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June Temperature Trends in the Southwest Deserts of the USA (1950–2018) and Implications for Our Urban Areas

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Abstract: Within the United States, the Southwest USA deserts show the largest temperature changes (1901–2010) besides Alaska, according to the most recent USA National Climate Assessment report. The report does not discuss urban effects vs. regional effects that might be evident in trends. Twenty-five temperature stations with ca. 68-year records (1950 to 2018) have been accessed from US Global Historical Climate Network archives. Land cover data are accessed from a National Land Cover Database. June results considering both urban and rural sites show an astounding rate per year change among sites ranging from −0.01 to 0.05 °C for maximum temperatures and 0.01 to 0.11 °C for minimum temperatures (−0.8 to 3.2 °C, and 0.8 to 8.0 °C for the entire period). For maximum temperatures, almost half of the sites showed no significant trends at a stringent 0.01 level of statistical significance, but 20 of 25 were significant at the 0.05 level. For minimum temperatures, over 75% of sites were significant at the 0.01 level (92% at 0.05 level of significance). The urban-dominated stations in Las Vegas, Phoenix, Tucson, and Yuma show large minimum temperature trends, indicating emerging heat island effects. Rural sites, by comparison, show much smaller trends. Addressing heat in our urban areas by local actions, through collaborations with stakeholders and political resolve, will aid in meeting future urban challenges in this era of projected global climate change and continued warming.

Keywords: June mean monthly maximum and minimum temperatures; desert SW USA; trends; urban; rural areas; local climate zones; land cover

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1. Introduction

The purpose of this paper is to present a view of the past ca. 68 years of temperature changes for the two desert areas of the Southwest USA (see Figure 1—these are the Mojave desert in Nevada and California, and the Sonoran desert in California and Arizona). The emphasis is on noting that in [1], no temperature trends comparing urban vs. rural sites are explicitly analyzed. In some earlier work prior to 1990 [2,3], substantial effects of urbanization on within temperature time series data in the Southwest and USA were identified. The recent national assessment [1] does, however, present ideas on urban vulnerabilities that are expected, and temperature changes of some individual sites are illustrated. For Las Vegas, Phoenix, and Tucson, there has been a large focus on climate and sustainability research in the past couple of decades (e.g., [4–7]). Future scenario data for SW USA show that significant changes are to come both for temperatures and precipitation in addition to changes that have already taken place [1,8,9]. As major population growth ensues and issues of water availability, energy, air quality, and health further intensify in the Southwest, increasing attention should be given to climate changes that the populous will experience in cities [10,11]. Urban area temperature rates of change are already an order of magnitude greater than rural areas, as demonstrated below, and, thus, it is imperative that more specific attention be given to changes for urbanized regions. It is gratifying to know that the emphasis on climate change in cities is apparently to come in more detail as part of the goals of [12].

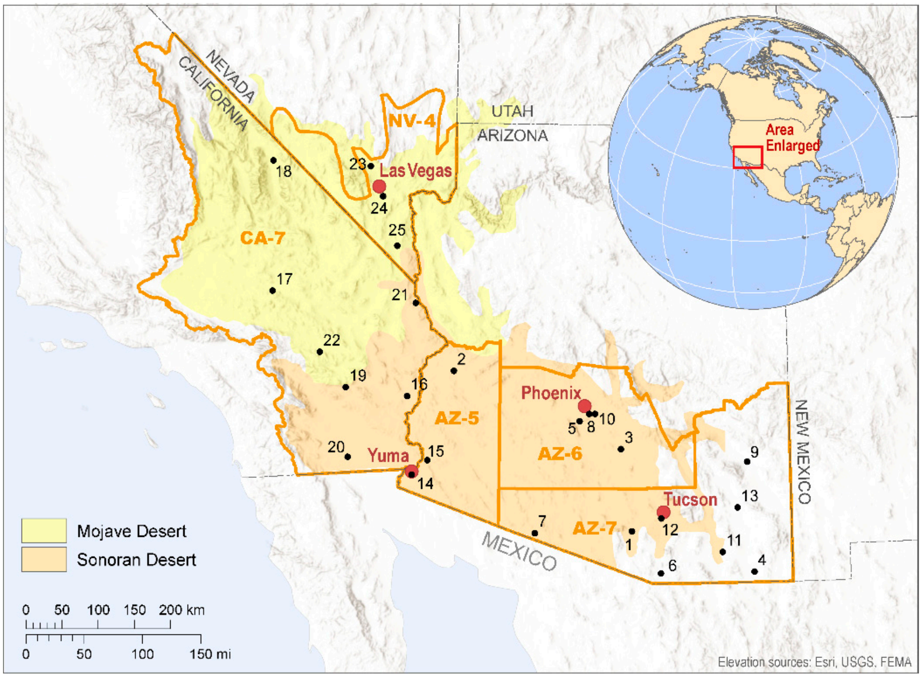

Figure 1. Five climate divisions designated by National Ocenaic and Atmospheric Administration (NOAA), individual stations, four major urban locations of Las Vegas, Phoenix, Tucson, and Yuma (see Tables 1–3).

