ORIGINAL PAPER

Heat waves and heat days in an arid city in the northwest of México: current trends and in climate change scenarios

Rafael O. García Cueto · Adalberto Tejeda Martínez · Ernesto Jáuregui Ostos

Abstract The aim of this work is to study heat waves (HWs) in Mexicali, Mexico, because numerous deaths have been reported in this city, caused by heatstroke. This research acquires relevancy because several studies have projected that the health impacts of HWs could increase under various climate change scenarios, especially in countries with low adaptive capacity, as is our case. This paper has three objectives: first, to analyze the observed change in the summer (1 June to 15 September) daily maximum temperature during the period from 1951 to 2006; secondly, to characterize the annual and monthly evolution of frequency, duration and intensity of HWs; and finally, to generate scenarios of heat days (HDs) by means of a statistical downscaling model, in combination with a global climate model (HadCM3), for the 2020s, 2050s, and 2080s. The results show summer maximum temperatures featured warming and cooling periods from 1951 until the mid-1980s and, later, a rising tendency, which prevailed until 2006. The duration and intensity of HWs have increased for all summer months, which is an indicator of the severity of the problem; in fact, there are 2.3 times more HWs now than in the decade of the 1970s. The most appropriate distribution for modeling the occurrence of HDs was the Weibull, with the maximum temperature as

co-variable. For the 2020s, 2050s, and 2080s, HDs under a medium-high emissions scenario (A2) could increase relative to 1961–1990, by 2.1, 3.6, and 5.1 times, respectively, whereas under a medium-low emissions scenario (B2), HDs could increase by 2.4, 3.4, and 4.0, for the same projections of time.

Keywords Heat wave · Heat day · Climate change · Statistical downscaling · Mexicali city

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Introduction

Heat waves (HWs) are periods of unusually hot weather that affect human health through heat stress and exacerbate underlying conditions, such as cardiovascular, cerebrovascular, and respiratory diseases (Kyselý 2004; Ebi and Meehl 2007), which can increase the incidence of mortality and morbidity in affected populations (EPA 2006). Although population-wide risks exist with these kinds of events, several specific risk factors—including age, income level, level of social isolation, working without air conditioning, and living in top floor apartments—may increase the risk of heat illness (Kovats and Ebi 2006; Sheridan and Dolney 2003; McMichael et al. 2008). The World Meteorological Organization (WMO) has not been able to comprehensively define HWs, as they vary in their characteristics and impact even in the same locality (Kyselý et al. 2000). However, some authors agree that such events could include the exceedance of local threshold temperatures in the area of interest (Robinson 2001; Tan et al. 2007); this definition identifies changes in HW frequency and duration. According to Robinson (2001), there are two aspects for the establishment of thresholds for HWs: (1) exceeding fixed absolute values, which, on first approximation, represent the lower limits for physiologic HWs; conditions above this value would affect most of the

