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Urbanization effects upon the air temperature in Mexicali, B. C., México

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RESUMEN

Se realizó un análisis temporal y espacial de la temperatura del aire en el dosel urbano de la ciudad de Mexicali, B. C. y alrededores rurales. A una base de datos de largo período (1950-2000) se aplicaron varias pruebas estadísticas para identificar la variabilidad temporal de la temperatura. Se observaron tendencias positivas y estadísticamente significativas de temperatura mínima, con un valor de 0.66 °C/década, en el área urbana, mientras que en las estaciones rurales se observaron valores menores; respecto a la temperatura máxima también se encontraron resultados estadísticamente significativos, pero con una tendencia negativa. Al realizar el análisis espacial, con una base de datos de época reciente (2000-2005), quedó de manifiesto la presencia de una masa de aire tibio nocturna en la atmósfera urbana, encontrándose que la diferencia máxima, entre la ciudad y sus alrededores, ocurre en invierno con un valor de 5.7 °C. Estos resultados sugieren que la urbanización, al igual que en muchas otras ciudades del mundo, afecta de manera importante al clima local, y se corrobora que en esta ciudad se ha desarrollado la isla de calor urbana.

ABSTRACT

A spatial and temporal analysis of the air temperature in the boundary layer of Mexicali City, B.C. and rural surroundings was carried out. Several statistical tests were applied to a long-term database (1950-2000) to identify the temporal variability of the temperature; positive and statistically significant trends of the minimum temperature were observed, with a value of 0.66 ºC/decade in the urban area, while in rural stations, smaller values were observed. Statistically significant results, but with a negative trend, were also observed with respect to the maximum temperature. When the spatial analysis was carried out, with a data base from a recent period (2000-2005), a nocturnal warm air mass in the urban atmosphere was present, and it was found that the maximum difference between the city and its surroundings occurs in winter with a value of 5.7 °C. These results suggest that urbanization, as well as in many other cities around the world, importantly affect the local climate and corroborate that in this city, an urban heat island has developed.

Keywords: Urbanization, air temperature, urban heat island, statistical tests.

1. Introduction

The process of urbanization produces radical changes in the nature of the surface and atmospheric properties of a region, because the natural vegetation is removed and replaced by non-evaporating and non-transpiring surfaces such as metal, asphalt and concrete. This alteration will inevitably result in the transformation of the radiative, thermal, moisture and aerodynamic characteristics and thereby dislocates the natural solar radiation and hydrologic balances (Oke, 1987). A result, product of the modification of incoming solar radiation is the urban-rural contrast in surface radiance and air temperatures. The difference in ambient air temperature between an urban area and its surrounding area is known as the effect of urban heat island (UHI); is one of climatic phenomenon more studied in all world (Jáuregui, 1997; Klysik and Fortuniak, 1999; Brazel *et al*., 2000; Comrie, 2000; Weng, 2003; Vicente-Serrano *et al*., 2005; Serra, 2007; Gaffin *et al*., 2008), and has given the certainty of climatic change in the cities (Changnon, 1992; Corburn, 2009), so while global average surface temperature has had, in the last fifty years (1956-2005) a warming rate per decade of 0.128 °C (IPCC, 2007), the trend of minimum temperatures at global level has been estimated in 0.204 °C/decade from 1979-2004 (Vose *et al*., 2005), and the average regional temperatures by 2030 in the southwest of the United States could be 2 to 3 °C higher than now (Sprigg and Hinkley, 2000), large urbanized regions are already routinely measured to be 2 to 6 °C warmer than surrounding rural regions (Karl *et al*., 1988; United States Department of Energy, 1996). So UHI are models for climate change research because the climate modifications that have occurred in large cities over the past century show similarities in terms of the rates and magnitude expected with projected future climate changes, and would be exacerbate the existing heat island phenomenon in cities by absorbing increased solar radiation. This will aggravate the problem because longer-term effects of global climate change and UHI effect, will lead to further increases in temperatures in an urban microclimate with negative implications for energy and water consumption, human health and discomfort, local ecosystems, and as impeller for the formation of some atmospheric pollutants (Stone and Rodgers, 2001; Arnfield, 2003; Shimoda, 2003; Hawkings *et al*., 2004; García-Cueto *et al*., 2007; Amirtham, 2009).

In a general way, two kinds of atmospheric UHI can be recognized according to the methods of temperature measurement: (i) the canopy layer heat island, and (ii) the boundary layer heat island (Voogt, 2002). The former consists of air between the roughness elements (tree canopies and buildings), with an upper boundary just below roof level. The latter is situated above the former, with a lower boundary subject to the influence of the urban surface (Weng, 2003). In contrast to the direct in situ measurement made of the atmospheric heat islands, the remotely sensed surface urban heat islands require information about the overlying atmosphere and surface radiative properties (Vogt and Oke, 2003; Li and Yu, 2008, Zhang and Wang, 2008). The primary surface controls of UHI development are surface controls, like the geometry of the buildings, known as sky view factor, and the thermal admittance; whereas the primary atmospheric controls are wind and clouds (Voogt, 2002). Heat island magnitudes are largest under calm and clear weather conditions. Another suggested cause of the UHI, to a lesser degree though, is anthropogenic heat and urban greenhouse effect (Oke *et al*., 1991).

With the aim of developing models and forecast climatic evolution, interest has been shown for the study of the climate and its modifications (Katsoulis and Theoharatos, 1986; Brazel *et al*., 2002), but in the last few years, the analysis of climatic modifications caused by man (urbanization, deforestation, etc.) seems to be important for the study of climatic changes at a local scale (Jin *et* *al*., 2005); therefore the analysis of thermometric information from a long series of data can provide interesting results concerning those interrelated objectives, since the variation of this parameter is considered indicative of climatic modifications.

