Theor Appl Climatol
DOI 10.1007/s00704-014-1279-8

ORIGINAL PAPER

Suitability of different comfort indices for the prediction of thermal conditions in tree-covered outdoor spaces in arid cities

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Received: 22 August 2013 / Accepted: 5 September 2014

Abstract Outdoor thermal comfort is one of the most influential factors in the habitability of a space. Thermal level is defined not only by climate variables but also by the adaptation of people to the environment. This study presents a comparison between inductive and deductive thermal comfort models, contrasted with subjective reports, in order to identify which of the models can be used to most correctly predict thermal comfort in tree-covered outdoor spaces of the Mendoza Metropolitan Area, an intensely forested and open city located in an arid zone. Interviews and microclimatic measurements were carried out in winter 2010 and in summer 2011. Six widely used indices were selected according to different levels of complexity: the Temperature-Humidity Index (THI), Vinje's Comfort Index (PE), Thermal Sensation Index (TS), the Predicted Mean Vote (PMV), the COMFA model's energy balance (S), and the Physiological Equivalent Temperature (PET). The results show that the predictive models evaluated show percentages of predictive ability lower than 25 %. Despite this low indicator, inductive methods are adequate for obtaining a diagnosis of the degree and frequency in which a space is comfortable or not whereas deductive methods are recommended to influence urban design strategies. In addition, it is necessary to develop local models to evaluate perceived thermal comfort more adequately. This type of tool is very useful in the design and evaluation of the thermal conditions in outdoor spaces, based not only to climatic criteria but also subjective sensations.

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1 Introduction

Indoor energy use and thermal comfort are mainly affected by predominant microclimatic conditions (Gaitani et al. 2007). Design of urban spaces modifies atmospheric factors that influence the energy balance of the human body; these variables affect human comfort and energy use in urban areas (Oke 2004; Correa et al. 2012). Thermal comfort has been studied mostly in indoor spaces such as offices, schools, and homes. However, many recreational and commercial activities take place outdoors, such as cultural and touristic events (Spagnolo and de Dear 2003). Outdoor thermal comfort is one of the most influential factors in the habitability of a space. The quantity and intensity of activities are affected by the level of discomfort caused by weather conditions (Givoni et al. 2003).

The concept of comfort has different definitions. For Tornero et al. (2006), the term "comfort," a state of well-being, is precise and ambiguous at the same time. This broad definition is not scientifically precise, since the idea of well-being can be very different for different disciplines. Many authors agree that thermal comfort normally refers to a state of climatic or thermal well-being, without excluding other conditions of material satisfaction. This state of well-being is a consequence of a certain balance between the individual and the environment, between physiological and environmental conditions; such balance is always of interest, and can be looked at from different perspectives.

From a strictly physiological perspective, thermal comfort is a balance between the human body's energy and the thermal environment. Brown and Gillespie (1995, p. 173) define it as "a state of energy balance of the human body in relation to the thermal environment whose result is between −50 and + 50 W." From a psychological point of view, thermal comfort is defined by the subject's sensation, which is the result of the body's heat regulation. A definition of this kind is given in

Published online: 21 September 2014

standard ASHRAE 55 (ASHRAE 2004, p. 7): "the condition of mind that expresses satisfaction with the thermal environment."

However, according to Auliciems (1998), an adequate definition includes both physiological and psychological aspects, in which thermal sensation is based on physical and psychological sensations generated by the thermal environment, activity, experience, and expectations. Accordingly, Nikolopoulou and Steemers (2003, p. 96) define it as "the psycho-physiological satisfaction of the human being with respect to the thermal environment." On the other hand, Humphreys and Nicol (1998) state that people adapt by means of bodily adjustments and make changes to their thermal environment in order to reduce discomfort and physiological stress.

In accordance with Nikolopoulou and Steemers (2003, p. 96), human thermal adaptation is "the gradual decrease of the response of the organism to repeated exposure to stimuli received from the specific thermal environment." In the context of thermal comfort, this description considers all processes which may improve people's balance between the thermal environment and their hygrothermal requirements. To study this adaptation, it can be divided into three categories: physical, physiological, and psychological.

It is therefore necessary to rely on proper tools to evaluate the thermal comfort perceived by a certain population adapted to certain climatic conditions, in this case, the Mendoza Metropolitan Area (MMA), Argentina, located in an arid zone.

This study presents a comparison between inductive and deductive thermal comfort models, contrasted with subjective reports, in order to identify which of the models can be used to most correctly predict thermal comfort in tree-covered outdoor spaces of the MMA. It is expected that indices which take into account thermal radiation factors will better predict thermal comfort than indices which do not. The objective of this paper is to provide tools for urban planners, i.e., identify the simplest possible model that provides useful and reliable information.

2 Materials and methods

2.1 City of study

Research was carried out in the MMA, located in central west Argentina (32° 40′ S, 68° 51′ W; 750 masl). It is the fifth largest city in the country, with a population of 1,055,679, and covers 168 km^2 (INDEC 2010).

According to the Köppen–Geiger classification, the climate of the city is arid: BWh or BWk depending on the isotherm (Kottek et al. 2006). It is characterized by cold winters (mean temperature in July 7.3 °C) and hot summers (mean temperature in January 24.9 °C), with significant daily and season thermal amplitude. Winds are moderate and scarce (average speed 11 km/h); the quantity and intensity of solar irradiance is high (annual average relative heliophany 63 %) and the annual average precipitation is 198 mm, 76 % of which falls between October and March (González Loyarte et al. 2009).

It is currently estimated that approximately one third of the world population lives in cities located in regions classified as extremely arid, arid or semi-arid (UNCCD-Zöi 2011). Cities in arid or semi-arid environments, where water supply is the main limiting factor for sustainable development, usually fall into one of the two models: Compact City or Open City. Compact Cities have continuous urban development, made up of narrow streets and buildings interspersed with small green spaces. From the climatic point of view, the city itself creates shade that decreases solar exposure during the summer, and, consequently, heat accumulation on hard surfaces (Cantón and Martinez 2009). In these cities, the use of vegetation is rare or nonexistent.

Open Cites have wide streets and relatively low buildings, where shade is generated by trees lining the streets and sidewalks, as well as in parks, squares, and other green spaces. MMA is an Open City, in which the urban forest is watered by a canal irrigation system (Ponte 2006). This has allowed for the growth of the characteristic "green tunnels" that form a true urban forest in the city. These qualities have been acknowledged both at local and international levels, hence the well-deserved term, "oasis city" (Bórmida 1986; National Geographic Society 1990; Alvarez Mancini 2000).

2.2 Field study

The field study was carried out on a pedestrian street with great influx of people in downtown MMA. Two monitoring points were placed, one in the center of the city block (Point 1) and the other on the western end of the block (Point 2). Point 1 (32° 53′ 26″ S; 68° 50′ 23″ O) was more exposed to solar irradiance and wind than Point 2 (32° 53′ 25″ S; 68° 50′ 27″ O). Figure 1 shows the hemispherical views from each monitoring point, both in summer and winter, used to estimate the sky view factor (SVF).