The two deserts are shown together with five NOAA climate divisions (see Figure 1 for climate divisions and individual sites used). Essentially, parts of CA-7 and NV-4 divisions represent the Mojave, while parts of southern CA-7, AZ-5, 6, and parts of 7 represent the Sonoran desert. To round out AZ-7, data for some sites adjacent to the Sonoran desert are used in SE Arizona. This paper explores the results of trend analysis for the period 1950–2018 for these divisions and individual sites with data from [13,14]. There are 25 sites with near full records (90% complete) over the period 1950–2018 chosen from within these divisions, particularly the four largest urban areas of Las Vegas (NV), Phoenix, Tucson, and Yuma (AZ). In summer, mean monthly maximum temperatures typically exceed 38 °C (100 °F) across both deserts, and the Mojave is the scene of the world's highest recorded temperature of 56.6 °C (134 °F) at Death Valley at −59 m below sea level (#18 in Figure 1). The overall region receives little rainfall on average, but the Sonoran desert does experience a so-called summer monsoon, with secondary amounts of rainfall in winter [15,16]. Summer rains usually commence in July. The Mojave, by contrast, does not have a summer monsoon regime but does receive winter precipitation. Values range from close to 0.0 to over 250 mm per year across these deserts with elevation effects on moisture and temperature from place to place. The sites range in elevation from below sea level to over 1400 m. The month of June is chosen for this paper, as a clearer signal of the urban effect on temperature change may typically be detected due to clearer, calmer weather and fewer precipitation effects on urban temperature changes during this month. Mean monthly maximum and minimum June temperatures are analyzed at the divisional scale and for individual sites across the region. The region is dominated by dry subtropical air masses, especially in the month of June [17]; however, temperature variability relates significantly to changing frequencies of several synoptic types through time, as discussed below.

Table 1. Stations used in analysis and descriptors of location.

STATION ID	NAME	MAP CODE	LATITUDE (°)	LONGITUDE (°)	ELEVATION (m)
		ARIZONA			
USC00020287	ANVIL RANCH	1	31.979	−111.384	841
USC00020949	BOUSE	2	33.943	−114.024	282
USC00021314	CASA GRANDE NM	3	32.995	−111.537	433
USW00093026	DOUGLAS BISBEE INT AP	4	31.458	−109.606	1251
USC00024829	LAVEEN 3 SSE	5	33.337	−112.147	346
USC00025924	NOGALES 6 N	6	31.455	−110.968	1055
USC00026132	ORGAN PIPE CACTUS NM	7	31.956	−112.800	512
USW00023183	PHOENIX AIRPORT	8	33.428	−112.004	337
USC00027390	SAFFORD AG CENTER	9	32.815	−109.681	900
USC00028499	TEMPE ASU	10	33.426	−111.922	356
USC00028619	TOMBSTONE	11	31.712	−110.069	1420
USW00023160	TUCSON INT AP	12	32.131	−110.955	777
USC00029334	WILLCOX	13	32.255	−109.837	1271
USW00003145	YUMA MCAS	14	32.650	−114.617	65
USW00003125	YUMA PROVING GROUND	15	32.836	−114.394	99
		CALIFORNIA			
USW00023158	BLYTHE ASOS	16	33.619	−114.714	120
USW00023161	BARSTOW DAGGETT AP	17	34.854	−116.786	584
USC00042319	DEATH VALLEY	18	36.462	−116.867	−59
USC00043855	HAYFIELD PUMPING PLANT	19	33.704	−115.629	418
USC00044223	IMPERIAL	20	32.849	−115.567	−20
USW00023179	NEEDLES AIRPORT	21	34.768	−114.619	271
USC00049099	TWENTYNINE PALMS	22	34.128	−116.037	602
		NEVADA			
USC00262243	DESERT NATIONAL WILDLIFE RANGE	23	36.438	−115.360	888
USW00023169	LAS VEGAS INT AP	24	36.072	−115.163	665
USC00267369	SEARCHLIGHT	25	35.466	−114.922	1079

Table 2. June division temperature data, linear regression of temperature on time (year) showing r values and significant levels (sig), and correlations with Dry Tropical and Dry Moderate June synoptic air mass frequencies (defined in the text). * correlation r value and significance level—temp vs. year; ** correlation r value—temp vs. SSC Type air mass frequency.

			Mean 1950–2018			**DM**	**DT**
Division	T_{max} °C	r *	sig *	°C/year	N years change (°C)	r **	r **
AZ-5	38.8	0.42	0.000	0.033	2.28	−0.81	0.55
AZ-6	38.3	0.36	0.002	0.025	1.73	−0.61	0.27
AZ-7	34.7	0.43	0.000	0.028	1.93	−0.68	0.41
CA-7	34.4	0.40	0.001	0.035	2.42	−0.67	0.73
NV-4	34.8	0.39	0.001	0.034	2.35	−0.75	0.82
Division	T_{min} °C	r *	sig *	°C/year	N years change (°C)	r **	r **
AZ-5	21.1	0.46	0.000	0.034	2.35	−0.69	0.33
AZ-6	20.2	0.52	0.000	0.042	2.90	−0.54	−0.03
AZ-7	16.5	0.45	0.003	0.033	2.28	−0.57	0.03
sCA-7	18.1	0.50	0.000	0.037	2.55	−0.65	0.70
NV-4	19.0	0.61	0.000	0.048	3.31	−0.51	0.71

Table 3. Time Trends of Mean June maximum and minimum temperature by site. * correlation r value and significance level.

