Building and Environment 85 (2015) 40–51

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Adaptive model for outdoor thermal comfort assessment in an Oasis city of arid climate

María Angélica Ruiz*, Erica N. Correa

CONICET – CCT Mendoza – Instituto de Ciencias Humanas, Sociales y Ambientales (INCIHUSA), Laboratorio de Ambiente Humano y Vivenda (LAHV), Av. Ruiz Leal s/n, Mendoza 5501, Argentina

A R T I C L E I N F O

Article history:
Received 12 September 2014
Received in revised form
14 November 2014
Accepted 17 November 2014
Available online 26 November 2014

Keywords:
Outdoor thermal comfort
Arid climate
Adaptive model
IZA
Predictive ability
Oasis city

A B S T R A C T

One of the determining factors for the use of outdoor spaces is the experienced thermal comfort by people. There is a wide range of thermal indices. However, previous studies in Mendoza Metropolitan Area, Argentina, revealed that the predictive ability from six thermal comfort indices of international spread is less than 25%. This high contrast reveals the need for proposing an adaptive model to predict the thermal comfort conditions of the adapted population to this "oasis city" of arid climate. For this purpose, monitoring of microclimatic parameters and field surveys about the perception of the people on a pedestrian street were carried out in both winter and summer. Fourteen Multiple Linear Regressions were performed and the Akaike's information criterion was used to the model selection. As a result, a new model has been developed: the "Thermal comfort Index for cities of Arid Zones (IZA)". The formula considers air temperature, relative humidity and wind speed, all significant, independent each other and readily available variables. We found that the IZA's predictive ability is 73%, demonstrating the efficiency of the proposed model. Designers and urban planners may use the IZA as a simple and useful tool to improve the design of outdoor spaces.

1. Introduction

The study on outdoor comfort could be used to support design decision of outdoor public spaces. Extending the use of the spaces through a good design practice has the potential of increasing outdoor activity, leading to increases in commercial revenue, property values, and opportunities for social interactions. In addition, a good outdoor microclimatic condition could improve the indoor comfort level and thus reduce energy consumption [1–5].

The thermal quality of the outdoor environment varies significantly from the typical controlled interior thermal environment. Outdoor environment have greater fluctuations in temperature, humidity, air movement, radiant heat, solar radiation. Moreover, the complexity of the outdoor environment influences the variety of these parameters. Humans feel comfortable in a wider range of thermal conditions when inhabiting exterior environments because they feel that do not have control over the factors that determine the thermal qualities of the space [6–9].

It is recognized that the thermal comfort is not defined only by the environmental parameters. Human psychology also has a strong influence in the perception of comfort. Therefore, it is important to include psychological adaptation parameters, namely naturalness, expectations, experience (short/long-term), time of exposure, perceived control, and environmental stimulation in order to suitable prediction of outdoor thermal comfort [10–12].

In the context of this research, outdoor thermal conditions have been assessed through field surveys in the Mendoza city, Argentina [13–15]. People's thermal perception has been evaluated on a 5-point scale, varying from "very cold" to "very hot", and has been defined as the Actual Sensation Vote (ASV) by Nikolopoulou et al. [16,17]. The subjective data collected from the interviews was compared with six thermal comfort models of broad international spread: the Temperature-Humidity Index (THI), Vinje's Index (PE), the Thermal Sensation (TS), the Predicted Mean Vote (PMV), the energy balance *S* from COMFA model and the Physiological Equivalent Temperature (PET) [18–23]. These models were selected because they are widely used and have different levels of complexity. Although we are aware that some recently developed indices have not been considered, each of selected ones uses variables and approaches relevant to this field research. The six indices were calculated by taking into account the environmental parameters recorded

* Corresponding author. Tel.: +54 261 5244310; fax: +54 261 5244001.
E-mail address: aruiz@mendoza-conicet.gob.ar (M.A. Ruiz).

http://dx.doi.org/10.1016/j.buildenv.2014.11.018
0360-1323/© 2014 Elsevier Ltd. All rights reserved.

for the duration of the interview, clothing levels and metabolic rate, for each interviewee. Results of this previous work revealed that there is a high contrast between subjective responses and the results produced by the different thermal comfort indices in both winter and summer. In fact, all models tested had very low percentages of predictive ability (under 25%). These results point to the need for a local model to properly assess the thermal comfort perceived by the inhabitants of the study city.

Therefore, this research focuses on the relationship between urban microclimatic variables and thermal perception. The hypothesis is that the prediction of thermal comfort in outdoor spaces requires a subjective approach for a given population adapted to certain climatic and cultural conditions. The goal is to propose an adaptive model or an empirical index to quantify the correlations between urban microclimatic variables and subjective variables (thermal perception). Although such empirical indices may be restricted to the geographical area or climate type, where the field survey was conducted, the advantage is its simplicity since does not require an iterative calculation. Likewise, the new model aims to predict the thermal comfort conditions of a population adapted to a given climatic condition, in this specific case, the Mendoza Metropolitan Area, Argentina, an oasis city in an arid area.

This new index is intended as a useful tool to assess the thermal behavior of outdoor spaces not only according to climatic criteria, but also to the subjective characteristics of users.

2. Study city

The research was conducted in the Mendoza Metropolitan Area (MMA) in central-western Argentina (32°40′S, 68°51′W, 750 m above sea level). It is the fifth largest city in the country with 1,055,679 inhabitants and 168 km^2 [24].

According to the Köppen-Greiger climate classification is an arid city: BWh or BWk depending on the isotherm used [25]. It is characterized by cold winters (average temperature in July: 7.3 °C) and hot summers (average temperature in January: 24.9 °C), with significant daily and seasonal thermal amplitudes. Winds are moderate and infrequent (average speed: 11 Km/h), the amount and intensity of solar radiation is high (percent of possible sunshine: 63%) and the average annual rainfall is 198 mm, with a concentration of 76% between October and March [26].

Currently it is estimated that approximately one third of the world population lives in extremely arid, arid or semi-arid regions [28]. Cities located in these areas display a compact urban model characterized by narrow streets and buildings with interlaced small-sized backyards. Created shades reduce the sun exposure in warmer seasons and, consequently, the heat accumulation on heavy material surfaces with high thermal admittance.

Although, MMA is located in a semi-arid region, it does not follow the aforementioned compact urban model. Their urban model is defined by its wide and tree-lined streets that form green tunnels (Fig. 1). The checkered frame contains the buildings while the main strategy for minimizing the sun exposure is the vegetal frame [29].

The forest matrix of Mendoza is accompanied by a system of irrigation canals formed by ditches [30]. The development of this matrix has allowed ‘green tunnels’ which give the feature of a real forest within the city. These qualities have been recognized locally and internationally and have earned the rating of the city as “oasis city” [31–33].

However, the intense forestation of urban canyons has been a decrease of available sky view factor (SVF) and increased roughness in the metropolitan area. Added to this, climatic characteristics (low frequency and intensity of winds and predominance of clear days) decrease the chances of passive cooling of the city by convection and radiation. Consequently the urban heat island reaches 10 °C, resulting in an increase of the needs of cooling [34]. The urban temperature increase has a direct effect on environmental pollution, energy consumption and thermal comfort — particularly in summer — [35–37]. Correa et al. [38] presents the geographical distribution of heating and cooling degree-days in Mendoza's Metropolitan Area taking into account the influence of urban heat island's intensity over the heating and cooling energy requirements in the city. The value of heating degree day (HDD) and cooling degree day (CDD) has been calculated from temperature data recorded at 16 fixed weather stations installed within MMA, measuring temperature and humidity in the urban canyons during a full yearly cycle. The calculation is performed using the Erbs's method and the interpolated data for the studied metropolitan area are mapped using GIS software. The results obtained have been compared with those data computations coming from nearest weather station, indicating that there is an under-estimation of CDD for the city downtown of approximately 20% respect to the value obtained from the nearest weather station, and in the case of HDD there is an over-estimation close to 50%.

