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Developing a Thermal Comfort Index for Vegetated Open Spaces in Cities of Arid Zones

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Abstract

The degree of thermal comfort that people experience in open spaces is one of the determinants for use, especially in areas with extreme climates. It has a wide range of indices in the international literature. However, the study of five indices (THI, PE, TS, PMV and COMFA) regarding subjective responses presented low percentages of predictive successes in the city of study, characterized by an arid climate and intense urban vegetation. Therefore, the aim of this work is to develop a new thermal comfort index to predict more accurately the thermal sensation of the local residents. For this, there were campaigns monitoring of microclimatic parameters and field surveys about the real sensation of the people on a pedestrian street of Mendoza Metropolitan Area (MMA) in both winter and summer. The proposed new model is established through the correlation of environmental variables and individual subjective responses. The multivariate correlation is performed by linear regression. The theory of Akaike's information is used as criterion to model selection. The new model IZA is a lineal relation of air temperature, relative humidity, wind speed and solar radiation, generally all available weather variables. We found a high correlation between subjective responses and the new model. Besides the Pearson coefficient which gives the new index is higher than other traditional indices evaluated. The percentage of success of the new index exceeds 85%, demonstrating the effectiveness of the proposed model. In conclusion, the use of IZA as a predictor of thermal comfort will allow a fair assessment of the effect of design and composition of space on your comfort conditions, without the need to carry out thermal perception surveys. This will facilitate the evaluation and decision-making regarding the thermal rehabilitation of open spaces.

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Keywords: thermal comfort; open spaces; objective methods; subjective methods; adaptation.

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1. Introduction

The study of thermal comfort has been approached mainly for indoor spaces like offices, schools and homes. However, many recreational and commercial activities, such as cultural and tourist events are developed in open spaces [1]. The thermal comfort of people in open spaces is one of the factors that influence the habitability of space, since the amount and intensity of the individual performing activities are affected by the level of discomfort experienced when exposed to climatic conditions of these open spaces [2].

Several authors agree that the term 'comfort' means a climatic or thermal welfare state, without excluding other conditions of material satisfaction. This state of well being is the result of a balance between man and his environment, between physiological and environmental conditions.

From a strictly physiological point of view it is possible to define thermal comfort as an energy balance between the human body and its thermal environment Brown & Gillespie [3]. While from a psychological point of view, a definition of thermal comfort sensation involves the person and is the result of human thermoregulation process [4].

However, according to Auliciems [5], a suitable definition is one that includes both physiological and psychological aspects. Thus, the thermal sensation is based on the physical and psychological sensations generated by stimuli of the thermal environment, activities, experiences and expectations.

According Nikolopoulou & Steemers [6], human thermal adaptation is considered as "the gradual decrease of the organism’s response to repeated exposure to a stimulus, involving all the actions that make them better suited to survive in such an environment".

The authors have conducted previous studies [7; 8; 9] where they have compared five models of thermal comfort of wide international diffusion: THI, PE, TS, PMV and COMFA [10; 11; 12; 13; 14] with subjective responses with inhabitants in Mendoza Metropolitan Area (AMM). It is found that there is a high contrast between subjective responses and the results provided by the different thermal comfort indices in both winter and summer. In fact, all evaluated mathematical models present very low percentages of predictive successes (under 25%). These results indicate the need for a local model to properly evaluate thermal comfort perceived by the inhabitants of the city of study.

Therefore, the aim of this research is to propose a method to quantify the correlations between urban microclimatic variables and the subjective perception of thermal sensation. This model will allow the prediction of thermal comfort conditions of the population adapted to a given climatic condition, in this specific case, Mendoza Metropolitan Area (AMM), inserted in an arid area.

This new index aims to be a useful tool in the design and evaluation of the thermal behavior of open spaces according not only to climate criteria but also to subjective characteristics.

2. Materials and Methods

2.1. City of study

The research was carried out in Mendoza Metropolitan Area (AMM), in west-central Argentina (32° 40' S, 68° 51' W, at 750 meters above sea level). It is the fifth largest city in the country with 168 km^2 and 1,055,679 inhabitants [15].

According to the classification of Köppen-Greiger city's climate is arid: BWh or BWk depending on the isotherm used [16]. It is characterized by cold winters (average temperature in July: 7.3 ° C) and hot summers (average temperature in January: 24.9 ° C), with large daily and seasonal temperature ranges. Winds are moderate and infrequent (average speed: 11 Km / h), the amount and intensity of solar radiation is high (relative heliophany annual average: 63%) and the average annual rainfall is 198 mm, with a concentration of 76 % between October and March [17].

