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Climate Change and Extreme Temperature Trends in the Baja California Peninsula, Mexico

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ABSTRACT: Climate change is one of the greatest threats that our civilization is facing because increases in extreme temperatures severely affect humans, the economy, and ecosystems. General circulation models, which adequately predict climate change around the world, are less accurate at regional levels. Therefore, trends must be locally assessed, particularly in regions such as the Baja California Peninsula, which is a thin mass of land surrounded by the Pacific Ocean and the Gulf of California. Herein, we discuss extreme temperature trends in the Baja California Peninsula and whether they are statistically significant based on the Spearman's nonparametric statistical test. For these purposes, 18 weather stations covering the entire region were analyzed, revealing that maximum temperatures for the hottest months are rising at a rate that is consistent with the RCP 8.5 scenario. Changes in minimum temperatures were also analyzed.

KEYWORDS: Global warming, extreme temperature trends, Mexico climate change, climate change regional study, Baja California Peninsula

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Introduction

According to the United Nations Office for Disaster Risk Reduction, during the 1998-2017 period, 5.3% of all global disasters originated from high temperatures, whereas droughts caused 4.8%, severe storms 28.2%, and hurricanes 43.4%.[1] In other words, 82% of natural disasters during this period were climate related. Only in Latin America and the Caribbean, during the 1990-2011 period, natural disasters affected more than 121 million people, including 42 077 casualties and almost 6 million homes being destroyed.[2] Moreover, many of these natural disasters are related to climate change.

The 2014 report by the Intergovernmental Panel on Climate Change (IPCC) clearly states that

> Changes in many extreme weather and climate events have been observed since about 1950. Some of these changes have been linked to human influences, including a decrease in cold temperature extremes, an increase in warm temperature extremes, an increase in extreme high sea levels, and an increase in the number of heavy precipitation events in a number of regions.

In addition, regarding the future:

> Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is very likely that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions.[3]

In particular, extreme heat events often increase the mortality and morbidity with influences that may differ according to people's age, location, and socioeconomic factors.[4]

The IPCC believes that the influences of climate change will not be uniform across the globe but will rather vary among regions and that average global temperatures are expected to increase between 1.4°C and 5.8°C by 2100.[3] These temperature-increase forecasts are based on the results from general circulation models. The IPCC has calculated the performance of these models by comparing their results with climate parameters observed in the 1980-1999 period. For temperatures, once the multimodel results are assessed (the average results from 23 general circulation models), estimation errors (the difference between the observed and modeled data) rarely exceed 2°C although individual models can generate errors of up to 3°C.[5] However, the IPCC has also reported that large scales are more accurately simulated than regional scales. Therefore, any analysis of vulnerability and climate change influence at the local or regional level must be based on the evidence observed. Hence, a regional analysis of climate change trends is important.

Owing to its geographical conditions, the Baja California peninsula is a case of special interest: it is a long and thin strip, surrounded by the Pacific Ocean and the Gulf of California, with a mountain range that crosses most of its length and temperatures in the Pacific Ocean and the Gulf of California tend to be different, which could have an influence on the maximum temperatures observed. Therefore, modeling the climate change effects is particularly difficult, and the changes that have been already observed must be assessed in detail to determine the existence of global warming trends as well as their magnitude. Moreover, the region has experienced extremely dangerous heat waves, with increasing maximum temperatures that reach 50°C. Therefore, the study of maximum temperatures in this region is of great interest.[6,7] Another difficulty in determining climate change trends in a region can be the existence of microclimates. For instance, the phenomenon of heat islands is widely documented in large cities,[8,9] but the effect of microclimates has also been observed in other conditions, such