3. Methodology

A broad and detailed description of the methodology used in this paper can be seen in Ruiz & Correa [39]. Nonetheless, here it will describe the following items: (a) the monitoring points, (b) the climatic data methodology, (c) the survey interviews methodology and (d) the statistical analysis and model development.

3.1. Monitoring points

The field study was developed in a central pedestrian street with large amounts of people. The place has shops, restaurants, shading

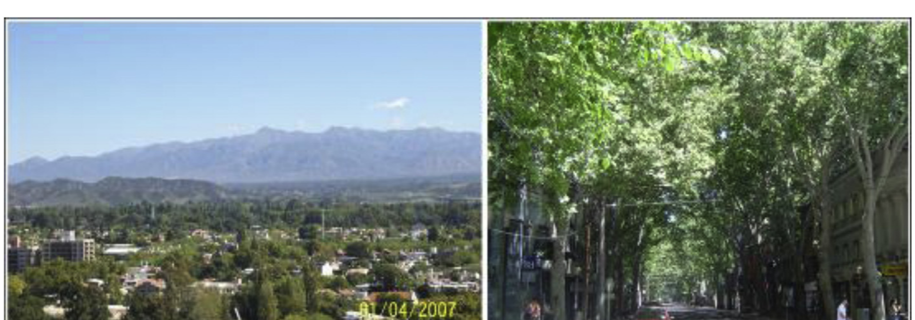

Fig. 1. Mendoza Metropolitan Area. Adapted from Martinez [27].

trees in alignment and seating. The local climate zone is LCZ 2Ab according to Stewart & Oke [40]. Two sites or monitoring points were selected: one in the center of the block (Point 1) and the other in the western end of it (Point 2). The width of the street is 30 m and the surrounded buildings are about 25 m of height. The criteria for selection of sites were its features in relation to solar radiation and wind access, so that the Point 1 is closed and the Point 2 is more open. Figs. 2 and 3 show the hemispherical views of each monitoring point, both summer and winter and a layout to the field study location.

Subjective questionnaires and microclimatic measurements were carried out in winter 2010 (22, 26 and 27 July) from 9:00 to 17:00 and in summer 2011 (19, 20 and 21 December) from 9:00 to 20:00. Fig. 4 shows images of the field study.

The nearest meteorological weather station to Mendoza Metropolitan Area is 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. Table 1 shows data from this meteorological weather station during measurements days.

3.2. Climatic data methodology

Monitoring climatic variables was according to ISO 7726 [41]. We used two mobile weather stations HOBO®, model H21-001, equipped with temperature and relative humidity sensor S-THB-M002, wind speed sensor S-WSA-M003, wind direction sensor S-WDA-M003, silicon pyranometer S-LIB-M003 and barometric pressure sensor S-BPA-CM10, located at 1.50 m height. The operating range is between −20 °C and +50 °C, and the sensors were set to record the conditions of the urban canyon every 5 min.

In addition, a globe thermometer for evaluation of mean radiant temperature was assembled. It consists of a matte black painted sphere according to the methodology of black globe of Moore [42] validated in the study city by Mercado et al. [43]. Within the sphere a data logger HOBO H12-003 with thermocouple type *T* copper-constantan was placed. To calculate the mean radiant temperature is performed a balance of thermal exchanges between the globe and the environment according to the formula from ASHRAE [44].

Moreover, vertical and horizontal surface temperatures were recorded every 15 min by two infrared thermometers FLUKE 66.

Fig. 5 shows mean microclimatic measurements in terms of seasonal and time.

3.3. Survey interviews methodology

While microclimate monitoring was carried out, people were also studied in their natural environment through observations and structured interviews. Personal information was taken from answers to a thermal comfort questionnaire, designed from the

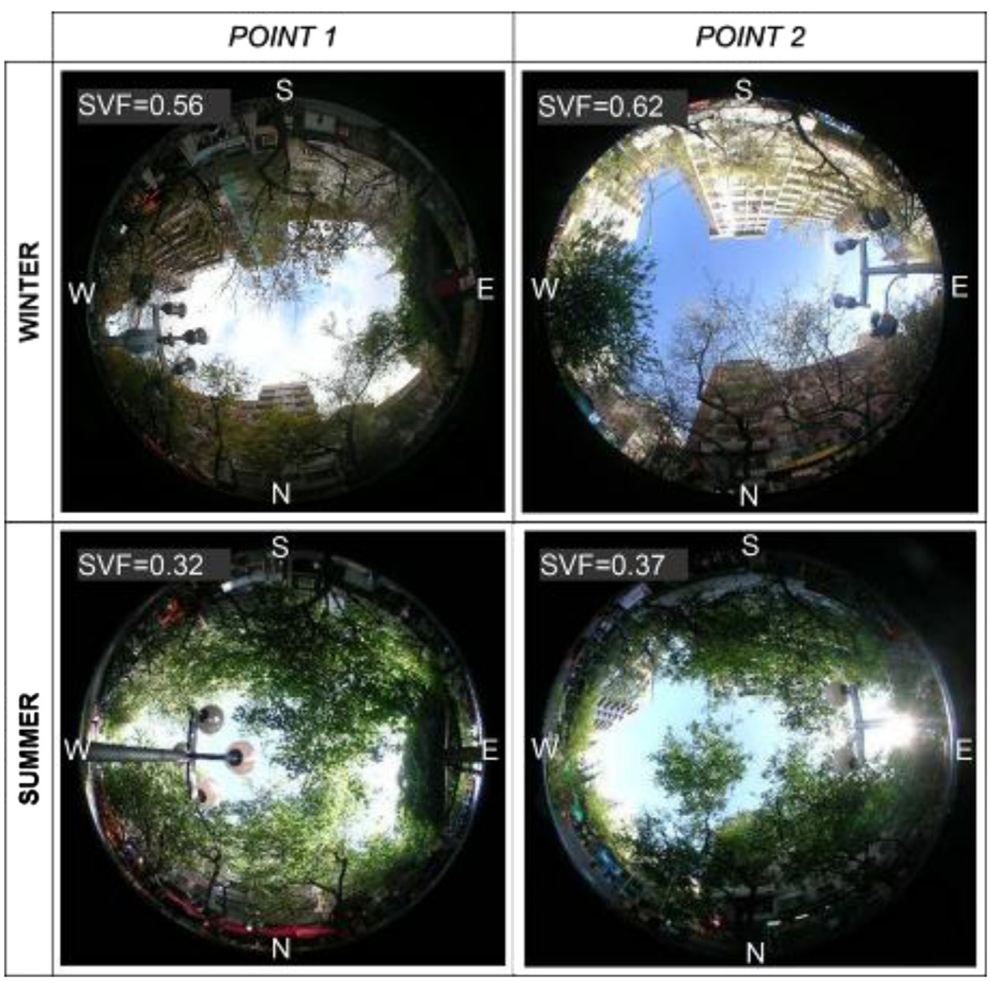

Fig. 2. Hemispherical views of each monitoring point in both of the seasons studied.

Fig. 3. Features of field study location.

principles established by the works of Nikolopoulou et al. [45], Kántor et al. [46], and Monteiro [47].