2.2. Field Study

The field study was developed in a pedestrian street, with a large influx of people in the center of the AMM. Two sites or bases were established for the study of several variables: one in the center of the block (Base 1) and the other in the West end of the same block (Base 2). The criterion for selection of sites was access to solar radiation and wind, so the Base 1 is more closed and the Base 2 is more open. Figure 1 shows the hemispherical views of each base, both in summer and winter, which are used for calculating the sky view factor (SVF).

Subjective questionnaires and microclimatic measurements have been carried out in winter 2010 (22, 26 and 27 July) from 9:00 am until 5:00 pm and in the summer 2011 (19, 20 and 21 December) from 9:00 am to 8:00 pm. Climatic conditions during the surveys were typical of the AMM. There were clear sky conditions and the wind was calm.

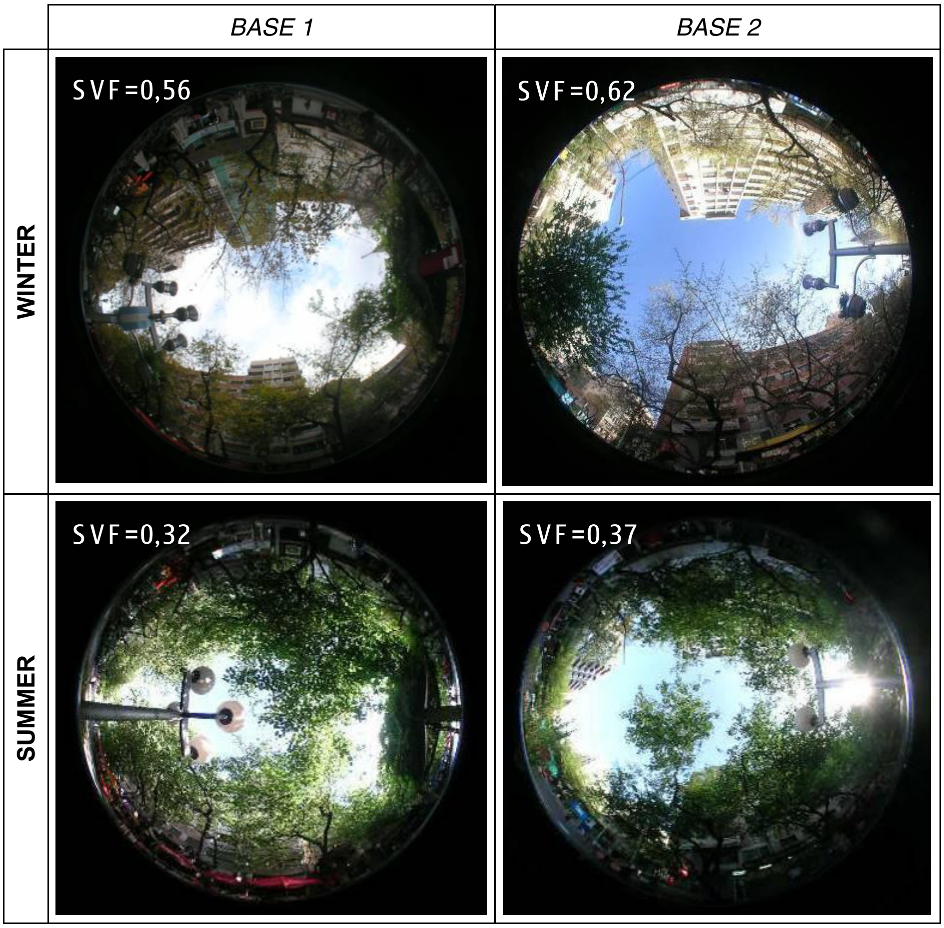

Fig. 1. Hemispherical views of each base and each season studied.

We used two HOBO® mobile weather stations; model H21-001, equipped with temperature and relative humidity sensor, wind speed sensor, wind direction sensor, pyranometer silicon and barometric pressure sensor, located at 1.50 m height.

Ambient temperatures measured during the campaigns ranged between 26.5 and 37.6°C in summer, and between 3.2 and 16.0°C in winter, with a corresponding relative humidity range of 19.6-29.7% in summer, and 26.3-60.1% in winter, while the solar radiation range was 8.1-1096.9 W/m2 in summer, and 14.4-649.4 W/m2 in winter; and the wind speed range was 0-1.5 m/s in summer, and 0-2 m/s in winter.

