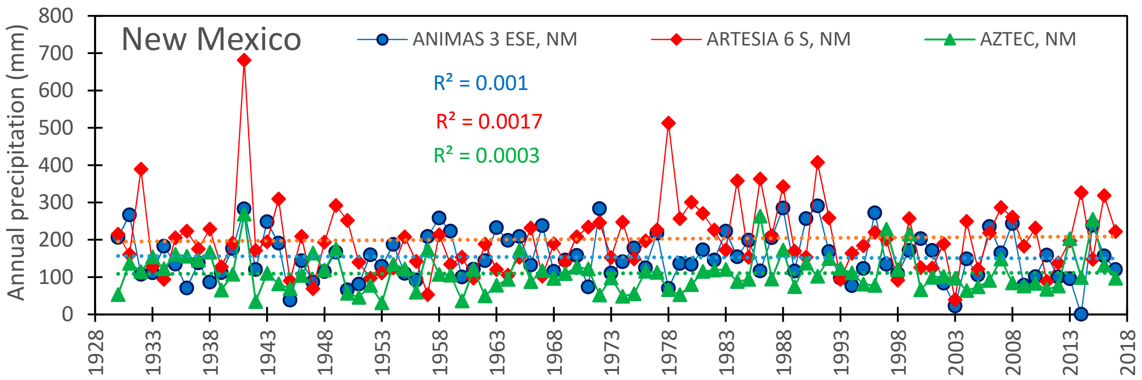
Trend in the crop growing season [May through September] total precipitation showed a non-significant variation at most of the stations except the Ajo and Alpine in Arizona where the seasonal precipitation showed a significant decreasing trend at Ajo (Z statistic value of −2.56) and a significant increasing trend at Alpine (Z statistic value of 3) (Table 2). A non-significant increasing trend in the crop growing seasonal precipitation was observed at Abernathy and Abilene in Texas, Artesia in New Mexico, Auberry and Blythe in California and Alton, Cedar City in Utah, and Alamosa in Colorado. A non-significant decreasing trend in the crop growing season precipitation was observed at Albany in Texas, Animas and Aztec in New Mexico, Roosevelt and Ash Mountain in California, Fort Lewis in Colorado, and Las Vegas and Tonopah in Nevada. These trends are confirmed by the regression lines presented in Figure 3. The greatest change in the crop growing season precipitation was 1.11 mm/year at Alpine.

**Table 2.** Summary of the Mann–Kendall trend test for annual and crop season precipitation.

| Locations | First Year | Last Year | Annual Precipitation | | | | Crop Season Precipitation | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Test Z | Signific. | β | B | Test Z | Signific. | β | B |
| Abernathy, TX | 1944 | 2017 | 1.27 | n.s. | 0.99 | 432.6 | 0.96 | n.s | 0.51 | 291.6 |
| Abilene R.A., TX | 1948 | 2017 | 0.79 | n.s. | 0.75 | 538.6 | 0.4 | n.s. | 0.31 | 315.4 |
| Albany, TX | 1930 | 2017 | −0.17 | n.s. | −0.14 | 677.3 | −0.03 | n.s. | 0 | 344.6 |
| Animas ESE, NM | 1930 | 2017 | 0.8 | n.s. | 0.27 | 237.5 | −0.05 | n.s. | 0 | 144.1 |
| Artesia S, NM | 1930 | 2015 | 1.91 | + | 0.87 | 252.5 | 1.23 | n.s. | 0.45 | 173.3 |
| Aztec R.N.M., NM | 1930 | 2010 | 1.23 | n.s. | 0.35 | 228.1 | −0.43 | n.s. | −0.1 | 107.5 |
| Ajo, AZ | 1930 | 2017 | −3.65 | *** | −1.27 | 236.2 | −2.56 | * | −0.6 | 118.8 |
| Alpine, AZ | 1930 | 2012 | 2.29 | * | 1.38 | 399.9 | 3 | ** | 1.11 | 214.4 |
| Roosevelt W.N.W, AZ | 1930 | 2017 | −0.64 | n.s. | −0.37 | 379.7 | −0.26 | n.s. | −0.1 | 125.7 |
| Ash Mountain, CA | 1930 | 2017 | −1.43 | n.s. | −1.35 | 670.1 | −0.55 | n.s. | −0.1 | 40.8 |
| Auberry NW, CA | 1930 | 2017 | 0.23 | n.s. | 0.19 | 562.9 | 0.5 | n.s. | 0.05 | 25.5 |
| Blythe, CA | 1930 | 2016 | −0.95 | n.s. | −0.22 | 98.3 | 0.49 | n.s. | 0.04 | 26.2 |
| Alton, UT | 1930 | 2017 | 1.39 | n.s. | 0.58 | 367.0 | 0.39 | n.s. | 0.11 | 147.5 |
| Cedar City M.A., UT | 1949 | 2017 | 1.7 | + | 0.82 | 228.7 | 0.61 | n.s. | 0.15 | 92.8 |
| Alamosa, CO | 1948 | 2017 | 1.34 | n.s. | 0.41 | 155.2 | 0.49 | n.s. | 0.1 | 94.5 |
| Fort Lewis, CO | 1930 | 2010 | −1.99 | * | −1.18 | 464.6 | −0.97 | n.s. | −0.3 | 196.8 |
| Las Vegas M.I.A., NV | 1949 | 2017 | −0.23 | n.s. | −0.08 | 105.9 | −1.29 | n.s. | −0.2 | 40.7 |
| Tonopah Airport, NV | 1955 | 2017 | −0.07 | n.s. | −0.02 | 117.8 | −0.84 | n.s. | −0.2 | 64.3 |

n.s., Non-significant. + Significant at 5%. * Significant at 1%. ** Significant at 0.1%. *** Significant at 0.01%.