ARIZONA	MAP CODE #	r *	Sig *	T_{max}/Year (°C)	r *	Sig *	T_{min}/Year (°C)
ANVIL RANCH	1	0.20	0.13	−0.013	0.23	0.08	0.021
BOUSE	2	0.26	0.05	0.021	0.64	0.00	0.059
CASA GRANDE NM	3	0.14	0.27	0.010	0.55	0.00	0.058
DOUGLAS BISBEE INT AP	4	0.49	0.00	0.035	0.37	0.00	0.026
LAVEEN 3 SSE	5	0.55	0.00	0.047	0.61	0.00	0.075
NOGALES 6 N	6	0.43	0.00	0.035	0.32	0.01	0.033
ORGAN PIPE CACTUS NM	7	0.34	0.01	0.026	0.49	0.00	0.048
PHOENIX INT AP	8	0.48	0.00	0.038	0.79	0.00	0.113
SAFFORD AG CENTER	9	0.38	0.00	0.026	0.58	0.00	0.054
TEMPE ASU	10	0.12	0.36	0.009	0.65	0.00	0.099
TOMBSTONE	11	0.30	0.01	0.024	0.54	0.00	0.043
TUCSON INT AP	12	0.56	0.00	0.043	0.58	0.00	0.049
WILLCOX	13	0.39	0.00	0.026	0.62	0.00	0.076
YUMA MCAS AP	14	0.20	0.11	0.016	0.58	0.00	0.045
YUMA PROVING GROUND	15	0.36	0.01	0.033	0.35	0.00	0.027
CALIFORNIA							
BLYTHE ASOS AP	16	0.27	0.03	0.031	0.16	0.18	0.012
BARSTOW DAGGETT AP	17	0.42	0.00	0.040	0.48	0.00	0.043
DEATH VALLEY	18	0.45	0.00	0.040	0.27	0.03	0.027
HAYFIELD PUMPING PLANT	19	0.40	0.00	0.036	0.15	0.22	0.011
IMPERIAL	20	0.31	0.01	0.025	0.24	0.05	0.019
NEEDLES AIRPORT	21	0.49	0.00	0.044	0.57	0.00	0.048
TWENTYNINE PALMS	22	0.12	0.15	0.016	0.53	0.00	0.052
NEVADA							
DESERT NATIONAL WILDLIFE RANGE	23	0.26	0.04	0.020	0.45	0.00	0.037
LAS VEGAS INT AP	24	0.29	0.01	0.026	0.81	0.00	0.096
SEARCHLIGHT	25	0.27	0.04	0.023	0.41	0.00	0.034

2. Data and Methods

Two sources of climate information were accessed from the website archives of the National Oceanic and Atmospheric Administration's National Centers for Environmental Information: (a) climate division data for June for maximum and minimum temperatures [13], and (b) individual station data from Climate Data Online link, which includes Global Historical Climate Network (GHCN) sites for the month of June (maximum and minimum temperatures) for the period 1950 to 2018 [14]. Temperatures are shelter height or so-called canopy layer air temperatures (particularly important to emphasize for urban sites [18]).

Detailed information about these databases may be found in [19–22]. In addition to temperature data, several sources were investigated to learn of the impact of land cover around individual sites, especially within 500 m of each site [23–28]. It was not possible to trace detailed land conditions at fine resolution back to 1950 for all sites. This remains as a future goal for analysis. The main focus in this regard is on the four major urban sites in the region—Las Vegas, Phoenix, Tucson, and Yuma. Metadata of individual sites were consulted from [14] for completeness of records, station shifts during the time period, instrument changes, and modernization that occurred throughout the national network. In addition, it was possible to provide estimates of land cover and to provisionally estimate a Local Climate Zone (LCZ) associated with each of 4 major urban stations using methods of [29,30]. There are 25 stations chosen, which have the most complete records for 1950–2018, although with some missing data for some sites (see Figure 1). These sites were 90% complete, and no major multi-year data gaps through time in the data. Central and northern AZ areas within the Mojave desert are excluded due to incomplete temporal records. A simple linear regression trend analysis and ANOVA were performed similar to [1], and identification of significant changes and rates of temperature changes over the time period were determined. The results are presented in Tables 1–3 for divisional and individual sites.

A more specific analysis was performed for four urban locations. The natural environment is used as a rural reference and not irrigated farm fields nor suburban areas to define rural to compare with urban environments. In [31], it has been noted that sites of irrigated landscapes in comparison to dry landscapes used as a rural reference station can influence urban vs. rural temperature determination by as much as 3 °C, virtually equivalent to dimensions of urban effects on temperature. In order to achieve standardizing using desert sites as rural, distances, and elevations from desert terrain to urban sites had to range from 25–60 km and 34–223 m elevation differences, assuring, at the same time, that intervening terrain is typically flat between the urban and desert sites chosen. Elevation alone could affect urban versus rural temperature comparisons on the order of 0.17 to 1.0 °C because, as illustrated below, there is a significant correlation between elevation and June mean monthly maximum and minimum temperatures among the 25 sites, but as will be seen below, these differences are relatively minor effects compared to land cover differences. All urban vs. rural comparisons include corrections for these elevation differences from the linear regression coefficient of temperature change per elevation.

