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Authors: Austria, Polioptro F. Martínez, and Bandala, Erick R.

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Maximum Temperatures and Heat Waves in Mexicali, Mexico: Trends and Threshold Analysis

Polioptro F. Martínez Austria and Erick R. Bandala

Posgrado en Ciencias del Agua Escuela de Ingeniería, Universidad de las Americas, Puebla. Sta. Catarina Martir, Cholula, Puebla, Mexico.

ABSTRACT: Maximum temperature trends and the corresponding heat wave thresholds in the northwestern city of Mexicali, Mexico, were analyzed using historical data from the site. We found that there seems to be an upward trend in temperature in the past decades, along with an increased number of days reaching maximum temperatures considered as heat waves. Despite the difficulty of establishing heat wave parameters, the trends of the analyzed field data clearly show their presence, mainly during July and August. This trend is also supported by the analysis of the number of admissions and casualties registered in hospitals in the city of Mexicali. This work is a warning on the frequency and duration of a very important climate change-related effect capable of jeopardizing the health of the population in the region and requiring more attention by decision makers and stakeholders. It also helps to document observed climate trends, as requested by the Intergovernmental Panel for Climate Change.

KEYWORDS: heat waves, trends, thresholds, northwestern Mexico, Mexicali

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CORRESPONDENCE: polioptro.martinez@udlap.mx

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Introduction

The amount of natural disasters and, most importantly, their social and economic impacts have been continuously increasing. According to the World Meteorological Organization,[1] 8,835 disasters due to droughts, floods, wind storms, tropical cyclones, extreme temperatures, landslides and fires, and epidemics or insect infestations, directly linked to meteorological and hydrological conditions, were reported worldwide between 1970 and 2012. As a result, 1.94 million deaths and 2.4 trillion dollars in economic losses have been estimated, the worst scenario occurring mainly in less-developed countries. For 2013 alone, according to the report of the Centre for Research on the Epidemiology of Disasters,[2] the cost of damages caused by meteorological disasters was 13,408 casualties and 52.4 billion dollars, which is 21% greater than the annual average for the 2003–2012 period.

Although the trends show a decrease in the amount of human life losses, probably related to better response plans and their application before and during the disasters, the toll remains high. Table 1 lists the disasters with the highest death toll that occurred worldwide during 2013. It is noteworthy that 8 of the 10 major events, in terms of human life loss, were closely connected to extreme climate events. Three of these events are specifically related to heat waves, a phenomenon that has historically received little attention compared with floods or droughts. In Mexico, no reliable statistics are available regarding the effects of heat waves or their mortality and morbidity ratio among the population.

Climate change will increase the average temperature and the probability of occurrence of extreme climate events, including heat waves.[3] It has been forecasted that the increase in the average temperature may reach 4°C throughout this century.[4] These predictions are based on the results from the general circulation models. The Intergovernmental Panel for Climate Change (IPCC) estimates the performance of these models by comparing their results with the climate parameters observed during the 1980–1999 period. For temperature, once the multi-model results have been analyzed for temperature (the average of 23 general circulation models), the estimated error (difference between observed and modeled data) was rarely >2°C, although individual models may show errors up to 3°C.[5] Nevertheless, the IPCC has pointed out that big scales are simulated with a greater accuracy than regional ones.

Therefore, the analysis of the impact and vulnerability to climate change at local or regional levels must be based on observed evidence. Thus, the fourth and fifth IPCC reports on climate situation are based not only on the results of general circulation models but also on the observed evidence. Nevertheless, the same reports indicate a noticeable lack of geographical balance between raw data and literature reports about the observed changes, with a marked dearth in developing countries. In addition, the reported trends and forecasts focus, above all, on average values. For example, while the average temperature forecasts for diverse scenarios are very common, no general forecasts for extreme temperatures are reported. However, the fifth IPCC report claims that the

Table 1. Ten natural disasters causing the highest number of deaths in 2013.[2]