In accordance with the aforementioned, the aim of this study is to analyze the temporal evolution of the air temperature in the surface atmosphere of Mexicali City from 1950 to 2000, and compare it with the trends registered at other weather stations near the city in similar periods. The stations are representative of the urban and rural areas, therefore the results found can show evidence of the role the urban surface has had on thermal variability. In order to back up the results obtained through the aforementioned procedure, the information obtained at 10 nearby stations of the climatic network in México and United States during the 2000-2005 periods is used and the thermal spatial analysis is presented.

2. Location and historical development of Mexicali City

Mexicali City is located to the northwest of Mexican Republic (Fig. 1); it is an urban settlement that was founded to beginnings of the first decade of the 20th century, which origin was the development of agricultural activities, though the economic globalization has displaced this one to give step to the industrial activities. For its latitudinal location (≅32° N), and geographical position in Baja California, its climate is arid, with only 75 mm of average annual rainfall and thermal extreme conditions: maximum temperatures that have overcome the 50 °C in the summer months and minimum temperatures, lower than 0 °C in the winter. Mexicali City borders in the northern part with California, USA which has one of the most dynamic economies of the world.

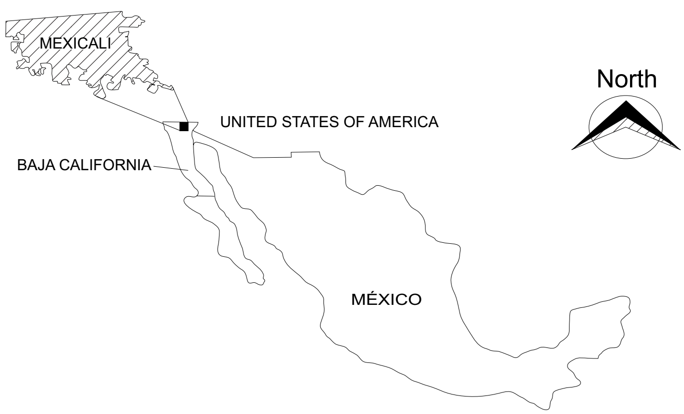

Fig. 1. Location of Mexicali, B. C. in Mexican Republic.

The valley where Mexicali is located shows a special situation for a study on urban climatology. There are cultivated fields on the north and south-southeast, which give it an oasis-like appearance, but on its western and eastern ends it has desert characteristics, which make a classical study of UHI development (as in humid climates) awfully complicated (Lougeay *et al*., 1996); if we add the fact that Mexicali City continues expanding, both in surface area and population, one of the classical questions asked long ago by Balling and Brazel (1986) regarding Phoenix, AZ, and which is still valid, is what would be the effect of the growing urbanization in a desert environment, as has been the case of several cities in the southwestern United States (Phoenix and Tucson, AZ) and northwestern México (Ciudad Juárez, Chih., San Luis, R. C., Son., Hermosillo, Son., Tijuana, B. C., Tecate, B. C., Ensenada, B. C., and Mexicali, B. C.).

The city of Mexicali has grown rapidly and this can be observed in Figure 2, where its development is shown (1932-2005). From being a small town of 4 km^2 at the beginning of the last century, it has increased its size to 142 km^2, which means a 3000% growth. The urban surface experienced a significant increase due to the demand of urban land to cover the needs of the growing population, as well as fulfilling the demands of new economic activities that have been established in the city. This major offer of urban land has also been reflected in a greater quantity of houses. In the 80s the growth rate of houses in Mexicali was one of the highest among the border cities after Tijuana and Ciudad Juárez (Álvarez de la Torre and Dorantes, 2004). In Figure 2 it can be seen that the northern urban limit is well defined by the international line, whereas the eastern, western and southern are more diffuse. This urban growth, as will be seen later, seems to have had an impact on the urban thermal distribution when compared with the rural areas.

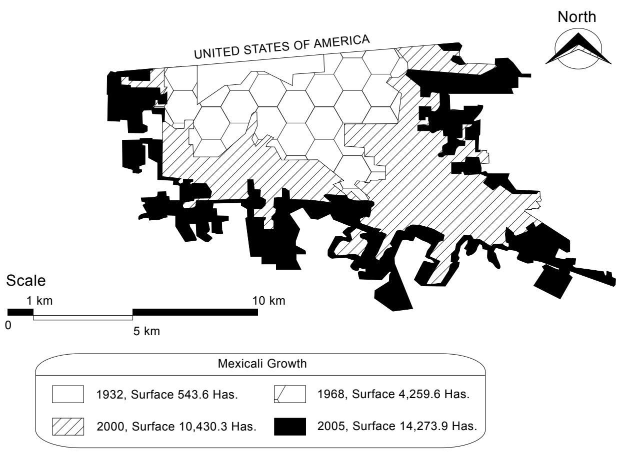

Fig. 2. Historical development of Mexicali, B. C., México (1932-2005).

3. Data base

In order to analyze the historical evolution of the temperature in Mexicali City and its surroundings, two data bases were made. One of them corresponds to the daily records of minimum and maximum temperatures at six weather stations obtained from México's Comisión Nacional del Agua (CNA), which includes the period from 1950 to 2000 (Table I). A test on the homogeneity of the records was performed at all the stations by using the Sved-Eisenhart method (García Cueto and Valdés, 1986) and the outcome showed that all of them had some trend or directional change within the sampling period. The other data base corresponds to a climatic network of rural and urban weather stations in Mexicali and its valley and the Imperial Valley, CA, which is also shown in Table I, from a contemporary period (2000-2005) of minimum and maximum daily temperature values with which a seasonal and spatial analysis was made. The location of the weather stations is shown in Figure 3.

