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A comparative simple method for human bioclimatic conditions applied to seasonally hot/warm cities of Mexico

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RESUMEN

El clima regional tiene implicaciones en el confort, la salud y la productividad de la población. En este artículo se presentan las evaluaciones bioclimáticas comparativas de siete ciudades cálidas de México. Se aplicaron los índices bioclimáticos de *disconfort, entalpia y esfuerzo frente al calor.* Se calcularon los periodos para los cuales es necesario el uso de aire acondicionado, a partir de estimaciones de radiación solar global y de temperatura y humedad horarias medias mensuales. Finalmente se muestra la utilidad y calidad del *Índice de esfuerzo frente al calor*, el cual requiere sólo de datos climatológicos comunes para poder comparar condiciones bioclimáticas de sitios similares.

Palabras clave: confort humano, ciudades tropicales, México.

ABSTRACT

The climate of a region is an environmental resource with important implications for things such as thermal comfort, health and productivity of the population. In this work the bioclimatic comfort was evaluated for seven seasonally warm/hot cities of Mexico by means of the following current indexes: *Discomfort Index, Enthalpy Index and Heat Strain Index.* Also, the periods during which it is necessary to use air conditioning in the studied cities were calculated from estimated global radiation and hourly data of temperature and relative humidity which made it possible to establish them with high precision. Finally, the useful of the *Heat Strain Index* is shown. It is a simple index needing available meteorological data to compare bioclimatic conditions of similar sites.

Key words: human comfort, tropical cities, Mexico.

1. Introduction

Human bioclimatic evaluations require the application of different procedures in different latitudes or climatic conditions. For example, in middle and high latitude countries attention is focused on cold conditions during the winter season and the hot waves in summer (Jendritzky, 1991; Taesler, 1991). For winter conditions in the USA the Wind-chill Index (National Meteorological Service, 1992) is used by both experts and common people. In Germany, for urban planning purposes, the German Meteorological Service uses the so called *Mitchel Modell*, which is based on the Fanger (1972) equations. Some other methods have been developed on the basis of the human body energy balance (Jendritzky, 1991; Höppe, 1984; Mertens, 1999). For the application of those procedures it is necessary to supply the models with complete and specific climatic and land use data.

In tropical countries this topic requires the consideration of other aspects. First, the uncomfortable cases are mainly caused by high temperatures and sometimes by high relative humidity, large sun duration and unavailable air conditioning systems for most of the population. Secondly the quality and quantity of the climatic data are not as frequent and accurate as are required for complex simulation models.

The aforementioned reasons have made it necessary to use other indexes with tropical conditions rather than the indexes used in middle latitude countries such the Wind-chill index or the complex human heat budget models. Obviously these indexes must not depend on special and sophisticated climatic data.

In India human bioclimatic evaluations have been frequently made from the 1970's to the present with simple indexes based on temperature and humidity data (Lahiri, 1984; Doesthali, 1999). Recently in Brazil the use of uncomplicated techniques are common in bioclimatic analysis for urban planning (Sad de Assis and Barros-Trota, 1999).

For all of Mexico Jáuregui (1990) presents a bioclimatic evaluation using the concept of *effective temperature* proposed by Missenard (1933). The results showed the contrasts of the environmental conditions for July and January at the end of the nocturnal cooling (6 a.m.) and when the maximal temperature occurs (2 p.m.). For Mexico City Jáuregui *et al.* (1997) have evaluated the impact of urban heat island on human bioclimatic sensations by means of the discomfort index proposed by Thom (1959).