The Spatial Synoptic Classification (SSC) catalog of Sheridan [32] was consulted to extract the month of June frequencies of several synoptic air mass types in order to relate to variations of temperatures for the period 1950–2018 and to learn of related shifts in frequencies in June over the 1950–2018 period [17]. The most frequent types for June in this desert region are the so-called DT (dry tropical) and DM (dry moderate). The DT (dry tropical) weather type is similar to the continental Tropical air mass; it represents the hottest and driest conditions found at any location. There are two primary sources of DT as a weather type (17): either it is advected from the desert regions, such as the Sonoran or Sahara Desert, or it is produced by rapidly descending air, whether via orography (such as the chinook effect) or strong subsidence [32]. The DM air is mild by comparison. It has no traditional analog but is often found with zonal flow in the middle latitudes, especially in the lee of mountain ranges. It also arises when a traditional air mass, such as continental Polar or maritime Tropical (MT), has been advected far from its source region and has, thus, been modified considerably (17). In [33], for the month of May over the period 1990–2004 in Phoenix, AZ, 64% of the days were typed DT with light winds (<5 m s^{-1}), and another 20% of days were DM associated with cool air intrusions related to troughs that had developed in the Western USA. Occasionally, in June, MT or MM (moist moderate) weather types do occur, but these are more typical from July to September in the SW and play a minor role in June. Generally, it holds true that when DM is prevalent, troughing over the Southwestern USA occurs with cooler upper level and surface temperatures. For example, a significant number of DM days (upwards of 5 per month) at Phoenix tend to reduce the mean monthly minimum temperature by over 1.5 °C [33].

3. Results

Table 2 lists mean June temperatures for the 1950–2018 period and trend analysis of each division's June mean maximum and minimum temperature (T_{max} and T_{min}) over this time period. June T_{max} averages 34.4–38.8 °C across the divisions (some 93.9 °F and 101.8 °F), with daily extremes considerably higher. At this division scale, all divisions have significant trends upwards for both June T_{max} and T_{min}. As indicated in [1], the SW USA region has the largest summer temperature increases compared to other US regions except for Alaska, increasing 1.0–1.5 °C in just the last few decades. Over the last almost 70 years, temperatures have changed 1.7–2.4 °C for T_{max} and 2.3–3.3 °C for T_{min} across these five climate divisions.

Daily catalogs of DT and DM frequencies for June for 1950–2018 are used here from [32] for Las Vegas (#24), Barstow-Daggett (#17), Yuma (#14), and Tucson (#12) to represent division synoptic types experienced across the region. Correlations between monthly frequencies of DT and DM, and mean monthly T_{max} and T_{min} for CA-7, NV-4, AZ-5, 6, and 7 were determined to learn if changes in the weather types are significantly related to temporal changes in T_{max} and T_{min} at these sites. The r values are listed in Table 2. This analysis provides insight into the year-to-year impacts of synoptic-scale drivers of T_{max} and T_{min} variations. There is a negative relation between climate division temperatures and frequency of DM weather types (DM induces cooling), similar to what was identified by [33] over a shorter 15-year time period. There is a positive effect of increases in DT weather types on T_{max} and T_{min} through time. However, there appears to be more variability of the strength of the regressions than for the DM type. The monthly T_{min} values for AZ-6 and 7 are not significantly correlated with changes in DT, because DT percentages of days for June are exceedingly high and minor shifts do not significantly impact temperatures for the month. In CA-7, DM has decreased over time, while DT types have significantly increased. In the more northerly NV-4, no significant changes have taken place for the DM frequencies, but a positive increase in frequencies has occurred for DT. In the AZ divisions, no significant changes in DT have taken place, but significant drop offs of DM frequencies have occurred, similar to short-term changes shown in [33].

Table 3 shows the 25 sites alphabetically by state with the numbers identifying their location in Figure 1. Across the five climate divisions, from 1950–2018 June T_{max} differs by 34.4 to 38.8 °C and for T_{min}, 16.5 to 21.1 °C (some 4–5 °C spread across the five divisions for both). Among the 25 sites, T_{max} ranges from 35 to 40.8 °C; T_{min}, 12.8 to 27.4 °C (a range of 5.8 °C for T_{max} and 14.6 °C for T_{min}). The 25 sites are representative for the divisional T_{max}, but illustrate, as expected, much more spatial variability in relation to the division data for T_{min}. Temperature trends among the 25 stations for T_{max} were significantly positive over time for 20 of the 25 sites, whereas 22 of the 25 sites showed strong significant increases over time for T_{min}. Holding aside the four urban sites (they are discussed below), the other 21 sites' rates of change per year (T_{max}/year) ranged from +0.02 to +0.044 °C/year (+1.4 to +3.0 °C over the period). For T_{min}, rates of change per year (T_{min}/year) ranged from +0.019 to +0.058 °C/year (or +1.3 to +4.0 °C). In [9], several sites are shown on a map as having T_{max} changes on the order of +1.5 °C for the period 1901–2010, and T_{min} changes of +3.0 °C for a few sites. Thus, over the shorter, recent, albeit mostly overlapping, 68-year period, there are comparable changes equivalent to the entire 110-year period of 1901–2010. Since just 1990, changes across the sites excluding urban sites ranged from +0.8 to 2.9 °C for T_{max} and +1.0 to +3.8 °C for T_{min}. The data results indicated in Tables 2 and 3 illustrate the continuing and, in fact, increasing rates of temperature changes for non-urban locations in the SW region, especially for T_{min}.