Fig. 1 Location of Mexicali, México

Fig. 3 Evolution of maximum temperature (Tmax) in seven overlapping 1-month periods during the summer in Mexicali City from 1951 to 2006
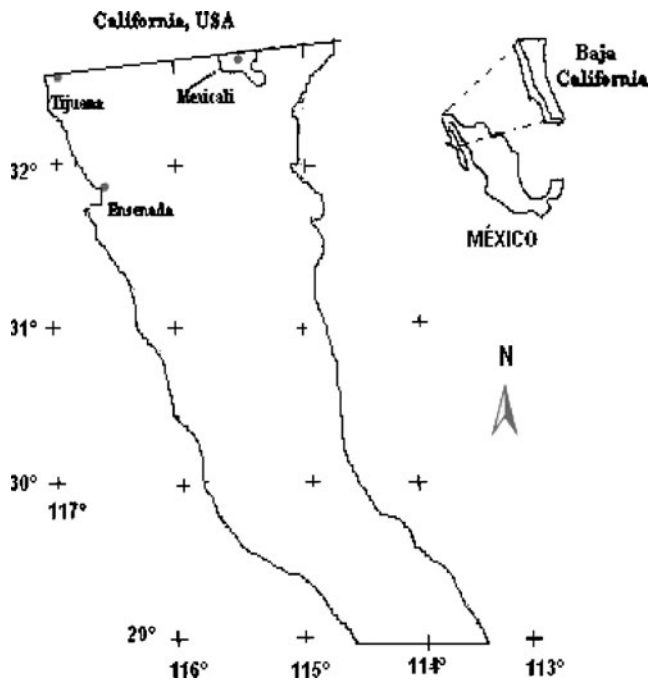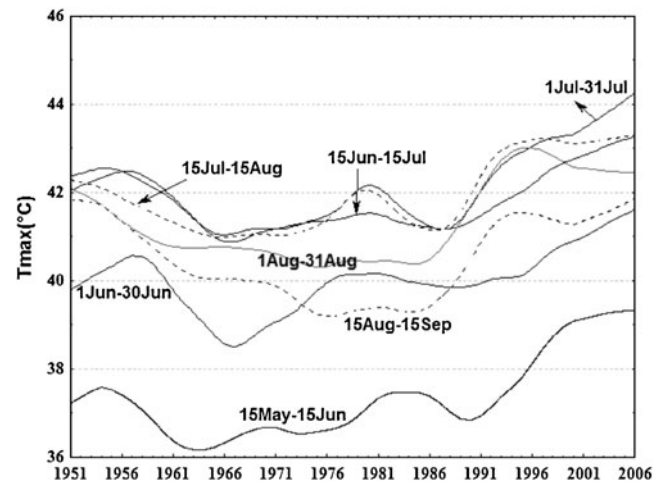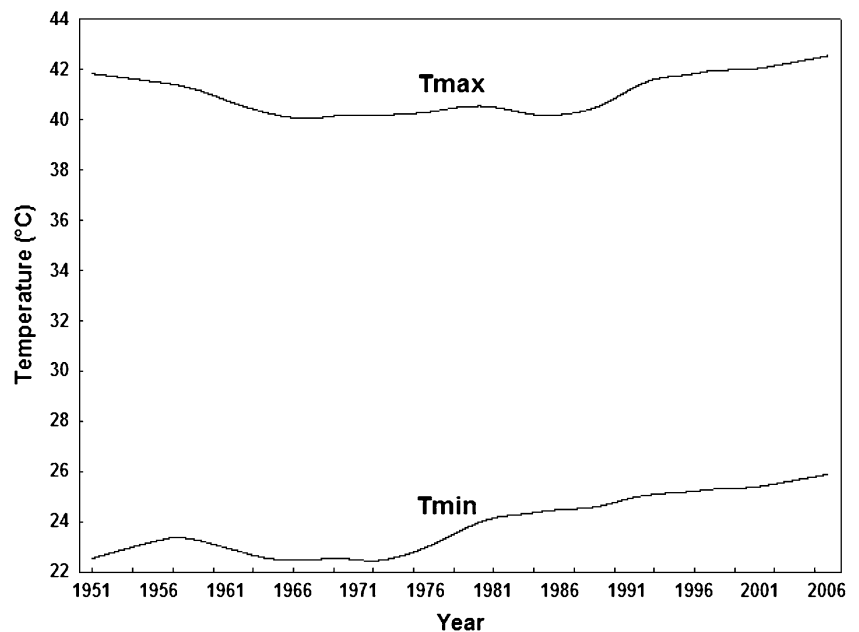
population and require some form of modification of activities to prevent discomfort or health problems (Tan et al. 2007; Kunkel et al. 1996; Kyselý 2004); and (2) deviation from normal, which is supposed to rely more on the sociological aspect of the excessive heat in which the adaptation to the prevailing climate in a certain place is considered, rather than on the physiological aspect, which takes account of the process of thermoregulation of the human body (and for which it makes sense to consider thresholds fixed). There are several possible approaches, i.e., exceedance

of a fixed percentile of all observed values, exceedance of the daily mean value by a fixed standard deviation, exceedance of the daily mean by a fixed absolute amount, etc. Many studies on HW have been undertaken, mostly in Europe and North America (Kunkel et al. 1996; Kyselý 2004; Diaz et al. 2002; Meehl and Tebaldi 2004; Kovats and Ebi 2006). An exceptionally extreme HW occurred in central and western Europe during the summer of 2003, and unusually large numbers of heat-related deaths were reported in France, Germany, and Italy (Stott et al. 2004). Some authors believe that this event was only one example of the "shape of things to come" (Beniston and Díaz 2004), and should be considered by decision-makers in planning responses to extreme heat-related events. Recently, there has been

Fig. 2 Evolution of maximum (Tmax) and minimum (Tmin) temperatures in summer from 1951 to 2006 in Mexicali City

Table 1 Statistics of maximum temperature (°C) in summer months in Mexicali City

	June				July				August				September			
	Mean	Tmax	SD	P90	Mean	Tmax	SD	P90	Mean	Tmax	SD	P90	Mean	Tmax	SD	P90
1951–1980	39.5	42.2	1.4	42.6	41.7	43.5	1.0	43.0	40.8	43.1	1.0	42.2	40.5	43.0	1.8	42.5
1981–1990	40.2	43.0	1.2	41.9	41.7	44.5	1.7	43.9	40.6	43.9	1.6	42.8	39.2	42.7	2.7	42.2
1991–2006	40.7	43.7	1.6	42.7	43.1	44.9	1.0	44.4	42.7	44.1	0.9	43.7	40.4	43.4	1.2	43.3

recognition that heat-related risks can be reduced through heat–health early warning systems, which alert decision-makers and the general public to impending dangerous hot weather and serve as a source of advice on how to avoid negative health outcomes associated with hot weather extremes (WHO 2003; Kovats and Ebi 2006; Sheridan 2007, Kalkstein and Sheridan 2007; Kalkstein et al. 2009). Although there are detailed studies on severe HWs, or extreme heat events (Karl and Knight 1997), and their impacts (Changnon et al. 1996), very little is known about their climatic behaviour, that is, their frequency, duration, and intensity, an exception being the study carried out by Abaurrea et al. (2007), which contains an excellent statistical modeling of those extreme heat events and provides their possible trajectories in a medium-term horizon, the 2050s, as an alternative to regional climate models (Schär et al. 2004; Sánchez et al. 2004).