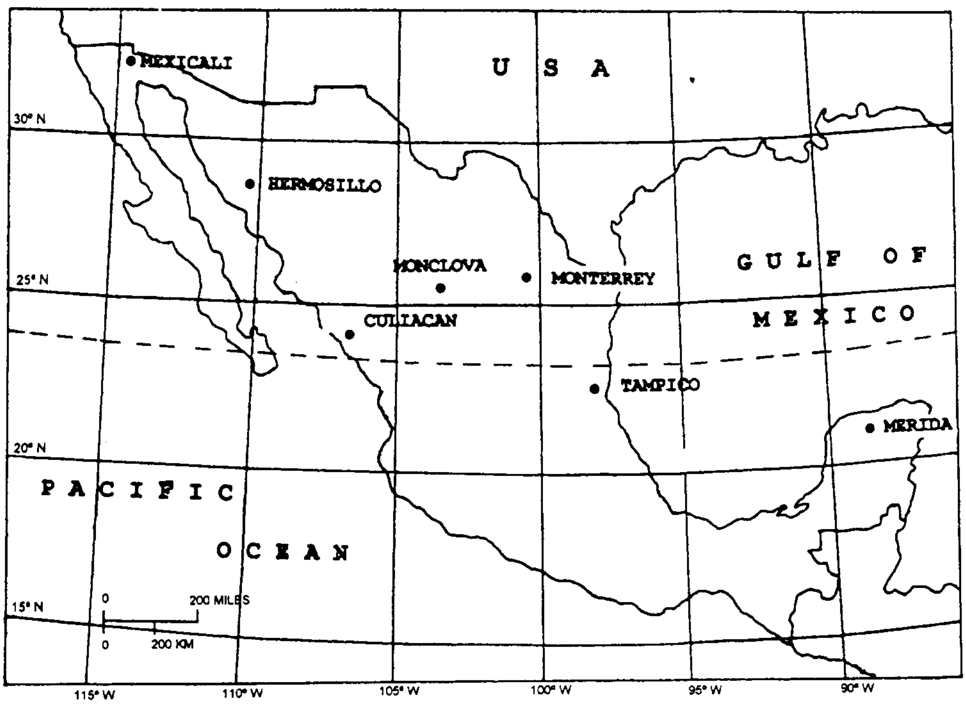

Fig. 1. Location of the studied cities.

In Mexico one of the most studied cities is Mexicali (see Fig. 1 for location), due to its contrasting climatic conditions (hot summer and cool winter). García and Valdés (1988) constructed a bioclimatic chart for temporal and spatial distribution of climatic characteristics needed to restore the comfort conditions. The analysis was based on the procedure proposed by Olgyay (1963). Acuña *et al.* (1988), through a design process named bioclimatic patterns, try to obtain an optimization of energy consumption and human comfort based on series of constructive, economic and cultural behavior in Mexicali. García (1990) carries out an analysis of Mexicali local climatic factors (solar radiation and wind) and their relationship to the temperature to define the best orientation of constructions in order to save energy and fulfill the necessities of environmental comfort.

In spite of simplicity of the method used in this paper, results allow comparison of the degree of stress of environmental conditions of hot-warm climates in the seven studied cities (Fig. 1 and Table 1). The procedure consists of simple indexes as the effective temperature (Missenard, 1933, cited by Gregorczuk and Cena, 1967) and the enthalpy (Böer, 1964, cited by Gregorczuk, 1968), which give the same results as the Fanger's (1972) energy balance equations when some variables are parameterized or not considered (Jáuregui *et al.*, 1997).

In this paper two simple indexes and one intermediate procedure will be used: the discomfort index, the enthalpy index and the heat strain index. The last index resulted very sensitive to different climatic conditions of the cities shown in Table 1, so that it may be applied for comparison purposes, not only depending on temperature and relative humidity (as is the case of the other two indexes).

Table 1. Location and climatic characteristics of the studied cities.

City	Lat. (N)	Lon. (W)	Alt. (m)	Tjan.	Tjul.	RH	Qg
Mérida	20^0 56'	89^0 38'	9	22.9	27.3	72	4.9
Tampico	22^0 14'	97^0 51'	12	18.9	28.0	79	4.8
Culiacán	24^0 48'	107^0 24'	84	19.9	29.7	66	5.0
Monterrey	25^0 41'	110^0 18'	512	14.9	29.1	64	4.6
Monclova	26^0 53'	101^0 26'	591	12.6	29.1	58	4.9
Hermosillo	29^0 04'	110^0 58'	237	16.6	32.6	43	5.1
Mexicali	32^0 40'	115^0 27'	4	12.4	33.1	46	5.1

Tjan and Tjul are the mean monthly temperatures in Celsius Degree for January and July; RH is the mean yearly relative humidity in %, and Qg is the mean daily global radiation in hw-h m^{-2}.