The first part of the questionnaire consists of individual issues related to sex, age, clothing, activity done before the interview and place of origin (to account for the acclimatization factor). The second part deals with subjective issues related to thermal perception and preference to solar radiation, wind and humidity. An image of summer questionnaire is found in Fig. 6.

In the present paper, we only analyze results concerning thermal perception (perceptual scale) through the question: “How do you feel at this exact moment?” We used a symmetrical 5-degree two-pole scale, which has been defined as the Actual Sensation Vote or ASV by Nikolopoulou et al. [45].

3.4. Statistical analysis and model development

The sample size may be estimated from population size, margin of error, confidence level and response distribution. Counting a population of approximately 1,000,000 inhabitants (MMA), with an error margin of 5%, trust level of 95% and a response distribution of 33% (comfort, discomfort caused by cold, or discomfort caused by heat), a minimum of 340 interviewees is required. For large populations, acceptable sample sizes range between 400 and 500 individuals [48]. The sample used in this work was made up of a total 622 questionnaires and it had a good balance of age (between 18 and 64), gender (61% men and 39% women) and distribution of the interviewees over time (57% in winter and 43% in summer).

The new proposed model is established through multiple linear regressions between Actual Sensation Vote (ASV) and some of the climatic variables. The proposal model is supported by complementary analytical studies of data collected empirically. The correlation of multiple variables is commonly done through linear regressions, as you can see in Givoni and Noguchi [49], Yin et al. [50] and Monteiro [47], which generates quite simple and easy to use equations.

Assuming the microclimatic variables are normally distributed in all seasons, within the range $[\mu - 2\ S\ E;\ \mu + 2\ S\ E]$ approximately

Fig. 4. Field study (a) Mobile Weather Station on the monitoring site; (b) Overview of urban canyon on which the field study was conducted; *y* (c) Interviewer and interviewee.

95.44% of the distribution is found.[1] In order to develop linear regressions, questionnaires carried out during one hour were considered to be under the same climatic situation, thus the 622 questionnaires were distributed into 84 different microclimatic situations. This procedure was made by two reasons. First, the microclimatic situations represent the number of environmental conditions actually monitored, and were applied in order to obtain representative values. The second reason is that the adoption of average values, referring to all questionnaires, facilitates analysis and improves the correlation (R^2).

A total of fourteen linear regressions were performed and the Akaike's information criterion or AIC [51] was used to select the model for the comfort evaluation of “oasis cities” embedded in arid areas. The model where AIC is minimized is selected as the best for the empirical data at hand. This concept is simple, convincing, and is based on deep theoretical foundations.

The AIC is not a test in any sense: no single hypothesis is made to be the null, no arbitrary a level is set, and no notion of significance is needed. Instead, there is the concept of a best inference [52]. In this method, inference may be based on the entire set of models (multi-model inference). Such inferences could be made if a parameter is in common over all models. This approach has the advantage that the model-averaged estimator often has better precision and reduced bias compared to the estimator of that parameter from only the selected best model [53,54].

4. Results

4.1. Correlations between ASV and microclimatic variables

Linear relationships between Actual Sensation Vote or ASV and microclimatic variables are considered. Fig. 7 shows the scatter plots and annual Pearson coefficients for each pair of variables.

The Pearson correlation coefficient *r* is a measure of the linear relationship between two random variables quantitative. It is independent of the scale of measurement of the variables and can take values between −1 and 1. A value of zero implies that no linear association exists and 1 means perfect association: if it is positive, direct association and, if it is negative, inverse association.

The highest coefficient is for the air temperature, it means that there is a positive linear relationship between variables, as well as happens with surface temperature and the globe temperature.

Solar radiation has a not very high significant correlation, while the wind speed does not present a significant linear correlation

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

Table 1
Data from the nearest meteorological weather station during measurement days.

	Air temperature (°C)		Relative humidity (%)		Wind speed (m/s)		Solar radiation (W/m^2)	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Minimum	−1.0	24.0	22.0	15.0	0.00	0.00	0	0
Media	6.9	29.6	45.4	26.4	1.61	2.84	155	339
Maximum	16.0	35.0	65.0	69.0	6.69	6.17	656	947

with the ASV. In large part the latter is explained by the fact that the air velocity varies in different environmental conditions, both cool and heat. Moreover, in cases of extreme heat, where the air temperature is higher than the exposed surface skin or clothing, increased air velocity causes heat gain by convection.

The correlation with absolute humidity is high and positive. In the study city winters are dry and summers are wetter, so it is expected that people feel hotter with higher values of water vapor per kilogram of air. For the relative humidity, the coefficient is high and negative. Direct consideration of this information may result in an erroneous interpretation. For instance that higher relative humidity leads to more comfortable perceptions in summer, or that higher absolute humidity leads to more comfortable perceptions in winter. It may have resulted from the particular combinations of solar radiation and humidity in the study city. When the humidity is low, the solar radiation is high and the subjects felt warm mainly because of solar radiation. Similar results were found in an experimental study conducted in Japan in 1994–1995 by Givoni et al. [2].

Moreover, when it is necessary to interpret the results, the annual Pearson coefficients might be confusing. Here, this occurs in the case of relative and absolute humidity.

When the seasonal analysis is made, the statistical results show that in summer, relative and absolute humidity have positive coefficients. This means that higher humidity generates greater ASV and as a consequence less comfort, as we expect. In winter, in contrast, relative humidity has a negative coefficient (although with a high *p*-value greater than 0.05). This may mean, higher relative humidity produces lower ASV, generating less comfort, or that the linear relationship between relative humidity and ASV is not very strong and it must not be take into account.

Other hand, the absolute humidity coefficient is positive (and significant *p-value*), which could be interpreted as that higher absolute humidity produces higher ASV and therefore more comfort. However, this statistical result masked the true rate of change of the ASV, since the response of the people is more associated with the air temperature variation that with the