Information on land cover around each of the 25 sites (urban is included) was obtained by access to [23–28], in addition to Bright Light Indices (BI) data from [25] and used by [34], an indication of the amount of urbanization. From these sources, it was possible to estimate % shrub (% shrub), % cropland (% crop), % developed land (% dev), and density of night lights (BI) within 500 m of each location. Percent developed includes sub-categories open, low intensity, medium intensity, and high intensity. For this research, total developed percentages were used. These data are analyzed together with T_{max}, T_{min}, T_{max}/year, and T_{min}/year. A correlation analysis was employed using spatial variables of latitude (LAT), longitude (LONG), elevation (ELEV), % shrub, % crop, % dev, and BI (see correlation matrix in Table 4). The land cover data and light data are from the recent decade.

ELEV significantly impacts T_{max} and T_{min} over the 25 sites (r = −0.89 and −0.77, respectively) as temperature generally decreases with elevation within the region. LONG does correlate with temperatures as, from southeast to northwest across the region, there is a general downward elevation change (of ca. 1500 m). LONG changes by 7°, whereas T_{max} increases by +2 °C and T_{min} by +5 °C. LAT changes by 5° among the sites and correlates with T_{min} (r = 0.43). The impact attains 4.7 °C across the region. However, T_{max}/year and T_{min}/year do not correlate with changes in ELEV. Significant correlations resulted between T_{min}/year and % shrub (r = −0.61), % dev (r = 0.74), and BI (r = 0.76). Fewer shrub environments were highly correlated with increased development and impervious surfaces around sites (r = −0.79). The Bright Lights Index increased with lessening % shrub (with r = −0.68). These findings are consistent with expected stronger land cover effects during minimum temperature time of day than during the heat of the day. However, when excluding the four large urban sites, there are no significant relations among the land cover variables and temperature variables, as overall most sites are dominated by high shrub percentages since 1950.

Table 4. Correlation matrix of location, land cover, and temperature variables. Land cover variables defined in the text. Underlined r values significant at 0.05 level.

	ELEV	T_{max}	T_{min}	T_{max}**/Year**	T_{min}**/Year**	**LAT**	**LONG**	**% Shrub**	**% Crop**	**% dev**	**BI**
ELEV	1	$\underline{-0.89}$	$\underline{-0.77}$	$\underline{-0.14}$	$\underline{-0.05}$	−0.26	$\underline{0.56}$	$\underline{-0.01}$	0.04	$\underline{-0.00}$	$\underline{-0.14}$
T_{max}		1	0.76	0.10	0.16	0.18	−0.30	$\underline{-0.03}$	$\underline{-0.02}$	0.04	0.11
T_{min}			1	0.36	0.16	$\underline{0.43}$	$\underline{-0.52}$	$\underline{-0.12}$	$\underline{-0.18}$	0.25	0.25
T_{max}/year				1	0.01	0.14	$\underline{-0.13}$	0.00	$\underline{-0.24}$	0.16	$\underline{-0.08}$
T_{min}/year					1	0.14	0.21	$\underline{-0.61}$	$\underline{-0.14}$	$\underline{0.74}$	$\underline{0.76}$
LAT						1	$\underline{-0.74}$	0.06	$\underline{-0.14}$	0.03	0.08
LONG							1	$\underline{-0.29}$	0.24	0.15	0.08
% shrub								1	$\underline{-0.24}$	$\underline{-0.79}$	$\underline{-0.68}$
% crop									1	$\underline{-0.26}$	$\underline{-0.18}$
% dev										1	$\underline{0.83}$
BI											1

Within the five divisions there are four major cities—Las Vegas, NV (#24), Phoenix (#8), Tucson (#12), and Yuma (#14), AZ, with current populations of ca. 0.62M, 1.55M, 0.5M, and 0.09M, respectively. The climate data used were from major airports either central to the metropolitan areas (i.e., Las Vegas and Phoenix) or on the edge but impacted by urban growth (Tucson and Yuma). Figure 2 illustrates regional and local placement of these sites and land cover within 500 m and at some distance from them. The June T_{max} and T_{min} time series and urban-rural differences ($T_{maxU\text{-}R}$ and $T_{minU\text{-}R}$) between the urban-affected airport sites and rural desert sites are shown in Figure 3 and listed in Table 5. Urban-rural station pairs in Table 5 are listed by #'s in Figure 1.

Table 5. UHI estimates ($T_{U\text{-}R}$). Mean urban-rural estimates (UHI) for 1950–2018, r value of UHI trends over time, significance level, rate of change of UHI/year, and recent 2010–2018 mean UHIs. See map code pairing #'s in (). Yuma Valley station near Yuma Airport with short record is used to show irrigated rural area comparison.

UHI Estimates ($T_{U\text{-}R}$**)**	**1950–2018**	**1950–2018**	**Sig Level**	**1950–2018**	**2010–2018**
Urban Area Airports	Mean $T_{U\text{-}R}$ (°C)	r of $T_{U\text{-}R}$ vs. Year	of r.	$T_{U\text{-}R}$/Year Rate	Mean $T_{U\text{-}R}$ (°C)
LasVegas $T_{maxU\text{-}R}$ (24–23)	0.20	0.05	0.709	0.001	0.90
LasVegas $T_{minU\text{-}R}$ (24–23)	4.79	0.80	0.000	0.057	6.50
Phoenix $T_{maxU\text{-}R}$ (8–3)	−0.59	0.48	0.000	0.028	−0.15
Phoenix $T_{minU\text{-}R}$ (8–3)	4.64	0.62	0.000	0.054	4.33
Tucson $T_{maxU\text{-}R}$ (12–17)	−0.21	0.81	0.000	0.058	4.08
Tucson $T_{minU\text{-}R}$ (12–17)	3.16	0.56	0.000	0.031	1.02
Yuma $T_{maxU\text{-}R}$ (14–15)	−0.03	0.44	0.001	−0.013	0.23
Yuma $T_{minU\text{-}R}$ (14–15)	−0.03	0.52	0.000	0.017	0.20
Yuma—Yuma Valley Max	1.10	0.70	0.000	0.073	n/a
Yuma—Yuma Valley Min	3.79	0.77	0.000	0.067	n/a