4. Methods

For the temporal analysis, the maximum and minimum temperatures that are daily values registered at the weather stations were grouped in monthly and annual averages. Starting from this information, to identify the temperature variability in the time series the following statistical tests were used. The skewness (z_1) and kurtosis (z_2) standardized coefficients were calculated to prove the null hypothesis which claims that the sample data come from a population with a normal distribution (Siegel, 1956). If the absolute value of z_1 or z_2 is greater than 1.96, a significant deviation of the curve is indicated at the reliability level of 0.95. If the temperature data are not normally distributed, several transformations must be applied to the temporal arrangements (Mitchel *et al*., 1966); the Von Neumann statistic was applied as a randomness test against unspecified alternatives (Mitchell *et al*., 1966), the value of this statistic was compared with a sample statistic whose value is 1.65, corresponding to a tail test with a reliability level of 95%.

Table I. Weather stations used in this study.

Weather station	Period	Latitude (°N)	Longitude (°W)	Altitude (masl)
Mexicali, B.C. (CNA)[1]	1950-2000	32.667	115.458	4.0
Imperial, CA	1950-2000	32.847	115.568	−18.0
Delta, B.C.	1950-2000	32.350	115.180	5.0
Riíto, Son.	1950-2000	32.190	114.990	13.0
Bataquez, B.C.	1950-2000	32.554	115.063	5.0
CAE	1959-1988	32.542	115.414	6.0
Mexicali, B. C. (UABC)[2]	2000-2005	32.620	115.440	14.0
Presa Morelos, B. C.	2000-2005	32.710	114.720	35.0
San Luis RC, Son.	2000-2005	32.46	114.840	24.0
MXLI Airport	2000-2005	32.628	115.246	22.0
Obs. Nuevo León, B.C.	2000-2005	32.410	115.180	11.4
Seeley, CA	2000-2005	32.793	115.690	−11.0
Calipatria, CA	2000-2005	33.125	115.513	−54.0
Meloland, CA	2000-2005	32.810	115.450	−15.0

*[1] and [2] are urban weather stations.

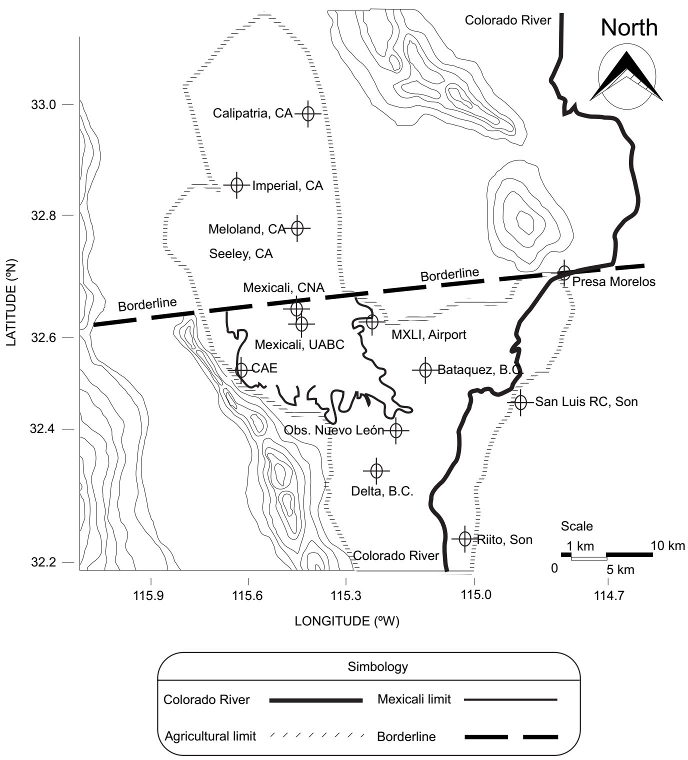

Fig. 3. Weather stations location.

To evaluate the trend, a simple regression analysis was performed with the year (and month) variable as independent, and the air temperature as dependent variable, determining the significance with a type I error of 5% ($\alpha = 0.05$). Both tests were applied to all rural and suburban weather stations. The analysis was carried out for all period (1950-2000), and for normal 30-year periods: 1951-1980, 1961-1990, and 1971-2000, in such a way that the results can be related to the growth of the city and the local modification. The Kendall-τ rank correlation was applied as a non-parametric alternative to reinforce the validity of the simple regression analysis.

The Mann-Kendall rank statistic was applied to identify any temporal linear or non linear trend in the annual data from all the stations (Balling and Ceverny, 1987), and the Spearman correlation coefficient was estimated as an alternative test because several terms from the time series were equal in value (and the ranks of these terms were "tied").

The annual and monthly temperature differences were calculated for both, maximum and minimum values, between the Mexicali station and each one of the other stations, and their resulting values were all analyzed. Means, standard deviations and correlation coefficients between the temperature differences and the year of record were all estimated. The Student *t* test to determine if the monthly and annual means in the sub-periods of air temperature values had shown any significant changes through time was used. The value of the statistical test was 1.96, which corresponds to a double-tailed test with 95% reliability.

In order to perform the spatial analysis, the 2000-2005 data base was used. Seasonal averages of the minimum and maximum temperatures were generated. Spring covered March, April and May; Summer: June, July and August; Fall: September, October and November; and Winter covered December, January and February. Finally, those seasonal values were plotted with the Surfer program using the Kriging interpolator, which has given good results in other studies (Anderson, 2002).

5. Results

5.1 Temporal analysis

Annual minimum temperatures for Mexicali Comisión Nacional del Agua (CNA) weather station during February, and its tendency for the 1970-2000 periods are shown in Fig. 4. Similar tendencies were estimated for all the months together with some basic statistics (Table II).