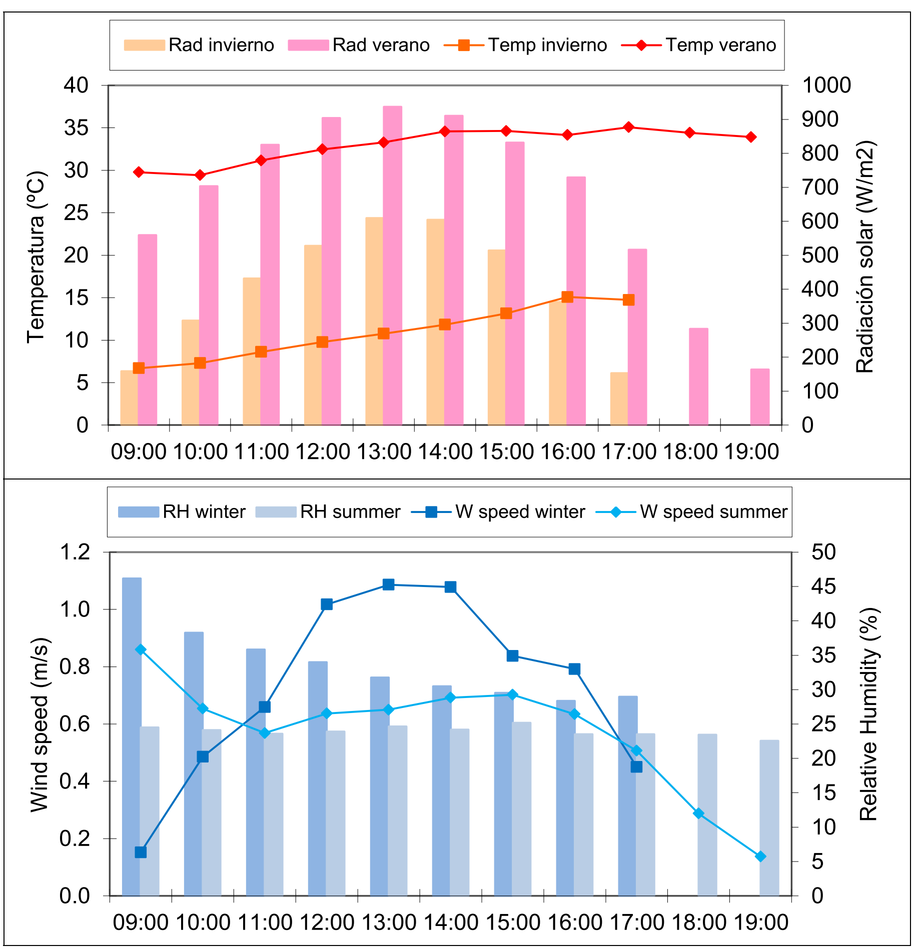

Fig. 5. Microclimatic measurements in terms of seasonal and time.

Date:	Interviewer:	Questionnaire N°:	Page N° 1
Reference Weather Station: 1 - 2		Reference hour:	

A. GENERAL DATA

Please tick where appropriate

1 - Age group:
☐ < 12 years ☐ 12-18 years ☐ 18-24 years ☐ 25-34 years
☐ 35-44 years ☐ 45-54 years ☐ 55-64 years ☐ > 65 years

2 - Gender:
☐ Male ☐ Female

3 - Are you consuming or have consumed some kind of food and/or drink in the last half hour?
☐ Cold drink ☐ Hot drink ☐ Food ☐ Cigarette

4 - Clothes:

☐	0.02	bare foot shoe	☐	0.15	skirt
☐	0.04	covered foot shoe	☐	0.20	dress
☐	0.05	tights/socks	☐	0.09	tank/T-shirt
☐	0.03	lycra tights	☐	0.12	long-sleeved T-shirt
			☐	0.15	short sleeve shirt
☐	0.06	shorts/Bermuda shorts	☐	0.20	long-sleeved shirt
☐	0.20	light long pants			
☐	0.25	thick long pants	☐	0.25	light jacket
			☐		Other: ....

5 - During the last half hour, what was your main activity?
☐ Sleeping ☐ Sitting ☐ Standing ☐ Paperwork ☐ Heavy Duty ☐ Walking slowly ☐ Walking quickly ☐ Other ....

6 - Are you local resident of MMA?
☐ Yes ☐ No. Where are you from? ....

7 - Why are you in the surroundings in this moment?
☐ Stagecoach ☐ Recreation ☐ Resident ☐ Work ☐ Tourist ☐ Other.......................

8 - How often do you use this space?
☐ Several times a day ☐ Once a day ☐ Several times a week ☐ Once a week ☐ Once a month ☐ Tourist ☐ Other ....

9 - What is your occupation?
☐ Student ☐ Employee ☐ Freelance ☐ Housewife ☐ Retired ☐ Unemployed

10 - What is your educational level?
☐ Primary ☐ Secondary ☐ Tertiary/University or higher

11 - What do you like more: the city or the countryside?
☐ I prefer the city ☐ I do not care. I like both ☐ I prefer a natural space

12 - Is there anything you do not like in this zone?
☐ Street design ☐ Street trees design ☐ Architectural design ☐ Air quality ☐ Noise level ☐ Other ....

B. CHARACTERIZATION OF SPACE

Please tick where appropriate

13 - At the moment, do you find it:
☐ -2. Very cold ☐ -1. Cool ☐ 0. Neither cool nor warm ☐ +1. Warm ☐ +2. Very hot

14 - What do you think of the sun at this moment?
☐ -1. You'd prefer more ☐ 0. OK ☐ +1. too much sun

15 - What do you think of the wind at this moment?
☐ -1. You'd prefer more ☐ 0. OK ☐ +1. too much wind

16 - What do you think of the humidity at this moment?
☐ -1. Dry ☐ 0. OK ☐ +1. Damp

Fig. 6. Summer questionnaire.

absolute humidity variation, which is low and almost constant in all arid climates, particularly in the dry season (winter) in MMA. For the days assessed in this research, the air temperature variation in winter was 13 °C while absolute humidity variation was 1.68 g/kg.

It is found that surface temperatures (horizontal and vertical surfaces) and globe temperature have high and positive linear correlations (greater than 0.87) with respect to the Actual Sensation Vote. In contrast, the mean radiant temperature has no significant linear relationship in the study area because the formula.