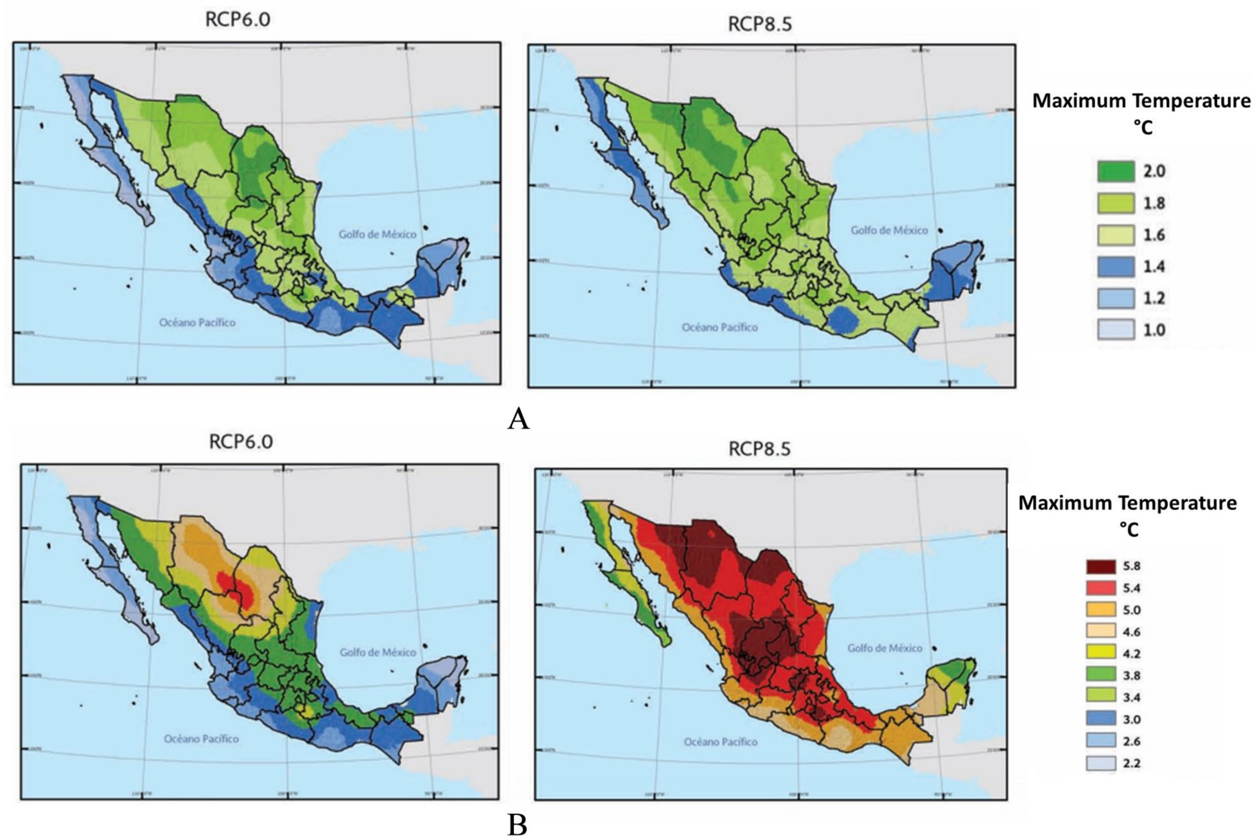


Figure 1. Average monthly maximum temperature anomalies in Mexico, spring-summer, as compared with the Baseline 1971-2000 Period. (A) 2015-2039 Period. (B) 2075-2099 Period.
Adapted from Instituto Mexicano de Tecnología del Agua.[10]

as in complex mountainous areas. This will be an aspect to take into account when analyzing the results.

According to the Atlas of Water Vulnerability in Mexico in the face of Climate Change,[10] as denoted in Figure 1, in the RCP 6.0 scenario, the average maximum spring–summer temperature is expected to increase by 1.2°C throughout most of the territory during 2015-2039, based on the 1971-2000 observations. In addition, the RCP 8.5 scenario reveals possible increases between 1.2°C and 1.4°C for the same period. Larger increases are expected on the East coast on the slope toward the Gulf of California. By the end of the century, increases would reach 3°C and 4.2°C in RCP 6.0 and 8.5 scenarios, respectively.

In this area, where temperatures regularly reach 47°C in the summer, these increases could hinder several economic activities and heavily increase the deaths during heat waves. Consequently, these temperature trends and temperature change rates must be particularly addressed.

Study Area

The Baja California peninsula is located in Northwestern Mexico. It penetrates the Pacific Ocean, creating the Gulf of California between its Eastern coast and Sonora and Sinaloa shorelines. Its approximate length is 1250 km, and it includes the Mexican states of Baja California and Baja California Sur. It extends from the Mexican–United States border to the large rock formations in Cabo San Lucas.[11]

Baja California hosts the 2 of the largest protected natural areas in Mexico: Valle de los Cirios and the Vizcaíno Desert. This area also exhibits different ecosystems, from marine to mountain forest, as exemplified in the San Pedro Mártir National Park, the rainiest region of the Peninsula.

The Baja California Peninsula (Figure 2) is politically divided into 2 states: Baja California and Baja California Sur. In the state of Baja California important cities such as Tijuana, Mexicali, Ensenada, Tecate, and San Quintín are located. On Baja California Sur, we may locate Loreto, Cabo San Lucas, San José del Cabo, La Paz, and Rosarito.[11]

The primary sources of surface water in the state of Baja California (Figure 3) are the Colorado and Tijuana rivers. The Colorado River, one of the largest in North America, ends its long course in the Gulf of California delta, and its waters are used for the irrigation of the Mexicali Valley and for supplying fresh water to the main cities in the Baja California state. However, the Colorado River waters are fully controlled by the United States, and according to the binational treaty between Mexico and the United States, 1.85 billion cubic meters are delivered to Mexico every year. The Tijuana River carries a reduced and sporadic flow. Underground water sources are also exploited, especially in the Mexicali Valley.

Figure 2. Baja California Peninsula. The states of Baja California and Baja California Sur are depicted.