Hemispherical digital images were used to calculate the SVF of urban spaces. At this point in the research, we developed the program PIXEL DE CIELO, which is accurate, easy-to-use free software that calculates SVF from hemispherical digital images in conditions with clear skies, dense urban canopy, and high reflectivity. It was created using Delphi 5.0 and runs on a window. PIXEL DE CIELO was used to calculate the SVF value of an urban environment based on fish-eye images in JPG format, taken by a digital camera, Coolpix 5400 with fish-eye lens FC-E9 (Nikon; Tokyo, Japan) (Correa et al. 2007; Córica and Pattini 2009). For

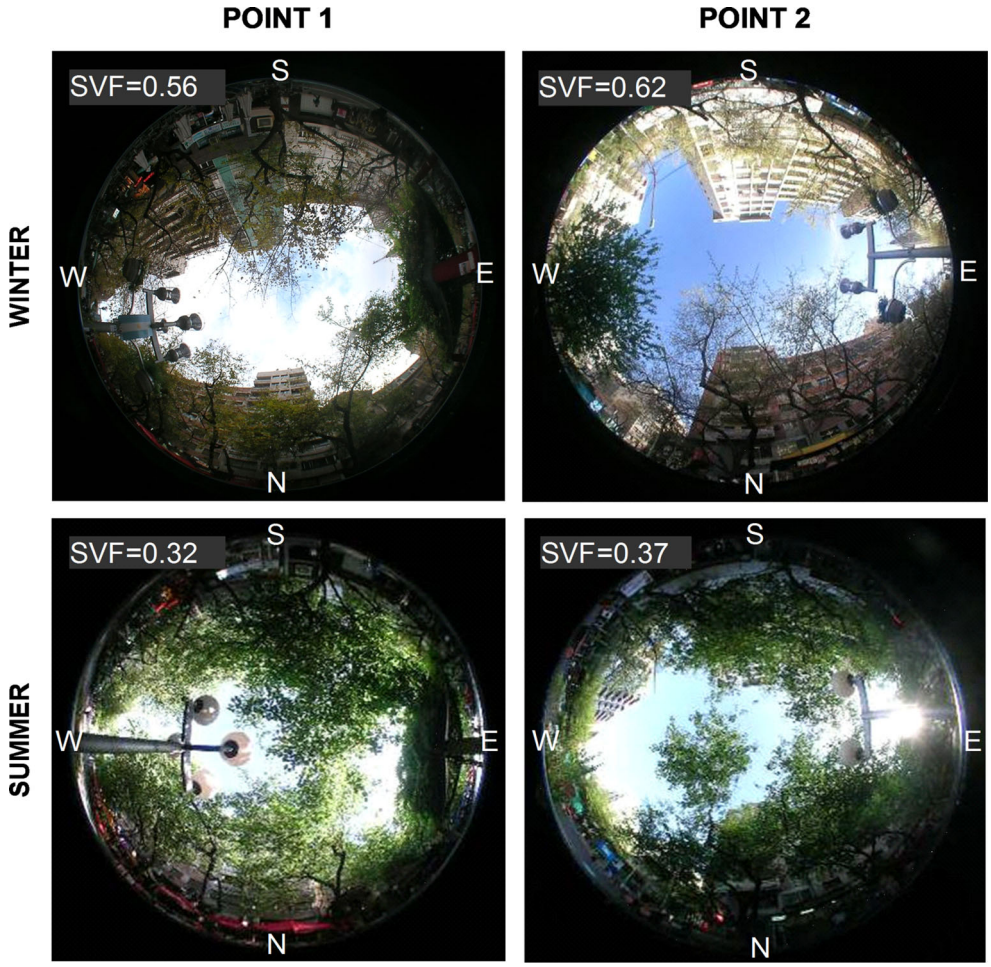

Fig. 1 Hemispherical views of each monitoring point in summer and winter. Photos were taken in January and June at 8:30 a.m., respectively

processing, an equiangular projection is assumed. The advantage of using a Nikon lens is that its projection is close to equiangular; a previous study found that the lens excludes only 0.3° of the field of view (Blennow 1995).

Interviews and microclimatic measurements were carried out in winter 2010 (July 22, 26, and 27) from 9 am to 5 pm and in summer 2011 (December 19, 20 and 21) from 9 am to 8 pm. All were typical days with cloudless skies.

Two mobile HOBO® H21-001 weather stations were used (ONSET; Bourne, Massachusetts, USA), equipped with silicone pyranometers, as well as sensors measuring temperature, relative humidity, wind speed, wind direction, and barometric pressure, at a height of 1.5 m. The operational range is between −20 °C and +50 °C. It was set to record conditions every 5 min. Figure 2 shows an image of the mobile weather station at the monitoring site.

Air temperature and relative humidity were monitored according to ISO 7726 (1998) standards, and combined sensors were placed inside six-plate radiation shields. Whiteman et al. (2000) reported that the root-mean-square temperature excess in this unaspirated shield for solar radiation of 1080 W/m^2 is only 0.4 °C in 3 m/s winds, 0.7 °C in 2 m/s winds, and 1.5 °C in 1 m/s winds. Many types of shields have been extensively tested (e.g., Fuchs and Tanner 1965; Crescenti et al. 1989; Anderson and Baumgartner 1998). The temperature sensors in unaspirated radiation shields provide acceptable accuracy for many meteorological and climatological investigations (Whiteman et al. 2000).

In the winter, mean air temperatures were 10.1 and 11.2 °C at Points 1 and 2, and mean relative humidity was 34.1 and 32.8 %, respectively. In the summer, mean temperatures were 32.6 and 32.7 °C at Points 1 and 2, and mean relative humidity was 22.7 and 26.0 %, respectively. Solar irradiance values are shown in Fig. 3.

To measure mean radiant temperature, we used a black sphere, following Moore's (1992) methodology, which has been validated by Mercado et al. (2009) in MMA. A HOBO H12-003 data logger with a Type T Copper/Constantan thermocouple (ONSET; Bourne, Massachusetts, USA) was placed within the sphere. Mean radiant temperature is the balance of thermal exchanges carried out between the globe and the environment, calculated with the ASHRAE formula (ASHRAE 2004). An additional "Littleman" thermometer was added, following Brown and Gillespie (1995), in order

Fig. 2 Mobile weather station at the monitoring site

to quantify the amount of radiation that would be received by a person outdoors. Vertical and horizontal surface temperatures were registered every 15 min by two infrared FLUKE 66 thermometers (FLUKE; Everett, Washington, USA).