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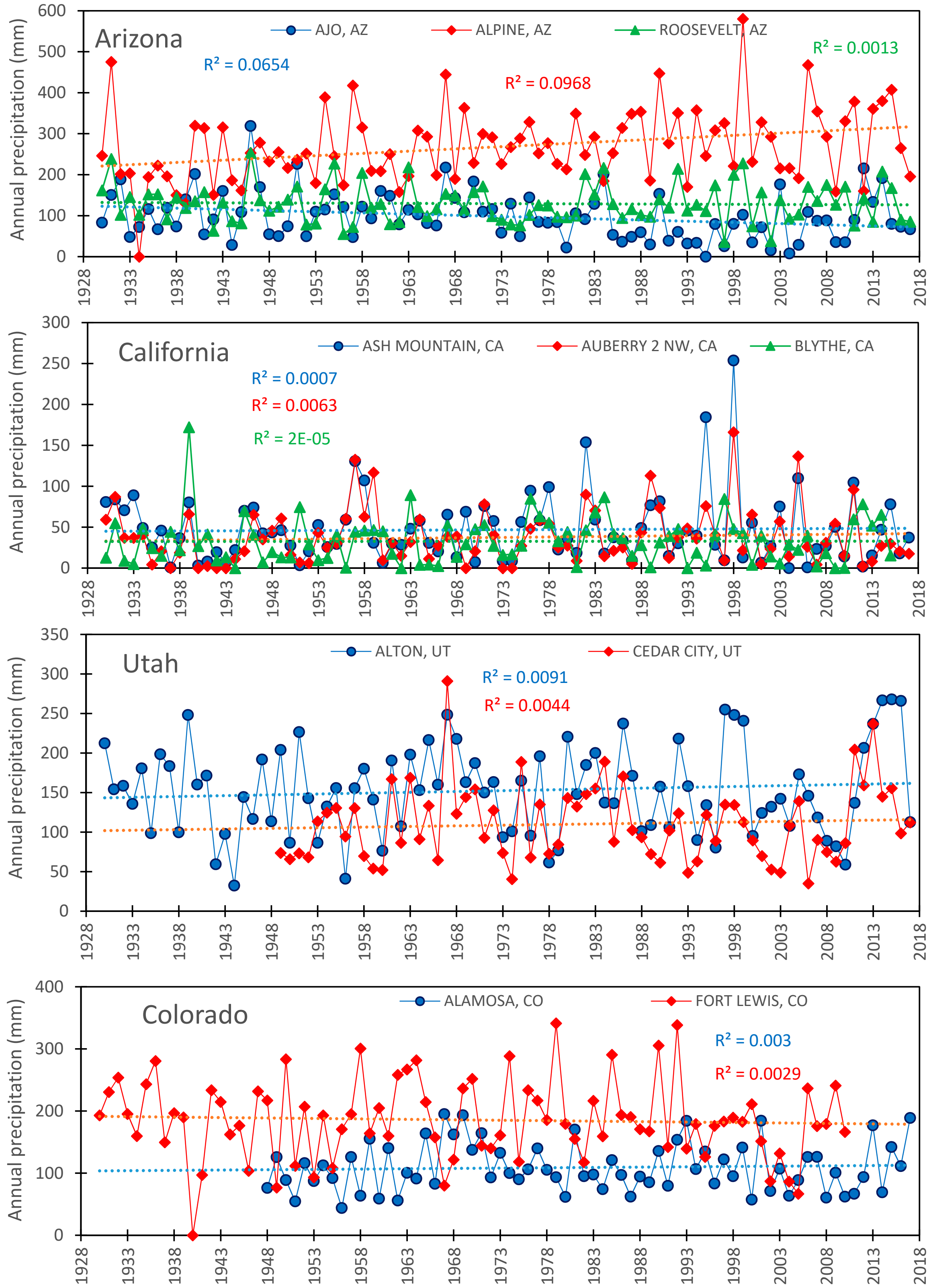