EVENT/MONTH	COUNTRY	NUMBER OF DEATHS
Cyclone Haiyan, November	Philippines	7,354
Flood, June	India	6,054
Heat wave, July	United Kingdom	760
Heat wave, April–June	India	557
Earthquake, September	Pakistan	399
Heat wave, May–September	Japan	338
Flood, August	Pakistan	234
Flood, July	P. Republic of China	233
Earthquake, October	Philippines	230
Flood, September–October	Cambodia	200
	Total	16,359

number of cold days and nights had decreased and that the amount of heat waves in Europe and North America had increased.[4] Nevertheless, forecasting changes for extreme temperatures is more complicated than for average temperatures, because it depends almost completely on observational evidence.

Although heat waves have significant effects on the environment and agricultural production, they are particularly important mainly due to their direct and indirect effects on human health. Among the direct ailments are those disorders that cause minor alterations as well as intensification of respiratory, kidney, or digestive system diseases. One of the most commonly reported effects is the collapse of the ability of an individual's body to regulate its temperature through the blood stream or by sweating. In extreme cases, these conditions may even lead to death. Elderly people and infants are especially vulnerable to heat waves.[6] Regarding the indirect effects, there are reports that refer to the influence of heat waves on the quality of water. For instance, it has been determined that heat waves favor the flourishing of harmful algae, cyanobacteria in particular, which are capable of producing toxins in water that may be consumed by humans, thereby causing intoxication risks for the population.[7] Similarly, it has been demonstrated that heat waves threaten environmental and social resilience through the reduction in food and water supplies, causing potential conflicts.[8] All these effects, such as the mortality due to heat waves, the environmental quality, and the population's characteristics, have been linked in the past.[9,10]

In Mexico, because of the current climatology and the foreseeable effects of climate change, a scientific study of heat waves is mandatory in order to prevent their impact and, mainly, generate proper prevention indexes and measures to protect the well-being of the population.

Methodology

Heat waves: definition and thresholds. A heat wave is generally defined as a period of time, usually of several days, when temperatures significantly higher than average are registered. This definition, though easy to understand, is nevertheless not very accurate when preventive measures need to be applied, or when the effects on human health or the environment need to be mitigated. The importance of heat waves becomes evident when their effects on human health are considered. At this point, because of the corresponding consequences, the definition of a threshold becomes necessary in order to define if temperature values higher than average should be considered as a heat wave. For this reason, several methods for determining thresholds or heat indexes to estimate the danger for human health have been developed.

A first set of heat indexes refers not only to ambient temperature but also to the thermal sensation experienced by people. This group of heat indexes considers, besides the ambient temperature, parameters such as relative humidity and human activity, among other factors. Under this set of indicators, the one used by the US National Oceanic and Atmospheric Administration (NOAA) defines the limits for apparent temperature and its effects on human health. Its calculation is performed in agreement with eq. (1):

$$H_i = -42.379 + 2.049T + 10.14R - 0.224TR - 6.83\times10^{-3}T^2 - 5.48\times10^{-2}R^2 + 1.22\times10^{-3}T^2R + 8.52\times10^{-4}TR^2 - 1.99\times10^{-6}T^2R^2 \quad (1)$$

where R stands for the relative humidity and T is the ambient temperature (°F).

NOAA's heat index considers a value in the range of 103°F–124°F as dangerous and values reaching 125°F or higher where heat strokes are very likely to occur as extremely dangerous.

Another widespread procedure to determine heat indexes is by establishing temperature thresholds, when the ambient temperature value becomes a threat for human health. For these cases, thresholds are set up by defining specific values or limit percentiles. The United Kingdom Meteorology Office, for example, has established a regional system with an average threshold of 15°C and 30°C during the night and day, respectively, for a duration of two or more consecutive days, to be considered as a heat wave.[11] Table 2 shows the regional limits suggested for the United Kingdom. In Mexico City, Jáuregui[12] used a maximum observed temperature ≥30°C for over three or more consecutive days as a heat wave threshold criterion. In the latter case, because of lack of information on health effects, the limit of 30°C is arbitrary.