Reference weather data was obtained from the Pegasus weather station (TECMES; Buenos Aires, CABA, Argentina) located at the premises of CONICET's Scientific and Technological Center of Mendoza (32° 53′ 47″ S; 68° 52′ 28″ O), 3 km from the monitoring points. The station was 3 m above the ground and free of obstructions within 20 m. It measured temperature, outdoor humidity, wind speed, wind direction, and solar irradiance every 15 min.

While the microclimatic monitoring was being carried out, people were also studied in their natural environment, through observation and structured interviews, in order to evaluate comfort levels and perception of the environment. The study of the subjective responses was carried out following Nikolopoulou et al. (2003), Kántor et al. (2007), and Monteiro (2008). The first part of the questionnaire consisted of items related to sex, age, clothing, and activity done before the interview and where they were coming from (to account for acclimatization). The second part addressed the perception of the thermal sensation on a 5-point scale, ranging from −2 (very cold) to +2 (very hot), going through 0 (neutral), which has been defined as the Actual Sensation Vote, or ASV (Nikolopoulou et al. 2003).

The sample included 667 people, 61 % men and 39 % women, and 80 % were between 18 and 64 years old. A minimum of 340 interviewees would be required for the data to be representative, based on a population of approximately 1 million, 5 % error, 95 % confidence level, and a response distribution of 33 % (comfort, discomfort caused by cold, or discomfort caused by heat).

3 Predictive models of thermal comfort

Six widely used indices with different levels of complexity were selected (Emmanuel 2005; Kakon et al. 2010; Gómez et al. 2004; Matzarakis and Mayer 1997; Picot 2004; Andrade and Alcoforado 2008). The inductive models were the Temperature-Humidity Index (THI), Vinje's Comfort Index (PE), and the Thermal Sensation Index (TS). The deductive models were the Predicted Mean Vote (PMV), the COMFA model's energy balance (S), and the Physiological Equivalent Temperature (PET). Although we are aware that some important indices have not been considered, each of the selected

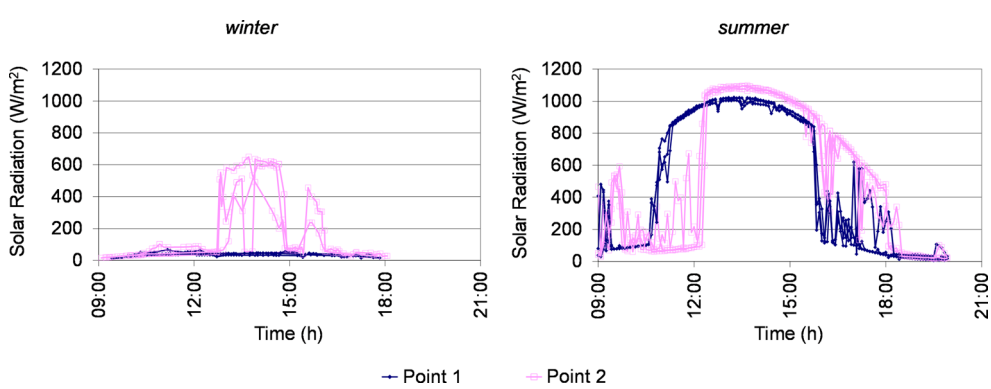

Fig. 3 Solar irradiance in winter 2010 (July 22, 26, and 27) and summer 2011 (December 19, 20 and 21) at both monitoring points

indices uses variables and approaches relevant to this paper. Besides, we would emphasize that all the indices have been calculated rigorously.

The Temperature-Humidity Index (THI) was developed by Thom (1959) to provide a general approach to changes in urban thermal stress over time and to develop useful guidelines for the design of cities (Deosthali 1999). The THI—also known as the Discomfort Index—is one of the variants on the popular Effective Temperature Index (ET). This combines dry-bulb and wet-bulb temperatures on a scale that imitates the thermal sensation of a human being. Later, Nieuwolt (1998) modified this index to use air temperature and relative humidity, since this data is more available. This requires air temperature (T_a) to be measured in Celsius and relative humidity (HR) as percentage, as shown in Eq. 1. According to Mather (1974), THI provides a simple means of describing the degree of thermal comfort in various combinations of temperature and humidity.

$$\mathrm{THI} = 0.8 \cdot T_a + \frac{\mathrm{HR} \cdot T_a}{500} \tag{1}$$

Like most of the comfort formulas, Vinje's Index and PE (Garnier 1972; Zowotorizka 1979; Balaras et al. 1993; Gómez et al. 2004) have evolved after decades of experiments, which simulate the physiological reactions of the human body. The first experiments used a special thermometer (Hill's Kata), which reached body temperature and then was left to cool during a certain period, thus simulating the cooling of the body. The drop in the temperature or the "cooling power" was caused by the combined effect of the air temperature, radiation exchange, and wind over the thermometer bulb. Vinje's bulb is essentially the mathematical expression of Hill's Kata thermometer's cooling rate. The formula (Eq. 2) expresses wind speed (v) in meters per second, dry-bulb temperature (T_a) in degree Celsius and indicates the cooling of the human body in mcal cm^{-2} s^{-1}. Under Zowotorizka (1979), this equation is only applicable when temperatures are between 0 and 20 °C, but it has also been used outside this range (Balaras et al. 1993).

$$\mathrm{PE} = 0.57.v^{0,42}.(36.5 - T_a) \tag{2}$$

Based on (Givoni and Noguchi 2000) experimental data, a predictive equation of an individual's comfort sensation in outdoor spaces was developed. By this formula, the thermal sensation (TS) (Givoni et al. 2003; Givoni and Noguchi 2000) is defined as the perception of cold or heat, on a scale ranging from 1 (very cold) to 7 (very hot). Level 4 is comfortable, which means the human body feels no thermal discomfort. This index (Eq. 3) uses air temperature (T_a, in °C); horizontal solar irradiance (RS, in W/m^2), wind speed (v, in m/s), relative humidity (HR, in %), and surrounding soil temperature (T_{ss}, in °C) (Gaitani et al. 2007). In this index, the cooling effect of high relative humidity values can be erroneous, due to the small number of subjects interviewed, and thus cannot represent the real effect of humidity. This may because of the particular combination of solar irradiance and humidity in Japan, where the research was carried out. Humidity is lower and temperature is higher, and subjects feel more heat, mainly due to solar irradiance (Gaitani et al. 2007).

$$\mathrm{TS} = 1.7 + 0.1118 \cdot T_a + 0.0019 \cdot \mathrm{RS} - 0.322 \cdot v - 0.0073 \cdot \mathrm{HR} + 0.0054 \cdot T_{ss} \tag{3}$$