Projected heat waves could become more frequent, more severe and longer lasting with climate change (WHO 2003; Meehl and Tebaldi 2004). Over the last 50 years, hot days, hot nights and heat waves have become more frequent and could affect the health status of millions of people in some parts of the world, particularly those with low adaptive capacity (IPCC 2007). Some studies have projected that the health impacts of HWs could increase under various climate change scenarios (Kalkstein and Greene 1997; Dessai 2003; Hayhoe et al. 2004; Blashki et al. 2007). However, these projections, which were carried out in developed countries, need to incorporate a variety of factors, such as the degree to which the population is acclimated to higher temperatures, the characteristics of the vulnerable population, and the extent to which effective adaptation strategies and meas-

ures have been implemented (Ebi and Meehl 2007; Sheridan and Dolney 2003).

The aim of this work is to study the HWs observed in Mexicali City, located in northwest Mexico, because in this arid city we find the highest temperatures in the whole country as well as numerous death reports, certified by the Forensic Department, that are attributable to heatstroke. The deaths, from this cause were begun to be assessed in the year 2000 and, in 2006, a total of 29 deaths were reported, the highest number registered. During a period running from May through September every year, the regional climate is hot and dry; the annual variation in the mean monthly temperature is 20.9°C, the mean monthly maximum temperature in summer is 40.1°C, and the maximum absolute temperature registered to date is 52°C. The importance of carrying out this study lies in the fact of the majority of studies about HWs have been carried out in Europe and the USA (Gover 1938; Karl and Knight 1997; Semenza et al. 1996; Braga et al. 2001; Basu and Samet 2003; Schär et al. 2004; Curriero et al. 2002), and very few studies have been done in Latin American countries (O'Neill et al. 2005; McMichael et al. 2008; Bell et al. 2008). The goals of this study were: (1) to analyze the change observed in daily maximum and minimum temperatures, (2) to characterize the seasonal evolution of the frequency, duration and intensity of HWs and heat days (HDs), and (3) to generate scenarios of HDs by means of a statistical downscaling model for the 2020s, 2050s, and 2080s.

Materials and methods

This study was performed in Mexicali City, which is located in northwest Mexico (32.55°N, 115.47°W and 4 m

Table 2 Statistics of minimum temperature (°C) in summer months in Mexicali City

	June				July				August				September			
	Mean	Tmin	SD	P90	Mean	Tmin	SD	P90	Mean	Tmin	SD	P90	Mean	Tmin	SD	P90
1951–1980	19.7	22.1	1.5	21.9	24.5	26.9	1.3	26.5	24.2	26.6	1.3	26.1	22.4	25.9	1.6	24.8
1981–1990	21.5	24.0	1.3	23.4	26.1	28.1	1.0	27.9	26.3	27.9	1.1	27.7	24.3	29.9	3.0	28.7
1991–2006	22.4	25.0	1.5	24.8	26.7	29.4	1.4	28.5	26.9	28.6	1.0	28.2	24.9	27.4	1.8	27.1

Fig. 4 Frequency of heat days in Mexicali City (1956–2005)
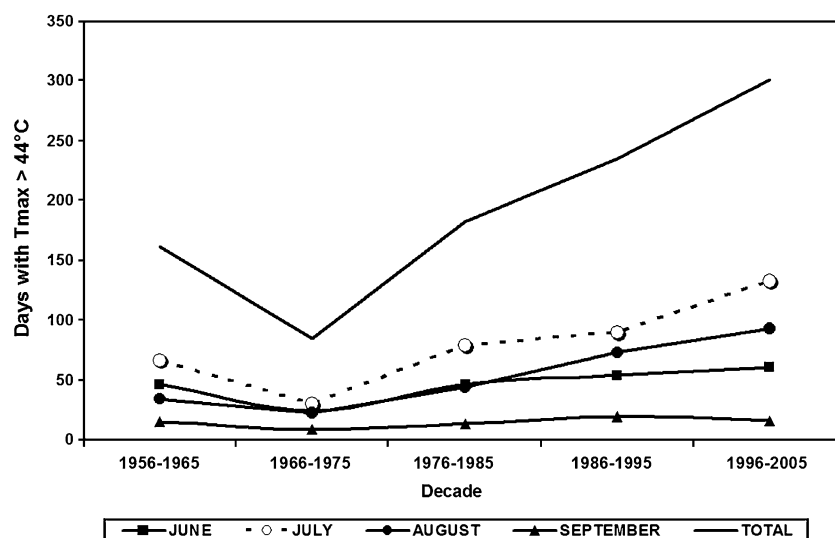
above sea level; Fig. 1). The performed analysis used two data groups: 1) observed, and 2) simulated. The observed meteorological data consist of daily maximum and minimum temperatures from 1 June to 15 September (hereafter "summer") of 1951 to 2006 and were provided by the Comision Nacional del Agua of Mexico. The period chosen was the most reliable and allowed us to perform a descriptive study of thermal variability and show the temporal evolution of frequency, duration, and intensity of HWs and HDs.

There are a number of ways to define an HW; in our study, we decided to use an "excess over a threshold", as this definition identifies changes in HW frequency and duration. We selected as threshold the maximum temperature exceeding the 90th percentile for one day to define a "heat day" (HD). The chosen threshold of daily maximum temperature was 44°C. Using this criterion, an HW is defined as a period with at least two consecutive HDs.

