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Is PET an adequate index to determine human thermal comfort in Mexico City?

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Abstract: The urban heat island (UHI) is mostly due to urbanization. This phenomenon in concert with the high temperatures caused by global climate change may profoundly affect human thermal comfort, which can influence human productivity and morbidity especially in spring/summer period. The main objective of this investigation was to determine changes in degree of thermal comfort of Mexico City's inhabitants and compare it with the physiological equivalent temperature (PET) to evaluate whether PET and its categorization are adequate to be applied in Mexico City. A series of microclimatological measurements to estimate PET were made in four sites including the city´s center. Concomitantly, a series of surveys of thermal perception were applied to 1300 passersby. The results show that PET has increased from 1990 to 2020 from 0.1208 °C/year to 0.1498 °C/year in the study sites, besides overestimating the degree of thermal comfort of people according to the stablished categories or classes. It is concluded that it is necessary to adjust thermal stress categories. Knowing the percentage of people without thermal comfort will lead us to determine different ranges in environmental parameters to define an acceptable environment for most people.

Keywords: intertropical cities; physiologically equivalent temperature; thermal comfort indices; urban heat island

1. Introduction

There are two mechanisms that alter or increase the temperature in urban areas: the urban heat island (UHI) and global climate change. The UHI phenomenon has led to increased air temperatures in urban areas compared with their rural surroundings [e.g., 1-4]. Air temperature rises in a city or urban area due to the redistribution and storage (heat) of solar radiation energy because of changes in land use. The UHI in Mexico City can be as high as 6 to 7 °C on average but can also be established during the day with intensities of up to 10 °C [5].

This increase in temperature implies a direct effect on the thermal comfort index, where undoubtedly people will experience more heat stress and with it a decrease in productivity, and human health [6-9]. Heat stress could also be the beginning of leading to morbidity until to mortality [10-12]. Additionally, temperature differences could be exacerbated by global climate change [13], and heat strokes or waves will increase or at least be enhanced by the effect of the UHI [14-17]. It is established that UHI phenomenon has been increasing through the years in the cities [18]. From these points of view, the UHI could be considered as a form of thermal pollution.

To determine the human thermal comfort are many indexes and the most adequately are those based on the human thermal balance as physiological equivalent temperature

(PET) and a categorization of human thermal perception and human physiological stress degree [19]. Human thermal balance depends on physical activity, type of clothes and environmental parameters as radiation, and air temperature and humidity [20], and the degree of acclimatization of the city´s inhabitants. However, and despite being human comfort indexes based on an energy balance between the person and their surroundings, it is advisable to verify if any of these indices can determine the degree of comfort in some other place where they were generated since acclimatization is different for each place in the world. For example, in Mexico City the annual average temperature is 15.0 °C, and 21.0 °C in Belo Horizonte, Brazil and 8.0 °C in Freiburg, Germany, and undoubtedly the acclimatization for the inhabitants of these cities must be different and there will probably be a bias in the categorization of human thermal comfort [21].

Exploring the behavior of these thermal comfort indexes is important in any city with different types of acclimatation. This must be the first step to know more precisely the performance of the physiological equivalent temperature to achieve a better environment in outdoors and housing to move to a more sustainable city identifying how people senses the thermal stress in order to design adequately the housing and the city.

The main objective of this investigation was to determine the changes in the degree of thermal comfort of Mexico City's inhabitants and compare it with the PET to evaluate whether PET and its categorization are adequate to be applied to Mexico City.

2. Materials and Methods

2.1. Study site

Meteorological data (irradiance, air temperature, relative humidity, wind speed and direction) were collected from the meteorological stations at Xalostoc (XAL), La Merced (MER) and Pedregal (PED) districts, these stations belong to the Mexico City´s urban meteorological network (RedMet). La Merced is part of the commercial and historical center of the metropolitan area of Mexico City (19.4285° N; 99.1277° W; 2245 m asl), while Xalostoc (19.5260° N; 99.0824° W; 2160 m asl) and Pedregal (19.3251° N; 99.2041° W; 2326 m asl) are located in suburban areas with a low grade of urbanization, in the northeast and southwest, respectively (Fig. 1). All surveys were performed around La Plaza de la Constitución (19.433° N; 99.133° W; 2229.7 m asl) in the mere political center of the country in completely open spaces and about 1.8 km from La Merced (Fig. 2). Mexico City has a highland subtropical climate. Mean annual precipitation (mean of 30 yr.) is 275.7 mm, and almost 88.5% occurs during the rainy season (May - September) [22]. Winds are light and predominantly from the northeast. Extreme maximum and minimum temperatures are registered in April and May (30.6 °C) and January and December (0.6 °C), respectively; mean annual temperature is 14.6 °C [22], with a marked UHI effect in the urban area [23]. The UHI effect was established during the daytime, with intensities of up to 10 °C [4].