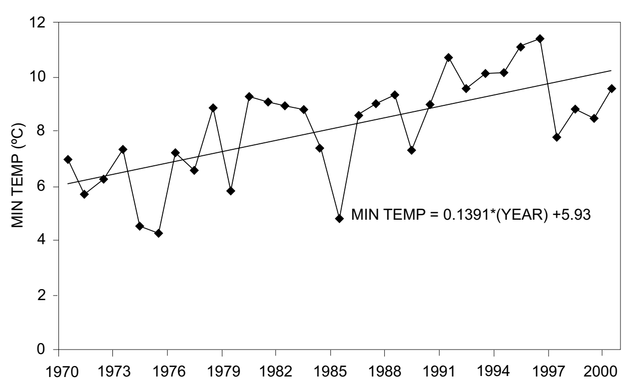

Fig. 4. Minimum temperature trend in Mexicali, B. C., February from 1970-2000.

Table II. Descriptive statistics of the time series of minimum temperature at Mexicali City (1950-2000).

Month	Mean	s	z_1	z_2	V	K-T	R^2	b
January	5.3	1.96	–0.52	0.62	1.06	0.43	0.37	0.084
February	7.5	1.80	0.38	–0.07	1.35	0.38	0.31	0.074
March	9.7	2.05	0.28	–0.32	1.19	0.38	0.36	0.075
April	12.7	2.11	0.01	–0.01	1.15	0.21	0.12	0.043
May	16.2	2.20	0.26	0.39	1.52	0.39	0.28	0.063
June	20.6	1.51	–0.01	0.89	0.98	0.41	0.34	0.069
July	25.2	1.31	–0.01	–0.88	1.51	0.33	0.21	0.045
August	25.2	1.49	0.21	–0.90	1.03	0.41	0.33	0.067
September	21.7	2.05	–0.66	1.03	1.34	0.31	0.20	0.061
October	15.8	2.38	–0.18	0.18	1.03	0.25	0.19	0.057
November	9.6	2.03	0.01	0.23	1.14	0.37	0.29	0.068
December	5.4	1.98	0.19	0.89	1.55	0.35	0.26	0.055
Annual	14.5	1.33			0.35		0.55	0.066
Statistical test			1.96	1.96	0.42			

In Table II, s is the standard deviation, z_1 is the skewness, z_2 is the kurtosis, V is the Von Neumann relation, K-T is a Kendall-τ non-parametric correlation coefficient, R^2 is the determination coefficient, and b is the slope of the regression line.

Both, the skewness and kurtosis shown in Table II, indicate that there is no significant deviation from normal in either month; therefore no transformation was applied to the data. According to the Von Neumann statistic, it can be observed that the monthly time series has components of randomness variance, except the annual series, which indicates some source of non-randomness variance. According to the determination coefficient found, and corroborated with the Kendall-τ non-parametric correlation coefficient, all the correlations found are significant (with a reliability level of 95%). On the other hand, the thermometric trend analysis, quantitatively expressed for the b parameter in Table II, indicates a trend toward temperature increase; at an annual level the warming is 0.066 °C/year (1.98 °C in 30 years), while at a monthly level the months showing the greatest warming are January (0.084), February (0.074) and March (0.075 °C/year).

For temporal series of maximum temperature, the behaviour of the data was found to be normal and random; only the last quarter of the year was statistically significant (with a type I error of 0.05), but with a negative trend. The month of October showed the highest value with –0.044 °C/year and December the lowest, with –0.035 °C/year. These results made it evident that the most important temperature modification has been in the minimum values.

The next step was to detect if the mean values of the minimum temperature, for normal periods (1951-1980, period I; 1961-1990, period II; 1971-2000, period III), have had any significant modification. The results found are shown in Table III.

From what is shown in Table III, it is possible to say that the difference in the minimum temperatures for the 1961-1990 and 1951-1980 periods are not significant at a 95% reliability level, except for the annual mean value. Nevertheless, when compared, the difference in the means among the 1971-2000 and 1961-1990 (III – II), and the 1971-2000 and 1951-1980 (III – I) periods, some statistical significance is found, which seems to be associated with the changes in the land use around the weather station and to the growth of the city.

Table III. Mean minimum temperature in Mexicali, B.C., for 1951-1980 (I), 1961-1990 (II), 1971-2000 (III) periods and Student t test application to show the significance in the difference of the means.

	1951-1980 (I)	1961-1990 (II)	1971-2000 (III)	Student's t (II-I)	Student's t (III-II)	Student's t (III-I)
January	4.4	4.8	6.0	0.87[a]	2.36	3.69
February	6.5	7.0	8.0	0.29[a]	2.75	4.12
March	8.8	9.4	10.4	1.53[a]	2.56	3.84
April	11.8	12.3	13.0	1.12[a]	1.57[a]	2.53
May	15.3	15.8	16.7	1.76[a]	2.32	4.26
June	19.7	20.3	21.3	1.65[a]	3.09	5.31
July	24.6	24.9	25.6	1.07[a]	2.04	3.09
August	24.2	24.8	25.6	1.85[a]	2.47	3.77
September	20.8	21.2	22.3	0.81[a]	2.23	2.86
October	15.0	15.3	16.3	0.66[a]	1.64	2.63
November	8.7	9.2	10.0	1.76[a]	2.34	4.58
December	4.7	5.0	5.8	0.87[a]	2.07	3.21
Annual	13.7	14.2	15.1	3.48	3.83	8.07

[a]Statistically non-significant values with the 95% reliability value.

It often happens that the most probable alternative for the randomness in a climatological series is some kind of trend, which may or may not be linear (Mitchell *et al*., 1966), as indicated in methods, Spearman rank correlation was estimated as alternative; therefore in Table IV the results of two tests for the mean annual minimum temperature for some weather stations are presented.

In Table IV it can be observed that annual minimum temperature trend, except for Delta weather station, is supported by the Mann-Kendall rank statistics and Spearman correlation coefficient, both with 95% reliability.

Table IV. Trend evaluation using the Mann-Kendall test (τ) and Spearman rank correlation (r_s) for the mean annual minimum temperature at some weather stations.