In a recent extensive research,[13] different heat indexes were analyzed and compared with the registered health effects during the analyzed dates. The authors found that simple indexes, based solely on temperature, may be most appropriate to apply in an alert system, but all the corresponding thresholds should be considered on a regional basis.

In a previous study by our research group,[10] an analysis of the different methodologies used for establishing different heat indexes was carried out. For this study, the index used for establishing the threshold for heat waves was the one suggested by the National Center for Disaster Prevention from the National Civil Protection System of Mexico. National Center for Disaster Prevention (CENAPRED) suggests the use of the temperature value corresponding to the 90th percentile[14] as a threshold in order to set up risk maps due to heat waves. The main advantages of this method are avoiding the use of average values and enforcing the use of regional raw temperature measurement values.

Geographical description of the study zone. In Mexico, with diverse climate zones, high temperatures may occur in some states, specifically in the northwestern part of the country. Nevertheless, not only the northwestern region of the country is affected but, according to recent studies, other sites such as Mexico City have also shown alterations in their temperature patterns, as well as significant increases in their average temperature.[15] Other cities located in the central, south, east, and northeast parts of the country have also shown similar trends.[16–18] Further studies on extreme temperatures in Mexico[19,20] have shown, in the decades after 1970, an increase in the maximum temperature in different zones, indicating a significantly greater rate than the trend exposed by minimum temperatures (Fig. 1). Contrasting trends were found between northwestern and central Mexico, compared to the rest of the country. Regionalized analyses in the north, east, and south of Mexico imply a considerable growing trend in the maximum temperature value and the frequency of hot days.[21]

A clear trend of particular interest in temperature rise affecting the population has been detected in the northwestern part of the country.[22] In some months during the 1971–2000 period, temperatures up to 47.5°C were measured in some cities in the region. The municipalities with the highest number of heat-related deaths were Mexicali, Hermosillo, San Luis Río Colorado, and Caborca.[23,24] The impact of heat waves in the city of Mexicali, particularly on vulnerability, morbidity, and mortality rates, shows an astonishing rise in the past few years.[22] Moreover, some previous studies suggest a rise during the free freezing period at the Sonora desert, although negative trends have also been detected toward its southernmost region.[25]

Mexicali is the capital city of the State of Baja California, located within the Mexicali Valley. According to the 2010 census, it has a population of 689,775 inhabitants. The Mexicali Valley is one of the most fertile areas in Mexico, maintaining more than 50 different crops with a similar production to that of the Imperial Valley, despite its low annual precipitation. The climate in this valley is considered arid, maintaining desert weather temperatures every year.

Mexicali is also the city in Mexico with the largest record of deaths caused by heat waves. As a result, the study of heat waves is of great importance. The data used for the analysis in this study were obtained from climatological station 2033, which has daily temperature registers since 1949 and is located

Table 2. Heat index thresholds within the United Kingdom.[11]

REGION	THRESHOLD TEMPERATURES	
	DAY MAX (°C)	NIGHT MIN (°C)
North East England	28	15
North West England	30	15
Yorkshire and the Humber	29	15
West Midlands	30	15
East Midlands	30	15
East of England	30	15
Southeast England	31	16
London	32	18
Wales	30	15