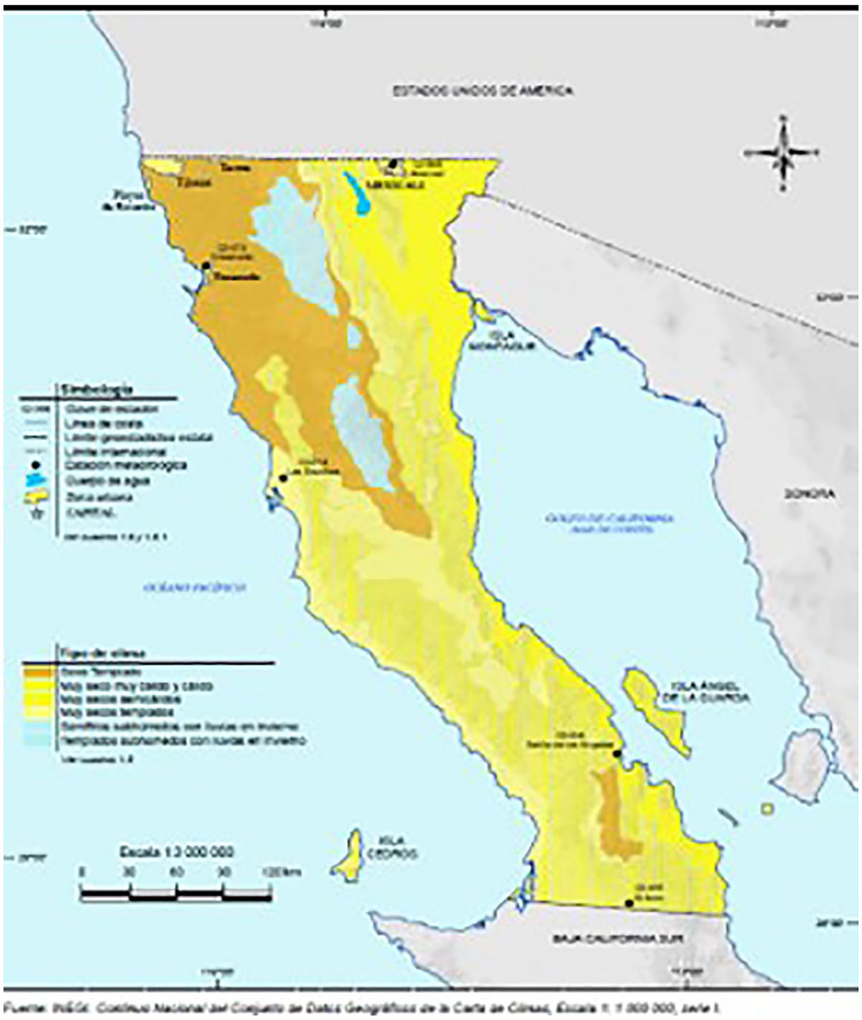
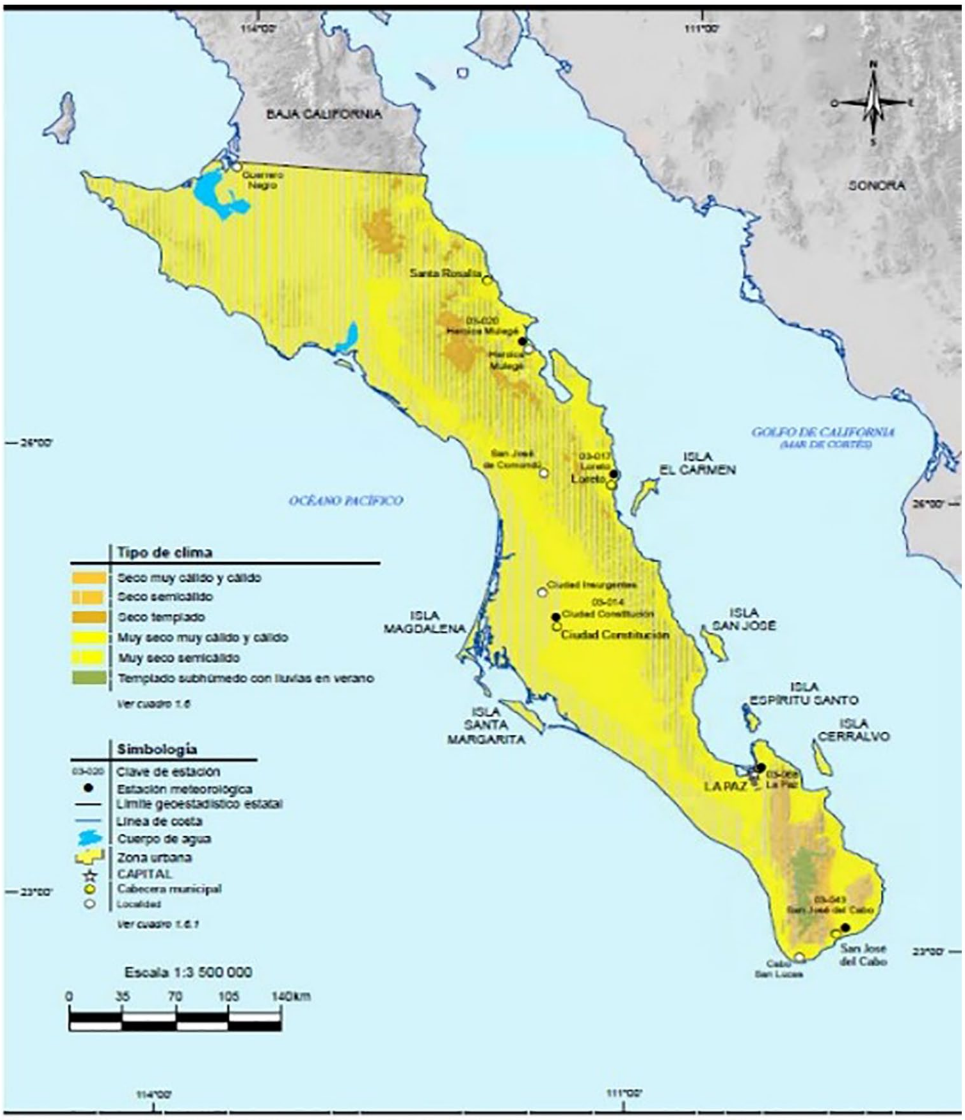


Figure 3. Climate in the Baja California state.[12]



Fuente: INEGI. *Continuo Nacional del Conjunto de Datos Geográficos de la Carta de Climas Escala 1:1 000 000, serie I.*

Figure 4. Baja California Sur Climate.[12]

Moving southward along the Pacific Ocean coast, the climate becomes desertic; however, it is not as extreme and hot as on the Gulf of California coast. Transition in climates, from Mediterranean to desert, can be found from San Quintin to El Rosario. To the east and near the Gulf, vegetation is extremely scarce and temperatures are extremely high in the summer. Desert climates may also be found on all Gulf of California islands.