To realize the modeling of the HDs the period 1961–1990 was taken as a baseline because daily predictors are available for this period, and because WMO currently uses it for climate change studies.

Moreover, General Circulation Models (GCM) suggest that the growing concentrations of greenhouse gases will have significant implications upon the climate on a global and regional scale, particularly an increase in the number of extreme events (Karl and Trenberth 2003). Yet, those models cannot be used for local impact studies due to their coarse spatial resolution (typically in a range of 50,000 km²) and their inability to consider important features at a scale lower than the grid used, like clouds and topography.

So-called "downscaling" techniques are used to bridge the spatial and temporal resolution gaps between what climate modelers are currently able to provide and what impact assessors require. From this perspective, regional or local climate information is derived by first determining a statistical model which relates large-scale climate variables (or "predictors", such as mean sea level pressure or geopotential height) to regional and local variables (or "predictands"; in this case, HDs) (von Storch 1999). To project changes in future HDs, the Statistical Downscaling Model (SDSM; Wilby and Dawson 2007) was used.

The SDSM can be briefly described as a stochastic downscaling and multiple regression techniques hybrid. Previous to the scenarios generation, a daily maximum temperature analysis was carried out through regression techniques versus statistically elicited predictors. The downscaled results in this case are 95% statistically significant. For model calibration, the sources were the National Centre of Environmental Prediction (NCEP) re-analysis data set, and daily predictor variables derived from the HadCM3 model, developed by Hadley Centre in 1988 (Pope et al. 2000). The HadCM3 model has a spatial resolution of 3.75° longitude by 2.5° latitude, and we get the data corresponding to the grid point (32.5°N, 116.25°W) closest to Mexicali City, for the time periods between 1961 and 2099. The resulting regression equations were calibrated, and an equal dispersion of the residuals was found for all the value series of the predictand (HDs) modeled. The accuracy of the resulting equations with the base downscaled scenario (1961–1990) was verified and compared to the observed values for the same period finding a good fitting.

Table 3 Frequency of HWs in Mexicali City from 1951 to 2006

Month	Number of events
June	76
July	110
August	73
September	25

Table 4 Duration of HWs in Mexicali City from 1951 to 2006

Consecutive days	
2–4	226
5–7	42
>8	16

To project future changes in HDs, the model was run 20 times. We defined the "present day" reference period as 1961–1990, and the future as the time period from the 2020s, 2050s, 2080s, and computed differences among these four periods. We used a medium-high emissions scenario (A2) and a medium-low emissions scenario (B2) for future greenhouse gas emissions as defined in the IPCC Special Report on Emissions Scenarios (Nakicenovic and Swart 2000). These describe CO_2 emissions growth intermediate between scenarios A1FI (more extreme) and B1 (lesser evolution).

Results

Descriptive temperature analysis

In this section, we analyze the observed change in the summer daily maximum temperatures during the period 1951–2006. To show the evolution of temperature mean values, and following the method proposed by Abaurrea et al. (2007), we plot the maximum (Tmax) and minimum (Tmin) mean temperatures for summer. This was performed with a LOWESS (Locally Weighted Smoothing Scatter Plots) procedure, which is a popular technique for curve fitting (Cleveland 1979). We applied the smoothing parameter of 0.50 for both maximum and minimum mean temperatures (Fig. 2). We can observe that the Tmax shows a decrease from 1951 to 1964, followed by a stable period

(1965–1990), then by a rising phase until 2006. Concerning the Tmin, we can see a short rising period (1951–1956), followed by a relatively stable phase until the late 1970s, and finally a rising phase (1977–2006).

In order to analyze more closely the temperature evolution during the summer, the smoothed Tmax curves corresponding to 7 overlapping 1-month periods: 15 May– 15 June, 1–30 June, 15 June–15 July, 1–31 July, 15 July–15 August, 1–31 August, and 15 August–15 September, were plotted (Fig. 3).

Figure 3 shows Tmax warming and cooling periods, from 1951 until the mid-1980s, and later we find a rising tendency which prevails until the present (2006). The greatest increase of almost 3°C, belongs to 1 –31 July period, followed by those belonging to 15 May–15 June and 1–30 June (almost 2°C). Another interesting period is 15 August–15 September, which shows an increasing trend beginning in 2000, after having reached a plateau in the mid-1990s. In the early 1990s, from 15 June to 15 July, it reached a peak and since then has remained constant; whereas the 15 July–15 August period also reached that plateau, but from there on it has shown a slightly rising tendency. The foregoing results show that nowadays warm temperatures in the summer season persist longer throughout than they did in 1986.

To complete this exploratory study, we show some monthly statistics [mean value, mean maximum (Tmax), mean minimum (Tmin), standard deviation (std) and 90th percentile (P90)] describing both maximum and minimum temperatures in summer (Tables 1 and 2). Three periods are considered: 1951–1980, 1981–1990, and 1991–2006. Table 1 shows that, starting from the second period (1981– 1990), the mean, mean maximum (Tmax) and extreme values (P90) increase every month. The variability also diminishes in the last period (1991–2006), except for June. The greatest thermal difference of mean values among the periods considered occurs during August, with 2.1°C between 1981–1990 and 1991–2006.