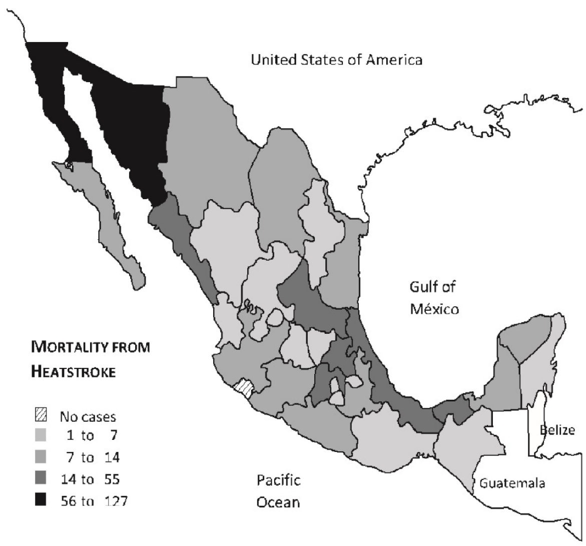

Figure 1. Total number of deaths in Mexico due to heat strokes in the period between 1979 and 2003.[24]

in this city. For the present study, data registered daily during the period from 1960 to 2011 were used for analysis, since they were considered sufficiently broad and as containing the most comprehensive information.

Statistical data analysis. There are various statistical tests to analyze the trends in climate data series, such as linear correlation (used by McCabe and Wolock[26]) and serial correlation techniques. In recent years, nonparametric estimation methods such as the Mann–Kendall and Spearman's Rho (SR) tests had been most commonly used. The latter has proven to be a robust test, when compared with other similar tests, and provides consistent results to those of Mann–Kendall test. Shadmani et al[27] used both tests to analyze runoff trends in Iran, with consistent results between the two. In this study, we use the Spearman nonparametric test.

For climate data series, statistical (D) SR test is obtained using eq. (2):

$$D = 1 - \frac{6\sum_{i=1}^{n}(R_i - i)^2}{n(n^2 - 1)} \tag{2}$$

where R_i is the range of the ith observation and n is the number of data in the sample. The standardized statistical Z_{SR} is given by eq. (3):

$$Z_{SR} = D\sqrt{\frac{n-2}{1-D^2}} \tag{3}$$

The null hypothesis used for this method is that there is a trend in the series. If $abs(Z_{SR}) > t_{(n-2,1-\alpha/2)}$, then the null hypothesis is rejected and there is a trend in the series, where $t_{(n-2,1-\alpha/2)}$ is the value of the statistics t in the table on Student's t distribution for a significance level α.

Results and Discussion

The impact of heat waves. Excessive heat has a significant impact on human health and mortality. Primary damage is caused by direct cellular toxicity when the body temperature exceeds 40°C, causing the following alterations: behavioral changes, central nervous system manifestations, convulsions, liver damage, delirium, coma, and heart problems. All the aforementioned conditions may lead to death.[23] The different factors contributing to the effect of extreme heat on people's health are as follows: (i) low socioeconomic level and the related lack of access to proper health services; (ii) age group; (iii) place of residence (ie, rural or urban area); (iv) previous or existing disease; (v) exposure to heat (ie, house structure and type of clothing); (vi) community's response to extreme heat events (ie, social prevention); and (vii) pollution level in the city of residence.[23]

The relationship between heat waves and their effects on human health also depends on the exposure time to high temperatures, the rate of temperature increase, and people's climate adaptation capacity. For example, for a person living in a tropical area the heat perceived due to high temperatures will generate a lower effect than in a person from a temperate zone; for the latter, high temperatures may become extremely dangerous.[28]

Worldwide heat wave frequency and intensity. During 2001–2010, the World Meteorological Organization registered 9 of the 10 hottest years in terms of the average temperatures.[29] In this period, not only the average temperatures increased but the extreme hot temperatures also reached a peak record. According to this report, some of the deadliest heat waves ever observed were registered during this period of time. Among these were those heat waves registered in 2006 in Europe, causing 66,000 deaths, and others at the Russian Federation in 2010 that left 55,000 casualties.

Heat waves have considerable effects not only in developing regions or countries but also in developed countries. For example, in France, one of the most harmful heat waves was registered in 2003, which turned out to be the most disastrous one in at least 50 years. The number of victims exceeded by 4% and 14% of the average previously observed in Lille and Paris, respectively, where thousands of people died in a few days.[30] Heat waves of different magnitudes have also occurred in the United States, in most cases resulting in a considerable number of victims. Anderson and Bell[28] studied the mortality caused by this phenomenon during the period from 1987 to 2005. Some of the death increase percentages stand out in different cities in the United States in different years: 109% in Los Angeles (1939), from 91% to 159% in St. Louis (1966), and 113% in New York (1948).