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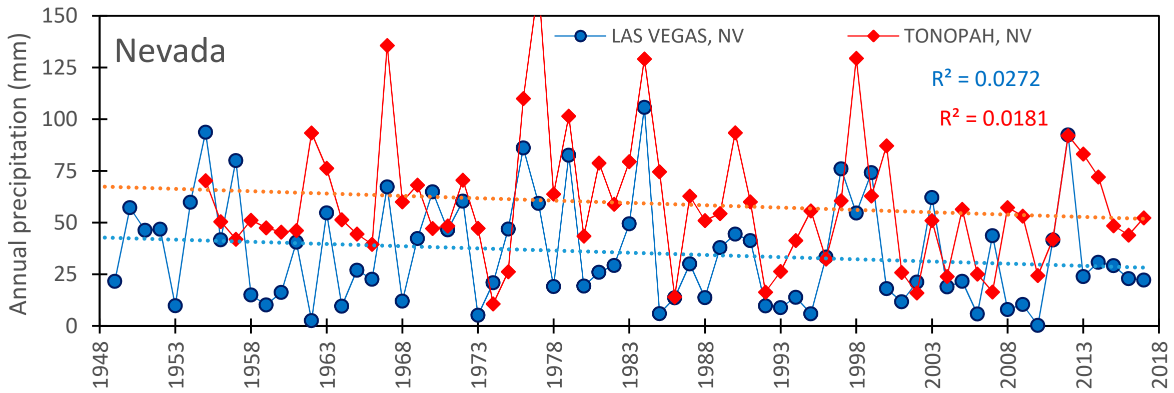


**Figure 3.** Temporal trend in crop growing season precipitation in the states of Texas, New Mexico, Colorado, Arizona, Utah, Nevada, and California.

The results of the non-significant variation in historical crop growing season precipitation under global warming call for awareness of an increase in crop evapotranspiration and supplemental irrigation requirements. Some sustainable water management strategies are important to be implemented and adopted to cope mostly with the increasing crop growing season aridity in the southwest United States with a semiarid and mostly arid climate at most parts of the region and high interannual variability in annual and crop growing season precipitation. The results of this study opposed the finding of Arriaga-Ramírez and Cavazos [31] who indicated that there were more significant trends in annual precipitation than seasonal precipitation in the southwest United States, especially in Arizona and New Mexico. In the present study, a global study period of 1930–2017 was considered, while Arriaga-Ramírez and Cavazos [31] used the 1950–2020 period dataset and the difference in the findings might be related to the study time periods used for the analysis. Diffenbaugh et al. [32] found that the southwest United Sates and northwest Mexico are the most persisting hot spots in the 21 century and are associated with a high variability in annual precipitation. Easterling et al. [33] reported that annual precipitation has decreased in much of the west and the southwest United States while it has increased in most of the northern and southern Plains, midwest and northeast United States during the 1901–2015 period.

At the southwest regional level, the average decade annual precipitation increased from the 1950s to 1990 and decreased up the 2017. This pattern was observed at most of the stations except at Abilene, Alton, and Ajo. The average decade annual precipitation showed a consistent increasing trend during the study period and is projected to continue increasing in the near future. A similar trend was observed at Alton, while at Ajo, the average decade annual precipitation literally decreased from the 1930s to 2010 and abruptly increased during the 2010–2017 period. These results contradict Kunkel et al. [34] who indicated that the southern portions of the southwest United States will experience the largest decrease in the annual precipitation while a slight increase is predicted for the northern portions. Southwest regional crop growing season average decade precipitation increased from the 1930 to 1990, with the lowest seasonal precipitation during the 1951–1960 decade. It decreased from the 1990s to 2010 and the growing season became wetter during the 2010–2017 period. A consistently increasing trend was observed in the crop growing season average decade precipitation at Alpine and the past decade growing season was wetter at Ajo, Blythe, Alton, Cedar City, and Las Vegas and Tonopah. The interannual precipitation variation at high altitude over Texas and over southwestern United States might be attributed to the interaction between mesoscale convective systems and topography modulates [35]. Stahle et al. [36] suggested that the 2000s drought is possibly associated with the projected trend in aridity for the region based on anthropogenic global warming. The large-scale atmospheric–oceanic oscillations have impacted hydrologic conditions in the western United States [37,38]. Variation in the annual total and seasonal precipitation could partly have been affected by El Niño–Southern Oscillation (ENSO), while both El Niño and La Niña are associated with floods, drought in the southwestern

United States and the global weather disturbances [37,39–43]. This phenomenon is mostly enhanced in the coastal southern California and across the southwest [43]. El Niño-Southern Oscillation (ENSO) phenomenon is the major driver for interannual variations of precipitation and the major source of seasonal predictive skill over the western United States [44]. ENSO brings summer (July–August) heavy flooding across the desert areas of inland southern California, southern Nevada, and across Arizona, New Mexico, and southern and central Colorado [43]. El Niño–Southern Oscillation (ENSO) is a recurring interannual global pattern of ocean–climate variability, driven by sea surface temperature and air pressure differentials in the tropical Pacific [39]. El Niño episodes affect North America and are associated with a deepened, southward-extended Pacific low pressure system, a persistent extended Pacific jet stream, and an amplified storm track that produces unusual wetness across the southern tier of the United States [43]. As the strong El Niño winter events of 1957/58, 1972/73, 1982/83, and 1991/92, 1997/98, 2009/10, 2015/16 across the western United States are well documented [44–47], the high annual precipitation in 1958 at all three station in Texas, Alton, UT, Fort Lewis, CO might be the impact of the El Niño of 1957/58. The El Niño of 1982/83 provoked the abrupt jump in annual precipitation at all three stations in California, while the El Niño of 1997/98 induced great precipitation al the stations in California, Nevada (Figure 2). A similar observation was noted at all stations in Texas, Auberry, CA and Ash Montain, CA for 2016. Their impact on the growing season precipitation was marked at Alpine, AZ; Ash Mountain, CA; Auberry, CA; Alton, UT; Las Vegas and Tonopah, NV (Figure 3). These results are in agreement with Corringham and Cayan [43] who reported that an increase in annual precipitation with large flood damage in the western United States was due to El Niño in the western United States. The frequency of the El Niño events might explain the long-term increasing trend in the annual precipitation at Abernathy and Abilene in Texas, Auberry, CA. In contrast, Ash Montain, CA and Fort Lewis, CO, with frequent El Niño events sowed a decreasing trend in annual precipitation. Therefore, the impact of the El Niños is not straightforward on the trend in the long-term annual precipitation. These results are in conformity with the findings of Ahmed et al. [48] who found that the annual and monsoon precipitation did not show any significant correlation with ENSO events in Bangladesh. Barros et al. [49] pointed that precipitation trends during the extreme phases of the ENSO constitute only a small part of the trends with a non-significant impact on the long-term trend in annual precipitation in southeastern south America. In contrast, other studies have also reported that El Niño–Southern Oscillation (ENSO) exerts great impacts on the interannual spring precipitation over southern China variability through atmospheric teleconnections [50–53]. Barros et al. [49] indicated that the trend in precipitation was positively correlated with ENSO events in central Argentina, however, the positive trend started in the early 1960s.