The state of Baja California Sur (Figure 4) is located to the south of Baja California Peninsula, limiting to the north with Baja California. At 712 029 inhabitants, according to the 2015 census, it is the second least populated state in Mexico, and at 73 922 km^2, it is the ninth largest state in terms of extension. Its capital and most populated city is La Paz with 244 219 inhabitants.[12] The state reports an annual average temperature of 30°C, with 35°C as the highest average temperature in the months of July and August and the lowest temperature of 0°C recorded in January. In the city of Loreto, extreme maximum temperatures of 40°C have been recorded in the months of May–September, emphasizing that rains are extremely scarce and only reported during summer, with a statewide total annual average precipitation under 200 mm.[13] Its surface water resources are also considerably reduced; therefore, the state depends almost completely on underground water and seawater desalination.

Methods

Eighteen weather stations were selected from the National Meteorological Service database, which were chosen according to their location, information continuity, and length of temperature records. In addition, as the selected stations are distributed throughout the Peninsula, the entire region is reasonably represented (see Figure 5).

In the state of Baja California, the following stations were analyzed: Bahía de los Ángeles, Boquilla de Santa Rosa, Chapala, Delta, El Arco, El Barril, El Mayor, El Rosario, El Socorro, La Puerta, and Mexicali. In the state of Baja California Sur, we analyze the following stations: Bahía Tortugas,

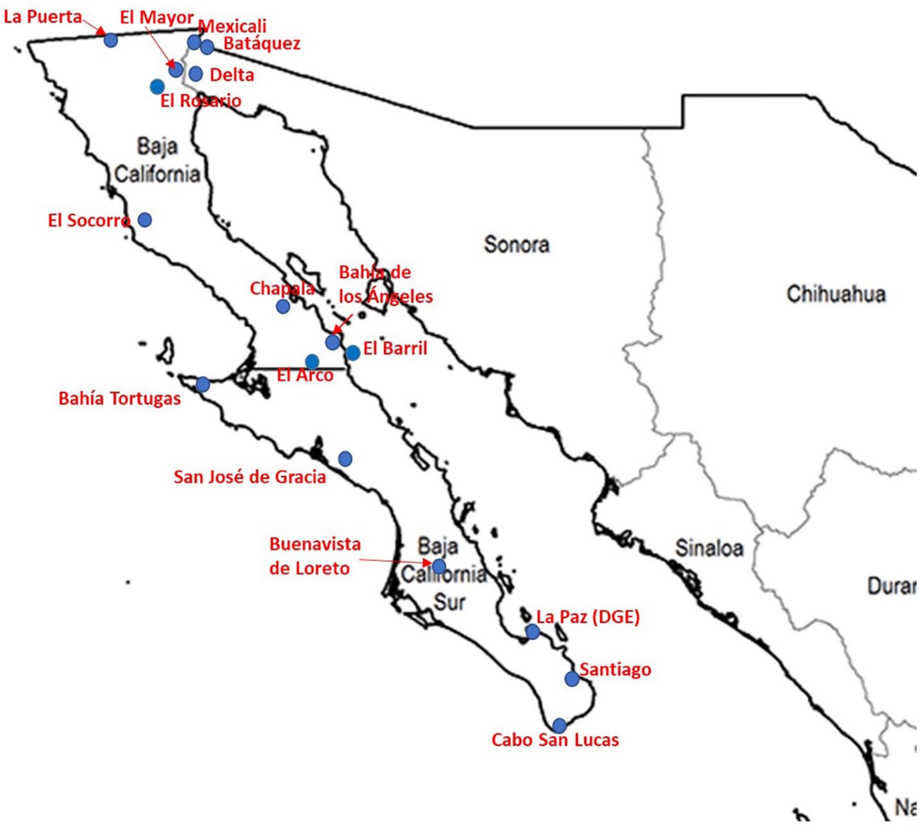


Figure 5. Location of weather stations in the Baja California Peninsula.

Buenavista de Loreto, Cabo San Lucas, San José de Gracia, Santiago, and La Paz.

The trend analysis was performed using 2 methods for both maximum and minimum temperatures. First, with the support of a spreadsheet, the trend was observed graphically and a linear regression analysis was performed. Owing to our interest in peak temperatures, the analysis was limited to the hottest months of the year.

Even when a trend is determined via inspection or regression, it is necessary to establish whether said trend is statistically significant. In recent years, nonparametric estimation methods, such as the Mann-Kendall test and the Rho Spearman test, had been the most widely used. The Rho Spearman test has proven to be a robust test when compared with other similar. The Spearman test provides results consistent with the Mann-Kendall test.[14-17] Sheng et al[18] conducted a comparative analysis of the performance of the Mann-Kendal and Spearman tests on hydrological data series and concluded that " results also demonstrate that these 2 tests have similar power in detecting a trend, to the point of being indistinguishable in practice."

For the climate data series, the D value from Spearman's test is obtained as per the following equation:

$$D = 1 - \frac{6\sum_{i=1}^{n}\left(R_i - i\right)^2}{n\left(n^2-1\right)}, \quad (1)$$

where R_i is the range of the ith observation and n is the amount of data in the sample. The standardized Z_{SR} statistic is given by

$$Z_{SR} = D\sqrt{\frac{n-2}{1-D^2}} \quad (2)$$

The null hypothesis used for this method is that there is no trend in the series. Hence, if $abs(Z_{SR}) > t\left(n-2,1-(-/2)\right)$, then the null hypothesis is rejected and there is a trend in the series. In this equation, $t\left(n-2,1-(-/2)\right)$ is the value from Student's t-distribution, at a significance level of α.

The months selected in the study were from May to September, and it was observed that the hottest temperatures in the region were reported in July and August by all the selected stations. Therefore, the results provided here concentrate in the month of August.

The Spearman method is easily programmable. In this case, the calculations were made using an Excel sheet.