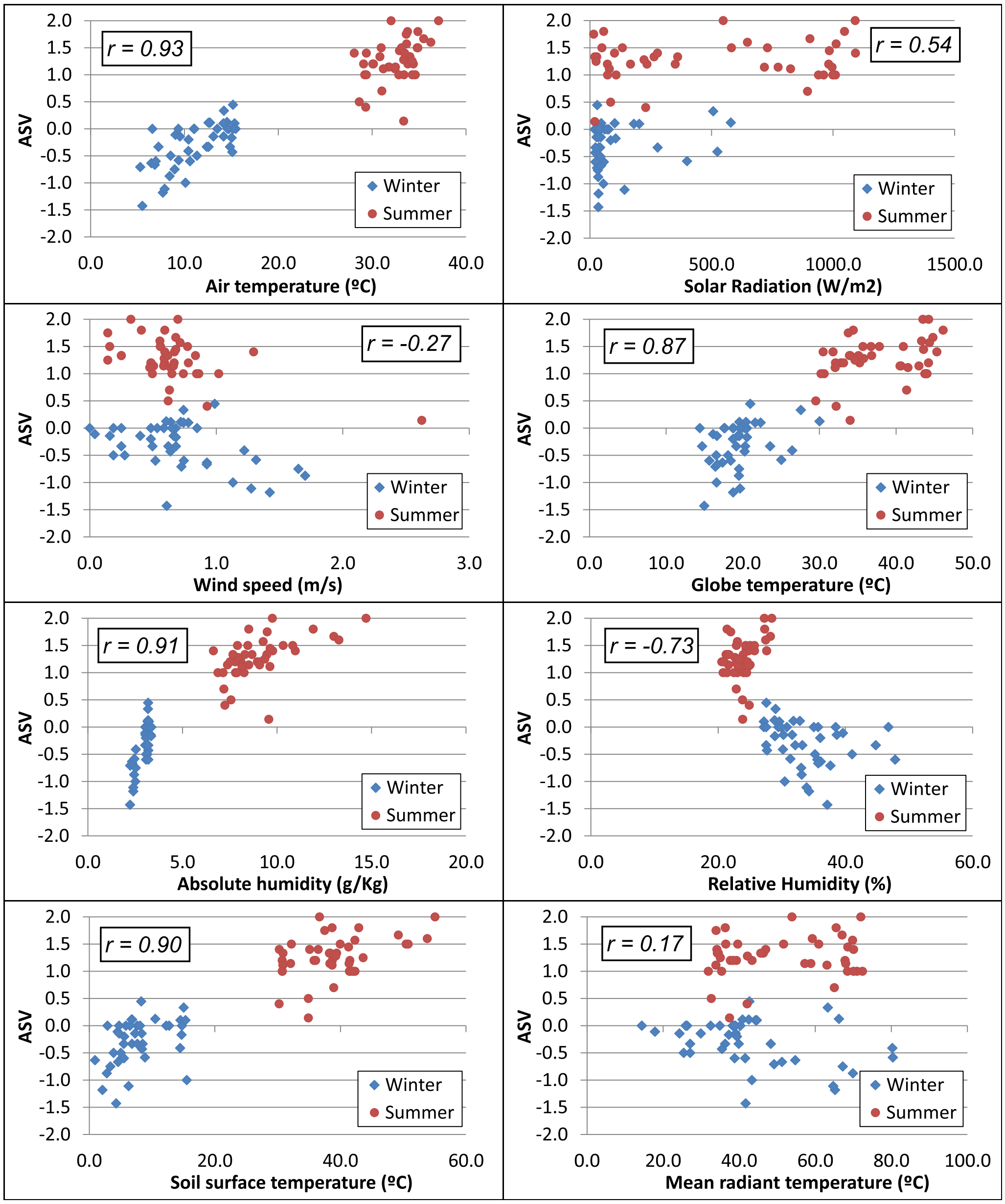

Fig. 7. Scatter plots and Pearson coefficients (r) between Actual Sensation Vote (ASV) and microclimatic variables.

The mean radiant temperature depends largely on wind speed, which is highly variable in both summer and winter.

4.2. Proposed adapted model

In order to have a tool for evaluating the thermal behavior of outdoor spaces according to climatic and subjective criteria has been developed a new model: the "Thermal comfort Index for cities of Arid Zones (IZA, for its acronym in Spanish)". Such is based on linear regression between the ASV and urban microclimate variables. The formula considers the three microclimatic variables commonly used in studies of thermal comfort and allows, within given limits, predicting thermal perceptions for a population adapted to the microclimate of the study city (Equation (1)).

$$\text{IZA} = -0.9796 + 0.0621 \cdot \text{Ta} - 0.3257 \cdot v + 0.0079 \cdot \text{HR} \quad (1)$$

where:

Ta: air temperature, in °C.
v: wind speed, in m/s.
HR: relative humidity, in %.

It sought to find the variables that were significant in the model, independent each other and readily available.

While it is known that relative humidity is affected by air temperature, in the study city winters are dry and summers are wetter, so that in this case there is higher correlation between air temperature and absolute humidity than between air temperature and relative humidity. It is important to include the humidity in the model, thus it was decided to include the variable which has less correlation with the temperature. Values of Variance Inflation Factor (shown below) confirm this decision.

With respect to radiative phenomenon, it is noteworthy that solar radiation or mean radiant temperature are not included in the model for arid areas where it is an abundant resource. This is because in the model selection process, those models that include any of these variables had low values of the coefficient of determination R^2, so they were relegated according Akaike's criterion.

This model is the result of the multi-model inference from a set of confidence with a cumulative Akaike weight of 0.8004. This means that the approximate probability that this is the best model of the set of models considered is around 80%.

Although the Akaike Information Criterion does not provide R^2 and p-value, weighted values of these parameters are reported as they are commonly used in scientific research. The coefficient of determination R^2 adjusted and weighted is high (0.7196). The weighted standard error is quite reasonable (0.2254), given the values assumed for the thermal perception: −2 to +2. When considering the value that has been assumed for p ($p < 0.05$), the value found (low to 2.2×10^{-16}) indicates that the variables contribute effectively to the prediction of the dependent variable.

The values of the constant and coefficients for each variable in the equation are shown in Table 2. The t-statistic proves the null hypothesis that the coefficient of the independent variable is zero, i.e., does not contribute to the prediction of the dependent variable. The value of t is the ratio of the regression coefficient and its standard error. The p-values determine statistical significance in a hypothesis test. The low p-values indicate the greater importance a given independent variable in predicting the dependent variable. In particular, all variables includes in the model are significant.

The variance inflation factor (VIF) indicates how much of the variation of a predictor variable is explained by the others. It is considered that a VIF higher than 5 is high, indicating that the variable will generate multicollinearity problems. In the new model, values of VIF are acceptable.

Finally, it is interesting to provide a scale of interpretation based on the average values of thermal perception. Hence, the interpretation scale associated to the IZA model is presented in Table 3.

Table 3
Scale of values and perceptions of the new thermal comfort model for arid zones.

Values of IZA	Perception
>1.5	Hot
0.5 to 1.5	Warm
−0.5 to 0.5	Neutral
−0.5 to −1.5	Cool
<−1.5	Cold

5. Discussion

The universal application of certain physiological models has been long debated. It is argued that the severe restrictions of environmental parameters in laboratory experiments are very different from those of the real spaces [55–57]. Even some of these indices have been developed for interior and then its use has transferred to outdoor spaces where microclimatic and individual variables oscillate in greater magnitude. Although some models have been developed based on experiences in outdoor spaces, they do not consider the climate of each city, and the adaptation of the local population to the same or cultural characteristics.

Moreover, Fanger and Toftum [58] state that a weakness of the adaptation models is that not include clothing or human activity that have a known impact on human heat balance and therefore on the thermal perception. They argue that while the adaptive model predicts quite well the thermal perception for buildings without air conditioning in hot regions of the world, the question remains how well it adapts to new types of spaces in the future in which the occupants may wear different clothes and change its pattern of activity.

Table 2
Weighted results to the constant and each variable in the proposed model.

	Coefficient	Standard error	t-statistic	p-value	VIF
Intercept	−0.9796	0.2278	−4.6490	0.0003	
Air temperature Ta	0.0621	0.0036	15.3418	1.60E-16	2.2368
Wind speed v	−0.3257	0.0660	−3.9583	7.44E-06	0.8689
Relative humidity HR	0.0079	0.0047	0.7960	0.0463	1.9152

According to the theory of heat balance at steady state, the human body is a passive recipient of thermal stimuli outdoors, instead of an active interaction with the person-environment system through multiple feedback loops [59]. It does not take into account changes in the human body, which play a key role in the determination of subjective thermal perception [60].

From the point of view of the principle of adaptation, Humphreys [61] points out the numerous strategies that people use to achieve thermal comfort. People are not inert receivers of the environment, but interact with them to optimize their conditions.

If a change such as to produce discomfort occurs, people react so they tend to restore their comfort [62]. Therefore self-regulation actions are performed. The human body responds to physiological adaptation when exposed to thermal environment. The thermoregulatory system of human body creates a heat balance within a wide range of environmental variables, and while this occurs, the thermal perception is expressed. Physiological models, such as the PMV [63] or the COMFA [64], are based on this theory. When the individual feels discomfort with the environment, tries to make adjustments to their behavior, including technological and environmental approaches to achieve their own thermal comfort.

Numerous researches [55,59] based on the thermal comfort in outdoor spaces show that the psychological self-regulation plays an important role in the determination of thermal perceptions of a human being. The study of thermal comfort in outdoor spaces particularly interests because in these ones the stimulation is continuous and variable and is difficult to have a high degree of control of the source of discomfort. Furthermore, the source of discomfort is not the only variable influencing physiological adaptation. It is also necessary to consider both aspects related to expectation and previous experiences as well as the configuration of the city.

From the analysis of this background, the authors propose a new empirical model of thermal comfort: the thermal comfort Index for cities of Arid Zone (IZA). This simple tool can be used to predict the thermal comfort conditions experienced by people of the city of study located in an arid and intensely vegetated context. Thus, urban planners have more elements to improve the design of outdoor spaces.