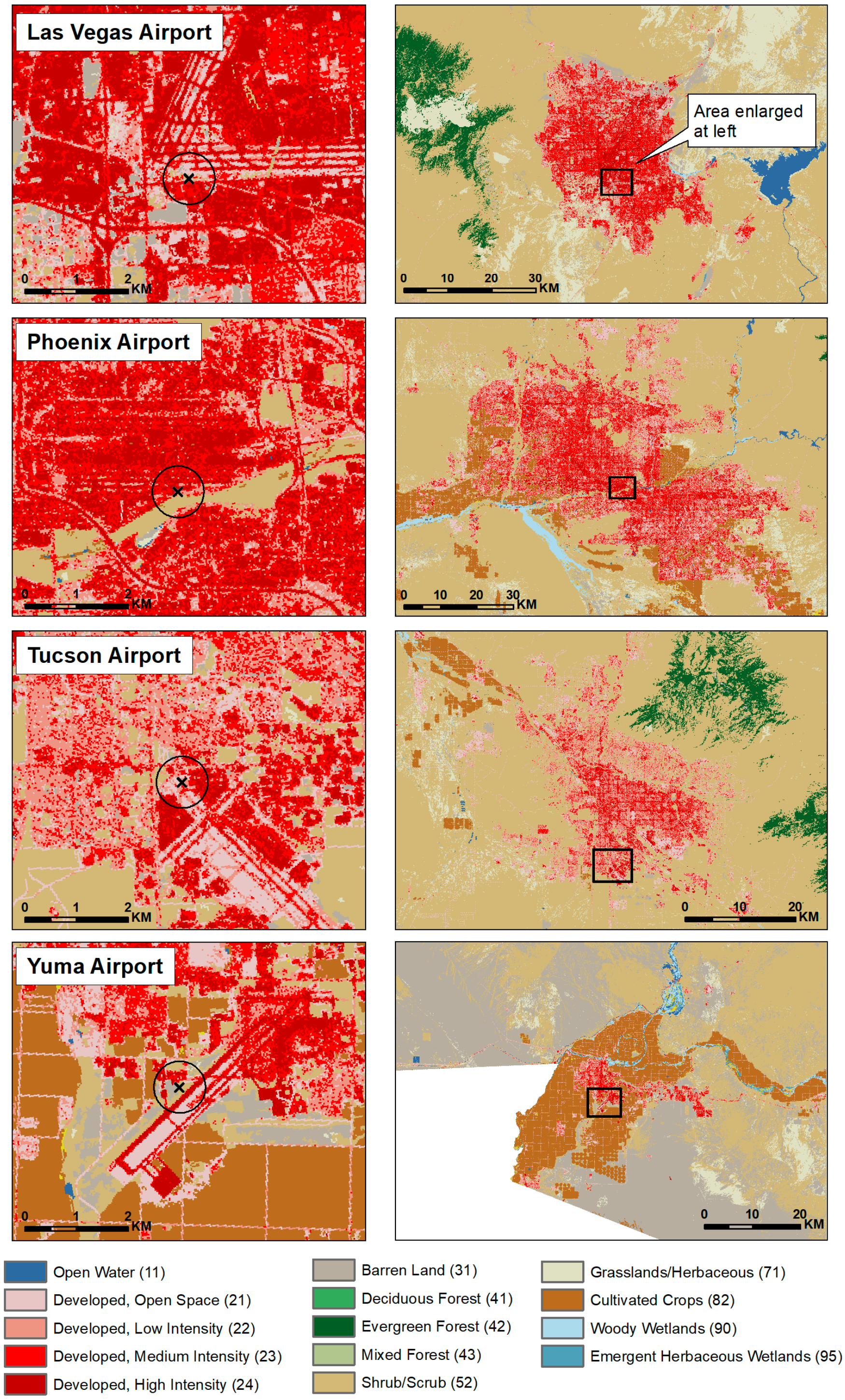

Figure 2. Four airport urban sites. Right panel shows urban extent and land cover; left panel is the zoomed-in view showing weather site placement and 500 m circle around each site. There have been some station moves locally within the airports over time. At times of T_{min} and T_{max}, prevailing wind regimes show SW for Las Vegas; E (night) to W (day) for Phoenix; SE (night) to SW (day) for Tucson; and NE (night) to SW (day) for Yuma.