2.2 Bioclimatic Index, Surveys and Meteorological Data

The PET index, defined as the physiologically equivalent temperature in any place (indoors or outdoors) is equivalent to the temperature of the air in which, in a typical interior arrangement (without solar radiation and wind), the heat load of the human body maintains the temperature of the skin and body equal to those under conditions in which it is evaluated [19,24]. PET can be estimated by the RayMan model [20,25]. For more information see Appendix A1. We chose this index because it is possible to modify the meteorological variables depending on the place of the study area, as well as the physiological characteristics of people as required obtaining a result of greater precision, likewise the result obtained is given in Celsius degrees, which facilitates its application and subsequent analysis.
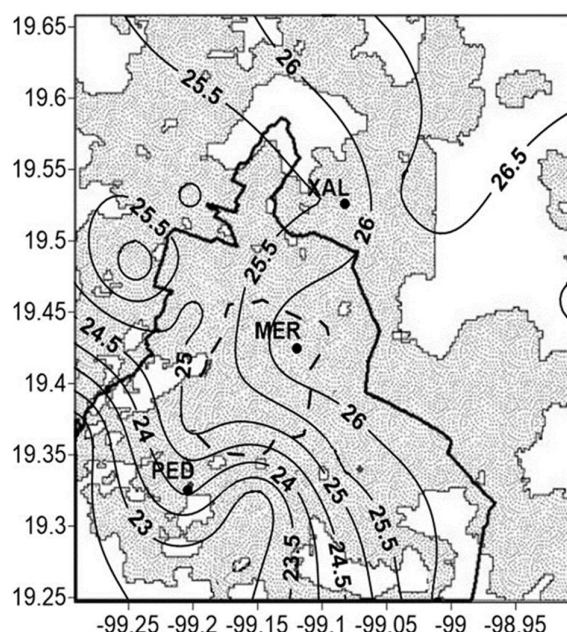
Figure 1. Location of the Metropolitan Zone of the Valley of Mexico and distribution of the air temperature (° C) in May 2016 at 14:00 hours local time. Mexico City is bounded by the black line. The stations of Xalostoc (XAL), La Merced (MER) and Pedregal (PED) are also shown.

The surveys were carried out with reference to [26], [27] and [28] and were divided into four parts: first, select the site where the survey was conducted, date and local time. The second, filter question to know the user's time within area and if their geographical location / residence in the last five years had been in Mexico City, in order to determine if the survey was appropriate, this was done due to possible complications because the lack of acclimatization of the users. The third, personal data such as gender, weight (kg), height (m), age, and level of studies, and the fourth to indicate the level of physical activity (W, W/m^2), type of clothing or thermal resistance of the dress (Iclo, clo). The last part, verbal and graphic scale of thermal perception was determined, as well as its perception with the atmospheric characteristics at that moment when the surveys were carrying out. We perform 1300 surveys, from 10:00 to 16:00 h, every 30 mins during the month of May and June 2019 and June 2021.

Concomitantly to the surveys, irradiance, air temperature and humidity, and wind speed were measured with a pyranometer (Eppley PSP, Campbell-Scientific), a temperature-humidity probe (HMP35C, Campbell-Scientific), and a thermal anemometer (03001, RM Young), respectively. All sensors were installed in a mobile station at 1.5 m height and connected to a data logger (21X, Campbell Scientific) that was programmed to store the data every second and generate averages for 1 minute and installed in an open space (Fig. 2). With this environmental data we calculate PET with the RayMan model according to personal data obtained in the survey, and the categories were assigned (Appendix A).

We analyzed all data available related to average annual irradiance, air temperature and humidity and wind speed from 1990 to 2020 and June 2021 to construct PET trends. The analysis was carried out with data from MER, XAL and PED from the RedMet of the Secretary of the Environment of Mexico City.

2.3. Statistical analyses

We analyzed data with XLSTAT statistical package to determine whether trends increase or decrease. We performed the Mann–Kendall test [29] to analyze whether physiologically equivalent temperature trends were significant. The purpose of the Mann–

Kendall test is to statistically assess if there is a monotonic upward or downward trend of the variable of interest over time [30,31]. Also, to discern if there were differences between calculated and observed PET physiology, numerical values were given to the thermal sensation categories (Appendix A) and were compared using a Kruskal-Wallis test. Statistical significance was considered at 95 % for all cases.