Then, three points are discussed: the implementation of the new IZA model, its comparison with the subjective responses and its comparison with the results of models developed in previous studies in other world cities.

5.1. Implementation of the new IZA model

It is noteworthy that the equation is derived from the data in certain environmental situations and use in other situations is subject to verification by correlation of results of possible extrapolations with the observed data. The limits observed in the survey of environmental and individual variables are presented in Table 4.

Table 4
Validity limits of microclimatic and individual variables.

	Winter		Summer	
Variables	Minimum	Maximum	Minimum	Maximum
Air temperature, °C	5.5	15.5	28.1	37.1
Relative humidity, %	27.2	47.8	20.6	28.4
Wind speed, m/s	0.0	1.3	0.1	2.6
Isolation value of clothing (clo)	0.8	1.3	0.3	0.5
Metabolic rate (met)	1.1	3.0	1.3	3.1

These limits attempt to give strength to the new model. Even though Eq. (1) does not include clothing or human activity, surveys have collected these data and are now set these limits that are representative of the habits and customs of the inhabitants of the MMA.

5.2. New IZA model and subjective answers

In order to evaluate the performance of the new proposed model, the comparison was done between the results obtained with the IZA and subjective throughout the year for the 84 responses microclimatic situations. It was found that the correlation with model parameter was 0.95 and the Pearson coefficient in relation to ranges was higher (0.90) than the six previously studied models. But the value that shows more convincingly the effectiveness of the proposed model is the predictive ability of 73%. This value highlights compared with percentages of predictive ability of all other assessed indices, which do not exceed 25% [13–15].

The results of this new model are also compared with those provided by the subjective responses from the 622 questionnaires, in both seasons and both monitoring points. The scatter plot can be seen in Fig. 8.

By and large, results corroborate what was stated in previous paragraph. The IZA significantly approaches the subjective responses of the interviewees. Winter results are found in the cool and neutral categories, and have less dispersion than the summer results. In the summer season, most of the results are found into warm category.

5.3. Comparison with results of other models

The results of this study and those obtained by Nikolopoulou et al. [16] and Monteiro [47], in seven European cities and in the city of Sao Paulo, Brazil are presented in Table 4. The parameter used is

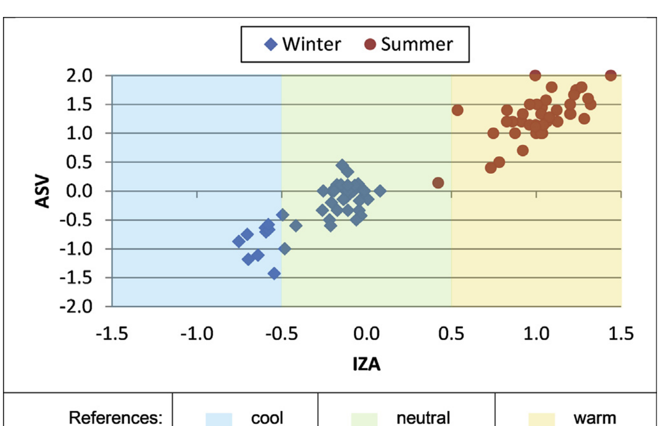

Fig. 8. Comparison between subjective responses and the new IZA model.

Table 5
Correlation of various models and their respective observed data. Ta: air temperature; Rad: solar radiation; *v*: wind speed; HR: relative humidity; Tmr: mean radiant temperature.

City	Model	R^2
Athens, Greece	$0.034\cdot Ta + 0.0001\cdot Rad - 0.086\cdot v - 0.001\cdot HR - 0.412$	0.27
Thessaloniki, Greece	$0.036\cdot Ta + 0.0013\cdot Rad - 0.038\cdot v + 0.011\cdot HR - 2.197$	0.51
Milan, Italy	$0.049\cdot Ta - 0.0002\cdot Rad + 0.006\cdot v + 0.002\cdot HR - 0.920$	0.44
Freiburg, Germany	$0.068\cdot Ta + 0.0006\cdot Rad - 0.107\cdot v - 0.002\cdot HR - 0.69$	0.68
Kassel, Germany	$0.043\cdot Ta + 0.0005\cdot Rad - 0.077\cdot v + 0.001\cdot HR - 0.876$	0.48
Cambridge, England	$0.113\cdot Ta + 0.0001\cdot Rad - 0.05\cdot v + 0.003\cdot HR - 1.74$	0.57
Sheffield, England	$0.07\cdot Ta + 0.0012\cdot Rad - 0.057\cdot v - 0.003\cdot HR - 0.855$	0.58
Sao Paulo, Brazil	$0.0698\cdot Ta + 0.0603\cdot Tmr - 0.306\cdot v - 2.858$	0.73
Mendoza, Argentina	$0.0621\cdot Ta - 0.3257\cdot v + 0.0079\cdot HR - 0.9796$	0.72

the coefficient of determination R^2 between the values given by each model and the observed data in each study city. The coefficient of determination of IZA model is the highest among the seven European models analyzed, and is very similar to Monteiro's model which was developed in a tropical city.

Regarding the sample sizes in European cities around 800–1900 questionnaires were applied in four seasons, while in Sao Paulo the study were 876 questionnaires during summer and winter and in the city of Mendoza were 622.

In this work we have followed the methodology of microclimatic situations according Monteiro, with in situ measurements of environmental variables. Therefore, it was expected that the coefficients of determination R^2 were similar in Mendoza and Sao Paulo. But there is a dissimilitude: Sao Paulo is a tropical city and Mendoza is in an arid area with a large seasonal variation. Furthermore, correlations presented by Nikolopoulou are based on data from the weather station so it is logical that their results less meaningful.

In Table 5 we can see that all models developed in Europe have the same variables: air temperature, solar radiation, wind speed and relative humidity. However the coefficients of some of the variables as solar radiation are very low, so the R^2 also are low.

It is noticeable that in a tropical city as Sao Paulo where the humidity is high during the all year, the model from Monteiro does not include this variable. It might be inferred that people has more sensibility to the variability of less prominent variables for characterize the local climate. Thus, the fact that the variables related to radiative exchanges are not meaningful in the perception of thermal comfort of the people in Mendoza could be explained by the high available solar radiation throughout the year.

6. Conclusions

This paper attempts to clarify part of the complexity of the issues related to the assessment of outdoors thermal comfort. Although the microclimatic conditions affect the use of outdoor spaces, a purely physiological approach is insufficient to characterize the habitability conditions in outdoor spaces. It emphasizes the need to investigate different ways to quantify outdoor comfort conditions.

Previous studies in the Metropolitan Area of Mendoza, oasis city in an arid area, demonstrated that none of the indices analyzed (THI, PE, TS, PMV, COMFA and PET) efficiently shows what the locals feel. Given these limitations, a new model was developed: the "Thermal comfort index for arid zones (IZA)". The formula considers the three microclimatic variables commonly used in studies of thermal comfort and allows, within given limits, predicting thermal perceptions for a population adapted to the microclimate of the city of study. A scale of interpretation based on the average values of thermal perception is provided.

This model is the result of the multi-model inference and the probability that this one is the best model of a set of confidence is around 80%.

In future studies, nonlinear regressions may provide more significant results according to the data type and the type of response variable. However, proposed IZA model has the great advantage over the models developed in other regions that has a high predictive ability of 73%. Besides, the new model has a good behavior against nine models of international literature.

The IZA will be useful to designers and urban planners, in order to estimate the degree of habitability of a public space. This is important as a careful design of the outdoor spaces could provide protection against the negative aspects and adequate exposure to the positive aspects of climate. As a consequence, the increase in the use of outdoor space throughout the year could improve business, tourism and recover depressed historical places.