	Mexicali	CAE	Imperial	Delta	Riíto	Col. Juárez	Bataquez
T	<u>0.417</u>	<u>0.349</u>	<u>0.213</u>	–0.054	<u>0.468</u>	<u>0.357</u>	<u>0.374</u>
τ_t*	0.185	0.262	0.195	0.189	0.189	0.225	0.207
r_s	<u>0.698</u>	<u>0.628</u>	<u>0.374</u>	–0.090	<u>0.657</u>	<u>0.524</u>	<u>0.522</u>
ts*	6.820	4.116	2.737	–0.629	6.103	3.635	3.921
t_{tables}	2.101	2.101	2.101	2.101	2.101	2.101	2.101

*The underlined values are significant with 95% reliability. The τ_t, t_s and t_{tables} values are presented for a comparison with the trend statistics; CAE is Campo Agrícola Experimental.

After having confirmed an ascending minimum temperature pattern in the urban area, and the trend in all the other places, linear trends from five rural stations were obtained to be compared with those of the urban station (Table V), and the differences in the urban-rural minimum temperature, to quantify the intensity of the UHI (Table VI).

Table V. Linear trends of minimum temperature of urban and rural stations[1].

Estation	d(km)	Períod	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MEX	0	1950-2000	0.066	0.084	0.074	0.075	0.043	0.063	0.069	0.045	0.067	0.061	0.057	0.068	0.055
IMP	30	1950-2000	0.016	0.044	0.039	0.036	0.005	0.026	0.024	0.022	0.017	0.022	–0.01	0.005	–0.01
CAE	10	1959-1988	0.068	0.119	0.091	0.084	0.067	0.098	0.083	0.016	0.007	0.057	0.090	0.052	0.081
BAT	20	1949-1957 1969-2002	0.05	0.056	0.080	0.093	0.075	0.037	0.036	0.043	0.066	0.061	0.031	0.024	0.029
RTO	50	1950-2000	0.057	0.089	0.094	0.069	0.046	0.059	0.037	–0.03	0.03	0.071	0.091	0.058	0.066
DTA	45	1950-2000	0.007	–0.01	0.021	0.032	0.00	0.023	0.012	–0.01	0.018	0.01	0.00	–0.01	–0.02

[1]All the underlined values are significant with a type I error of 0.05 (α = 0.05); d refers the distance between urban weather station (MEX) and rural weather stations (IMP: Imperial; CAE: Campo Agrícola Experimental; BAT: Bataquez; RTO: Riíto; DTA: Delta).

Table VI. Linear trends of minimum temperature differences between Mexicali city and those selected in the rural surroundings between 1950 and 2000*

Weather stations	Period	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MXLI-IMP	1950-2000	0.052	0.030	0.021	0.027	0.038	0.041	0.042	0.057	0.044	0.039	0.060	0.064	0.047
MXLI-DELTA	1950-2000	0.056	0.08	0.05	0.039	0.05	0.041	0.057	0.046	0.047	0.059	0.057	0.072	0.074
MXLI-BAT	1949-1957 1969-2002	0.016	0.008	0.027	0.009	0.011	0.022	0.027	0.05	0.043	0.025	0.037	0.054	0.036
MXLI-RTO	1950-2000	0.007	–0.01	–0.02	0.002	0.002	0.005	0.032	0.070	0.036	–0.001	–0.034	0.009	–0.016
MXLI-CAE	1959-1988	0.016	–0.013	–0.003	–0.001	–0.01	0.002	0.000	0.047	0.05	0.034	0.011	–0.00	–0.00

*All underlined values are significant with a type I error of 0.05 (α = 0.05).

Table V shows the positive and significant trends of the minimum temperatures, with a higher degree of warming for Mexicali City (MEX), except for CAE weather station, which stopped operations in 1988; in figure 5 there is a similar period, and therefore comparable, for Mexicali urban weather station, with a slightly greater trend than that of CAE weather station.

On the other hand, positive and statistically significant trends that document the warming of Mexicali weather station in comparison to the rural stations used can be observed in Table VI. Here we find the greatest annual trend in thermal differences at the Delta station, with 0.056 °C/year, followed by Imperial station, with 0.052 °C/year. As regards monthly trends, the greatest urban effect and therefore the most notorious difference, is found at Delta station, where they have 0.072 and 0.074 °C/year in November and December, respectively.

According to Jáuregui (1997) the thermal differences in urban-rural minimum temperature show the degree of the intensity of the UHI more clearly. The annual variation and the trend of the intensity of the UHI, between Mexicali urban station and Imperial rural station, are presented in Figure 6. The importance of the role of urbanization when modifying the thermal admittance and reducing the ventilation in the nearby zone during the period of the thermometric data is clear; this corroborates it, and gives an example of the impact of an anthropogenic alteration upon the native conditions of a region: in the analyzed case we pass from a cold island, with a mean magnitude of –1.3 °C (between 1960 and 1980) to a heat island, with a maximum intensity of 2.3 °C (2000).

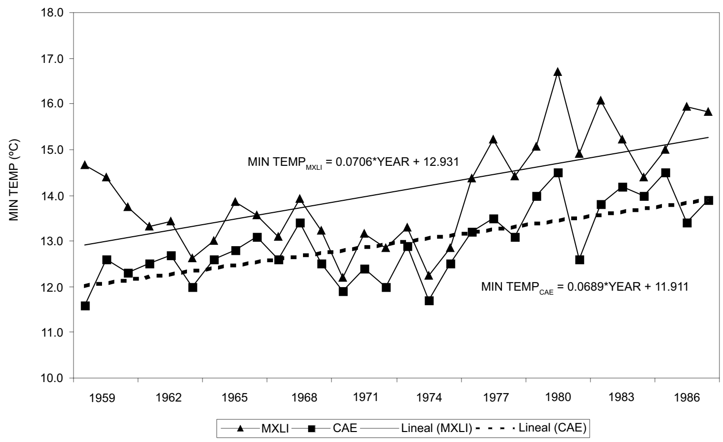

Fig. 5. Mean annual minimum temperature trend in Mexicali (urban weather station) and Campo Agrícola Experimental (CAE) (rural weather station) from 1959 through 1988.