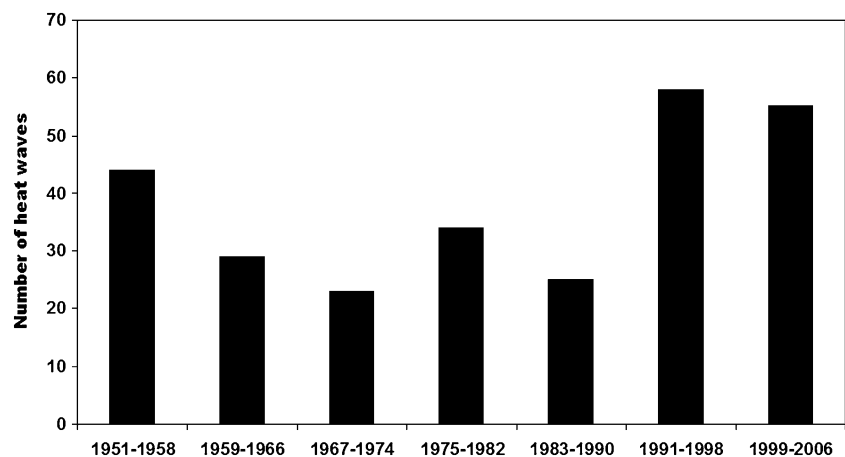**Fig. 5** Frequency of heat waves in Mexicali City for period 1951–2006

Table 5 Summer mean, maximum number and 50th and 90th percentiles of HWs per decade in Mexicali City

HW Period	Mean frequency	Maximum frequency	50th percentile	90th percentile
1951–1960	5.6	9	6.0	8.0
1961–1970	2.9	7	3.0	6.5
1971–1980	3.0	5	3.0	5.0
1981–1990	4.0	8	4.0	7.5
1991–2000	7.2	12	6.5	11.5
2001–2006	6.8	8	7.5	8.0

In the case of the Tmin (Table 2), a rising tendency in all the estimated statistics (mean, Tmin and P90) was found. The standard deviation values (SD) show little variability and homogeneous values between periods, even with the increasing trend. The difference between the mean of the first period (1951–1980) and the last one (1991–2006) rises from 2.2°C to 2.7°C, which is a value higher than that obtained for the mean of Tmax.

Heat days evolution

The number of occurrences of HDs per decade in summer is shown in Fig. 4. There is an increasing trend in July and August, which are the months when deaths due to "heatstroke" have been reported. In the last 4 years, 44 persons died in Mexicali City, victims of the high temperatures: 7 in 2004, 6 in 2005, 29 in 2006, and 7 in 2007.

Heat waves behaviour

When the definition previously declared was applied, 284 HWs were found. Table 3 shows that HWs are more frequent in July, when they mostly lasted from 2 to 4 days (Table 4).

Figure 5 shows that the frequency of HWs in Mexicali City displays a marked increase, particularly since 1990; in the last 15 years (1991–2006), we had 113 HWs, while in period 1975–1990 there were 59 HWs, an increase of almost 100% in only 15 years.

Three variables were used to summarize the severity of each HW: the length (L), which is the number of days the event lasted; the maximum intensity (Imax), which refers to the maximum value of the Tmax excess over the selected threshold during the spell, and the mean intensity (Imean), which is the ratio between the total excess, defined as the cumulative differences between Tmax over threshold and the length of the event: $Imean = \sum \Delta T / \sum L$, the sums are realized if $\Delta T > 0$, $(\Delta T = T_{max} - T_{treshold})$.

To describe their characteristics and evolution, some basic statistics are shown in Tables 5 and 6. For each decade, except the last period, which includes only 6 years (2001–2006), we show the mean and maximum number of HWs, and 50th and 90th percentiles (Table 5); this same information for the three severity variables is shown in Table 6. From the analysis of these tables, we observe that: (1) After a decrease in the 1960s and 1970s, the mean length of the HW had grown until becoming stable, and (2) the maximum and mean intensity values also show a rising tendency, although they reached a peak in the 1990s and currently (2001–2006) their values have stabilized with respect to those in the former period. During the last period, the length of the HWs shows a record: 20 consecutive days with a temperature above the threshold selected (not shown).

In order to analyze the HWs seasonal profile we calculated, per month and decade, the mean annual occurrence rate and 90th percentile of the severity variables (Table 7). The frequency of HW occurrences since the 1960s has increased in June through September, and the

Table 6 Summer mean, maximum values and 50th (*P50*) and 90th (*P90*) percentiles of severity variable distributions of HWs per decade, in Mexicali City