Acknowledgments

The authors wish to thank Angela Di Blassi to provide assistance in statistical analysis.

This work was supported by the Agencia Nacional de Promoción Científica y Tecnológica (ANPCYT) [grant numbers PICT 2006- 2415, PICT 2011-0611]; and the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) [grant number PIP 2011-00640].

References

[1] Höppe P. Improving indoor thermal comfort by changing outdoor conditions. Energy Build 1991;15–16:743–7.
[2] Givoni B, Noguchi M, Saaroni H, Pochter O, Yaacov Y, Feller N, et al. Outdoor comfort research issues. Energy Build 2003;35:77–86. http://dx.doi.org/10.1016/S0378-7788(02)00082-8.
[3] Johansson E, Emmanuel R. The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka. Int J Biometeorol 2006;51(2):119–33.
[4] Thorsson S, Honjo T, Lindberg F, Eliasson I, En-Mi L. Thermal Comfort and outdoor activity in Japanese urban public places. Environ Behav 2007;39(5): 660–84.
[5] Djongyang N, Tchinda R, Njomo D. Thermal comfort: a review paper. Renew Sustain Energy Rev 2010;14(9):2626–40.
[6] Spagnolo J, de Dear R. A field study of thermal comfort and semi-outdoor environments in subtropical Sydney Australia. Build Environ 2003;38(7): 21–38. http://dx.doi.org/10.1016/S0360-1323(02)00209-3.
[7] Bouden C, Ghrab N. An adaptive thermal comfort model for the Tunisian context: a field study results. Energy Build 2005;37(9):952–63. http://dx.doi.org/10.1016/j.enbuild.2004.12.003.
[8] Andrade Henrique, Alcoforado Maria-João, Oliveira Sandra. Perception of temperature and wind by users of public outdoor spaces: relationships with weather parameters and personal characteristics. Int J Biometeorol 2011;55(5):665–80. http://dx.doi.org/10.1007/s00484-010-0379-0.
[9] Md Din Mohd Fadhil, Lee Yee Yong, Ponraj Mohanadoss, Ossen Dilshan Remaz, Iwao Kenzo, Chelliapan Shreeshivadasan. Thermal comfort of various building layouts with a proposed discomfort index range for tropical climate. J Therm Biol 2014;41:6–15. http://dx.doi.org/10.1016/j.jtherbio.2014.01.004.
[10] Nikolopoulou M, Steemers K. Thermal comfort and psychological adaptation as a guide for designing urban spaces. Energy Build 2003;35:95–101. http://dx.doi.org/10.1016/S0378-7788(02)00084-1.
[11] van Hoof Joost, Hensen Jan LM. Quantifying the relevance of adaptive thermal comfort models in moderate thermal climate zones. Build Environ 2007;42(1):156–70. http://dx.doi.org/10.1016/j.buildenv.2005.08.023.
[12] Abdel-Ghany AM, Al-Helal IM, Shady MR. Human Thermal Comfort and heat stress in an outdoor urban arid environment: a case study. Adv Meteorol 2013:1–7. http://dx.doi.org/10.1155/2013/693541.
[13] Ruiz MA, Correa EN. Confort térmico en espacios abiertos. Comparación de modelos y su aplicabilidad en ciudades de zonas áridas. Rev Averma – Av Energías Renov Medioambiente 2009;13(01):71–8.
[14] Ruiz MA, Correa EN. Índices deductivos de confort térmico y su adaptación para espacios abiertos vegetados en zonas áridas. Casos de estudio: Cañones urbanos forestados. Rev Averma – Av Energías Renov Medioambiente 2010;14(01):81–8.
[15] Ruiz MA. Efectos microclimáticos de la vegetación en ciudades de zonas áridas. Incidencia sobre los consumos energéticos y la calidad ambiental del hábitat [PhD Thesis]. Salta, Argentina: Universidad Nacional de Salta; 2013.
[16] Nikolopoulou M, Lykoudis S, Kikira M. Thermal Comfort models for open urban spaces. In: Nikolopoulou M, editor. Designing open spaces in the urban environment: a Bioclimatic approach. Athens. Centre for Renewable Energy Sources; 2004. p. 2–6. EESD, FP5.
[17] Pantavou K, Theoharatos G, Mavrakis A, Santamouris M. Evaluating thermal comfort conditions and health responses during an extremely hot summer in Athens. Build Environ 2011;46(2):339–44. http://dx.doi.org/10.1016/j.buildenv.2010.07.026.
[18] Emmanuel R. Thermal comfort implications of urbanization in a warm-humid city: the Colombo metropolitan region (CMR), Sri Lanka. Build Environ 2005;40:1591–601. http://dx.doi.org/10.1016/j.buildenv.2004.12.004.
[19] Kakon AN, Nobuo M, Kojima S, Yoko T. Assessment of thermal comfort in respect to building height in a high-density city in the tropics. Am J Eng Appl Sci 2010;3:545–51. http://dx.doi.org/10.3844/ajeassp.2010.545.551.
[20] Matzarakis A, Rutz F, Mayer H. Modelling radiation fluxes in simple and complex environments—application of the RayMan model. Int J Biometeorology 2007;51(4):323–34.
[21] Tseliou Areti, Tsiros Ioannis X, Lykoudis Spyros, Nikolopoulou Marialena. Technical note: an evaluation of three biometeorological indices for human thermal comfort in urban outdoor areas under real climatic conditions. Build Environ 2010;45(5):1346–52. http://dx.doi.org/10.1016/j.buildenv.2009.11.009.
[22] Krüger Eduardo, Drach Patricia, Emmanuel Rohinton, Corbella Oscar. Urban heat island and differences in outdoor comfort levels in Glasgow, UK. Theor Appl Climatol 2013;112(1/2):127–41. http://dx.doi.org/10.1007/s00704-012-0724-9.
[23] Hwang Reuy-Lung, Lin Tzu-Ping, Cheng Ming-Jen, Lo Jen-Hao. Adaptive comfort model for tree-shaded outdoors in Taiwan. Build Environ 2010;45(8): 1873–9. http://dx.doi.org/10.1016/j.buildenv.2010.02.021.
[24] Instituto Nacional de Estadística y Censos. Censo nacional de población, hogares y viviendas 2010: total del país, resultados provisionales. Buenos Aires: Instituto Nacional de Estadística y Censos; 2010. INDEC, http://www.censo2010.indec.gov.ar/.
[25] Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World map of the Köppen–Geiger climate classification updated. Meteorol Z 2006;15(3): 259–63. http://dx.doi.org/10.1127/0941-2948/2006/0130.
[26] González Loyarte MM, Menenti M, Diblasi MA. Mapa bioclimático para las travesías de Mendoza (Argentina) basado en la fenología foliar. Rev la Fac Ciencias Agrar 2009;41(1):105–22. http://bdigital.uncu.edu.ar/3121.
[27] Martinez CF. Incidencia del déficit hídrico en forestales de ciudades oasis: caso del Área Metropolitana de Mendoza, Argentina [PhD Thesis]. Mendoza, Argentina: Universidad Nacional de Cuyo; 2011.
[28] United Nations Convention to Combat Desertification – UNCCD. Desertification. A visual synthesis. Bonn: United Nations Convention to Combat Desertification (UNCCD) Secretariat; 2011. http://www.unccd.int.
[29] Correa EN, Ruiz MA, Cantón MA, Lesino G. Thermal comfort in forested urban canyons of low building density. An assessment for the city of Mendoza, Argentina. Build Environ 2012;58:219–30. http://dx.doi.org/10.1016/j.buildenv.2012.06.007.
[30] Ponte JR. Historia del regadío. Las acequias de Mendoza, Argentina. Scr Nova Rev Electrónica Geogr Ciencias Sociales 2006:X(218). http://www.ub.edu/geocrit/sn/sn-218-07.htm.
[31] Bórmida E. Mendoza, modelo de ciudad oasis. Rev Summa 1986;226:68–72. http://www.um.edu.ar.
[32] McPherson EG. Functions of buffer plantings in urban environments, agriculture. Ecosyst Environ 1988;22:281–98. http://dx.doi.org/10.1016/0167-8809(88)90026-6.
[33] Hong Bo, Lin Borong. Numerical studies of the outdoor wind environment and thermal comfort at pedestrian level in housing blocks with different building layout patterns and trees arrangement. Renew Energy – Int J 2015;73:18–27. http://dx.doi.org/10.1016/j.renene.2014.05.060.
[34] Correa EN. Isla de Calor Urbana. El Caso del Área Metropolitana de Mendoza [PhD Thesis]. Salta, Argentina: Universidad Nacional de Salta; 2006.
[35] Radhi Hassan, Sharples Stephen. Quantifying the domestic electricity consumption for air-conditioning due to urban heat islands in hot arid regions. Appl Energy 2013;112:371–80. http://dx.doi.org/10.1016/j.apenergy.2013.06.013.
[36] Santamouris M. On the energy impact of urban heat island and global warming on buildings. Energy & Build 2014;82:100–13. http://dx.doi.org/10.1016/j.enbuild.2014.07.022.
[37] Souza LCL, Postigo CP, Oliveira AP, Nakata CM. Urban heat islands and electrical energy consumption. Int J Sustain Energy 2009;28(1–3):113–21. http://dx.doi.org/10.1080/14786450802453249.
[38] Correa EN, de Rosa C, Lesino G. Urban heat island effect on heating and cooling degree days distribution in Mendoza's metropolitan area and environmental costs. EUROSUN. In: 1st international conference on solar heating, cooling and buildings. 7th–10th October. Lisbon. Portugal; 2008.
[39] Ruiz MA, Correa EN. Suitability of different comfort indices for the prediction of thermal conditions in forested open spaces in arid zone cities. Theor Appl Climatol 2014. http://dx.doi.org/10.1007/s00704-014-1279-8.
[40] Stewart ID, Oke TR. Local climate zones for urban temperature studies. Bull Amer Meteor Soc 2012;92:1879–900. http://dx.doi.org/10.1175/BAMS-D-11-00019.1.