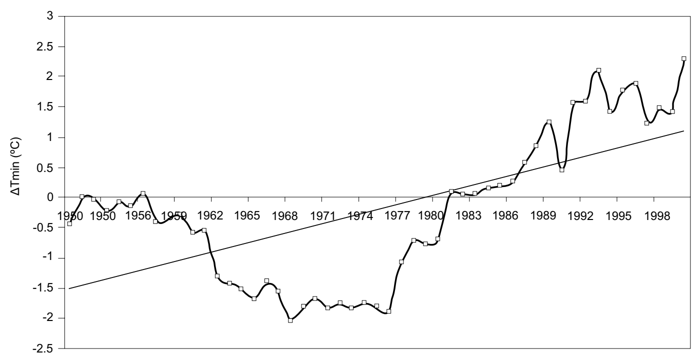

Fig. 6. Annual variation and linear trend of the cold/heat island intensity between Mexicali weather station (urban) and Imperial Valley weather station (rural), from 1950 through 2000.

Figure 7 shows the seasonal variation of the cold/heat urban island, between Mexicali and CAE weather stations in 1959-1988 periods. From this, it can be seen that the intensity of the nocturnal heat island in Mexicali was greater during the dryer months of the year: March, April, May and June, with a mean intensity of 1.6 °C, and September, October and November with a mean intensity of 1°C. This seasonality of the nocturnal heat island, with the highest values during the dry season, is in accordance with the results obtained by Oke (1991) and Jáuregui (1993).

On the other hand, the cold urban island in the diurnal period, can be explained because the urban site has a thermal inertia greater than the rural site; consequently, the urban materials take more time to get hot, compared with those from the rural environment which get hot more rapidly, and this is reflected in the air temperature.

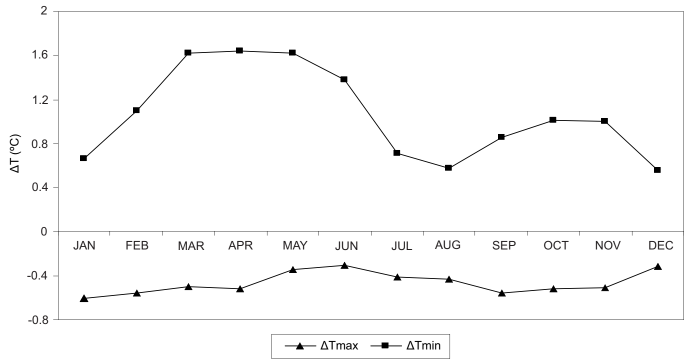

Fig. 7. Seasonal variation of cold/heat island intensity between Mexicali (urban) and Campo Agrícola Experimental (CAE, rural), from 1959 to 1988 period.

5.2 Spatial analysis

Seasonal averages of UHI intensity and maximum temperature, between the years 2000 and 2005, are presented in Tables VII and VIII, respectively.

Table VII. Maximum intensity of UHI (°C) at Mexicali City (2000-2005).

Spring	Summer	Autumn	Winter
5.4	5.2	5.0	5.7

Table VIII. Seasonal averages of maximum temperature (°C), from 2000 to 2005.

Weather station	Station number	Spring	Summer	Autumn	Winter
Mexicali, B.C. (CNA)[1]	1	31.8	42.5	32.2	21.5
Mexicali, B.C. (UABC)[2]	2	32.1	42.2	33.3	22.6
Presa Morelos, B.C.	3	31.8	42.5	34.5	22.9
San Luis RC, Son.	4	32.0	42.3	34.2	23.1
Riíto, Son	5	31.7	42.2	35.1	23.3
MXLI Airport	6	30.3	40.4	32.1	21.6
Obs. Nuevo León, B.C.	7	32.1	42.8	33.0	21.9
Seeley, CA	8	30.6	40.5	31.9	22.0
Calipatria, CA	9	30.0	40.2	31.7	21.3
Meloland, CA	10	30.4	40.6	31.8	21.6

* [1] and [2] are urban weather stations.

According to Table VII, the greatest intensity of the UHI is during winter, with a value of 5.7 °C, and the least intensity during autumn, with 5.0 °C.

Respect to the comparisons of the average seasonal values of maximum temperature, Table VIII shows that, even when the urban zone presents high values, there are some places in Mexicali valley, e.g., in weather stations as Obs. Nuevo León or Riíto, which exceed the values for the city.

It is also notorious that the three weather stations (Seeley, Calipatria, and Meloland) located to the north of the urban zone show the lowest values, both minimum and maximum temperatures; this seems to be associated with the fact that they are in intensive farming zones, relatively free of urban influence, and whose altitudes are the lowest in the region (for example Calipatria is at 54 meters below sea level).

The spatial distribution of minimum temperature during spring is shown in Figure 8a. Here it can be seen that the highest values are located in the urban zone, i.e. the UHI is very clearly located, a situation which is repeated in Figures 8b, c and d, where the seasonal minimum temperature distributions in summer, autumn and winter are shown, respectively.

The spatial distribution of maximum temperature (Figures 9a to d for spring, summer, autumn and winter, respectively), shows that even when the city presents relatively high values, still higher ones are present toward south-south eastern from urban zone. The lowest values are localized to the north of Mexicali City, i.e. towards the farming fields of Imperial Valley.