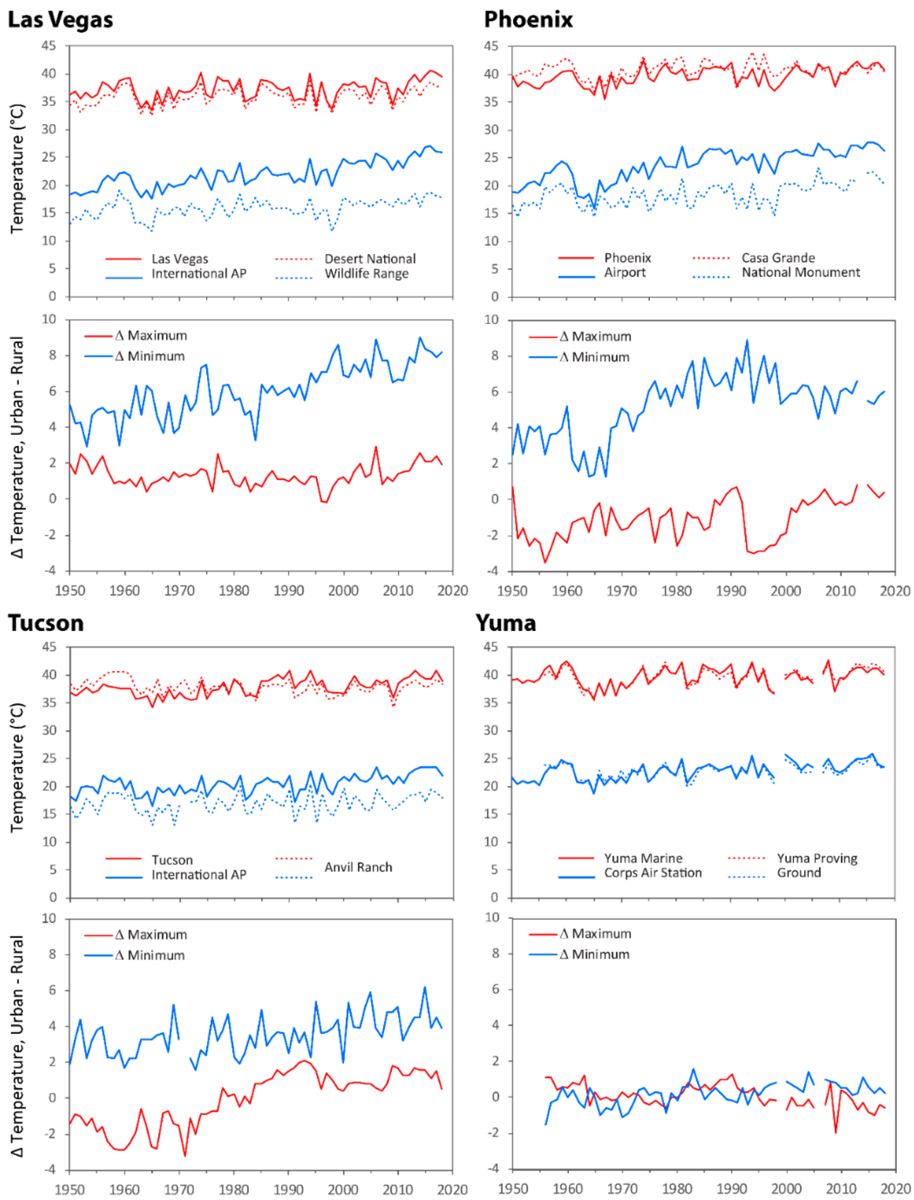

Figure 3. Four urban airport sites and rural reference sites showing June maximum and minimum temperatures and urban-rural time series (see Figure 2). Red lines refer to maximum temperatures; blue lines, minimum temperatures. Lower panel per site provides a measure of the day and night urban-rural estimates (UHI). All values in °C.

It should be emphasized that the airport sites, although having urban effects, are not necessarily representative of all LCZ zones found in these cities, nor the cities as a whole. A major reason is the airport geographical position within or peripheral to the cities, and because they only represent basically a few kinds of urbanized LCZs that have been recently classified by researchers [30,31]. The urban sites chosen are typical of LCZs E (which after [30], is labeled bare rock or paved) and some secondary effects of LCZ 6 and 8 (open low rise and large low rise, typical of effects of commercial buildings located on airports). The rural sites are, for the most part, LCZ C (bush, scrub desert with land cover mostly sand or bare soil). The airport sites were in LCZ C or D prior to major urbanization near and around them. In [26], for example, land cover changes for the Phoenix airport were analyzed since the airport's construction and substantiated this premise.

It is quite apparent that major temperature changes have occurred since 1950 at the urban-impacted airport sites relative to the rural desert sites, due to development near and around the airports, particularly for T_{min} (see Figure 3). Rates of change of $T_{maxU\text{-}R}$ and $T_{minU\text{-}R}$ (or $T_{maxU\text{-}R}$/year and $T_{minU\text{-}R}$/year) are as follows: +0.001, +0.028, +0.058, and −0.013 °C/year for $T_{maxU\text{-}R}$/year; and +0.057, +0.054, +0.031, and +0.017 °C for $T_{minU\text{-}R}$/year for station pairs of Las Vegas-desert, Phoenix-desert, Tucson-desert, and Yuma-desert, respectively. This corresponds to 1950–2018 overall changes of +0.07, +1.93, +4.0, and −0.90 °C for $T_{maxU\text{-}R}$ (r values for the trend analysis are 0.05, 0.48, 0.81, and 0.44, respectively, and with the exception of Las Vegas, station changes over time are statistically significant at the 0.05 level). For $T_{minU\text{-}R}$ the overall changes are +3.93, +3.73, +2.14, and +1.17 °C (r values are 0.80, 0.62, 0.56, and 0.52 for the trend analysis and are statistically significant at the 0.05 level). The larger changes of $T_{minU\text{-}R}$ at Las Vegas and Phoenix likely relate to their more central locales within each metropolitan area, larger airports, and larger urban area expansions through time. Tucson and Yuma sites are more peripherally located and not "surrounded" as much by urban or city surfaces (see Figure 2). At the smaller city of Yuma, the immediate grounds of the airport, in a sense, resembles desert terrain, with further away landscapes consisting of much-irrigated agriculture beyond the airport in addition to the smaller city area. Daytime changes over time are smaller than nighttime by comparison for each respective pairing, with the exception of Tucson's changes for $T_{maxU\text{-}R}$. Indeed, the $T_{maxU\text{-}R}$ changes for Tucson of +4.0 °C may be due to station or instrument issues through time in addition to major land use changes [35]. The rates of change of +0.057, +0.054, +0.031, and +0.017 °C for $T_{minU\text{-}R}$/year for station pairs of Las Vegas-desert, Phoenix-desert, Tucson-desert, and Yuma-desert, respectively, rank generally with BI Indices of 109, 94, 50, and 50 and % dev land of 90%, 91%, 50%, and 20%. For recent data since 2010, June $T_{maxU\text{-}R}$ and $T_{minU\text{-}R}$ values averaged +0.9 and +6.5 °C for Las Vegas; −0.15 and +4.33 °C for Phoenix; +4.08 and +1.02 °C for Tucson; and +0.23 and +0.20 °C for Yuma. Overall, the differences of $T_{minU\text{-}R}$ across the sites are generally consistent with variations of the BI index and % dev values.