The Predicted Mean Vote (Fanger 1972) is based on the balance of heat in the human body. The human being is in thermal balance when the inner production of heat is equal to the loss of heat in the environment. In a mild environment, the human thermoregulatory system automatically tries to modify the skin temperature and the secretion of sweat to maintain heat balance. This model's physiological response has been compared to over 1300 subjects' thermal sensation votes (ISO 1994). In the PMV (Eq. 4), M is the metabolic rate and L is the thermal load on the body, defined as the difference between the inner production of heat and the loss of heat in the environment (ASHRAE 2004). Thermal load takes into account metabolic rate, external work, partial water vapor pressure, air temperature, mean radiant temperature, surface temperature of clothing, thermal resistance of clothing, convective heat transfer coefficient, and relative air velocity.

$$\mathrm{PMV} = \left(0.303 \cdot e^{-0.036 \cdot M} + 0.028\right) \cdot L \tag{4}$$

It must be taken into account that according to Standard ISO 7730 (ISO 1994), value of external work is equal to zero for most activities and advises the use of PMV only for values between −2 and +2. Moreover, it is advisable to apply PMV when the parameters are found between the following limits:

- Metabolic rate 46–232 W/m^{-2}
- Thermal resistance of clothing 0–0.31 W/K/m^{-2}
- Air temperature 10–30 °C
- Mean radiant temperature 10–40 °C
- Wind speed 0–1 m/s^{-1}
- Partial pressure of water vapor 0–2700 Pa
- Relative humidity 30–70 %

In MMA, these variables often fall outside these limits, especially during the summer.

The COMFA method (Brown and Gillespie 1995) is based on the formula shown in Eq. 5, which expresses the energy

balance of a person in an outdoor environment (Gaitani et al. 2007). In this formula, M is metabolic rate, R_{abs} is absorbed solar and soil radiation, Conv is heat gain or loss by convection, Evap is heat loss by evaporation, and $TR_{emitted}$ is emitted terrestrial radiation. All terms are in watts per square meter. When S is near zero, a person should feel comfortable. If the balance shows a positive value, the person receives more energy than it loses, meaning it could feel discomfort caused by heat. A negative value indicates discomfort from cold.

$$S = M + R_{abs} - \mathrm{Conv} - \mathrm{Evap} - \mathrm{TR}_{emitted} \quad (5)$$

In order to estimate absorbed solar and soil radiation R_{abs}, there are different alternatives: (a) estimating solar and soil radiation from local weather station data, and the proportion absorbed by a person, (b) estimating the radiation absorbed by a person using atmospheric variables from the upper part of the atmosphere, (c) using a "radiation thermometer" to estimate R_{abs}, and (d) estimating shade, or heat radiation under trees, based on the porosity of the canopy.

In this study, R_{abs} is calculated with (a) and (c). Option (a) consists of two elements: total solar radiation absorbed and the absorbed soil radiation. The human body is represented as a vertical cylinder within a sphere of influence. The upper hemisphere is generally dominated by the sky and objects above the ground, while the lower hemisphere is generally dominated by the ground surface. To calculate direct solar irradiance transmitted through the canopy, horizontal solar irradiance is required, both global and diffuse, based on data from the Pegasus weather station and from tree permeability values, which were taken from previous research (Cantón et al. 1994). The diffuse components were estimated from diffuse irradiance and the sky view factor (SVF), calculated by processing of digital hemispherical images (Correa et al. 2007). This method of calculating energy balance is referred to as "S with SVF".

For option (c), a "Littleman" thermometer was used (Brown and Gillespie 1995), which estimates the amount of radiation received by a person in an outdoor environment. The "Littleman" is located at a height of 1.5 m and is made up of an aluminum copper-colored cylinder, 10 cm tall and 1.3 cm in diameter, within which there is a mercury thermometer with 0.5 °C precision. The cylinder shape is similar to a standing person, and the color (Munsell 7.5 YR 7/3) has a 37 % albedo, similar to that of a clothed person, thus the instrument mimics a person standing in a specific environment, in terms of solar and soil radiation absorption. The cylinder is filled with something, like sand, which conducts heat well. An acrylic tube with a "reflecting" cap protects the thermometer. This method's energy balance is referred to as "S with Te".

The Physiologically Equivalent Temperature (PET) is based on a physiological model: the MEMI heat-balance model for the human body (Höppe 1984). PET has been defined as

> a thermal index which serves to assess the thermal component of different climates. Apart from being based on physiological considerations, it uses a more universally known unit of measurement (°C), which is important for those who are less familiar with current human biometeorological terminology. One of its most important features is that it enables the thermal component of microclimates in urban settings to be determined (Matzarakis et al. 1999, p. 76).

RayMan software has often been used in studies conducted in mid-latitude cities with similar conditions (Kakon et al. 2010; Matzarakis et al. 2007; Müller et al. 2014; Krüger et al. 2013). This software is well suited for determining microclimatic changes in different urban structures, as it calculates the radiation fluxes of different surfaces and their changes (Gulyás et al. 2006). Although it is known that the mean radiant temperature is slightly underestimated by RayMan when the sun is low in the sky (Matzarakis et al. 2010; Thorsson et al. 2007), in locations with a relatively high position of the sun simulation results of mean radiant temperature by RayMan are quite good, as a study of Lin et al. (2010) showed in Taiwan. In this sense, urban planning professionals, who are not experts in climatology, have a tool available to them which is not overly complicated.

Each of these indices has its own scale of thermal sensation. These scales vary in terminology and ranges. In order to compare the six indices, their ranges and the subjective answers were standardized. Table 1 presents the equivalent category, reported sensation, and thresholds for each index.

In order to facilitate the discussion of results, a classification of these models was carried out, bearing in mind Monteiro and Alucci's (2006) criteria (Table 2). The models were classified according to three criteria: (1) prediction target: physiological reaction (heat stress) or thermal sensation (thermal comfort), (2) predominant modeling method: inductive or deductive, and (3) main criterion for interpretation: analogy, physiological criteria, and qualitative criteria.

When the interpretation is made by analogy, equivalent temperatures must always be adopted. It is common to later establish levels of interpretation for the equivalent temperature values. In cases without an analogy, a certain factor is set, or the relationship between various factors. In the case of thermal stress indices, factors are physiological. In the case of thermal comfort indices, factors are based on physiological variables or arbitrary scales. In both cases, there are subsequent correlations with subjective reports. Hence, although both have a subjective, qualitative interpretation, the indices can be termed physiological or qualitative, based on the overall emphasis and the nature of the scale employed and emphasis employed.