2. Data and methods

The *Normales Climatológicas 1951-1980* (Servicio Meteorológico Nacional, 1982) made available the mean monthly values of temperatures (maxima and minima), the mean monthly daily sunny hours and the mean monthly relative humidity and pressure. With this information the mean monthly values of the bioclimatic indexes were calculated. In this section the process to estimate and evaluate each one of them will be indicated.

Hourly mean monthly temperature and humidity

Hourly temperature data were calculated from monthly means of maximum (Tmax) and minimum temperatures (Tmin) from *Normales Climatológicas 1951-1980, SMN* (Servicio Meteorológico Nacional, 1982). These data are useful in order to make climatic (not meteorological) comparisons between cities and not precisely to establish the real values of the indexes for each site. The used estimation model provides a smoothing procedure. In this way the comparisons were based on homogeneous and normal data. This means that calculated bioclimatic indexes like this are representative of one normal (average of 30 years) and *homogeneous* (smooth) condition.

The mean monthly hourly temperature (Thor) for each city was calculated with the equation:

$$Thor = Tmin + y(Tmax - Tmin) \qquad (1a),$$

where

$$y = [at^b]\exp[ct] \qquad (1b)$$

Here a, b and c are parameters which depend on the season and the latitude (Table 2). t is in hours as a function of local time (H) and local sunrise time (Ho):

$$T = H - Ho \text{ if } H \geq Ho$$

$$T = H + 24 - Ho \text{ if } H < Ho$$

For the case of mean monthly temperatures the accuracy of the equations 1 (Tejeda, 1991) is greater than the model of De Wit *et al.* (1978), which is the best model according to a review made by Reicosky *et al.* (1989).

Table 2. Values of a, b and c in equation 1(b) as a function of latitude and time of year for Mexico (Tejeda, 1991).

Months	Latritude	Values		
		a	*b*	*c*
March to October	≥ 23.5°N	0.026	3.190	-0.375
November to February	≥ 23.5°N	0.023	3.436	-0.421
January to December	< 23.5°N	0.096	2.422	-0.339

On the other hand, the mean monthly minimum relative humidity (RHmin) values were estimated from the combination of the mean monthly vapor pressure and the maximum saturation vapor pressure. The argument is based on the fact that the vapor pressure is almost invariant between the time of occurrence of the mean and minimum relative humidity (approximately between 10 or 11 a.m. and 2 or 3 p.m., respectively). This idea was first proposed by Geiger (1957).

The mean monthly vapor pressure values result from the mean monthly of temperature and relative humidity data, and the saturation vapor pressure (Es) is derived from the application of a third order polynomial to the mean monthly maximum temperature. This polynomial is a regression model of Es in mb with a correlation coefficient equal to 0.9997 and a standard error of regression of 0.5 mb in comparison with observed values of Es for temperatures between 10°C to 50°C (Tejeda, 1994):

$$Es = 6.6x10^{-4}T^3 + 4.6x10^{-3}T^2 + 4.58x10^{-1}T + 6.63 \qquad (2a)$$

The next step was to obtain the mean monthly maximum relative humidity (RHmax) from the observed value of mean monthly relative humidity and the estimated mean monthly minimum relative humidity.

Finally, it is obvious that the curve of the daily relative humidity is inverted with respect to the temperature curve. Since from equations 1 y has values between 0 and 1, it is possible to use the previous process for the estimation of the mean monthly hourly relative humidity (RHhor) with the expression:

$$Rhhor = RHmin + (1 - y)(RHmax - RHmin) \quad (2b)$$

Solar global radiation

The daily mean monthly solar global radiation (Q_g in kW h/m^2) was estimated with the yearly model (Glover and McCulloc, 1958):

$$Q_g = Q_E \left[0.26 + 0.57\left(\frac{S}{So}\right)\right] \quad (3)$$

where Q_E is the daily astronomical radiation and So is the astronomical sunshine both for the 15th of each month and S is the mean monthly sunshine from heliographic observations (Servicio Meteorológico Nacional, 1982). Eq. 3 shows a correlation coefficient of 0.91 with the available data from Solar Atlas for Mexico (Hernández *et al.*, 1991), while the original version for the comparison of observed and estimated data gave a correlation coefficient of 0.85