In England, more than 1,500 people died because of high temperatures caused by a heat wave in 2013. In July of the same year, the hottest day was experienced, beating the 2006 record and surpassing 30°C (90°F).[31] In India, heat waves are quite commonly experienced, but the most intense ones have been registered in recent years, between 2010 and 2014. An overwhelming proportion of deaths, 43.1%, corresponding to 1,350 casualties related to heat waves were calculated in May 2010. A total of 22,960 deaths due to traffic accidents were linked to heat strokes in 2012.[32]

Trends in temperature and heat waves in Mexicali. Figure 2 depicts the maximum monthly average temperatures reached during the analysis period, while Figure 3 shows the maximum registered temperatures. As shown in the figure, the maximum registered temperature occurred in 1955, reaching 52°C, although there is no information about its effects on the health of the population in that region. The second most important maximum temperature was recorded in 2005 (50.5°C), and then in 2006 (48°C). For this last period, there are data about the health effects, which will be discussed later. The dotted line shown in Figure 3 corresponds to the trend observed in the set of maximum registered temperatures. There is a clear trend toward greater temperatures within the analyzed period that may also be corroborated with the

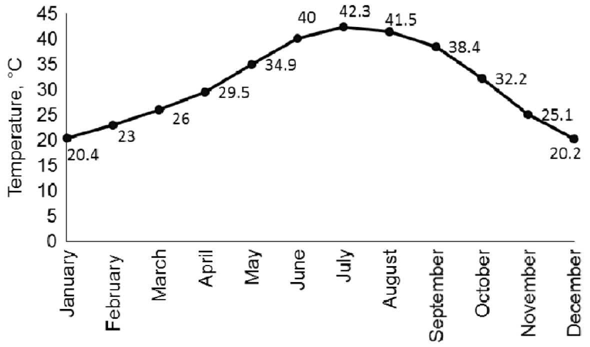

Figure 2. Monthly average maximum temperatures in the city of Mexicali.

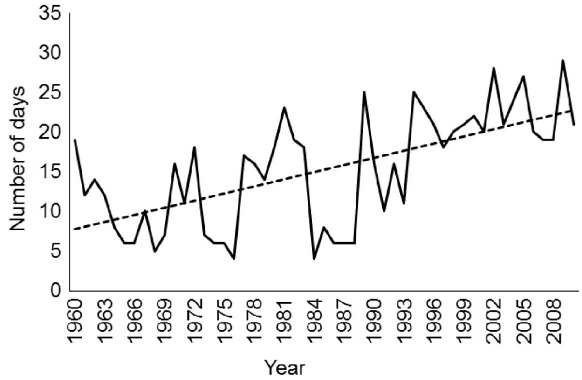

Figure 4. Number of days in which the monthly average maximum temperature is exceeded in Mexicali during July.

number of days in every month, where the maximum average temperature exceeded during the hottest months (July and August), as shown in Figures 4 and 5. Thus, in July 2006, the month's maximum average temperature surpassed during 20 days, while in 2009, the average maximum temperature exceeded during 29 days, practically the whole month. A similar trend was found during August.

When the Spearman's rho test is applied to the variables in Figures 3–5, using a confidence level of 0.01, the results shown in Table 3 were obtained. The Spearman's rho test hence showed the existence of a statistically significant trend.

In a decadal perspective (1960–1969), during July, the temperature went beyond the monthly average by 10 days. Later, during the 2000–2009 decade, this value increased up to 23 days. For August, temperature values higher than the monthly average were observed for 13.6 and 21.1 days during 1960–1969 and 2000–2009, respectively, evidencing a clear trend, not only toward higher temperatures but also toward a larger number of days with excessive heat.