While microclimate monitoring was conducted, people were studied in their natural environment through structured interviews and observations, to evaluate the comfort conditions people experience and their perception of the environment. The study of subjective responses took place on the basis of the principles established by the work of Nikolopoulou et al. [18], Kántor et al. [19], y Monteiro [20]. The first part of the questionnaire consists of items related to sex, age, clothing, activity prior to the interview and origin (to take into account the factor of acclimatization).

The second part includes the thermal environment perception, which was reported on a 5-point scale, ranging from -2 (very cold) to +2 (very hot), through zero (neutral) and has been defined as the actual Sensation Vote or ASV [18].

The sample consists of a total of 667 questionnaires. Counting a population of approximately 1,000,000 inhabitants (AMM), with a margin of error of 5%, a confidence level of 95% and the response distribution of 33% (comfort, discomfort due to cold or discomfort due to the heat), is need a minimum of 340 respondents. The sample consisted of 61% male and 39% female, and 80% of respondents in the age group between 18 and 64 years.

Considering that microclimatic variables are normally distributed in each season, in the interval [μ - 2σ; μ + 2σ] is found approximately 95.44% of the distribution. Therefore, the comparison was made between models and between them and the subjective responses, and was based on 622 questionnaires that are within that range, both in winter and summer, after removing the outliers.

2.3. Development of a new mathematical model

The proposed new model is established by correlation of environmental variables and individual subjective responses. The proposal is supported by complementary analytical data collected empirically. Multivariate correlation is commonly performed by linear regression, as seen in Givoni & Noguchi [21], Nikolopoulou [22] y Monteiro [20], which generates equations quite simple and easy to use. Regressions were performed for the mean values of the microclimatic conditions and not for the entire data set individually for three reasons. First, the mean values represent the number of effectively studied environmental situations and can be considered that the large number of questionnaires are applied in order to obtain representative values. The second reason is that the adoption of mean values, referring to all questionnaires, facilitates the analysis. Finally, consideration of average values also facilitates comparison of results with those of other models.

We used the Akaike criterion for model selection for "oasis cities" inserted in arid areas between the total linear regressions performed. Akaike [23] found a formal relationship between Kullback-Leibler information [24] —a dominant paradigm in information and coding theory— and maximum likelihood — the dominant paradigm in statistics— [25]. This finding makes it possible to combine estimation and model selection under a single theoretical framework-optimization. Akaike's breakthrough was deriving an estimator of the expected, relative Kullback-Leibler information, based on the maximized log-likelihood function. This led to Akaike's information criterion (AIC).

The model where AIC is minimized is selected as best for the empirical data at hand. This concept is simple, compelling, and is based on deep theoretical foundations (i.e., Kullback- Leibler information) [26]. 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, given the data and the set of a priori models, and further developments provide strength of evidence for each of the models in the set.

Rather than base inferences on a single selected best model from an a priori set of models, inference can be based on the entire set of models (multi-model inference). Such inferences can be made if a parameter is in common over all models. This approach has both practical and philosophical advantages [27; 28; 29]. Where a model-averaged estimator (called Akaike weight) can be used, it often has better precision and reduced bias compared to the estimator of that parameter from only the selected best model.

In this study we used a "confidence set" of models for which the sum of the Akaike weights is approximately 0.95.

3. Results

The results of the multivariate correlation from in situ measured variables to predict the thermal sensation without the need for field studies are presented here. The formula henceforth called thermal comfort Index for cities Dry Areas (IZA) is presented in the following equation:

$$IZA = -1{,}3032 + 0{,}0647 \cdot Ta - 0{,}3673 \cdot v + 0{,}0110 \cdot HR + 1{,}61 \cdot 10^{-5} \cdot Rad + 0{,}0005 \cdot Ta \cdot HR$$

Since:
Ta: air temperature, in °C
v: wind speed, in m/s
HR: relative humidity, in %
Rad: horizontal solar radiation, in W/m2

This model is the result of multi-model inference of a set of confidently with an accumulated Akaike weight of 0.9465. This means the approximate probability that this is the best model of the set of models considered is of the order of 95%.

Although the Akaike Information Criterion does not require R^2 or p-value, are reported weighted values of these parameters as they are commonly used in scientific research. The weighted and adjusted determination coefficient R^2 is high (0.8586). The weighted standard error is quite reasonable (0.2555), given the values assumed by the thermal sensation: -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.

Table 2 presents the results of the constant of the equation and each variable considered. The t-statistic tests the null hypothesis that the coefficient of the independent variable is zero, that is, it does not contribute to the prediction of the dependent variable. T-value is the ratio of the regression coefficient and its standard error. P-values given refer to the prediction of a dependent variable with a linear combination of independent variables. The lower p-values indicate the greater importance of a given independent variable in predicting the dependent variable. In particular, the most important variables are: air temperature, wind speed and the interaction of temperature and relative humidity with p-values less than 0.05.