The annual changing rate in the annual precipitation slightly decreased with latitude at the rate of 0.027 mm/degree, while it increased with longitude and elevation at the rate of 0.05 mm/degree and 0.0004 mm/m (Table 6). A similar trend in the growing season precipitation was observed at the rates of −0.03 mm/degree, 0.02 mm/degree, and 0.0001 mm/m in for the latitude, longitude, and elevation, respectively (Table 6). With a semiarid to arid climate, the southwest United States, the southern part of the region is characterized by an arid desert climate, while the mountainous northern part consists of alpine climates and receives very large amounts of snow during winter months. Moreover, the precipitation amount decreased from the eastern side (southern Colorado) to the western side (California) of the southwest United States. Sheppard et al. [54] indicated that the southwest United States is located between the mid-latitude and subtropical atmospheric circulation regimes, and this positioning relative to shifts in these regimes is the fundamental reason for the region's climatic variability which is emphasized by the physiographic and topographic relief, rain shadow effects from mountain ranges, the geographical proximity to the Pacific Ocean, the Gulf of California, and the Gulf of Mexico. Over all, Arizona, New Mexico, and Texas registered the highest crop growing season precipitation due to the summer moisture from the Gulf of Mexico, Gulf of California, and the eastern tropical pacific [55].

### 3.2. Trend Analysis in Annual Maximum and Minimum Temperatures

Trend analysis of historical annual maximum temperature data revealed that 56% of the weather stations showed a significant increasing trend out of 75% of the station with an increasing maximum temperature (0.94 < Z-statistics < 7.39) (Table 3). An annual increase in maximum temperature varied with stations and ranged from 0.004 to 0.031 °C/year. Only one station (6.3%) showed a significant decreasing trend at 0.1% of significance in the average annual maximum temperature with a Z-statistics of −2.85 and a Sen's slope of −0.010 °C/year across the southwest United States. Both stations in each of the states of Arizona, Colorado, Nevada, and Utah showed temperature rise and two out three stations in New Mexico and California showed a decrease in crop season maximum temperature. The greatest increase in maximum temperature was observed at Alton (UT) and the lowest increase was observed at Abilene (TX). These variations in the annual average maximum temperature represent air warming of 0.6 to 3.1 °C over a century and air cooling from 0.2 to 1.0 °C over a century with dominant warming phenomenon at the regional scale of the southwest United States.

**Table 3.** Summary of the Mann–Kendall trend test for annual and crop season maximum temperature.

| Locations | First Year | Last Year | Annual Maximum Temperature | | | | Crop Season Max. Temperature | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Test Z | Signific. | β | B | Test Z | Signific. | β | B |
| Abilene, TX | 1948 | 2017 | 0.94 | n.s. | 0.006 | 24.1 | −0.6 | n.s. | −0.005 | 32.8 |
| Albany, TX | 1918 | 2017 | −2.85 | ** | −0.01 | 26.2 | −4.61 | *** | −0.024 | 35.0 |
| Animas, NM | 1930 | 2017 | −1.2 | n.s. | −0.005 | 25.6 | −1.94 | + | −0.01 | 33.6 |
| Artesia, NM | 1918 | 2017 | −0.91 | n.s. | −0.003 | 25.3 | −1.24 | n.s. | −0.006 | 33.3 |
| Aztec, NM | 1930 | 2017 | 4.39 | *** | 0.018 | 18.8 | 4.21 | *** | 0.019 | 28.5 |
| Alamosa, CO | 1948 | 2017 | 2.83 | ** | 0.019 | 13.8 | 3.61 | *** | 0.019 | 23.4 |
| Fort Lewis, CO | 1918 | 2017 | 1.5 | n.s. | 0.006 | 14.2 | 2.25 | * | 0.008 | 23.2 |
| Alton, UT | 1918 | 2017 | 7.39 | *** | 0.031 | 13.8 | 7.63 | *** | 0.035 | 22.3 |
| Cedar, UT | 1949 | 2017 | 1.93 | + | 0.01 | 17.6 | 2.1 | * | 0.012 | 27.2 |
| Ajo, AZ | 1918 | 2017 | 4.24 | *** | 0.013 | 28.4 | 2.4 | * | 0.007 | 36.6 |
| Roosevelt, AZ | 1918 | 2017 | 3.91 | *** | 0.013 | 26.6 | 3.77 | *** | 0.013 | 35.3 |
| Ash Mountain, CA | 1927 | 2017 | 3.72 | *** | 0.013 | 23.8 | 2.8 | ** | 0.012 | 32.0 |
| Auberry, CA | 1918 | 2017 | −0.52 | n.s. | −0.002 | 23.3 | −0.25 | n.s. | −0.001 | 31.5 |
| Blythe, CA | 1918 | 2017 | 1.25 | n.s. | 0.004 | 31.1 | 3.55 | *** | 0.011 | 39.3 |
| Las Vegas, NV | 1949 | 2017 | 3.35 | *** | 0.016 | 25.4 | 2.29 | * | 0.01 | 35.6 |
| Tonopah, NV | 1955 | 2017 | 3.51 | *** | 0.022 | 17.5 | 3.45 | *** | 0.023 | 27.0 |