Period	Lengtgh				Lmax				Lmean			
	Mean	Max	P50	P90	Mean	Max	P50	P90	Mean	Max	P50	P90
1951–1960	1.4	2.3	1.5	2.0	3.5	5.0	3.1	4.8	1.3	1.7	1.3	1.7
1961–1970	0.7	1.8	0.8	1.6	1.8	3.7	1.9	3.5	0.9	1.8	0.9	1.6
1971–1980	0.8	1.3	0.8	1.3	2.3	2.9	2.5	2.8	0.9	1.4	1.0	1.3
1981–1990	1.0	2.0	1.0	1.9	2.9	5.4	2.5	5.3	1.2	1.8	1.3	1.8
1991–2000	1.8	3.0	1.6	2.9	4.7	8.0	4.8	6.8	1.5	2.4	1.5	2.1
2001–2006	1.7	2.0	1.9	2.0	4.6	6.5	4.3	6.5	1.4	1.8	1.4	1.8

Table 7 Mean number of HW and 90th percentile of severity variable distributions per month and decade in Mexicali City

Period	Mean frequency				Length (90th percentile)				Lmax (90th percentile)				Lmean (90th percentile)			
	Jun	Jul	Aug	Sep	Jun	Jul	Aug	Sep	Jun	Jul	Aug	Sep	Jun	Jul	Aug	Sep
1951–1960	4.8	8.8	4.0	2.7	8.5	12.5	12.0	8.0	4.4	4.3	2.7	2.4	1.9	1.9	1.0	1.5
1961–1970	1.7	2.8	2.6	0.4	5.5	5.5	9.0	2.0	3.4	2.2	2.5	1.4	1.7	1.2	1.5	1.0
1971–1980	3.5	3.8	0.4	0.8	8.0	8.5	2.0	4.0	2.6	2.5	1.5	1.6	1.7	1.2	1.1	0.8
1981–1990	3.9	5.9	3.4	1.4	11.0	15.0	11.5	4.5	4.6	3.9	4.2	2.9	2.1	1.8	1.8	1.9
1991–2000	5.3	9.9	10.4	1.0	14.5	17.0	15.5	5.0	4.3	6.7	5.4	2.0	2.3	2.1	2.9	1.0
2001–2006	6.3	14.0	6.3	2.0	12.0	25.0	8.0	5.0	3.2	6.5	4.0	2.5	3.0	2.6	2.4	1.7

length of events has also increased since the 1960s for all months, which is an indicator of the seriousness of the problem. The maximum and mean intensities also show a growing behavior, but seem to have stabilized according to the reports in the last two periods.

Modeling of heat days

The goal in this part of our study is to propose a model to estimate HDs, and see if they are more frequent as the summer seasonal Tmax increases; the period of years for this modeling was from 1951 to 2006. The HD occurrence was modeled with the distribution of the Generalized Extreme Values (GEV):

$$G(z; \mu, \sigma, \xi) = \exp\left[-\{1 + \xi(z - \mu)/\sigma\}^{-1/\xi}\right]$$

where $-\infty < \mu < \infty$, $\sigma > 0$ and $-\infty < \xi < \infty$ are the location, scale and shape parameters respectively. The Maximum Probability method for estimating the parameters was used. The extremes package (Gilleland and Katz 2006) of R (R Development Core Team 2004) was used because it is an open source. It is particularly well oriented to climatic applications and has the ability of incorporate information about co-variables in order to estimate parameters. Table 8 shows the HD values with and without co-variables, and Fig. 6 a diagnosis of such adjustment.

When the probability and quantile graphs were observed (Fig. 6), it suggested that the underlying suppositions for the GEV distribution are reasonable for the HD data. According to the shape parameter (ξ), the most adequate distribution for modeling the HD occurrence is the Weibull. The inclusion of the maximum temperature as a co-variable in the location parameter (μ) of GEV generated a meaningful improvement (at the level of 5%) upon the initial adjustment which was corroborated with the statistical test of probability that with a 74.3 value is greater than the critical X^2, with a degree of freedom of 3.84. The obtained model is summarized in Table 6, on the right side, where the location parameter is modeled as a linear

regression in the following manner: $\mu(x) = \mu_0 + \mu_1 x$, where x is the maximum temperature. We can see that, when the maximum temperature increases, the location parameter values become more positive, indicating that the HD are present more frequently as the maximum temperature increases.

Heat days projections

The heat days scenarios for the 2020s and 2080s are shown in Figs. 7 and 8 under forcing of the HadCM3 model, emissions scenarios A2 and B2, and its comparison with the scenario base (1961–1990). We can see an increase in the monthly frequency, as well as an earlier onset and a later ending of HDs (air temperature >44°C).

For the 2020s, July and August would present the larger increases in HDs, relative to baseline 1961–1990, in both emission scenarios A2 and B2 (Fig. 7). The major increase in the relative frequency of HDs will be in May, compared with June and September, which might cause serious impacts on human health, since people might not yet be prepared for the warm season. It is also notable that the 2020s will have bigger increases in HDs with emission scenario B2 than with A2, which indicates that the

Table 8 Parameters of HD adjustment and the incorporation of maximum temperature as a co-variable in the location parameter (lower half)

Parameter	Estimator	Standard error
Location (μ)	6.74638	0.61265
Scale (σ)	3.96961	0.45372
Shape (ξ)	-0.20528	0.12009
Log negative probability: 159.489072		
Location (μ_0)	-122.10346	8.13580
Location (μ_1)	3.16577	0.19792
Scale (σ)	2.42660	0.27415
Shape (ξ)	-0.49597	0.09589
Log negative probability: 122.352439		