The bioclimatic indexes

a) The discomfort index (DI; Thom, 1959) provides a feeling that would be expected if relative humidity were about 50%. It is valid with a wind speed below than 1 m/s, without direct solar radiation, for one person wearing office clothing (1 clo in terms of the definition of Gagge *et al.*, 1941) and at rest:

$$DI = 0.4(T + Tw) + 4.8 \quad (4)$$

with T and Tw representing the air and ventilated wet bulb temperatures in degrees Celsius. The hourly mean monthly values of Tw were calculated from the respective data of T and RH by using an iterative method on the psychrometric equation (Bindon, 1965; Tejeda, 1994).

b) The effective temperature (ET) has the same meaning of DI and it is a direct function of the air temperature and the relative humidity (Missenard, 1933 cited by Gregorczuck and Cena, 1967):

$$ET = T0.4(T - 10)(1 - RH/100) \quad (5)$$

c) The enthalpy (I) estimates the heat content (kcal/kg) of the air (Böer, 1964 cited by Gregorkzuk, 1968)

$$I = 0.24(Tw + 1.555Es/p) \quad (6)$$

with p representing the local pressure (the mean monthly values were used). The saturation vapor pressure (Es) and the Tw were calculated from Tejeda (1994).

d) The heat strain index (HIS) is an intermediate stept between the complete evaluation of the human-body energy balance and the simple indexes (Tudela, 1982). The HIS is the heat production of a person and his potential heat exchange with the environment by means of radiative exchange and convection divided by the capacity of the atmosphere to evaporate the sweat. Its implementation in this work follows the procedure of Givoni and Sohar (1968) and De Freitas and Riken (1989):

$$HIS = \{M + (11.6 + 15v^{0.5})(Tr - 35)\}/\{17.6v^{0.3}(42 - e)\} \quad (7)$$

For the methabolic heat production (M) this paper only considered the case of a person doing light work equivalent to 150 watts, according to Munn (1970, p. 192) and two times the minimum value gave by Werner (1998) for one person at rest. In relation to wind speed (v) a typical indoor value of 0.5 m/s was considered, and e is the air vapor pressure obtained from the mean monthly hourly data of temperature and relative humidity. Finally the radiative temperature (Tr) was parameterized as the air temperature (T) plus one increment (ΔT) that is a function of the daily mean monthly solar global radiation (Qg) so:

$$Tr = T + \Delta T$$

with

$$\Delta T = 0°C \text{ if } Qg < 3kwh\ m^{-2};$$

$$\Delta T = 1°C \text{ if } 3kwh\ m^{-2} \leq Qg \leq 5kwh\ m^{-2}$$

and

$$\Delta T = 2°C \text{ if } Qg > 5kwh\ m^{-2}.$$

The $HSI = 0$ condition means thermal comfort; negative values indicate cool or cold if they approach to 1; and positive ones indicate a warm feeling which may reach extreme stress (harmful to health) when it exceeds 0.8. If $HSI > 1$ it is physically impossible to feel comfort since the atmosphere prevents evaporation of sweat produced by the body to cool itself.

The underlying parameterizations in equations 3, 4, 5 and 6 are valid for a person with minimum physical activity, without direct solar radiation and with ventilation almost 0.5 to 1 m/s.

Those conditions are the same for a person doing office-work at the indoor of a house similar to a meteorological shelter. The use of the same conditions for all studied cities in all applied indexes have allowed useful comparisons.

Thermopreferendum and cooling needs

The purpose of this section is to provide the method to incorporate the acclimation in the comparison procedure. Auliciems (1992) found that for a relative humidity of 50% the preferred air temperature for comfort (*Thermopreferendum, Tp*) is:

$$Tp = 0.31Tm + 17.6^{0}C \tag{8}$$

with Tm the outdoor mean monthly temperature. The Eq. 7 has a correlation coefficient of 0.8 for a sample size of almost 100 cases.

Therefore the calculated values for all used bioclimatic indexes (DI, ET, I and HIS) considering $T = Tp$ and $RH = 50\%$ can be named as the *preferred index value* (Xp). For every index the difference between the maximum (warmer month) and minimum (cooler month) preferred index value determines the comfort interval (ΔX). In this way it was possible to fix one comparative feeling scale:

$$X > (Xp + 3\Delta X/2) \quad \text{Hot}$$

$$(Xp + \Delta X/2) < X \leq (Xp + 3\Delta X/2) \text{ Warm}$$

$$(Xp - \Delta X/2) \leq X < (Xp + \Delta X/2) \text{ Comfort}$$

$$(Xp - 3\Delta X/2) \leq X \leq (Xp - \Delta X/2) \text{ Cool}$$

$$X < (Xp - 3\Delta X/2) \qquad \text{Cold}$$

with $X = DI, ET, I$ or HSI.