Heat indexes and temperature thresholds for the city of Mexicali. Díaz-Caravantes et al[23] reported a mortality analysis related to the excessive natural heat in Mexico during 2002–2010. They found that 383 people died during this period, most of them in the northwestern part of the country. As expected, the highest number of deaths occurred in the course of the summer, specifically during July. From a regional point of view, the greatest number of victims were in Mexicali, Baja California (70), followed by Hermosillo (48), San Luis Río Colorado (19), and Caborca (17), in Central Sonora; Tabasco (13); and Ciudad Valles, San Luis Potosí (12). These authors[23] observed an extraordinary heat wave generated in Mexicali during July 2006, producing an unusual number of casualties (35) corresponding to half of the total amount registered within the study period.

Jaramillo-Ramírez et al[33] reported the statistics on admissions and deceases at Mexicali's General Hospital during 2006–2010. For this period, the effect of heat waves during 2006 was clearly observed, as shown in Table 4. From the analyzed sample, the occurrence of an exceptional heat wave during the period of July–August, 2006 seems evident.

Worldwide, there are several criteria for determining the threshold of a heat wave, and in many places, they are still under discussion. As the city of Mexicali is located in Mexico, in this study, we decided to use the threshold recommended by the CENAPRED,[14] which is the scientific branch of the national system of civil protection. CENAPRED also recommends development of this threshold for designing risk maps. Moreover, in the 2014 meeting, WMO "Task team on

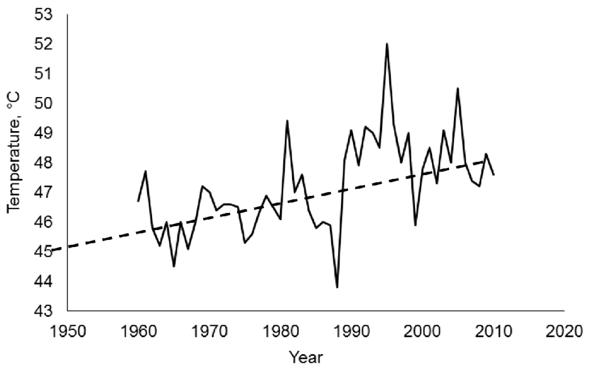

Figure 3. Maximum temperatures registered in Mexicali during 1960–2010.

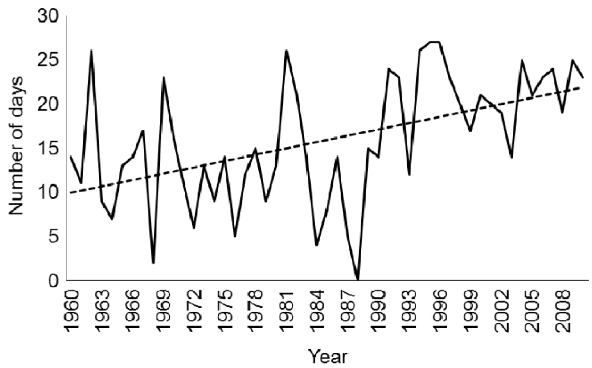

Figure 5. Number of days in which the monthly average maximum temperature is exceeded in Mexicali during August.

Table 3. Spearman's rho test results.

VARIABLE	$\lvert Z_{SR} \rvert$	$t_{(n-2,1-\alpha/2)}$	SPEARMAN RHO TEST RESULT
Maximum monthly temperature	5.215	2.68	There is a tendency
Number of days that exceed the threshold (July)	5.404	2.68	There is a tendency
Number of days that exceed the threshold (August)	4.252	2.68	There is a tendency

definitions of extreme weather and climate events" also recommended the use of the 90th percentile.[34,35]