Fig. 6 Adjustment diagnosis of the GEV distribution for HD in Mexicali City. Quantiles and the return level refer to the number of observations
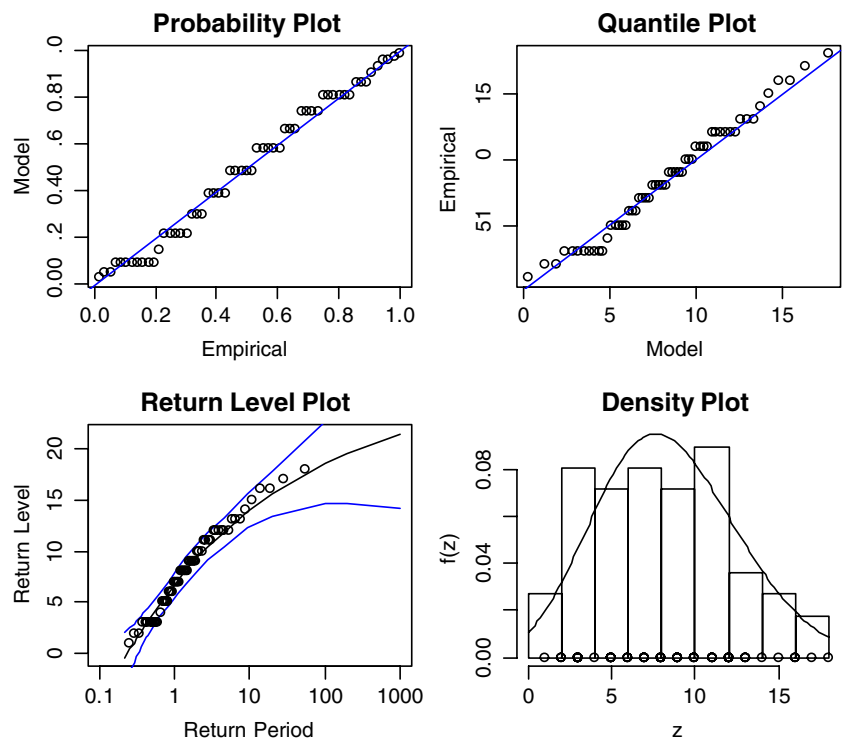
reduction of greenhouse gas emissions (B2) has a clear effect, for the 2020s exhibits more warming because it also provides for a major redistribution of wealth that short-term would increase the emissions from developing countries (see Figs. 7 and 8 and Table 9).

The 2080s will be a period with a much greater frequency HDs (Fig. 8), relative to the base scenario of 1961–1990, and will also feature an earlier beginning and later retreat, that is, the warm period in Mexicali City will be more severe and longer. The scenario of HDs for the 2050s, not shown, has intermediate values between those of the 2020s and 2080s.

The HadCM3 model, under emissions scenario A2, projected an increase in the average HD frequency of about 93% for the 2020s—from 1.1 to 2.1 HDs per year, 226% for the 2050s—from 1.1 to 3.6 HDs per year, and 407% for the 2080s—from 1.1 to 5.6 HDs per year. The average duration of HDs was projected, under emissions scenario B2, to increase by 122% for the 2020s—from 1.1 to 2.4 HDs per year, 208% for the 2050s—from 1.1 to 3.4 HDs per year, and 265% for the 2080s—from 1.1 to 4.0 HDs per year (Table 6). In summary, the HDs would appear with more frequency, and would have an earlier beginning and later retreat, that is, the warm period in Mexicali City would

Fig. 7 HDs observed (1961–1990) and modeled with A2 and B2 emissions scenarios for the 2020s
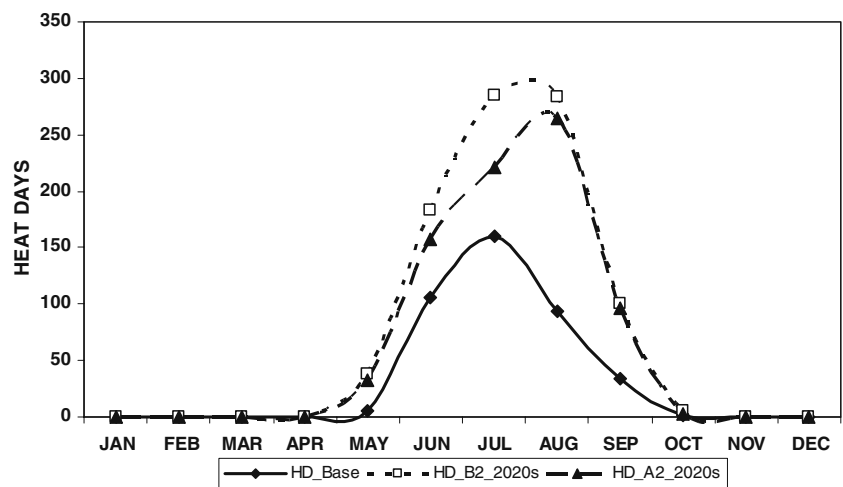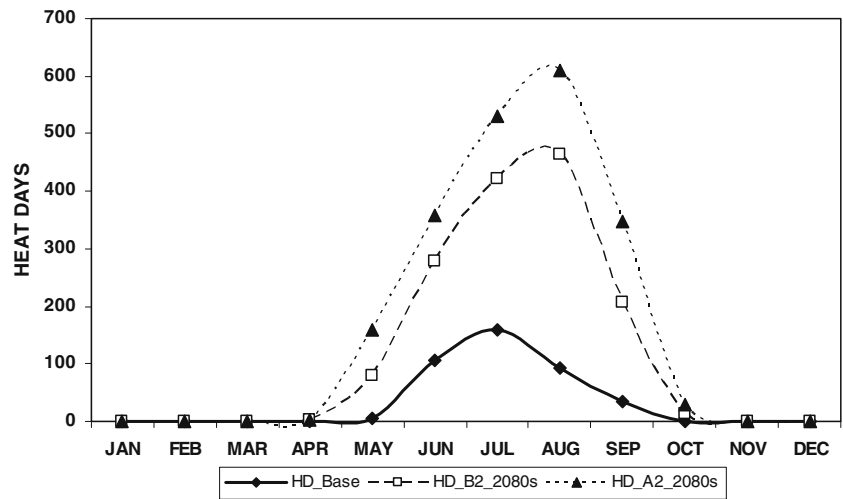
Fig. 8 HD observed
(1961–1990) and modeled
with A2 and B2 emissions
scenarios for the 2080s