n.s., Non-significant. + Significant at 5%. * Significant at 1%. ** Significant at 0.1%. *** Significant at 0.01%.

The average annual minimum temperature showed a significantly increasing trend at 69% of the stations and 25% of the station with a non-significant increasing trend (Table 4). Only one station showed a non-significant decreasing trend in the annual average minimum temperature. Change in the minimum temperature represents a minimum temperature rise from 0.1 to 8 °C over the last century across the southwest Unites States. The greatest rise was observed at Las Vegas (NV), followed by Auberry (CA), while the lowest rise was observed at Cedar (UT). A negligible decrease in the minimum temperature was observed at Artesia (NM). These results show evidence of warming with an overall increase in maximum and minimum temperatures at the United States southwest region scale. These results are in agreement with Alexander et al. [56] who found a positive shift in the distribution of daily minimum temperature throughout the globe. They reported that the daily maximum temperature also increased but at a smaller magnitude. Evidence of significant positive trends in both maximum and minimum temperatures in the United States during the 1895–2017 period were reported by Gil-Alana [57] who found a higher increase in the minimum temperatures compared to the maximum temperature. Similar results were reported by Turkey and Sumer [58] who found a weak warming and cooling in the maximum temperature in comparison with significant warming of minimum temperature across Turkey. Arora et al. [59] reported 100-year temperature increase values of 0.92 and 0.09 °C in the maximum and minimum temperatures, respectively, over India. Gil-Alana and Sauci [60] indicated that the highest increase in air temperature was about 2.9 °C over the last 100 years observed at New Jersey and Rhode Island in the United States. Positive trend in air temperature was reported in Bangladesh during the 1961–2008 period [61]. For the period of 1966–2005 in Iran, Tabari and Talaee [62] reported an increase of 0.09 and 0.44 °C per decade in maximum and minimum temperatures, respectively. The change in the annual maximum and minimum temperatures increased with latitude at the rate of 0.003 °C/degree for Tmax and 0.007 °C/degree for Tmin while it decreased with the longitude at the rates of −0.0007 °C/degree and for Tmax and −0.0016 °C/degree for Tmin, respectively (Table 6). The change in temperatures is greater in the inland locations than the coastal region (Table 6). These results are consistent with the finding of Vose et al. [63] who reported that warming rates are greater at higher latitudes, driven in part by a decrease in snow cover and thus surface albedo. In other words, the northern regions of the contiguous United States have slightly more warming than other regions [63]. The average temperatures decreased with elevation due to adiabatic cooling [54].

**Table 4.** Summary of the Mann–Kendall trend test for annual and crop season minimum temperature.

| Locations | First Year | Last Year | Annual Minimum Temperature | | | | Crop Season Min. Temperature | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Test Z | Signific. | β | B | Test Z | Signific. | β | B |
| Abilene, TX | 1948 | 2017 | 2.14 | * | 0.008 | 11.0 | 0.24 | n.s. | 0.001 | 19.8 |
| Albany, TX | 1918 | 2017 | 0.81 | n.s. | 0.003 | 10.6 | −1.38 | n.s. | −0.004 | 19.2 |
| Animas, NM | 1930 | 2017 | 4.24 | *** | 0.028 | 4.5 | 3.99 | *** | 0.027 | 12.6 |
| Artesia, NM | 1918 | 2017 | −0.42 | n.s. | 0 | 6.7 | 1.99 | * | 0.007 | 14.9 |
| Aztec, NM | 1930 | 2017 | 4.8 | *** | 0.021 | 0.5 | 4.19 | *** | 0.016 | 9.2 |
| Alamosa, CO | 1948 | 2017 | 1.2 | n.s. | 0.006 | −4.9 | −0.1 | n.s. | 0 | 4.9 |
| Fort Lewis, CO | 1918 | 2017 | 2.8 | ** | 0.013 | −2.8 | 3.65 | *** | 0.014 | 5.0 |
| Alton, UT | 1918 | 2017 | 2.06 | * | 0.006 | −0.8 | −0.56 | n.s. | −0.002 | 6.7 |
| Cedar, UT | 1949 | 2017 | 0.24 | n.s. | 0.001 | 2.0 | −0.64 | n.s. | −0.003 | 10.5 |
| Ajo, AZ | 1918 | 2017 | 7.25 | *** | 0.027 | 13.8 | 6.66 | *** | 0.022 | 21.4 |
| Roosevelt, AZ | 1918 | 2017 | 4.99 | *** | 0.017 | 11.9 | 3.26 | ** | 0.012 | 20.2 |
| Ash Mountain, CA | 1927 | 2017 | 0.64 | n.s. | 0.002 | 10.1 | 0.34 | n.s. | 0.002 | 16.4 |
| Auberry, CA | 1918 | 2017 | 7.34 | *** | 0.046 | 5.7 | 6.67 | *** | 0.052 | 11.5 |
| Blythe, CA | 1918 | 2017 | 7.06 | *** | 0.028 | 11.3 | 6.83 | *** | 0.025 | 19.3 |
| Las Vegas, NV | 1949 | 2017 | 9.66 | *** | 0.08 | 6.6 | 8.96 | *** | 0.078 | 15.5 |
| Tonopah, NV | 1955 | 2017 | 6.14 | *** | 0.03 | 0.2 | 5.02 | *** | 0.035 | 7.7 |