Table 1 Standardized ranges of indices and correlated subjective reports

Equivalent category	Sensation	THI	PE	TS	PMV	S (COMFA)	PET	ASV
4	Very hot						>41	
3	Hot	≥30		>6.5	>2.5		35 to 41	
2	Warm	26.5 to 29.9		5.5 to 6.5	1.5 to 2.5	>150	29 to 35	>1.5
1	Slightly warm	20 to 26.4	<5	4.5 to 5.5	0.5 to 1.5	50 to 150	23 to 29	0.5 to 1.5
0	Neutral	15 to 19.9	5 to 11	3.5 to 4.5	−0.5 to 0.5	−50 to 50	18 to 23	−0.5 to 0.5
−1	Slightly cool	13 to 14.9	>11	2.5 to 3.5	−1.5 to −0.5	−50 to −150	13 to 18	−0.5 to −1.5
−2	Cool	−1.7 to 12.9		1.5 to 2.5	−2.5 to −1.5	< −150	8 to 13	< −1.5
−3	Cold	< −1.7		<1.5	<−2.5		4 to 8	
−4	Very cold						<4	
References		Deosthali 1999	Gómez et al. 2004	Based on Gaitani et al. 2007	Based on ASHRAE 2004	Brown and Gillespie 1995	Matzarakis et al. 1999	Nikolopoulou et al. 2003

Table 3 shows the variables used by each model, following Monteiro and Alucci's (2006) criteria.

The models were inputted into spreadsheets, facilitating the processing of a great amount of input and output data. For the particular case of the *S* index of the COMFA model, the free version of the program Engineering Equation Solver was used, the PMV was solved with QuickBASIC software, in accordance with regulation ISO 7730 (ISO 1994) and the PET, with RayMan software.

Assuming the microclimatic variables are normally distributed in all seasons, within the range [μ−2SE; μ+2SE] approximately 95.44 % of the distribution is found.[1] Therefore, a graphic comparison among models and subjective answers was carried out, based on the 622 questionnaires within that same interval, both in winter and summer, after removing outliers. In order to compare the different models, questionnaires carried out during 1 h were considered to be under the same climatic situation, thus the 622 questionnaires were distributed into 84 different microclimatic situations.

For each of these one-hour microclimatic situations in MMA, the indices of the above models were calculated and compared to the corresponding subjective responses, following Monteiro (2008). The first comparison was based on the correlation (Pearson's correlation coefficient) between the model calculation and thermal sensation reported in the field. The second was the correlation between the corresponding standardized category (−4 to +4) and the reported thermal sensation. The thresholds for interpretation of the indices can be found in Table 1. The final comparison was made using the percentage of correct predictions for each model (predictive ability).

[1] Where μ is the arithmetic mean of the population and SE is the standard error for the sample mean.

4 Results and discussion

4.1 General analysis

The results of the comparison between the different models and the subjective responses are shown in Table 4. All results are significant, with the *p* values lower than 0.05. In general, Pearson's correlation coefficient is relatively high in all cases (above 0.78), in relation to the parameter of each model. This means that all model parameters are linearly correlated with the subjective perception of thermal sensation. The correlation with the ranges of each category is related to the ranges and number of categories on the standardized scale. Pearson's coefficient is disparate in this case and varies between 0.55 and 0.87, depending on the model. The interpretation can be improved in the future by calibrating the ranges of each index.

On the other hand, the predictive ability does not surpass 25 % in any of the evaluated models. These low values indicate the poor prediction potential of these indices for MMA.

The THI index presents the highest correlation with the model (0.93) and a high correlation with the standardized scale. It has also one of the highest predictive ability percentages (21 %).

Table 2 Suggested model classification

Model	THI	PE	TS	COMFA	PMV	PET
Prediction target: stress (E)/comfort (C)	C	E	C	C	C	C
Main method: inductive (I)/deductive (D)	I	I	I	D	D	D
Main interpretation criterion: analogy (A), physiological criteria (Pf), qualitative criteria (Pc)	A	A	Pc	Pf	Pc	A

Table 3 Variables used by the different models

Models			Inductive models			Deductive models		
			THI	PE	TS	PMV	S (COMFA)	PET
Variables	Climate	Global radiation			X		X	X
		Diffuse radiation					X	X
		Solar altitude					X	X
	Micro-climate (urban)	Air temperature	X	X	X	X	X	X
		Relative humidity	X		X	X	X	X
		Surface temperature			X		X	
		Ground temperature			X		X	
		Mean radiant temperature				X		X
		Wind speed		X	X	X	X	X
		SVF					X	X
		Building albedo					X	X
		Ground albedo					X	X
	Human	Metabolic rate				X	X	X
		Permeability of clothing					X	
		Isolation value of clothing				X	X	X
		Skin temperature					X	
		Skin emissivity					X	
		Skin albedo					X	X
		Clothing albedo					X	
	Tree canopy	Permeability					X	

The Pearson coefficient for Vinje's model is quite high and negative (−0.88) due to the fact that its scale is inverted, compared to the field survey and to the one that used other indices. Discomfort caused by heat is reflected by low PE values, unlike the other indices that describe the cooling ability of the human body. The correlation with PE ranges is the lowest (0.55), which is explained by the fact that this index has only three categories. The percentage of predictive ability is the highest (25 %).

The thermal sensation index TS has a high correlation both with the model and the standardized scale, and the predictive ability is 20 %.

The PMV presents a low correlation with the model parameter, 0.78, a 0.75 correlation with the ranges, and a low predictive ability.

The correlation and predictive ability for the *S* energy balance of the COMFA model varied according to how the index was calculated. When calculated with SVF, values were considerably higher than with "Littleman" temperatures, which had a low value of predictive ability (7 %) and a low Pearson coefficient, compared to the model (78 %).

The PET presents the lowest correlation with the model, 0.73, but a high correlation with the standardized scale, 0.86. The percentage of predictive ability is the lowest (3.57 %).

As mentioned above, these criteria were determined for a set of data from 84 microclimatic situations, which fall within the interval: mean±twice the standard deviation of each variable. Table 5 provides the ranges of the variables in winter and summer.

Table 4 Values of the correlations between the subjective results and the results of each predictive model for the entire year

Model/index		Correlation with model result	Correlation with subjective category	Predictive ability
Inductive models	THI	0.93	0.86	21.43 %
	Vinje-PE	−0.88	0.55	25.00 %
	TS	0.90	0.86	20.24 %
Deductive models	PMV	0.78	0.75	16.67 %
	COMFA-S with SVF	0.91	0.87	23.81 %
	COMFA-S with Te	0.78	0.72	7.14 %
	PET	0.73	0.86	3.57 %

Table 5 Microclimatic variable ranges in the 84 microclimatic situations

Variable	Winter		Summer	
	Minimum	Maximum	Minimum	Maximum
Air temperature (°C)	5.5	15.5	28.1	37.1
Mean radiant temperature (°C)	14.4	80.4	31.9	72.0
Relative humidity (%)	27.2	47.8	20.6	28.4
Wind speed (m/s)	0.0	1.3	0.1	2.6

Human variables were based on clothing and metabolic rate (Table 6), by the habits of MMA's inhabitants. The low percentage of predictive ability is explained by the source of each index and the different degree of individuals' adaptation to the weather. The rigorous restrictions of the environmental parameters in the laboratory experiments are very different to those of real spaces (Auliciems 1998; de Dear and Brager 2002). Some of these indices have even been developed for indoor environments and then applied to outdoor spaces where the microclimatic and individual variables oscillate much more. Even though some models have been developed on the basis of outdoor studies, they were carried out in areas with different climates in different types of cities, and thus neither the peculiarities of each studied city nor inhabitants' adaptation are taken into account.