Figure 2. Locations where surveys and atmospheric variables measurements were carried out to calculate the physiological equivalent temperature. The surveys were performed in the areas marked with rectangles and the mobile micrometeorological stations were installed at the points indicated with a closed circle. The surrounding buildings have six (building 1), five (building 2), four (building 3) and three (building 4) storeys. Modified from Google Earth.

3. Results

3.1. Bioclimatic index tendency

Figure 3 shows the trend of PET index from 1990 to 2020 in the three studied weather stations: XAL, MER and PED. In these graphs it is noticed that there are positive tendencies in the three stations (P<0.05, R^2 = 0.6967, 0.5600 and 0.3973, respectively). Although in Pedregal the PET increment is high (0.1368 °C/year) and that of La Merced is about 0.1208 °C/year, in Xalostoc the tendency registered was the highest (0.1498 °C/year), probably indicating that in Pedregal, the PET increment could be low compared with Xalostoc where the PET increment is remarkable. While in La Merced apparently the PET increasing is lower.

3.2. Daily physiologically equivalent temperature

Figure 4 shows the results of the average physiologically equivalent temperature (PET) in La Merced throughout the day in the months of May and June (dry hot season) in 2020. PET in the dry warm season was distributed in the three major categories: cold, comfortable, and warm. The lowest PET was 10 °C which refers to a perception of fresh (moderate cold stress) for approximately 5.5 hours from 02:00 local hour (lh) until about 07:30 lh, and from 20:30 lh to midnight (≈ 4.5 h). From 17:00 to 20:00 lh, PET was set in the comfortable category (without thermal stress), so that from 10:00 to 16:30 lh thermal sensation up to a maximum of 33 °C (perception of warm and moderate heat stress), being approximately 3.5 h, while in May PET occurrence is similar to that of April. There were not significant PET differences between April and May. It is interesting to note that mainly in May and June the perceptions of thermal stress reach two antagonistic categories,

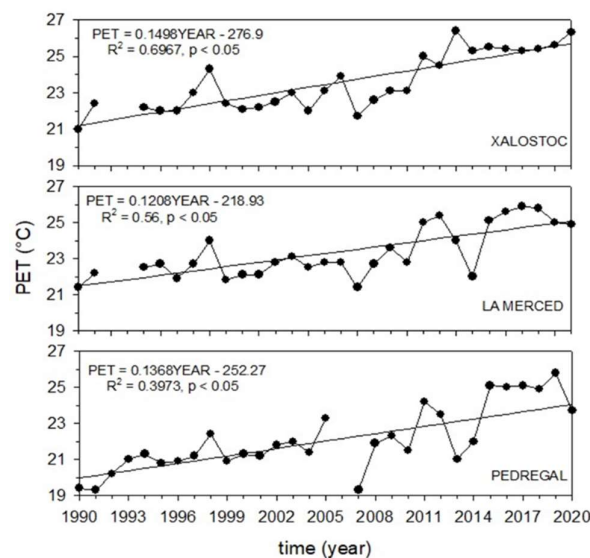between moderate cold stress from 05:00 to 07:30 lh, and moderate heat stress from 09:30 to 17:00 lh.

Figure 3. Trend of the physiological equivalent temperature (PET) in annual average from the year 1990 to the year 2020 in the three studied meteorological stations.

3.3. Calculated and observed thermal perception

Figure 5 shows the relative frequency of observed thermal perception (OTP) which was derived from surveys of people, compared to the thermal perception calculated or predicted (TPC) by the RayMan model fed with the microclimatic data collected at Plaza de la Constitución site. Predicted or calculated thermal perception is distributed from class 1 (cold) to 7 (hot), predicting the highest percentage in the slightly warm category (48%) and a very high percentage below this class (41%) with a 12% on comfortable class, and just only 11% above this category 5.
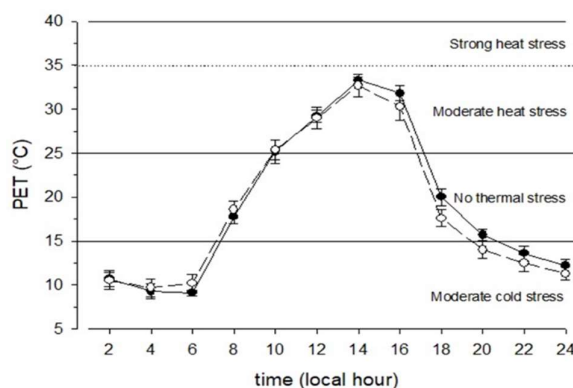