n.s., Non-significant. + Significant at 5%. * Significant at 1%. ** Significant at 0.1%. *** Significant at 0.01%.

The annual temperature amplitude showed a decreasing trend at 10 stations, representing 63% of the stations and an increasing trend in the annual thermal amplitude at 6 stations (37%). However, thermal amplitude decrease was significant at 7 stations and the increasing trend was significant at three stations (Alton, Cedar City, and Ash Mountain) (Table 5). The increase in the minimum temperature varied greatly with locations from 0.1 to 7 times and averaged 1.8 times the increase in the maximum temperature. These results demonstrate the higher increase in the minimum temperature compared to the maximum temperature as reported by Mix et al. [64]. Mix et al. [64] found that the minimum temperature increased by 0.2 °C per decade, while the maximum temperature increased by 0.1 °C per decade in the San Luis Valley in Colorado. The asymmetric trends in maximum and minimum temperatures was reported by IPCC [65]. Ghasemi [66] also indicated greater increased in minimum temperature (0.34 °C per decade) than the maximum temperature (0.15 °C per decade) in Iran, while Folland and Karl [67] stated that the minimum temperature increases in general twice faster than the maximum temperature over the globe and Peng et al. [68] reported three times greater increase in the minimum temperature compared to the increase in the maximum temperature in the Philippines.

**Table 5.** Summary of the Mann–Kendall trend test for annual and growing season temperature amplitude.

| Locations | First Year | Last Year | Annual Temp. Amplitude | | | | Crop Season Temp. Amplitude | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Test Z | Signific. | β | B | Test Z | Signific. | β | B |
| Abilene, TX | 1948 | 2017 | −1.11 | n.s. | −0.005 | 13.4 | −0.91 | n.s. | −0.004 | 12.9 |
| Albany, TX | 1918 | 2017 | −3.56 | *** | −0.014 | 16.0 | −3.8 | *** | −0.018 | 15.8 |
| Animas, NM | 1930 | 2017 | 0.05 | n.s. | 0 | 15.4 | −4.72 | *** | −0.036 | 20.9 |
| Artesia, NM | 1918 | 2017 | 0.66 | n.s. | 0.002 | 18.5 | −2.16 | * | −0.008 | 18.0 |
| Aztec, NM | 1930 | 2017 | −0.37 | n.s. | −0.002 | 18.4 | 0.76 | n.s. | 0.004 | 19.3 |
| Alamosa, CO | 1948 | 2017 | 1.67 | + | 0.008 | 19.2 | 3.09 | ** | 0.02 | 18.3 |
| Fort Lewis, CO | 1918 | 2017 | −1.98 | * | −0.008 | 17.0 | −0.73 | n.s. | −0.003 | 18.1 |
| Alton, UT | 1918 | 2017 | 5.46 | *** | 0.023 | 14.5 | 6.93 | *** | 0.037 | 15.5 |
| Cedar, UT | 1949 | 2017 | 1.95 | + | 0.012 | 15.3 | 2.95 | ** | 0.015 | 16.9 |
| Ajo, AZ | 1918 | 2017 | −3.62 | *** | −0.012 | 14.6 | −5.72 | *** | −0.014 | 15.2 |
| Roosevelt, AZ | 1918 | 2017 | −0.82 | n.s. | −0.003 | 14.4 | 0.14 | n.s. | 0.001 | 15.2 |
| Ash Mountain, CA | 1927 | 2017 | 2.52 | * | 0.011 | 13.6 | 2.54 | * | 0.013 | 15.4 |
| Auberry, CA | 1918 | 2017 | −5.97 | *** | −0.051 | 18.0 | −5.53 | *** | −0.055 | 20.5 |
| Blythe, CA | 1918 | 2017 | −5.13 | *** | −0.021 | 19.6 | −4 | *** | −0.016 | 19.8 |
| Las Vegas, NV | 1949 | 2017 | −9.26 | *** | −0.065 | 19.1 | −9.57 | *** | −0.07 | 20.3 |
| Tonopah, NV | 1955 | 2017 | −2.51 | * | −0.012 | 17.5 | −2.55 | * | −0.014 | 19.7 |

n.s., Non-significant. + Significant at 5%. * Significant at 1%. ** Significant at 0.1%. *** Significant at 0.01%.