Table 2. Results weighted to the intercept and each variable of the model proposed.

	Coefficient	*Standard Error*	*t-statistic*	*p-value*	*VIF*
Intercept	*-1.3032*	*0.3130*	*-4.7679*	*0.0004*	
Temperature Ta	*0.0647*	*0.0068*	*10.6421*	*0.0002*	*7.5650*
Wind speed v	*-0.3673*	*0.0781*	*-4.4577*	*1.11E-05*	*2.9743*
Relative humidity HR	*0.0110*	*0.0065*	*1.1130*	*0.0635*	*0.7527*
Solar radiation Rad	*1.61E-05*	*2.68E-05*	*0.1571*	*0.1440*	*0.4039*
Ta:HR	*0.0005*	*0.0002*	*0.8442*	*0.0012*	*5.1109*

The variance inflation factor (VIF) indicates how much of the variation of a predictor is explained by the other. It is considered that a VIF greater than 5 is high; indicating that this variable will generate collinearity issues. High values of VIF for the variables of air temperature and interaction between relative humidity and temperature show collinearity.

We evaluated the possibility of removing the relative humidity because is known in advance the correlation presented with air temperature and replace it by the specific humidity but this variable has greater correlation with temperature because the summer is the wet season in city of study so the correlation with the temperature is even higher. Therefore, it was decided to keep these variables in the model because they are considered of great importance for determining the thermal comfort.

The proposed model is associated with the scale of interpretation associated thereto in Table 3.

Table 3. Values scale and sensations of the new thermal comfort Index for cities Dry Areas (IZA).

IZA Values	*Sensation*
> 1.5	*Very hot*
0.5 a 1.5	*Hot*
-0.5 a 0.5	*Neutral*
-0.5 a -1.5	*Cold*
< -1.5	*Very cold*

Finally, Table 4 provides the limits considered for correlations in all situations in which this model is valid.

Table 4. Limits for the microclimatic variables in which the new model is valid.

	WINTER		*SUMMER*	
Variable	*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*

3.1. New model IZA and subjective responses

In order to evaluate the performance of the new proposed model, the comparison was made between the results obtained with the IZA model for 84 microclimatic situations and subjective responses throughout the year. It was found that the correlation with the parameter of the model was 0.95 and the Pearson coefficient in relation to the range was higher than all other models previously evaluated (0.91). However, the success rate is the value that most strongly demonstrated the effectiveness of the proposed model, since the percentage of hits is 85.71%. This value contrasts with the percentage of correct prediction of other previously studied indices, which do not exceed 25% [7; 8; 9].

We also compared the results of this new model with those provided by the subjective responses in 622 questionnaires, in both seasons and sites studied. The graphs describing this comparison can be seen in Figure 2.