Figure 4. Daily development of the physiological equivalent temperature (PET) during the month of May (open symbols) and June (closed symbols) of the year 2019 and 2020. The symbols are the averaged PET, and the bars represent the standard error. The different classes of human perception are shown.
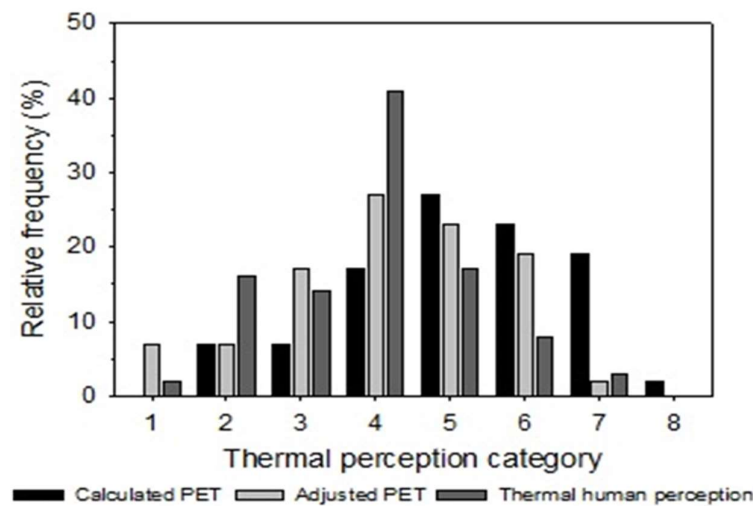
Figure 5. Relative frequency of the thermal perception of Mexico City's inhabitants, as a result of surveys at the Plaza de la Constitución, and the calculated physiological equivalent temperature (PET) using the RayMan model.

4. Discussion

The increase of the physiological equivalent temperature in Mexico City is evident. The three chosen stations registered this increment; and although in La Merced the increase in PET is small, this index will probably continue increasing at La Merced, because of the effect of global climate change and other variables that affect PET such as air humidity and wind speed, for example. On the other hand, the sites XAL and PED because they are in the perimeter of the city probably undergo a change greater than that of La Merced. However, these changes are not only influenced by urbanization but also by global climate change, since it is expected that minimum temperatures increase more than maximum temperatures [32]. According to the tendencies of each of the studied stations, there would be an increase in PET up to 25.2, 24.4 and 25.7 °C annual average, for XAL, MER and PED, respectively, with its direct effect in the hot dry season when air temperatures could be reach up to 30.4 °C [33] towards the year 2050. It means that PET could reach up to 40 °C situated in the strong heat stress (very hot category) considerably affecting PET daily march. This increase in temperature will also affect the daily development of PET, however this behavior could be less extreme than it is today, ranging from moderate stress due to cold to moderate heat stress. Currently, in the early morning Mexico City's inhabitants take coats to carry out their daily activities, towards the noon people does not know where to put the coat.

Additionally, it is expected that heat waves would also increase, Jauregui [34] found that in a very long period from the year 1877 to 2000 heat waves incremented in a 750% registering two hot spells in the decade 1877-1887, to 17 heat waves in the 1991-2000 decade in Mexico City. April and May are the months with the highest number of hot spells, resulting from moderate to severe heat stress based on PET, regardless of the hot and dry season.

Furthermore, apparently PET is overestimating thermal perceptions of the Mexico City's inhabitants for one class or category at least. However, it is possible to adjust the thermal perceptions or the grade of physiological stress in order to generate better predictions or scenarios to better understand the degree of discomfort experienced by the inhabitants of this city.

It is evident that the surveys reflect the state of thermal perception of people with a better precision than the actual categorization or classification (Appendix A). Probably this discrepancy may be due to the acclimatization of people that depends mainly on the average temperature of the site, for example moving the class of the thermal perception / degree of physiological stress only one class, it means that the class of slightly warm for the actual categorization, be the comfortable class for people. Therefore, increasing temperatures can negatively affect human thermal comfort, which can lead to health issues and affect human productivity, mainly in the spring/summer seasons [35,36].