5 Season and field analysis

Given that MMA is located in an arid region characterized by wide seasonal thermal amplitude, comparative graphic analysis was carried out between each model and the subjective reports for each site and season. The results of the analysis are shown in Figs. 4 and 5, and the correlation values between the subjective reports and the results of the predictive models for each season are in Tables 7 and 8.

Both in winter and summer, the subjective results show that Point 2 (which has a higher sky view factor) was perceived as warmer than Point 1. This shows that it was more comfortable in winter and less comfortable during summer for the MMA's inhabitants.

Table 6 Human variable ranges in the 84 microclimatic situations

Variable	Winter		Summer	
	Minimum	Maximum	Minimum	Maximum
Isolation value of clothing (clo)	0.8	1.3	0.3	0.5
Resistance of clothing (m/s)	133.6	213.1	47.0	83.1
Permeability of clothing (m^2/s)	60	103	141	184
Metabolic rate (met)	1.1	3.0	1.3	3.1

During winter, a great number of people say they did not feel cold or heat, but neutral was perceived by 47 % at Point 1 and 63 % at Point 2. Point 1 (which has the lowest SVF) was perceived as "slightly cool" by 34 % of the interviewees, but only 21 % at Point 2. It is interesting that relatively small variations in SVF (the difference between the monitoring points is about 0.06) caused considerable variations in subjective responses. Figure 3a shows that solar irradiance received during this season was very different at each monitoring point. Although the SVFs were similar, there was a more solar irradiance at Point 2 in the winter, because the solar altitude was relatively low. During this season, the calculated indices indicate higher degrees of discomfort than those expressed in interviews.

During the summer, people tend to feel further from the neutral values perceived in winter. At Point 1 (lower SVF), 47 % reported a "slightly warm" sensation, but only 25 % at Point 2 (higher SVF). Thirty-five percent perceived the space as "hot" at Point 1 and 52 % at Point 2. Figure 3b shows that during the summer, solar irradiance was much higher and more similar at both monitoring points than during the winter, because solar altitude was higher. The difference between points can be explained by the hours of the day with solar irradiance. At Point 2, there was solar irradiance only during at midday and during the afternoon.

In general, the models predict subjective answers better at Point 2 than Point 1. For each case from Point 1, results are similar to those in winter, i.e., indices overestimate the level of thermal discomfort in relation to what people perceive. This shows the impact of shade. People report a comfort in summer because of shade (attenuation of direct solar irradiance). However, according to the radiation balance, the incidence of vegetation is not very evident, due to its spectral behavior. Therefore, it is important to evaluate the effectiveness of models' comfort prediction in cities located in arid regions with many trees and extensive shade.

The predictive indices show lower percentages of people (close to 0 %) in the "neutral" category than the ones shown by the subjective answers (close to 20 %), at both monitoring points during summer. This means that these indices underestimate the real level of comfort of the inhabitants of MMA. The exception seems to be the *S* balance of model COMFA.

In winter, there is not a big difference between inductive and deductive models. All indices tend to show cold discomfort, except PMV which predicts that people are hot. This issue is related to the origin of PMV. In contrast, the inductive models are more rigorous than deductive models in the summer.

The differences between subjective reports and the predictive models are similar to the results obtained by other

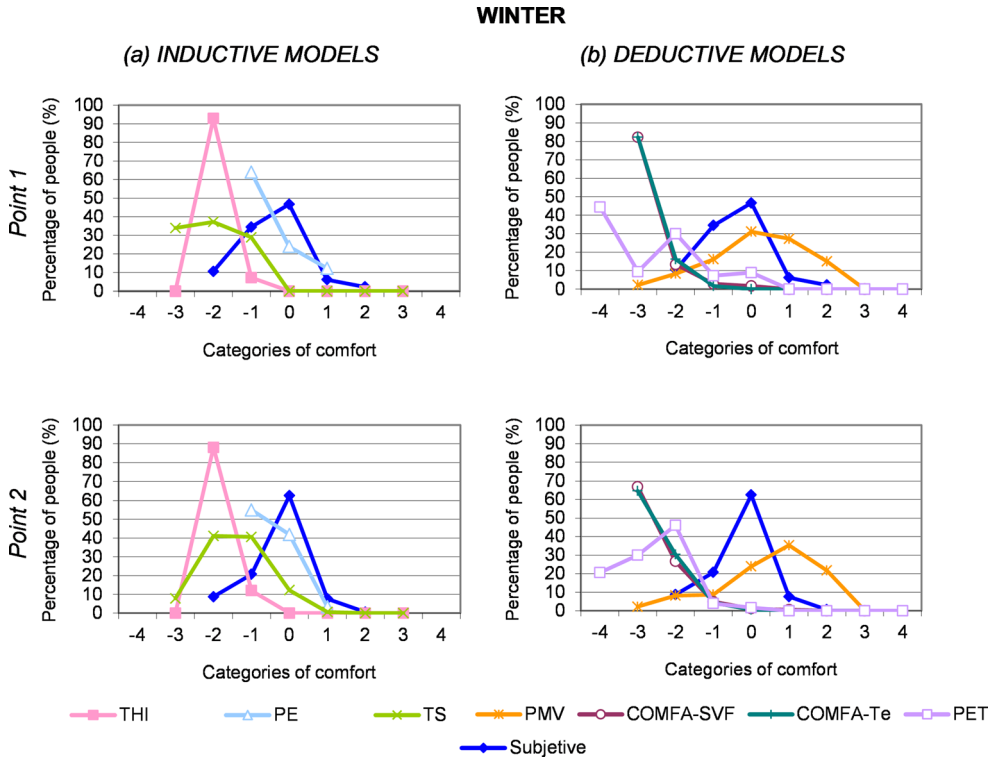

Fig. 4 Comparison of the percentage of people in each comfort category at Points 1 and 2 in winter

researchers in other climates (Nikolopoulou and Steemers 2003; Thorsson et al. 2004; Kántor et al. 2007). Thus, from the analysis of these data, it is evidently necessary to take into consideration the adaptation processes of the inhabitants of MMA in order to effectively determine the degree of comfort in different spaces.