For indexes DI and ET a calculation of Cold-Hours-Degree (CHD) and Hot-Hours-Degree (HHD) was made for every month through the following relationships:

$$CHD = \sum \mid Xi - Xp + \Delta X/2 \mid \text{ if } Xi > (Xp + \Delta X/2),$$

and

$$HHD = \sum \mid Xi - Xp - \Delta X/2 \mid ifXi < (Xp - \Delta X/2),$$

CHD and HHD represent the cooling and heating needs respectively. Obviously if $(Xp - \Delta X/2) \leq Xi \leq (Xp + \Delta X/2)$ the situation can be considered as comfortable ($CHD = HHD = 0$).

Considering the enthalpy (I), the needs for cooling (CN) and for heating (HN) were evaluated as the average during the considered period so:

$$CN = \{\sum \mid Ii - Ip + \Delta I/2 \mid\}/n \text{ if } Ii > (Ip+\}\Delta I/2)$$

$$HN = \{\sum \mid Ii - Ip - \Delta I/2 \mid\}/n \text{ if } Ii < (Ip - \Delta I/2)$$

n is the sample size in each case.

3. Results

Results from the comfort indexes will be described for two seasons of the year: warm period (from May to October) and cold period (from November to April). Due to the results obtained with Thom's (1959) and Missenard's (1933) indexes were very similar, only the first index will be described. Table 3, obtained from hourly sensations, presents the comparison of the percentage of sensation during the period May–October, obtained for each city, according to Thom's index. From Table 3 it can be seen that Culiacán is the city with most discomfort during the warm season, and the city of Monclova experiences the least discomfort.

Table 3. Percentage of time-feeling according Thom's index (average for May–October 1951–1980).

City	Hot	Warm	Comfort	Cool	Cold
Mérida	10	42	47	0	0
Tampico	21	53	45	0	0
Culiacán	31	39	26	5	0
Monterrey	8	35	42	10	0
Monclova	14	29	40	14	4
Hermosillo	24	32	28	13	8
Mexicali	27	26	26	13	8

Mexicali is in fourth place and its difference with respect to Culiacán is about 15%. The percentage difference in every sensations (from hot to cold) between Culiacán and Mexicali is only 0.7%, and between Mexicali and Hermosillo is 1.4%. With regard to comfort, the city of Monterrey is the most comfortable, together with Mérida (both with 42% of the year). Culiacán and Mexicali are the least comfortable cities, with comfortable conditions 25.7% and 26.4% of the time.