To counteract the effect of high urban temperatures, air conditioning systems have been installed, however this practice increase energy consumption. The total sale of electricity in Mexico City in 1996 was 121.579 GWh of which 28.4 GWh (23.4%) was consumed by the domestic sector, 5.69 GWh was required to cool the spaces inside the buildings (air conditioners, evaporative cooling and fans), and 8.52 GWh in the shopping centers and services of the metropolitan area [37]. Furthermore, air conditioning systems efficiency is very low and acting "putting" the heat from the indoors to outdoors maybe exacerbating the heat island and increasing the greenhouse gases. Two strategies emerge from this study, one on the mitigation and adaptation to the urban heat island and global climate change.

In terms of mitigation and adaptation to global climate change and to the urban heat island, there are many strategies such as reducing greenhouse gases emissions and reforesting the urban area, implicitly vegetation becomes a carbon sink, but also locally reduces the temperature by transpiration. Ballinas and Barradas [4] found that to reduce the air temperature by 1 °C in a Mexico City´s area, 63 large Eucalyptus camaldulensis would be required per hectare, whereas to reduce the air temperature by 2 °C only 24 large Liquidambar styraciflua trees would be required. This means that an adequate strategy to cope with UHI and climate change would be to increase evaporative surfaces in the urban area. However, not only evaporative surfaces are the only solution to mitigate UHI and climate change, but other alternatives could also be the restructuring or establishment of an urban fabric by alternating different architectural elements and / or using new materials.

Physiological equivalent temperature is an adequately index as long as there is an adjustment to adaptation in mean temperature of each city. In Mexico City the average temperature is 15 °C, in Belo Horizonte and Germany it is 20.8 °C and 10.3 °C, respectively. Thus, thermal perception in neutral comfort is higher in Belo Horizonte (16 to 30 °C PET) and lower in two German cities (18 to 28 °C PET), with thermal perception ranging from 18 to 22 °C in Mexico City, as we see, the range of cities includes light warm and warm perception [21].

The results show that neutral range in Brazil is from 16 °C to 30 °C PET and that hot range starts at 32 °C PET. In Germany, neutral range is from 18 °C to 28 °C PET and hot range starts at 35 °C PET. The very hot category starts in lower values of the PET index in Brazil (36 °C) than in Germany (38 °C)

Decision makers need the best available scientific information to set policies and allocate resources. This decision to focus on the scientific challenge of heat island mitigation should be respond directly to the needs of the region to benefit.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of in-terest.

Appendix A1

The RayMan Model

The Rayman model is based on the German standard VDI 3789 Part II [38,19] and in VDI-3787 Part I [39,19]. With the Rayman model the average radiant temperature, the bioclimatic indexes and micrometeorological data can be calculated in all the environments, so this model has application in climatology, urban climatology and human bioclimatology (ibid). This model transforms the radiation fluxes at medium radiant temperature (T_{MRT}) forming the PET, SET* and PMV indices, as well as the energy flows and MEMI body parameters are part of the Rayman model and require the determination of T_{MRT}) [20]. The different ways of entry of radiation fluxes can be modified by obstacles, whether natural or artificial, for this reason the environmental morphological properties are important, for which the calculation of the mean radiant temperature is also required [20]. The SVF aerial view factor index (Sky View Factor) is a way to calculate radiation through hemispheric photography. So then for any type of urban structure through the Rayman model it is possible to calculate the average of each hour, each day and each month, the duration of the shadow, the long and short waves of the radiation flux with or without the topography data and obstacles in urban structures [25]. In addition, studies have been conducted that have proven the efficiency of the Rayman 2.0 model in hot and humid environments as well as in simple and complex environments [20]. Table A1 shows the different degrees of thermal perception and physiological stress according to PET comfort intervals.

Table A1. Intervals of the equivalent physiological temperature (PET, °C). Values hold only for an internal heat production of 80 W and a heat transfer of clothing of 0.9 clo [19].

Class	PET	Thermal perception	Grade of physiological stress
0	< 4.1	Very cold	Extreme cold stress
1	4.1– 8.0	Cold	Strong cold stress
2	8.1–13.0	Cool	Moderate cold stress
3	13.1–18.0	Slightly cool	Slight cold stress
4	18.1–23.0	Comfortable	No thermal stress
5	23.1–29.0	Slightly warm	Slight heat stress
6	29.1–35.0	Warm	Moderate heat stress
7	35.1– 41.0	Hot	Strong heat stress
8	> 41.0	Very hot	Extreme heat stress

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