[41] Standard 7726 ISO. Ergonomics of the thermal environment. Instruments of measuring physical quantities. International Organization for Standardization; 1998.
[42] Moore F. Test modules. In: Balcomb JD, editor. Passive solar buildings. Cambridge, MA: The MIT Press; 1992. p. 293–329.
[43] Mercado MV, Esteves A, Filippín C, Flores Larsen S. Sistema de calefacción radiante solar pasivo. Diseño, construcción de un prototipo y obtención de resultados. Energías Renov Medio Ambiente 2009;23:53–61.
[44] ASHRAE. ASHRAE standard 55: thermal environmental conditions for human occupancy. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers; 2004.
[45] Nikolopoulou M, Lykoudis S, Kikira M. Thermal comfort in urban spaces: field studies in Greece. In: Proceedings of the fifth international conference on urban climate. Lodz, Poland: IAUC-WMO; 2003.
[46] Kántor N, Unger J, Gulyás A. Human bioclimatological evaluation with objective and subjective approaches on the thermal conditions of a square in the centre of Szeged. Acta Climatol Chorologica 2007;40–41:47–58.
[47] Monteiro L. Modelos preditivos de conforto Térmico: quantificação de relações entre variáveis microclimáticas e de sensação térmica para avaliação e projeto de espaços abertos [PhD Thesis]. São Paulo: Universidade de São Paulo, Brasil; 2008.
[48] Johansson E, Thorsson S, Emmanuel R, Krüger E. Instruments and methods in outdoor thermal comfort studies – the need for standardization. Urban Clim 2014. http://dx.doi.org/10.1016/j.uclim.2013.12.002.
[49] Givoni B, Noguchi M. Issues and problems in outdoor comfort research. In: Proceedings international PLEA 2000 conference. Cambridge: Passive & Low Energy Architecture; 2000.
[50] Yin JiFu, Zheng YouFei, Wu RongJun, Tan JianGuo, Ye DianXiu, Wang Wei. An analysis of influential factors on outdoor thermal comfort in summer. Int J Biometeorol 2012;56(5):941–8. http://dx.doi.org/10.1007/s00484-011-0503-9.
[51] Akaike H. Information theory as an extension of the maximum likelihood principle. In: Petrov BN, Csaki F, editors. Budapest: second international symposium on information theory, Akademiai Kiado; 1973. p. 267–81.
[52] Anderson DR, Burnham KP, Thompson WL. Null hypothesis testing: problems, prevalence, and an alternative. J Wildl Manag 2000;64:912–23. http://dx.doi.org/10.2307/3803199.
[53] Henderson AR. Chemistry with confidence: should clinical chemistry require confidence intervals for analytical and other data? Clin Chem 1993;39:929–35.
[54] Goodman SN, Berlin JA. The use of predicted confidence intervals when planning experiments and the misuse of power when interpreting results. Ann Intern Med 1994;121:200–6.
[55] Schweiker Marcel, Brasche Sabine, Bischof Wolfgang, Hawighorst Maren, Wagner Andreas. Explaining the individual processes leading to adaptive comfort: exploring physiological, behavioural and psychological reactions to thermal stimuli. J Build Phys 2013;36(4):438–63. http://dx.doi.org/10.1177/1744259112473945.
[56] Knez I, Thorsson S, Eliasson I, Lindberg F. Psychological mechanisms in outdoor place and weather assessment: towards a conceptual model. Int J Biometeorol 2009;53(1):101–11.
[57] Vanos J, Warland J, Gillespie T, Kenny N. Thermal comfort modelling of body temperature and psychological variations of a human exercising in an outdoor environment. Int J Biometeorol 2010:1–12.
[58] Fanger PO, Toftum J. Extension of the PMV model to non-air-conditioned buildings in warm climates. Energy Build 2002;34:533–6. http://dx.doi.org/10.1016/S0378-7788(02)00003-8.
[59] Brager GS, de Dear RJ. Thermal adaptation in the built environment: a literature review. Energy Build 1998;27:83–6.
[60] Mahmoud Ayman, Hassaan Ahmed. Analysis of the microclimatic and human comfort conditions in an urban park in hot and arid regions. Build Environ 2011. http://dx.doi.org/10.1016/j.buildenv.2011.06.025.
[61] Humphreys MA. Field studies and climate chamber experiments in thermal comfort research. In: Oseland N, Humphreys MA, editors. Thermal comfort: past, present and future. Watford: building research Establishment; 1994. p. 52–69.
[62] Nicol F. Adaptive thermal comfort standards in the hot-humid tropics. Energy Build 2004;36(7):628–37.
[63] Fanger PO. Thermal comfort [doctoral thesis]. New York: McGraw Hill; 1972.
[64] Brown RD, Gillespie TJ. Microclimatic landscape design: creating thermal comfort and energy efficiency. New York: John Wiley & Sons Inc.; 1995.