### *3.3. Trend Analysis in Crop Growing Season Maximum and Minimum Temperatures*

Crop growing season maximum temperature showed a significant increasing trend at 11 stations, representing 68.8% and a decreasing trend at 5 stations (43.8%) (Abulene, Albany, Animas, Artesia, and Auberry) of which two are significant (Table 3). Crop growing season maximum temperature increased at the rates varying from 0.07 to 0.35 °C per decade and averaged 0.15 °C per decade with more emphasis at Alton, AZ (Z-statistic = 7.63). On regional average, there was increase in the growing season maximum temperature at the rate of 0.08 °C per decade.

The crop growing season minimum temperature had increased during the study period at 12 stations (75%) and showed a non-significant decreasing trend at four stations. (Table 4). An increase in the crop growing season minimum temperature was significant at 10 stations and the increasing rates varied from 0.01 to 0.78 °C per decade and averaged 0.2 °C per decade. The greatest increase in the minimum temperature was observed at Las Vegas (NV), while the greatest decrease was observed at Albany (TX). The regional crop growing season minimum temperature had increased at the rate of 0.18 °C per decade, which is higher than the increase in the growing season maximum temperature. This was reflected in the growing season temperature amplitude which showed a decreasing trend at 63% of the stations. Temperature amplitude showed a significant increasing trend at 25% of the stations. The change in the crop growing season maximum and minimum temperatures increased with latitude at the rate of 0.0007 °C/degree for Tmax and 0.001 °C/degree for Tmin, while it decreased with the longitude at the rates of −0.0012 °C/degree for Tmax and −0.0019 °C/degree for Tmin (Table 6). Overall, the crop season minimum temperature increased faster than the maximum temperature. The results of this study are in agreement with Mix et al. [64] who found a significant increase in the growing season maximum and minimum temperature across the San Luis Valley in Colorado except at Alamosa station. Quian et al. [69] observed an increase in the crop growing season temperatures across Canada for the 1911–2000 period with early onset of the growing season, early end of the spring frost, and increased in the accumulated thermal units by crops and extension on the growing season duration and frost free period [70]. Similar findings were reported by Zhang et al. [71] who showed an increase in annual and seasonal maximum and minimum temperatures for the 1900–1998 period in Canada.

**Table 6.** Summary of the linear relationship between average annual and growing season precipitation and temperatures and temperature amplitude.

| Parameters | | Latitude | | Longitude | | Elevation | |
|---|---|---|---|---|---|---|---|
| | | Regression Equation | $R^2$ | Regression Equation | $R^2$ | Regression Equation | $R^2$ |
| **Annual precipitation** | Test Z | y = 0.0703x − 2.2524 | 0.0104 | y = 0.0837x + 9.4206 | 0.1122 | y = 0.0009x − 0.8825 | 0.2007 |
| | Slope β | y = −0.0271x + 1.0619 | 0.0059 | y = 0.051x + 5.7224 | 0.1592 | y = 0.0004x − 0.3171 | 0.1167 |
| | B | y = −11.732x + 753.43 | 0.0196 | y = 7.0354x + 1115.6 | 0.0533 | y = −0.0496x + 401.9 | 0.0407 |
| **Growing season precipitation** | Test Z | y = −0.056x + 2.0252 | 0.0114 | y = 0.0557x + 6.1866 | 0.0853 | y = 0.0005x − 0.5242 | 0.0984 |
| | Slope β | y = −0.0316x + 1.182 | 0.0374 | y = 0.021x + 2.3791 | 0.1244 | y = 0.0001x − 0.1017 | 0.0902 |
| | B | y = −22.836x + 943.62 | 0.2697 | **y = 14.247x + 1709.5** | **0.7949** | y = 0.0073x + 133.63 | 0.0032 |
| **Average annual Tmax** | Test Z | y = 0.5461x − 17.151 | 0.2372 | y = −0.1807x − 17.888 | 0.182 | y = 0.0012x + 0.73 | 0.1136 |
| | Slope β | **y = 0.0029x − 0.0916** | **0.3699** | y = −0.0007x − 0.0631 | 0.1357 | y = 7e−06x + 0.0015 | 0.2201 |
| | B | **y = −1.8529x + 87.49** | **0.6151** | y = −0.016x + 20.429 | 0.0003 | **y = −0.0069x + 30.122** | **0.8655** |
| **Average growing season Tmax** | Test Z | **y = 0.7442x − 24.387** | **0.3472** | y = −0.2341x − 24.045 | 0.2407 | y = 0.0016x − 0.0458 | 0.1713 |
| | Slope β | **y = 0.0043x − 0.1431** | **0.4835** | y = −0.0012x − 0.1242 | 0.2632 | y = 1e−05x − 0.0036 | 0.2584 |
| | B | **y = −1.6826x + 90.32** | **0.5657** | y = −0.016x + 29.258 | 0.0004 | **y = −0.0065x + 38.518** | **0.8627** |
| **Average annual Tmin** | Test Z | y = −0.0053x + 3.9961 | $2 \times 10^{-5}$ | y = −0.2588x − 24.801 | 0.2699 | y = −0.0014x + 5.3891 | 0.1104 |
| | Slope β | y = 0.0007x − 0.0064 | 0.0067 | y = −0.0016x − 0.1604 | 0.2271 | y = −8e−06x + 0.0284 | 0.0717 |
| | B | **y = −1.8415x + 70.278** | **0.5446** | y = 0.0085x + 6.3253 | $8 \times 10^{-5}$ | **y = −0.0074x + 13.864** | **0.8881** |
| **Average growing season Tmin** | Test Z | y = −0.0659x + 5.3938 | 0.0023 | y = −0.2707x − 26.856 | 0.2686 | y = −0.0014x + 4.639 | 0.0991 |
| | Slope β | y = 0.001x − 0.0182 | 0.011 | y = −0.0019x − 0.1945 | 0.2755 | y = −8e−06x + 0.0266 | 0.0669 |
| | B | **y = −1.9291x + 81.401** | **0.6165** | y = 0.1156x + 26.197 | 0.0155 | **y = −0.0071x + 21.569** | **0.846** |
| **Average annual temperature amplitude** | Test Z | y = 0.2935x − 11.719 | 0.035 | y = 0.1058x + 10.315 | 0.0319 | y = 0.0027x − 4.4474 | 0.2951 |
| | Slope β | y = 0.0004x − 0.0209 | 0.0013 | y = 0.0011x + 0.108 | 0.0834 | y = 1e−05x − 0.025 | 0.2221 |
| | B | y = 0.243x + 7.9584 | 0.0706 | y = −0.0312x + 13.069 | 0.0082 | y = 0.0004x + 16.072 | 0.0186 |
| **Average growing season temperature amplitude** | Test Z | y = 0.7772x − 28.843 | 0.188 | y = 0.0671x + 5.9679 | 0.0098 | y = 0.0032x − 5.1767 | 0.3316 |
| | Slope β | y = 0.003x − 0.114 | 0.0643 | y = 0.0009x + 0.093 | 0.0436 | y = 2e−05x − 0.03 | 0.2401 |
| | B | y = 0.2779x + 7.8162 | 0.0727 | y = −0.1468x + 1.3808 | 0.142 | y = 0.0006x + 16.975 | 0.029 |