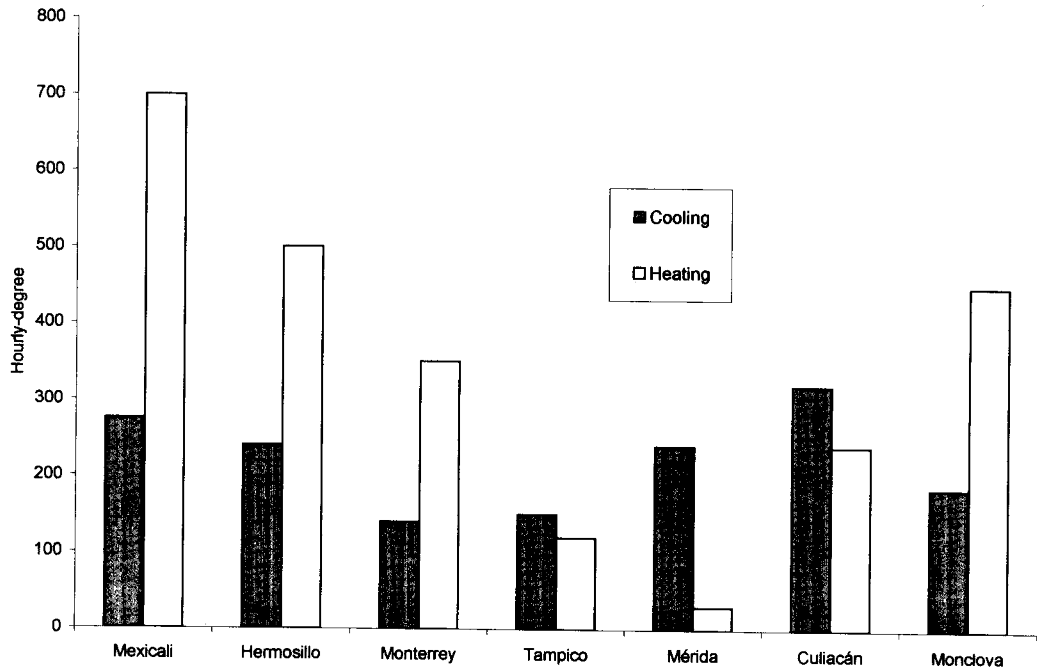

Fig. 2. Yearly needs of heating and cooling according to Thom's index.

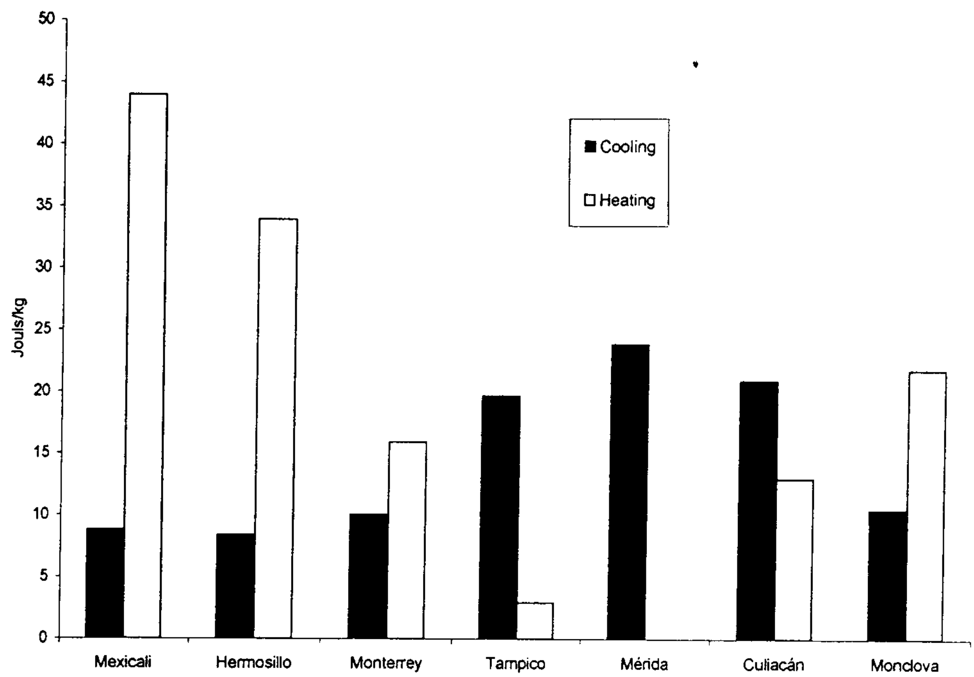

Fig. 3. Yearly needs of heating and cooling according to Enthalpy index.

Something similar to Table 2 was done for analysis of the cold period with Thoms (1959) index, and equally for the enthalpy in the two periods: warm and cold. Mexicali is the city with the highest percentages of discomfort by both indexes (during the cool period): however, using enthalpy concept during the warm period Tampico, Mérida and Culiacán are the cities with the highest percentage of discomfort.

Figures 2 and 3 show the annual heating needs (degree–hours) according to Thom (1959) and the enthalpy (cal/kg). Applying both indexes results coincide with the heating needs (maximum for Mexicali and almost null for Mérida). However, they differ considerably as to cooling needs. Using Thom's (1959) concept Mexicali occupies second place in annual requirements, but if enthalpy model is used Monterrey, Tampico, Culiacán and Mérida are above Mexicali. In summary, the cooling needs evaluated from these indexes are higher in direct proportion with atmospheric humidity.