Results and Discussion

Minimum temperatures

One of the observed effects from global warming is that minimum temperatures increase along with maximum temperatures, often at a different rate. Figures 6 and 7 show the minimum August temperatures for the state of Baja California and Baja California Sur, respectively. Figure 6 reveals a trend toward an increase in minimum temperatures during the period

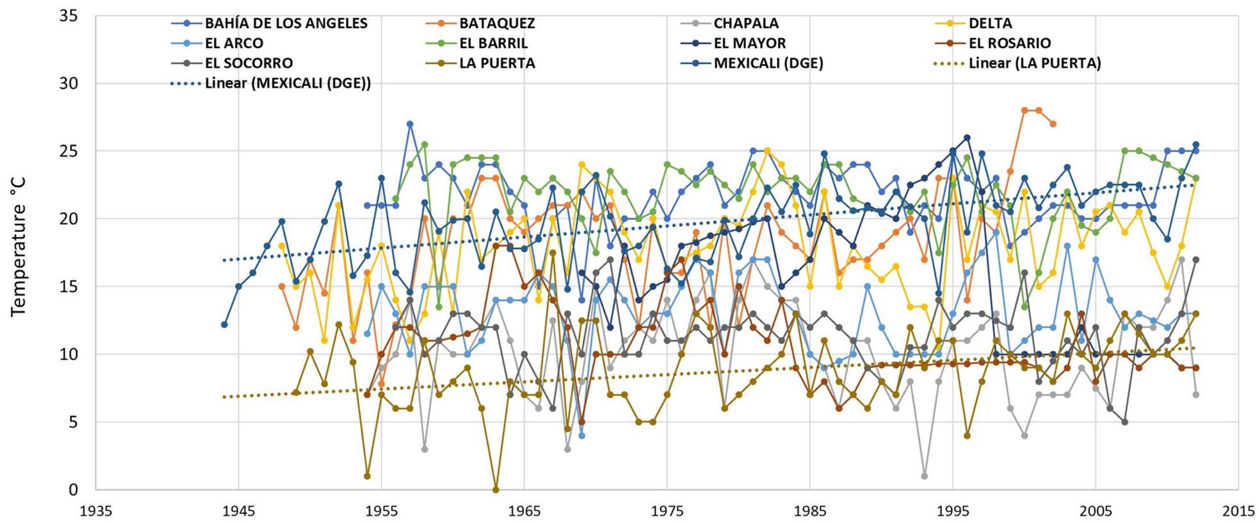


Figure 6. Minimum temperatures in Baja California state in August.

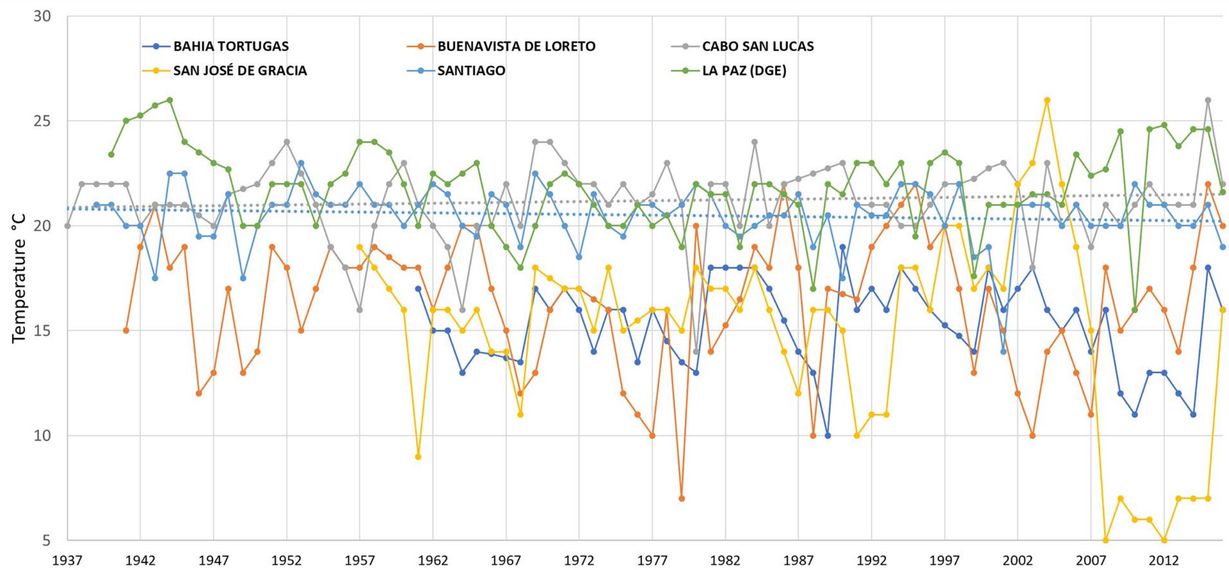


Figure 7. Minimum temperatures in the state of Baja California Sur in August.

under analysis in the state of Baja California. To better observe this phenomenon, we have included the trend lines of the 2 stations with the longest record period: Mexicali and La Puerta. In Mexicali, for example, the trend line has risen from 17°C to 22°C between 1945 and 2014. In the case of Baja California Sur, increased minimum temperature trends are not as clear, as it may be observed in Figure 7, which also included the trend lines for the stations with longest records.

Results from Spearman's trend analysis are denoted in Tables 1 and 2. For the state of Baja California, in most of the stations (7 out of 12), there is a statistically significant trend of increasing minimum temperatures for the month of August. The exceptions are the Bahía de los Ángeles, Chapala, El Arco, El Barril, and Socorro stations. The first 4 are extremely close to the southern part of the state, covering the central area of the peninsula, and located to the east of the peninsula toward the Gulf of California. The El Socorro station is located within a bay, which could favor the occurrence of a microclimate. In the rest of the stations, located in the northern area of the peninsula, wherein the Gulf of California does not exert a direct influence, a statistically significant increase in temperatures can be observed, including the stations located at higher elevations, such as La Puerta station.