This phenomenon of adaptation can be based on the following considerations. First, it must be taken into account that some of the objective indices were developed in areas with entirely different climates than MMA, and most for indoor settings. The comfort ranges in these environments are much narrower, due to the fact that thermal conditions are more

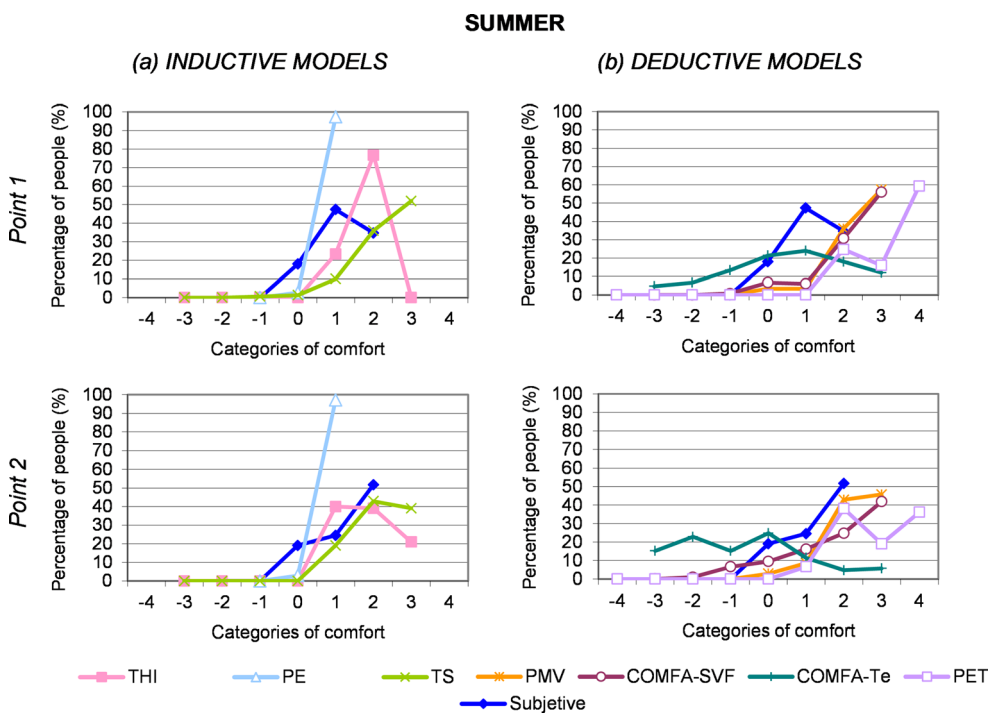

Fig. 5 Comparison of the percentage of people in each comfort category at Points 1 and 2 in summer

Table 7 Correlation values between the model calculations and reported sensations in the winter

Model/index		Correlation with model result	Correlation with subjective category	Predictive ability
Inductive models	THI	0.69	0.26	0.00 %
	Vinje-PE	−0.59	0.10	30.95 %
	TS	0.68	0.60	9.52 %
Deductive models	PMV	0.19	0.08	28.57 %
	COMFA-S with SVF	0.66	0.55	0.00 %
	COMFA-S with Te	0.50	0.44	2.38 %
	PET	0.73	0.58	2.38 %

constant and closer to indoor comfort levels. Given the results, it would not be suitable to use indoor comfort ranges without adjusting them for outdoor studies (Kántor et al. 2007).

The relation between shade and comfort sensation is culturally rooted in the perception of the inhabitants of MMA, given that this is an intensely forested and open city located in an arid context, where the shade provided by the urban forest is the main means of reducing solar irradiance. However, trees are not a total barrier against solar irradiance, and permeability varies under wavelength. In accordance with Oke (1987), vegetation allows 20–34 % of shortwave solar infrared radiation through, which is absorbed in great measure by the hard surfaces of the urban environment, and re-emitted as longwave IR radiation. People can therefore expect to feel fairly comfortable in a tree-covered open space in the summer, but while they are there, they perceive the IR radiation coming from the surrounding surfaces, which results in discomfort caused by heat. This is reflected in model calculations, but not in the subjective reports.

Villalba et al. (2005) have predicted a rise in temperatures in the Andean region and an increase in the summer precipitation in subtropical regions with little relief, such as where MMA is located. This change can affect the future degree of comfort perceived in summer from two perspectives. First, it has already been said that people generally have wider ranges of thermal comfort outdoors than indoors, which may be related to the amount of clothing. This can increase considerably in winter but cannot be decreased beyond a certain point in summer. Second, psychological factors represent 50 % of the ASV variation of the interviewees according to Nikolopoulou and Steemers (2003), thus it would be expected that memory and expectations have a great influence on the degree of perceived comfort.

In terms of the THI index, both monitoring points are very similar in winter, when 88 and 93 % of people, depending on the point, felt cool. This high percentage of cold discomfort contrasts with the reality of the people interviewed. The variables considered by this index (air temperature and relative humidity) do not usually vary considerably during this season (Fig. 4a). In summer, however, the THI index at Point 1 (with lower SVF) had the highest number of people reporting "warm," with 77 %, and 23 % reporting "slightly warm." On the contrary, at Point 2, these two categories were practically the same, 39 and 40 %, respectively, and the rest of the people (21 %) reported being "hot" (Fig. 5a). Regarding data from Tables 7 and 8, this index has low winter values (0 % predictive ability) and improved summer values, with 43 % predictive ability.

Depending on Vinje's PE index, most people perceive a "slightly cool" sensation at both monitoring points in the winter (between 55 and 64 %). The rest of the responses at Point 1 are distributed as follows: 24 % "neutral" and 12 % "slightly warm," and at Point 2, 42 % "neutral." This is the only index that shows that during a few hours, Point 1 was

Table 8 Correlation values between the model calculations and reported sensations in the summer

Model/index		Correlation with model result	Correlation with subjective category	Predictive ability
Inductive models	THI	0.46	0.42	42.86 %
	Vinje-PE	−0.49	0.42	23.81 %
	TS	0.34	0.30	30.95 %
Deductive models	PMV	0.30	0.19	4.76 %
	COMFA-S with SVF	0.39	0.41	47.62 %
	COMFA-S with Te	−0.05	−0.05	11.90 %
	PET	0.13	0.08	4.76 %

cooler than Point 2, and at other times warmer. This behavior is explained by wind speed (Fig. 4a). In summer, the PE index was very similar at both monitoring points: 97 % "slightly warm" (its only positive category) and 3 % "neutral" (Fig. 5a). If this model had more categories, it is expected that 97 % would be distributed among them, as with the rest of the indices. Solar irradiance is considered to be one of the most determining parameters in the design of spaces in arid zone cities; therefore, we can assume that the results of this index do not faithfully represent energy exchanges in open urban spaces. In both winter and summer, Vinje's PE has medium values of correlations and predictive ability (Tables 7 and 8).

In the case of the TS index, which involves a greater number of variables, the curves representing the results of the survey and the model calculation are not in agreement in one category in winter (Fig. 4a). The same happens at Point 1 during summer, but it does not occur at Point 2 (higher SVF). According to the calculation, most people (52 %) at Point 1 should have been "hot," which does not agree with what the people actually reported (Fig. 5a). The TS has a high correlation (0.68) but has a low predictive ability (almost 10 %) in winter (Table 7). In summer, it has 31 % predictive ability (Table 8).