The *HSI* was calculated as intermediate procedure with the intention to compare it with the results obtained form the application of simple indexes. Here, the bioclimatic evaluation for Mexicali , Cualiacán and Mérida (the three cities with more contrasted results) will be shown.

Figure 4 shows that during most of the year the monthly average of the heat strain is greatest in Mexicali. That is so say, Mexicali has the most rigorous summers and winters (according to the other indexes as well). Figure 5 shows that between 1 and 8 p.m. the situation in Mexicali may be serious for the health of persons staying in the shade with minimum ventilation and light clothing, as the *HIS* value of 0.8 is surpassed.

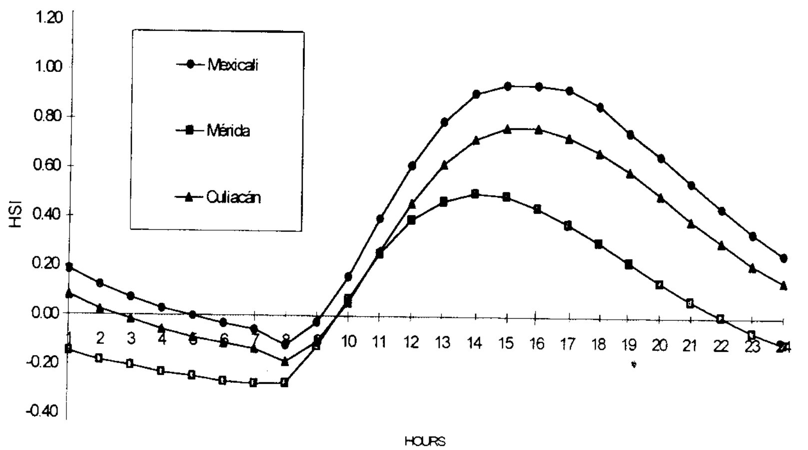

Fig. 4. Monthly values of the heat strain index for Mexicali, Mérida and Culiacán.

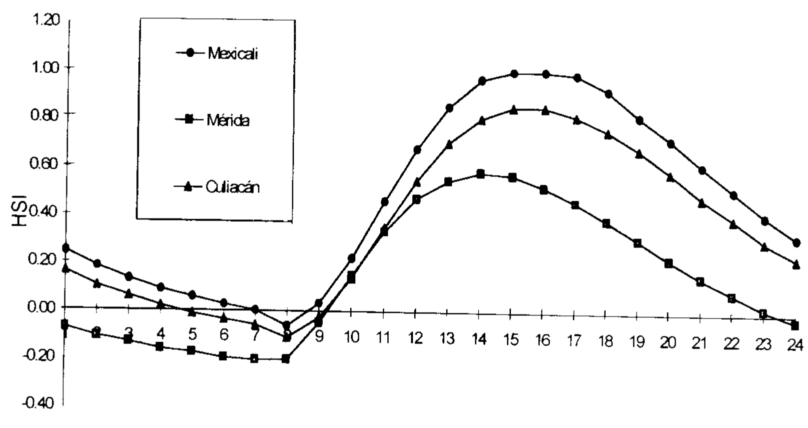

Fig. 5. Hourly values of the heat strain index during July (average 1951–1980) for Mexicali, Mérida and Culiacán.

4. Concluding Remarks

First it is interesting to examine the results for Mexicali, a desert city: by some indexes it is more comfortable than other cities, and from the HSI Mexicali has the most rigorous climatic conditions of the considered places.

a) According to Thom's index, Mexicali occupies second place in annual cooling needs, just below Culiacán, followed by Mérida, Hermosillo, Tampico, Monterrey and Monclova, in that order.

b) According to the enthalpy concept Mexicali occupies fifth place in annual cooling needs, below Mérida, Culiacán, Tampico and Monterrey. Obviously for this index the air humidity plays a very important role.

c) By using the HSI Mexicali presents a greater thermic effort than the more humid cities, such Culiacán and Mérida.

In addition the procedure presented here provides available comparative mean monthly hourly information for heating and cooling needs. This procedure is based on the estimation of mean hourly monthly temperature and relative humidity from current and unsophisticated climatic data.

Finally, the usefulness of an intermediate index (the HIS), which was possible by means of the use of a solar global radiation estimation model was shown. This was previously calibrated for Mexico and was used here as indicator for the parameterization of radiative temperature.

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