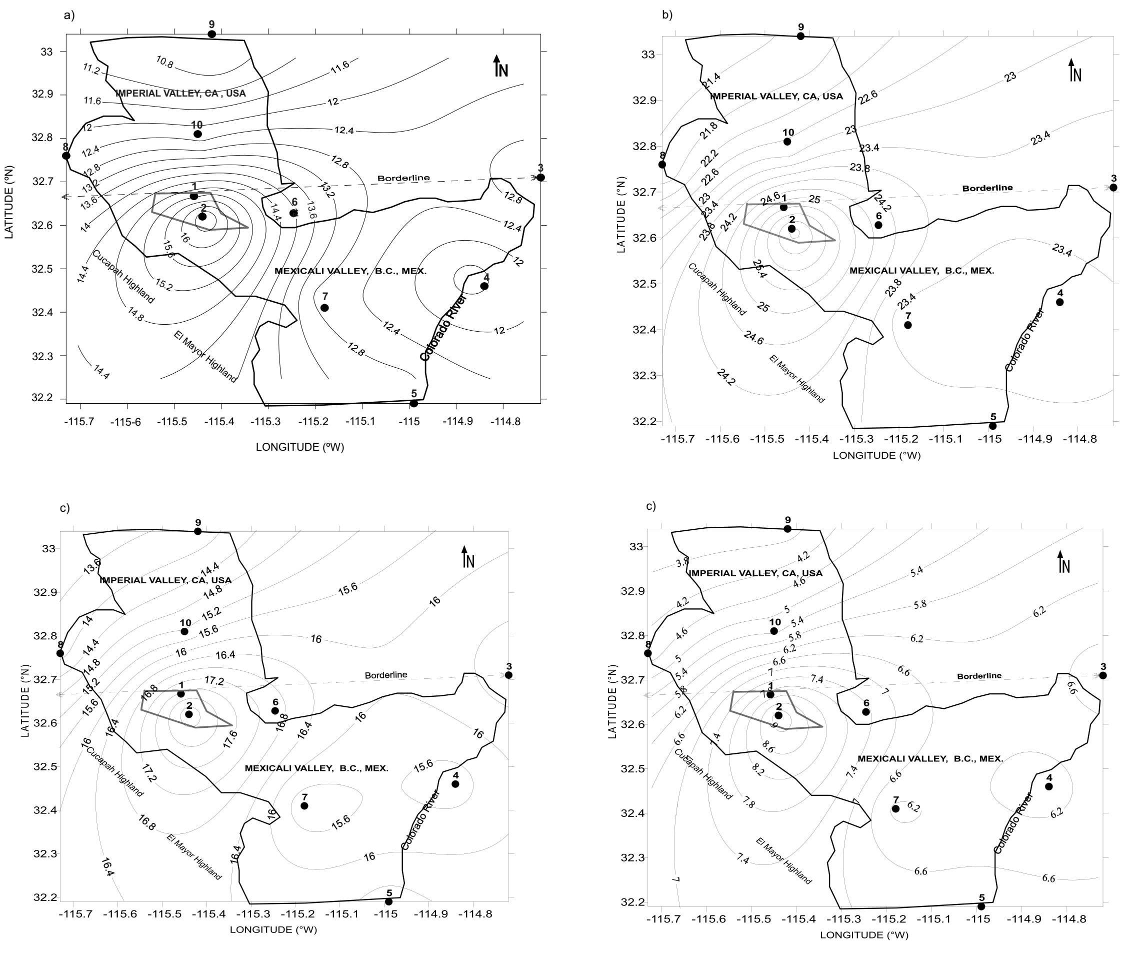

Fig. 8. Minimum temperature (°C) in Mexicali and its valley, B. C., Méx., and Imperial Valley, CA, USA, from 2000 to 2005 (The polygon at the borderline represents Mexicali city). a) Spring, b) Summer, c) Autumn, d) Winter.