In the state of Baja California Sur (see Table 2), no statistically significant trends in minimum temperatures were found.

Maximum temperatures

Figures 8 and 9 show the maximum temperature results in the peninsula. For the state of Baja California, with the exception of the Bahía de los Ángeles station, there are trends of increasing maximum temperatures throughout the region. Figure 8 denotes the information of some of the representative stations for the

Table 1. Results of the trend analysis on minimum temperatures using the Spearman method, Baja California.

STATION	NAME	MONTH	Z_{SR}	$t(n-2, 1-(\alpha/2))$	TREND
2002	Bahía De Los Ángeles	July	0.841	2.003	NO
		August	0.048	2.003	NO
2005	Boquilla Santa Rosa De Lima	July	15.216	2.024	YES
		August	7.882	2.024	YES
2006	Chapala	July	1.416	2.002	NO
		August	0.373	2.002	NO
2011	Delta	July	0.775	1.998	NO
		August	8.270	2.009	YES
2015	El Arco	July	0.905	2.003	NO
		August	0.702	2.003	NO
2016	El Barril	July	0.903	2.004	NO
		August	0.827	2.004	NO
2020	El Mayor	July	4.571	2.030	YES
		August	3.981	2.030	YES
2022	El Rosario	July	2.084	2.013	YES
		August	3.380	2.012	YES
2023	El Socorro	July	3.025	2.005	YES
		August	0.115	2.005	NO
2030	La Puerta	July	3.933	2.000	YES
		August	3.114	2.000	YES
2033	Mexicali (Dge)	July	6.064	1.997	YES
		August	5.552	1.997	YES

Table 2. Results of the trend analysis on minimum temperatures using the Spearman method, Baja California Sur.

STATION	NAME	MONTH	Z_{SR}	$t(n-2, 1-(\alpha/2))$	TREND
3002	Bahía Tortugas	July	0.877	2.005	NO
		August	0.333	2.005	NO
3004	Buenavista De Loreto	July	1.121	1.993	NO
		August	0.521	1.993	NO
3005	Cabo San Lucas	July	0.734	1.993	NO
		August	1.018	1.993	NO
3055	San José De Gracia	July	1.938	2.002	NO
		August	1.192	2.002	NO
3062	Santiago	July	2.510	1.992	YES
		August	0.553	1.992	NO
3074	La Paz (Dge)	July	0.016	1.993	NO
		August	0.930	1.993	NO

month of August as well as the trend lines for Mexicali and Boquilla Santa Rosa. Here, it can be observed that although temperatures in the south of the state are lower, there is still a clear positive trend. Table 3 summarizes the results of Spearman's trend analysis, wherein with only one exception, the trends in this state are statistically significant.

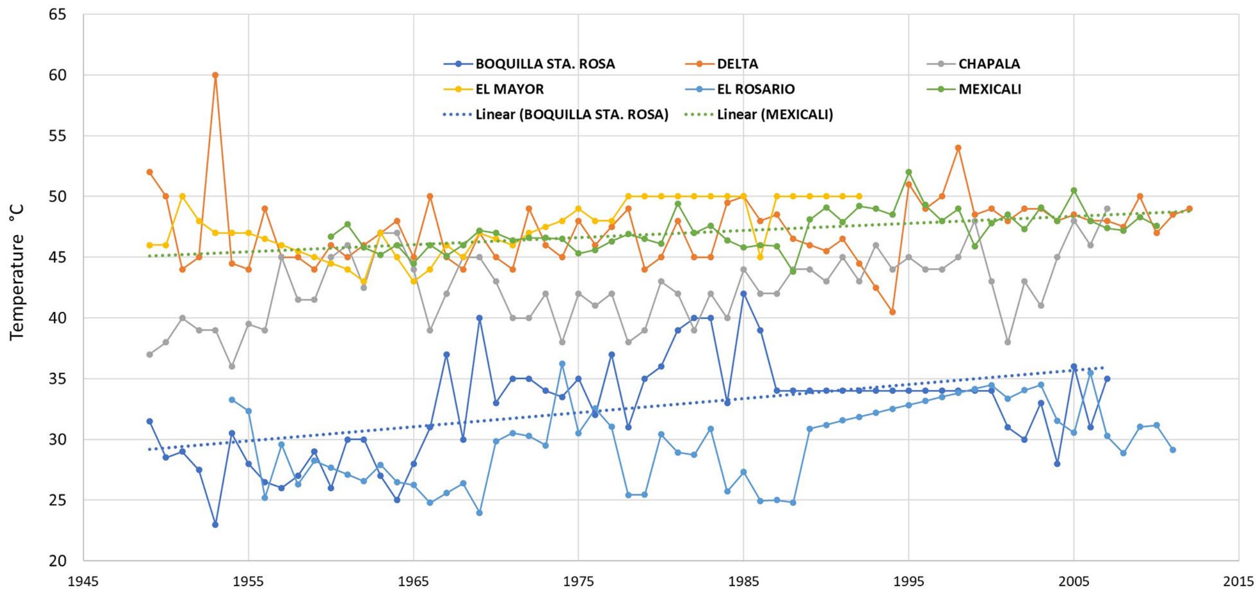


Figure 8. Maximum temperature-Baja California in August.