4. Discussion and Conclusions

The $T_{minU\text{-}R}$ values (what might be cautiously called the UHI as represented by a specific urban LCZ) compare favorably with previous research. In [36], estimates are presented of maximum nocturnal heat island intensities for North America, Europe, and wet and dry Sub-tropical environments, with the dry Sub-tropical cities' UHIs ranging from ca. 4 to 7 °C for populations of 0.05 M to 5.0 M. For the cities of Las Vegas and Phoenix, $T_{minU\text{-}R}$ is consistent with dry Subtropical places in Africa, India, and the Middle East cited by [36]; whereas, values for Tucson and Yuma are considerably less relative to the population, indicating their peripheral siting and their limited representation for more central urban LCZ locations in these places. In a past analysis by [37], individual stations in Phoenix indicated a range from 2–6 °C for UHI, consistent with this present analysis. As mentioned above, [31] suggest for the Phoenix UHI that values could be different by ~3 °C depending on using dry desert versus moist agricultural irrigated surfaces as rural, indicating the importance of maintaining consistency in choosing a rural reference for the natural environmental setting. Using modeling, [6] illustrates an increase in early morning UHI of 2–3 °C, in a simulation of changing shrub landscape to urban for the Phoenix area. Similarly, [4] also simulates a ~3 °C UHI for summer for Las Vegas as a whole. For Tucson [7], in a previous analysis using station data, a UHI of ~3 °C was also found using more central urban sites than the Tucson airport station as the choice of an urban site. Unfortunately, most of these sites have either been discontinued or have too short a record for long term climate change analysis. As mentioned, the landscape in the Yuma area consists of irrigated agriculture surrounding the airport station. If this agriculture area is used as a rural reference selection (what is called the Yuma Valley station) instead of desert (see Table 5), the $T_{minU\text{-}R}$ is 3.8 °C and, thus, becomes substantially larger than using the natural desert as a rural reference, affirming the message of [31]. It is imperative to stipulate a UHI based on specifying the LCZ for urban and rural, if individual sites are used, especially in a long-term trend analysis. A classification of the nature of the rural reference site is recommended, striving to make it be representative of a relatively stable, unchanging, natural environment of the region. In [38], researchers developed a simulation of diurnal temperature range (DTR) outcomes for various LCZs in urban areas in comparison with a rural dry area—an LCZ D. An LCZ E (similar to that used in the present study) was analyzed relative to a rural area (similar to the present analysis) and resulted in decreases of DTR of ca. 7 °C [38]. With smaller $T_{maxU\text{-}R}$ changes than $T_{minU\text{-}R}$ over time at Las Vegas and Phoenix shown in this analysis, the DTRs at these airports averaged over the last 10 years have reduced by 7.8 °C and 6.0 °C, respectively, similar to the analysis of [38].

The above analysis at the division level and individual site level points to large temperature changes in the SW desert region. Regional signals of change are substantial, as indicated by rural changes of ca. 2.0 °C and 2.5 °C for June maximum and minimum temperatures. Urban areas, in many ways, are already experiencing some general scenario predictions of future temperature changes for the SW USA, with >5 °C changes. The results here do not point to any relaxing of temperature trends overall for this ca. 70-year period, generally similar to findings of [39]. However, understanding metadata in evaluations of trends of individual sites remains critical in interpretations of results. Important details over the time period need to be further assessed, especially high-resolution land cover around sites within 500 m of sensors. Furthermore, wholesale changes in sensors have occurred in the NOAA national network, and many station moves may affect results (the sites of #6, 10, and 13 in Figure 1 are cases in point, where although the records are long, there have been many station moves, and rates of change are questionable). A great deal of effort is underway to address urban mitigation of extreme temperatures, and academics and stakeholders are developing plans to cope with expected increases in heat effects for the future [12,40–48]. A combination of historical assessments as to where we have been, together with forward-looking analysis using scenario constructs and verifiable modeling in concert with local stakeholder engagement, will likely aid in addressing climate issues in this critical and rapidly growing desert environment in the SW USA.

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