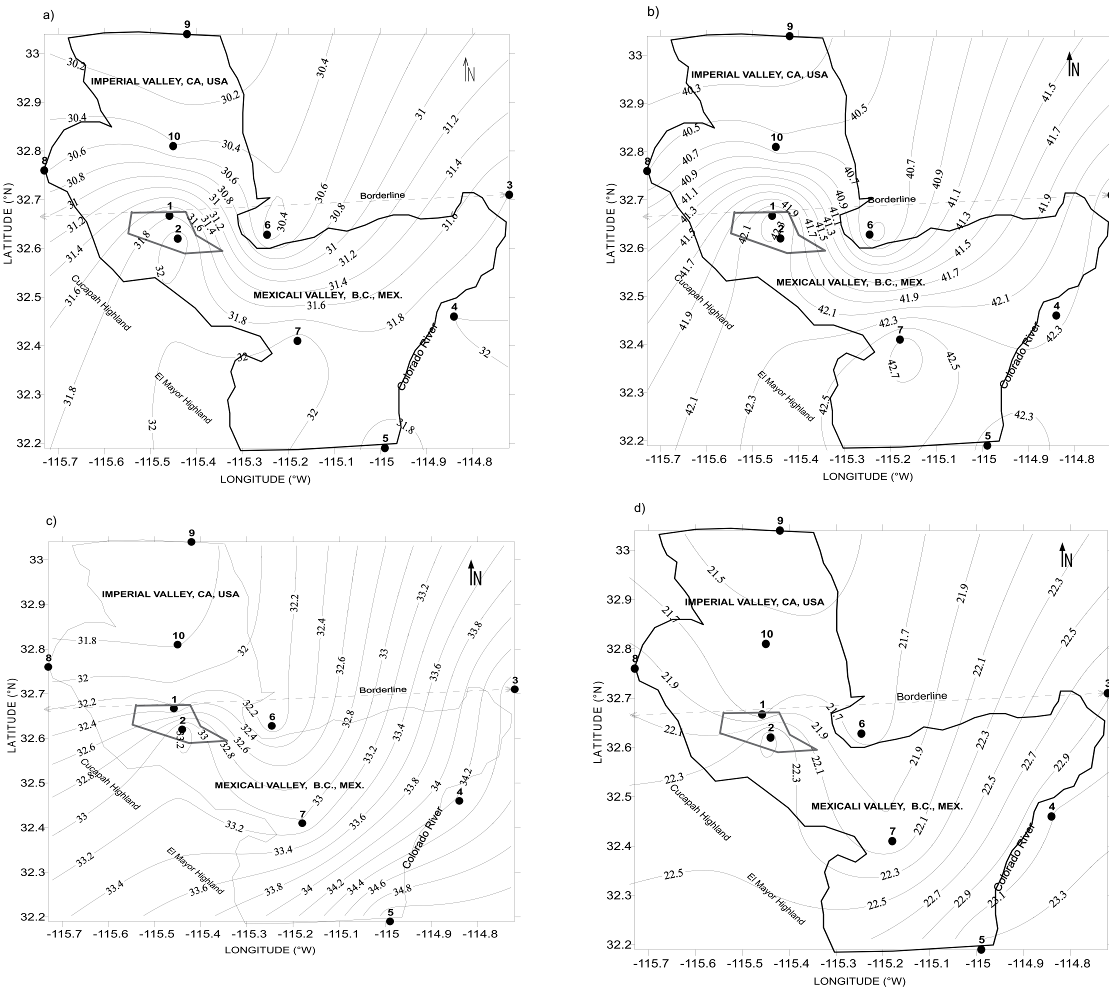

Fig. 9. Maximum temperature (ºC) in Mexicali and its valley, B. C., Mex., and Imperial Valley, CA., USA, from 2000 to 2005 (The polygon at the borderline represents Mexicali City). a) Spring, b) Summer, c) Autumn, d) Winter.

6. Discussion

The replacement of agricultural land by urban landscape in the last quarter of the 20th century notably incremented the urbanized surface of Mexicali, from 42.6 km^2 at the end of decade of 1970s, to 142.7 km^2 in the year 2005, that is, a growth higher than 300%, in only 35 years. This change of porous land to non-permeable land (asphalt, pavement, etc.), must have increased the sensible heat dissipation in detriment of the latent heat in the energy balance of the surface/atmosphere interface; therefore, there is now a greater availability of energy to heat the air. So, the growth of the city and the anthropogenic activity, together with population growth, the massive use of cars and air conditioning systems, has affected the partition of water and energy balances (García Cueto *et al.*, 2004), which seems to have caused the changes in local and regional temperatures, above all in their minimum values, and has created a well-defined urban micro-climate; at Mexicali city increase in annual minimum temperature during 1950-2000 reaches 0.66 °C/decade. When compared, the difference in means of the minimum temperature between 1961-1990 with 1971-2000 periods, and

1951-1980 with 1971-2000 periods, a statistical difference was found, which seems to be related to two factors: changes in the local land use, and therefore in thermal admittance around the weather stations (micro-scale changes), and to the growth of the city, maybe reducing the ventilation by a sky view factor augmented (meso-scale changes). The change of cold island (–1.3 °C at the end of 1980s) to heat island (2.3 °C in year 2000) at Mexicali city shows the importance of the modifications in the landscape.

The mean maximum temperatures show different behavior pattern compared with mean minimum temperatures, maybe caused by thermal inertia of urban materials; in the last four months of the year, the trend of maximum temperature, at urban weather station, was negative and statistically significant in the period 1950-2000.

Upon comparing Mexicali urban weather station findings with those of the rural weather stations, positive and significant trends of minimum temperatures were found at most of the stations analyzed, with a clearer heating trend at Mexicali city. The most outstanding and significant difference in the urban-rural minimum temperature was that from Delta weather station, with 0.056 ºC/year.

The trend towards a warmer urban climate is evident in isotherms of both minimum and maximum temperatures, as is shown in Figures 8 and 9. The higher values of minimum temperature, for all seasons, were observed in urban weather stations (CNA and UABC), which illustrates the development of the UHI; yet, it is also present a secondary maximum, except in spring (Fig. 8a), of minimum temperature in rural areas far from the city, especially in a south-eastern direction, that seems to be connected to the geothermal activity of Cerro Prieto. Going north towards Imperial Valley, both minimum and maximum temperatures, in all seasons show lowest values, probably due to intensive farming and a lower urbanization rate, as compared with Mexicali.

7. Conclusions

The replacement of irrigated agricultural land by urban landscapes, anthropogenic activity and population growth, appear to be the major factors responsible for the observed changes in the temperature patterns at Mexicali city. With the long data base (1950-2000) it was found that Mexicali urban weather station the minimum temperature showed a tendency to increase; at decadal level the heating rate was 0.66 ºC, while the months that showed the highest heating were January (0.084 ºC/year), February (0.074), and March (0.075). Likewise, Mexicali city changed from being a cold island (1960-1980) to a heat island with a maximum intensity of 2.3 ºC in the year 2000, when it was compared with rural weather station of Imperial, CA.

With more updated information (2000 to 2005), the greatest intensity of UHI was in winter with a value of 5.7 ºC, and the lowest intensity in autumn with 5.0 ºC. It was seen that the lowest values, both minimum and maximum temperatures, are found in areas of intensive farming and relatively free of urban influence.

Upon performing a spatial analysis of minimum temperature, it can be seen that the highest values are located in the urban zone during all seasons of the year. In general, the city shows relatively high values of maximum temperature, but they are even higher for the south-southeast of the urban zone, while the lowest values are found towards the farming fields of the Imperial Valley, CA.

The results shown suggest that the urbanization process has led to a warmer climate in Mexicali city when compared with its surroundings, and that the UHI effect is comparable to the heating caused by the global climate change. Accordingly with Brazel and Crewe (2002), policy makers who are planning for future water and energy requirements must begin to more carefully consider the spatial patterns associated with the climate of the growing Mexicali city. It is clear that the elaboration of future climate scenarios concerning the thermal climate is a pending task because of the increase in greenhouse gases and one that forces us to ask whether it will be possible to achieve the adaptation process when both, UHI and climate change, are taken into account.

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