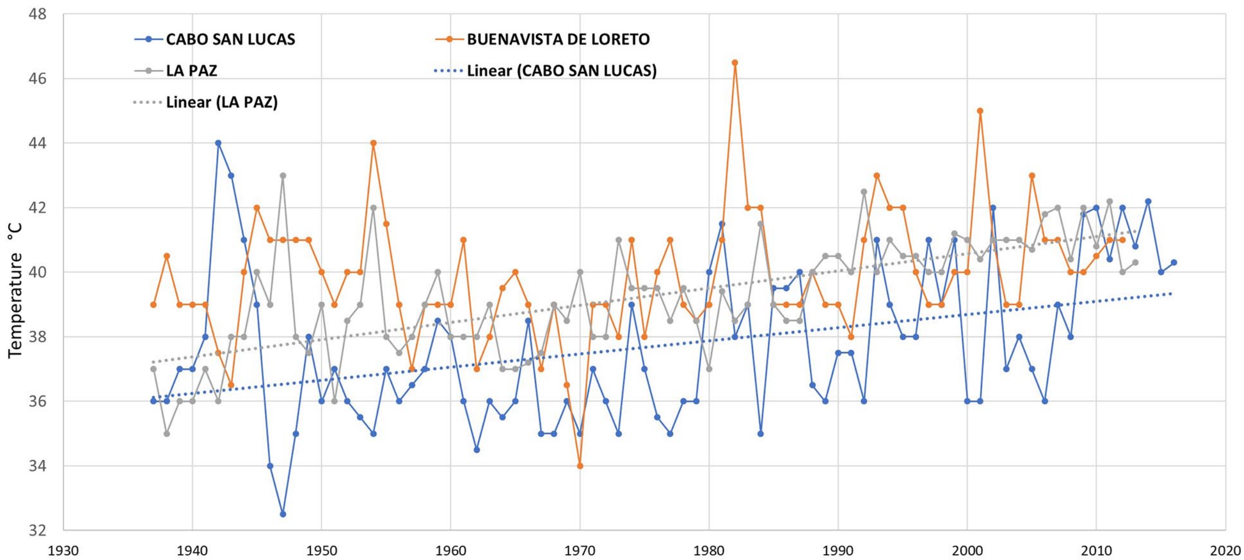


Figure 9. Maximum temperature-Baja California Sur in August.

In the case of Baja California Sur, unlike the minimum temperatures, there is a clear trend of increasing maximum temperatures, as denoted in Figure 9, which illustrates the variation in maximum temperatures in 3 selected stations as well as the linear trend lines for 2 of them. The trend would indicate, for example, at La Paz station, an increase from 37°C to 42°C in the period between 1940 and 2010. That is, an increase of 5°C throughout this period or approximately 0.4°C per decade. Spearman's trend analysis, as evidenced in Table 4, indicates that the trend is statistically significant in the month of August at 4 of 6 stations assessed.

Considering the entire peninsula for the month of August, the hottest in the region, the increase in maximum temperatures is consistent throughout the Baja California peninsula, and in most cases, it is statistically significant. Conversely, the minimum temperatures are increasing differently. This shows that the distribution of temperature probabilities in the peninsula is not only shifting but also deforming, as predicted by the IPCC for changes in extreme events.[19] The results from this behavior report that if only the average temperature is analyzed, a wrong perception of the warming occurring throughout the peninsula is obtained. If, for instance, the Chapala station is considered (see Figure 10), minimum temperatures are increasing at a much higher rate than maximum temperatures, which modifies the trend line of average temperatures. This also proves the importance of assessing changes in extreme temperatures.

Figure 11 shows, in red, the stations where a statistically significant trend of increasing maximum temperatures was determined. As it can be observed, maximum temperatures are

Table 3. Statistical trend test. Maximum temperatures. Baja California stations.

STATION	NAME	MONTH	Z_{SR}	$t(n-2, 1-(\alpha/2))$	TREND
2002	Bahía De Los Ángeles	July	0.448	2.004	NO
		August	0.448	2.004	NO
2005	Boquilla Santa Rosa De Lima	July	5.36	2.014	YES
		August	5.36	2.014	YES
2006	Chapala	July	4.02	2.003	YES
		August	4.02	2.003	YES
2011	Delta	July	2.44	2.02	YES
		August	2.44	2.02	YES
2015	El Arco	July	2.04	2.009	YES
		August	2.04	2.009	YES
2016	El Barril	July	2.59	2.012	YES
		August	2.59	2.012	YES
2020	El Mayor	July	7.92	2.03	YES
		August	7.92	2.03	YES
2022	El Rosario	July	2.249	2.017	YES
		August	2.249	2.017	YES
2023	El Socorro	July	7.92	2.03	YES
		August	7.92	2.03	YES
2030	La Puerta	July	2.87	2.002	YES
		August	2.87	2.002	YES
2033	Mexicali (DGE)	July	4.809	2.009	YES
		August	4.809	2.009	YES

Table 4. Statistical trend test. Maximum temperatures. Baja California Sur stations.