be more severe and longer. For the 2050s and 2080s, even April and October could have this kind of extreme event as projections show in Table 9.

Concluding remarks

The results show that in Mexicali City warm temperatures occur in the summer season; from 1951 until the mid-1980s, daily maximum temperatures had warming and cooling periods, and later we find a rising tendency which prevails until the present (2006). Many methods exist for characterizing the definition of an HW. Here, for the period

1 June–15 September, from the summers of 1951 to 2006, an HD is defined as a daily maximum temperature exceeding 90th percentile (44°C). Using this criterion to characterize the heat spells, an HW is defined as a period with at least two consecutive HDs.

Using the above definition, 284 HWs from 1951 to 2006 were identified; these were most frequent in July, and most lasted from 2 to 4 days. In the last 15 years (1991–2006) the city had 113 HWs, while in the period 1975–1990 there were 59 HWs, an increase of almost 100% in only 15 years. An analysis of HWs, grouped in periods of 8 years, shows that these events increased from 23 per 8 years in the 1970s to 55 per 8 years at the beginning of the twenty-first century.

Table 9 Base scenario of heat days (1961–1990), and in future emissions scenarios A2 and B2 for the 2020s, 2050s, and 2080s in Mexicali City

Month	Evolution of heat days						
	Actual (1961–1990)	Climate change					
		2020s		2050s		2080s	
		A2	B2	A2	B2	A2	B2
January	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0
April	0	0	0	1	1	2	1
May	6	32	38	53	67	158	79
June	106	157	184	307	241	358	279
July	160	221	285	374	361	531	422
August	94	265	284	409	393	610	464
September	34	96	101	156	166	347	208
October	1	3	5	9	7	30	14
November	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0
Annual	401	774	892	1,309	1,236	2,034	1,467
Heat days/year	1.1	2.1	2.4	3.6	3.4	5.6	4.0

The severity variables, length, average intensity and maximum intensity, which characterize the HWs, have grown since the 1960s, but they reached a high point in the 1990s and currently (2001–2006) their values are stabilized. The frequency of occurrence, of HDs and HWs, has increased since the 1960s, especially in July and August, which is an indicator of the severity of the problem, since during that time there were deaths caused by heatstroke.

The most adequate distribution for modeling the HD occurrence with a daily maximum temperature as a co-variable was the Weibull distribution. According to scenarios generated by a statistical downscaling model, we found that with emissions scenario A2, for the 2020s, 2050s, and 2080s, the HDs will increase relative to the 1961–1990 period by 2.1, 3.6, and 5.1 times, respectively. Under scenario B2, these increases are estimated at 2.4, 3.4, and 4.0 for the same period. The choice of these emissions scenarios (A2 and B2) were made because they are intermediate between scenarios A1FI (more extreme) and B1 (lesser evolution), which allows us to assess a range of future conditions under increasing greenhouse gases.

Finally, it is clear that for Mexicali, one of the Mexican cities with a great annual thermal variability, HWs and HDs, according to the observed trends and future projections obtained, are and will continue be a growing danger with serious health consequences if no measures are taken in order to reduce the risk. Measures for preventing the effects of heat waves have proven effective (Palecki et al. 2001; Ebi et al. 2004), and include: (1) individual measures (lightweight clothing, cool environment, rehydration, acclimatization, reduction of excess weight, etc.); (2) emergency planning (knowledge about social factors, i.e. the living conditions and numbers of elderly, mentally ill and other vulnerable people, the capacity of hospitals and other health facilities to treat patients with related illness, and studies of behavioural responses to hot weather); (3) heat health warning systems (when a certain temperature or temperature/humidity threshold is, or would be, surpassed); and (4) reduction of heat stress in outdoor or indoor environments. These measures, individually or together, should be evaluated by the Health Sector and Civil Protection of Mexicali City to prevent more deaths related to HWs in the future.

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