Figure 6 depicts the records of maximum temperatures for June–September in 2006 and 2010 in Mexicali. The dates correspond to the months with the largest number of admissions to the hospital and deaths due to a heat stroke. The dotted horizontal line represents the 90th percentile threshold. The deadliest heat waves during this period occurred in 2006 and 2009, although the heat wave in July–August 2006 clearly shows more harmful effects than the rest. Nevertheless, when the maximum registered temperature values were analyzed, the maximum values reached were practically the same (ie, >48°C) in both cases. The rationalization for the higher impact of heat waves in 2006 is the long duration of high temperature values, maintained beyond the threshold during a long-lasting period of 17 days. On the other hand, in 2009, although high temperatures were registered, significant oscillations were found during the period. Nevertheless, both events were found to be statistically similar.

When the heat index suggested by the NOOA, proposed in eq. (1), was used for the average maximum temperatures and relative humidity during July–August of 2006 and 2009 in Mexicali, all values were found practically within the extreme danger zone. Figure 7 depicts the heat index values estimated based on the average temperatures and humidity for the time periods described. As seen, the whole period is located within the danger zone, and many of the temperature values registered appear in the extreme danger zone. It was not possible to distinguish any significant difference in these results to explain the difference in the number of patients admitted to the hospital during the study period. We believe that the reason for these differences could be found in nonmeteorological effects, such as the population's preparedness and activities.

Conclusions

The main finding of this study is the existence of a clear upward trend of extreme temperature values, as well as a greater number of heat wave events in Mexicali, Mexico. Moreover, the duration of heat wave episodes has also been found to be increasing. This trend has been proved by the use of Spearman's nonparametric method. An analysis of two heat wave indexes and thresholds was also included. The heat index recommended by the NOAA was found to be not very useful for the city of Mexicali, since all the data recorded during July–August of the analyzed years continue to appear within

Table 4. Admissions and deaths due to heat stroke at Mexicali's General Hospital.[33]

YEAR	MONTH	NUMBER OF ADMISSIONS	NUMBER OF DEATHS	MAXIMUM AMBIENT TEMPERATURE (°C)
2006	May	1	Null	34.6
	June	2	Null	37
	July	32	10	48.1
	August	3	1	42.4
2007	July	3	1	42.5
	August	1	0	45.1
	September	7	5	46.2
2008	June	3	Null	47.1
	July	1	Null	41
	August	2	1	43.1
2009	July	11	5	47.1
	August	1	Null	46.1
2010	June	1	Null	37
	July	4	Null	47.2
	August	4	Null	46.4