STATION	NAME	MONTH	Z_{SR}	$t(n-2, 1-(\alpha/2))$	TREND
3002	Bahía Tortugas	July	0.04	2.00	NO
		August	0.36	2.00	NO
3004	Buenavista De Loreto	July	2.4	1.99	YES
		August	1.99	1.99	YES
3005	Cabo San Lucas	July	4.49	1.99	YES
		August	4.95	1.99	YES
3055	San José De Gracia	July	1.44	2.00	NO
		August	1.34	2.00	NO
3062	Santiago	July	0.40	1.99	NO
		August	2.26	1.99	YES
3074	La Paz (Dge)	July	7.65	1.99	YES
		August	7.85	1.99	YES

increasing in almost the entire Peninsula. The 3 stations that report an exception, as commented in the "Introduction" section and as a hypothesis, are probably located in areas with specific microclimates, which influences the results. The Bahía de Tortugas station is located in a small closed bay, the El Barril station is located in an area protected by an overhang of the

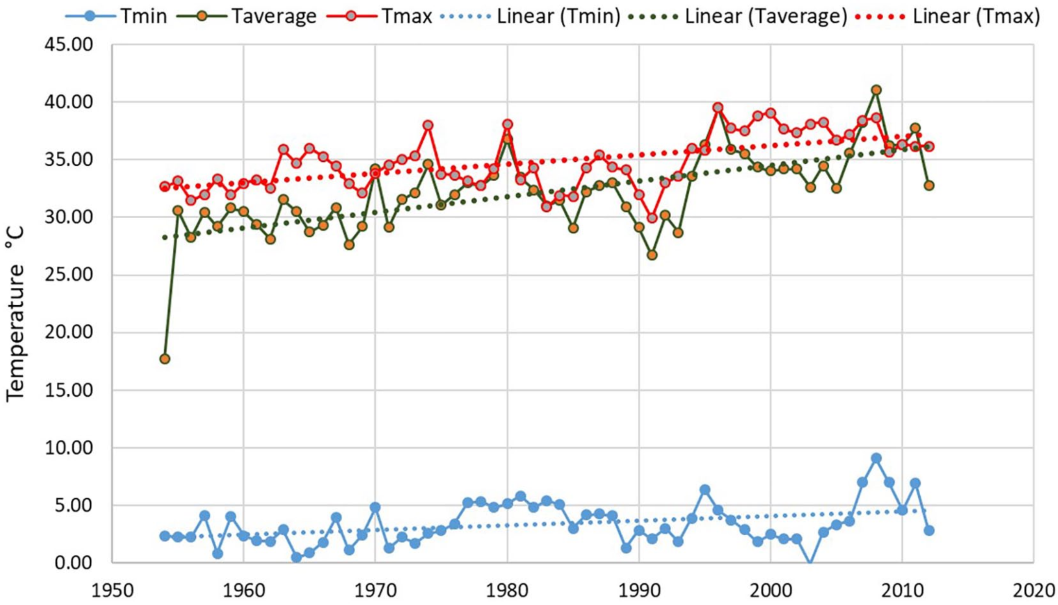


Figure 10. Comparison among maximum, minimum, and average annual temperatures at the Chapala station.

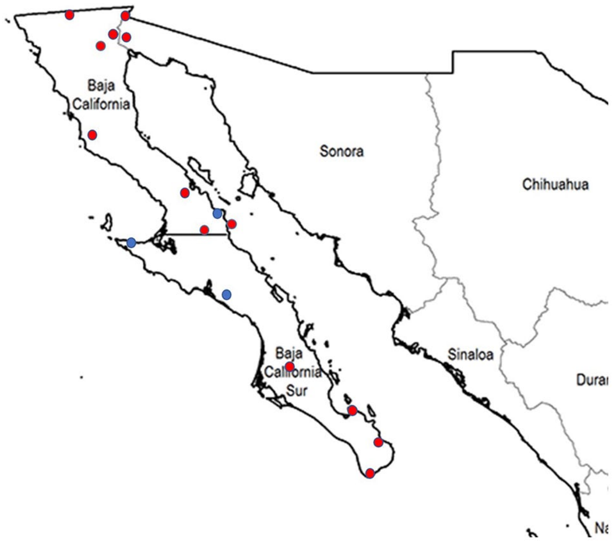


Figure 11. Stations with significant (red) increasing trend in maximum temperature.

Table 5. Maximum temperature increase by decade.

STATION	INCREASE PER DECADE (°C)
Bataquez	0.523
El Arco	0.257
El Barril	0.456
La Puerta	0.424
Delta	0.202
Chapala	0.809
El Mayor	1.091
El Rosario	0.914
Mexicali	0.59
Cabo San Lucas	0.406
Buenavista de Loreto	0.207
Santiago	0.228
La Paz	0.532

peninsula and at the foot of a mountainous area, and finally, the San José de Gracias station is located at the foot of the central mountain chain of the Peninsula. The influence of microclimate, however, would require detailed investigation that is beyond the scope of this article.

The rise in extreme temperatures is consistent with the predictions of climate change models for this region. The Gulf of California does not seem to have a major influence on this process because the stations near this water body reveal the same increasing behavior.

According to the climate change scenarios prepared by the Mexican Institute of Water Technology[10] for the 2015-2039 period, increases between 0.30°C and 0.4°C per decade could be expected in the RCP 6.0 scenario and between 0.4°C and 0.5°C in the RCP 8.5 scenario (see Figure 1).

Unfortunately, the trend lines from the stations under study throughout the region denote that the scenario that would occur is closer to RCP 8.5 scenario. Table 5, which includes the stations with statistically significant growth trends, reveals that the trend observed ranges from 0.23°C to 0.8°C per decade.

Conclusions

It is evident from the extreme temperature analysis in the Baja California peninsula that there has been a significant growth in maximum temperatures and that the trend observed is statistically significant. Minimum temperatures are also rising but at a different rate and are statistically significant only in the northern part of the peninsula. The observed increase in maximum temperatures is consistent with the expectations from the climate change models for the peninsula,[10] based on the RCP 8.5 scenario.

Author Contributions

PFMA conceived and designed experiments. PFMA and JAJP analyzed the data. PFMA and JAJP wrote the first draft of the manuscript. PFMA agree with the manuscript results and conclusions. JAJP and PFMA made critical revisions and approved final version and both authors reviewed and approved of the final manuscript.

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