PMV is the only index which shows that the monitoring points are warmer in winter, and has a significant discrepancy with the subjective reports. Most people reported being "slightly warm," 28 and 34 % at Points 1 and 2, respectively (Fig. 4b). Correlation values are low in winter, although predictive ability is high, 29 % (Table 7). In summer, an overestimation of heat is also observed by people and, in contrast with the subjective reports, this index predicts that Point 1 (lower SVF) would have been less comfortable than Point 2, with 88 and 73 % of the people in the "hot" category (Fig. 5b). The PMV has low summer correlation values (Table 8).

In the case of the COMFA model during winter, the difference in the calculation of *S* (using SVF or Te) did not affect the amount of people that fell within each category. The model corroborates that Point 1 (lower SVF) has, as it had, lower solar irradiance (Fig. 4b). Both calculation methods have low correlation values and predictive ability in winter (Table 7). However, in summer, differences are observed between the two calculation methods.

The summer *S* value, obtained using the street's SVF and horizontal solar irradiance (obtained from a nearby weather station) is the most closely correlated with the subjective reports. At Point 1, the greatest difference between the two approaches is of 41 % in the "slightly warm" category. At Point 2, the COMFA with SVF underestimates the number of people who feel "hot" (10 % fewer; see Fig. 5b). The COMFA-SVF is the index with the best predictive ability of almost 48 % (Table 8). This might be explained by the fact that it includes key parameters for outdoor thermal comfort. This index (calculated with SVF) is the only one that considers the attenuation of solar irradiance from the trees.

It is important to mention that the *S* energy balance of the COMFA model, based on the "Littleman" temperature (T_e), is the only index that predicted that most people would not feel discomfort in summer: 59 % at Point 1 and 51 % at Point 2. It even predicted that Point 2 (higher SVF) was less hot than Point 1, with 24 and 11 % in the "slightly warm" category (Fig. 5b). The difference with the SVF calculation (and the rest of the models) suggests that the temperature of the "Littleman" does not adequately represent solar irradiance. The values of correlations and predictive ability are low in this season (Table 8).

For the PET index, which has nine categories, it can be observed that both monitoring points present differences in winter. As Fig. 4b shows, at Point 1, most people (44 %) were "very cold," a few "cold" (9 %), and some "cool" (30 %). At Point 2, some people (20 %) were "very cold," some "cold" (30 %), and most "cool" (46 %). For the summer, this index presents similar results at both monitoring points. The major difference of 23 % is in the category "very hot" (Fig. 5b). The only notable correlation is with the model calculation (0.73 %) in winter (Tables 7 and 8).

6 Selection of a predictive model of thermal comfort for the design of outdoor spaces in arid cities

The selection was made considering the comparative results of the indices and subjective reports, taking into account the possibilities offered by each. It is important to observe that all predictive indices have certain limitation due to the nature of human beings and the combined effects of atmospheric variables, which vary widely in time and space. Likewise, all the predictive models show a low predictive ability, and it is thus recommended to calibrate ranges of subjective answers in future research, in order to obtain a better description of comfort levels. However, if only the summer is considered (which is the season with the most rigorous conditions), then predictive ability becomes interesting. Therefore, model selection was done just for this season.

In practice, the selection of the model used to determine comfort is conditioned by one's objective. When the aim is to diagnose of the degree and frequency when a space is comfortable or uncomfortable, the inductive methods with fewer variables are adequate. Particularly in arid regions, THI is suggested for evaluating the comfort of streets. THI is relatively simple with a scale of seven categories, which, according to the results, seems adequate to describe outdoor spaces in MMA. This index has a 43 % predictive ability and can perceive differences between spaces with different characteristics such as the sky view factor, and it is useful both for

summer and winter, considering the standardization of sensation categories.

When the goal is to urban design strategies that maximize habitability, it is necessary to turn to the deductive methods. The use of the COMFA with SVF is suggested for arid cities, since it makes a more adequate differentiation of the monitoring points, has a higher correlation with subjective categories, and shows the highest predictive ability (48 %). Moreover, its equation allows for a more accurate evaluation of the impact of the interrelationships between climatic, morphological, and vegetation variables on the human body. Therefore, it is possible to detect heat transfer mechanisms, over which urban design has more impact, and thus can be optimized. The *S* balance adequately follows the prediction of thermal comfort in summer.

It is important to mention that the degree of accuracy of the methods for determining thermal comfort in MMA is influenced mainly by the quantification of solar irradiance in a given space, and by the radiation mechanisms associated with this energy flux. In that sense, intense vegetation of this city is a key factor influencing outdoor thermal comfort.

7 Conclusions

A comparative study of six thermal comfort models has been carried out in order to identify which of them can be used to adequately estimate and predict thermal comfort in tree-covered outdoor spaces in MMA, an intensely forested and open city in an arid region. From the methodological point of view, it is important to note that the study of thermal comfort in MMA differs greatly from other regions, since the city is located in an arid zone with an extensive urban forest and has large daily and seasonal thermal amplitudes. Hence, there is strong variability during winter and summer. This situation is very different than in subtropical climates with lower temperature variability, which makes it difficult to apply a single comfort index in all places. It is important to note that all models have certain limitations, due to the nature of human beings and the combined effects of atmospheric variables, which vary widely in time and space. This is shown by the predictive models' low percentages of predictive ability (lower than 25 %).

Despite this low indicator, some recommendations on the use of the indices for arid regions can be given, as per the research goals: (a) diagnose the degree and frequency of when a space is comfortable or not, and (b) influence urban design strategies whose goal is to maximize habitability in outdoor spaces. In the first case, less complex inductive methods with fewer variables are adequate. In particular, THI is suggested to evaluate comfort on the streets. In the second case, it is necessary to resort to deductive methods. The COMFA model with SVF is suggested.

On the other hand, subjective reports reveal that during winter, between 47 and 63 % of people expressed that felt neither cold nor hot, in other words, "neutral". There is a high contrast between the subjective answers and the results provided by the different indices of thermal comfort during the winter. These indices overestimate the degree of thermal discomfort with respect to reported sensations. In the summer, people tended to feel further from the neutral values than in winter: 77–82 % of the people said they felt some state of heat discomfort. The indices predicted a lower percentage of people (close to 0 %) in the "neutral" category than the reported "neutral" sensations (close to 20 %), which means that these indices underestimate the real level of comfort of the inhabitants of MMA in the summer.

In conclusion, the comparison of the models and the subjective reports shows a great deviation between the modeled predictions and people's perceptions, mainly in the winter. Hence, it can be inferred that the inhabitants of MMA are more adapted to winter than summer conditions. These results signal the need to develop local models to evaluate perceived thermal comfort more adequately. This type of tool is very useful in the design and evaluation of the thermal conditions in outdoor spaces, based not only to climatic criteria but also subjective sensations.

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