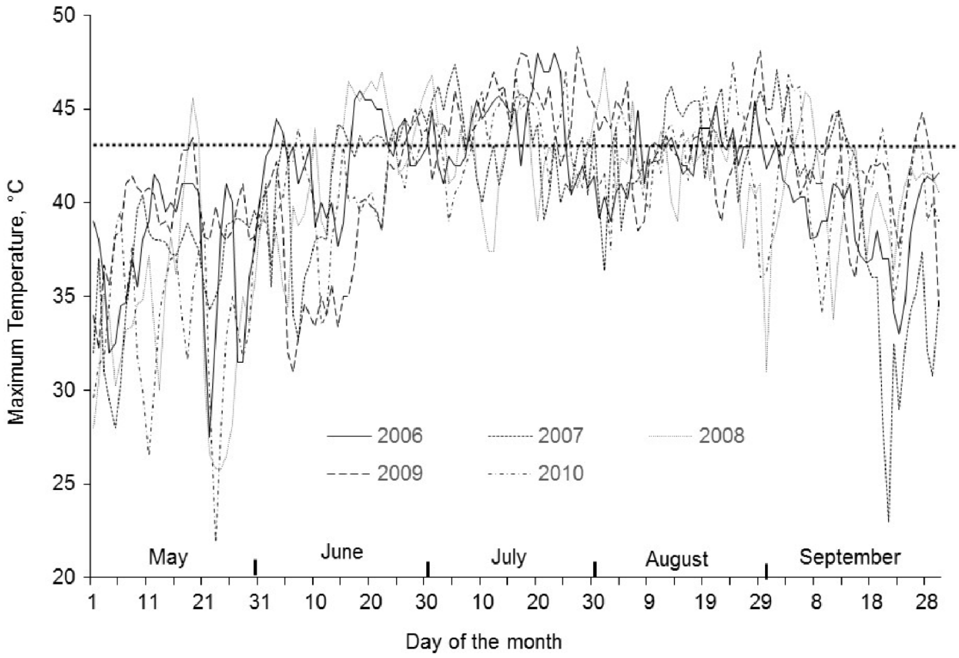

Figure 6. Maximum temperature in Mexicali, during June–September, in the period 2006–2010.

the danger or extreme danger zone. Thus, determining a clear correlation between the heat index and the number of people admitted to the hospital is quite complex.

A statistical threshold was found to be more useful if the design of an alert system in Mexicali is envisioned. In this case, suggesting the application of the temperature corresponding to the 90th percentile as a threshold for heat waves seems to be useful. This threshold, suggested by CENAPRED, was also found to be useful for designing risks maps. In this latter case, the threshold corresponds to 42.8°C in Mexicali. However, since no data on daily admissions to hospitals are available, and hospital admissions for heat stroke are related not only to temperature but also to other variables such as occupation and income, a clear link between temperatures and illness could not be established. Till date, the information on hospital admissions only identifies the years and dates when the most dangerous heat waves were recorded. Thus, an urgent need for better registers and national statistics becomes evident.

The maximum temperatures in Mexicali during 1969–2011 showed a clearly increasing trend. As a result, the design and application of alert systems for the region is highly recommended, together with a support plan for the most vulnerable population. In this case, the vulnerable population may include not only children and elderly people but also

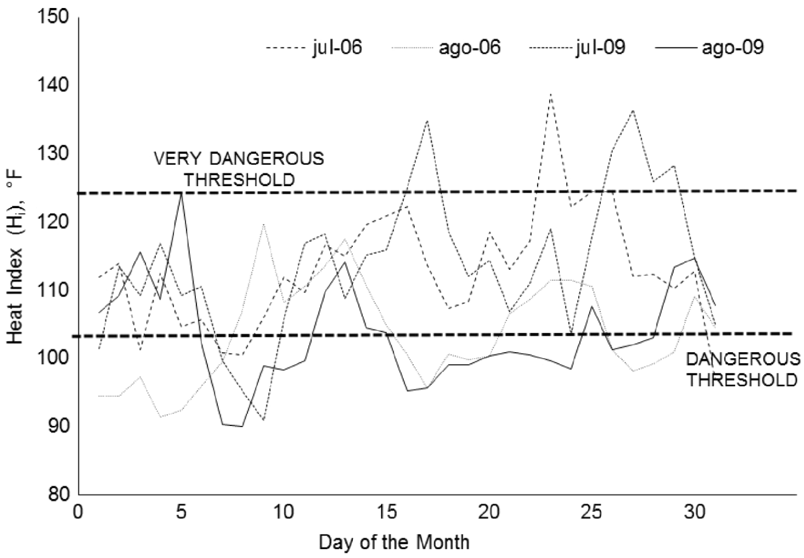

Figure 7. Heat index calculations based on average temperature and humidity during July–August of 2006 and 2009 in Mexicali.

those practicing outdoor activities and/or without immediate access to proper health services. The system should alert the population and authorities to enforce the corresponding protection measures in the presence of heat waves, ie, when the maximum temperature reaches the 90th percentile for two or more days.

Author Contributions

Conceived and designed the experiments: PFMA and ERB. Analyzed the data: PFMA. Wrote the first draft of the manuscript: ERB. Contributed to the writing of the manuscript: PFMA. Agree with manuscript results and conclusions: PFMA and ERB. Jointly developed the structure and arguments for the paper: PFMA and ERB. Made critical revisions and approved final version: ERB and PFMA. Both authors reviewed and approved of the final manuscript.

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