## 4. Conclusions

Trend analysis in the ground-based historic annual and crop growing season precipitation and maximum and minimum temperatures at eighteen weather stations across the southwest United States is performed using the Mann–Kendall test and Sen's slope estimator and simple linear regression method. Precipitation data covered the 1930–2017 period, while the temperature data covered the 1902–2017 period. Annual precipitation showed increasing trends at 55.6% of the stations while the crop growing season total precipitation showed a non-significant variation at most of the stations. Annual maximum temperature increased at 75% of the stations at the rates that varied from 0.6 to 3.1 °C per century and annual minimum temperature had increased at 69% of the stations at the rates that varied from 0.1 to 8 °C over the last century, revealing a temperature rise across the southwest United States. However, the minimum temperature had increased at a greater rate than the maximum temperature. Crop growing season maximum and minimum temperatures had a significant increasing trend at 69 and 75% of the stations, respectively. This study revealed a change in climate across the southwest United States which calls for some specific actions of water resources management and planting under sustainable environment. The decrease in annual and crop growing season precipitation at some locations and the increase in temperatures might be translated in the increase in crop evapotranspiration demand versus reducing available water resources. Adaptation strategies to climate change should be adopted and urgent collaborative actions should be taken at different levels of decisions from the crop producers, environmentalists, crop consultants, universities researchers, policy makers, and others to tackle the effects of climate change and to create favorable crops production and sustainable environmental conditions for the present and future generations. This study shows an increase in precipitation at most of the stations and an increasing trend in air temperatures across the southwest United States, and the future research may investigate the trend in crop and reference evapotranspiration and the aridity index across the region on the monthly time scale mostly during the crop growing season to better understand the distribution patterns and the variability in the crop growing season. This future study may help in better water management and planning under rainfed and irrigated agriculture and environmental and hydrological studies. Therefore, adaptation efforts to climate change should target conservative water resources management technologies, crop breeding for more drought, and heat tolerant varieties to increase crop productivity under adverse weather, and promote and support surface runoff water harvesting and the development of small-scale irrigation across the southwest United States and other regions with similar climate. Moreover, similar study might be conducted at the global scale using ground climate data paleoclimate data to understand climate change and patterns across the globe with similarities and divergences among similar and different climatic zones.

**Author Contributions:** Study conception and design: K.D. and K.K.; Data analysis and processing: K.D., K.K., A.B. Writing—original draft preparation, writing—review and editing, visualization; K.D., K.K., A.B., L.D., P.M.N. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was not supported by external funding agency.

**Acknowledgments:** Authors are grateful to the United States Department of Commerce, National Oceanic and Atmospheric Administration National (NOAA) for the precipitation and temperature data set used in this study. We are also very appreciative to the New Mexico State University for the full support of this research.

**Conflicts of Interest:** The authors declare no conflict of interest.

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