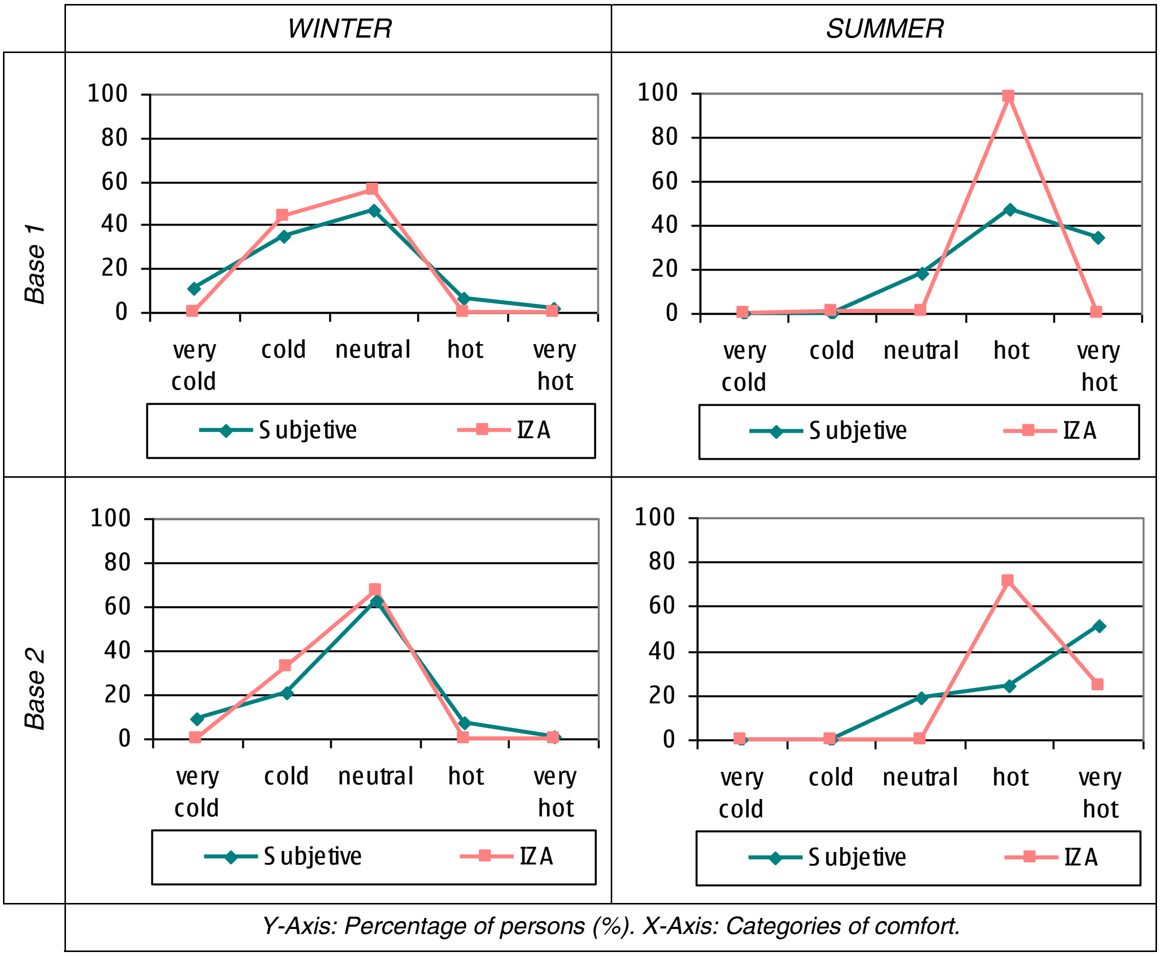

Fig. 2. *Comparison of the number of people in each category of comfort according to subjective responses and IZA, for base 1 and base 2, in winter and summer.*

The winter results corroborate what was said in the previous paragraphs. The IZA significantly adjusts to the subjective responses of the interviewees. In the Base 1, the biggest difference between the two approaches is 10% in the "cold" range and the Base 2 a difference of just over 12%.

However, the situation is not so favorable in summer. In the case of Base 1, 98% of IZA predictions are in the "hot" range, while only 47% of residents of the city of study is in that category. In the Base 2 there are also discrepancies between subjective and predictive approach since the first approach places more people at the range "very hot" (52%), while the second predicts that 71% feel only "hot". It is estimated that this lack of adjustment in the summer is given, as anticipated, by the multicollinearity between the temperature and the relative humidity, which is most evident in this season.

In previous works [7; 8; 9], we find that the percentage of hits of energy balance S of COMFA model is not greater than 24% over the all year. However, during the summer season this index shows good behavior. Furthermore, this physiological index has the advantage of disaggregating the various types of heat flows, so as to act on those that are most critical. Therefore, for the summer is recommended COMFA index for calculating thermal comfort conditions in arid town.

3.2. Results of other models

Table 5 presents the results of the correlations IZA model with the data observed in this study and the results of the correlations of the models proposed by Nikolopoulou [22] and Monteiro [20], which are obtained from the data observed in seven European cities and in the city of Sao Paulo, Brazil. The Pearson correlation coefficient IZA model is the highest among the nine indices analyzed.

General methodology is similar in all of the studies. In European cities the sample size was around thousand questionnaires applied, while in São Paulo the study was 876 questionnaires and in the city of Mendoza was 622.

Some considerations are given below. First, the correlations presented by Nikolopoulou are based on weather station data therefore expects its results less meaningful. Second, we have followed the methodology according microclimatic situations of Monteiro. Therefore, it is logical that the coefficients of determination R^2 are similar in San Pablo and Mendoza.

Table 5. Correlation between various models and observed data.

City	R^2
Atenas, Grecia	*0,27*
Milán, Italia	*0,44*
Kassel, Alemania	*0,48*
Thessaloniki, Grecia	*0,51*
Cambridge, Inglaterra	*0,57*
Sheffield, Inglaterra	*0,58*
Friburgo, Alemania	*0,68*
San Pablo, Brasil	*0,73*
Mendoza, Argentina	*0,76*

4. Conclusions

This work has attempted to elucidate some of the complexity of the issues involved in the evaluation of thermal comfort conditions in open spaces. Although micro-climatic conditions affect the use of open spaces, purely physiological approach is insufficient to characterize the habitability conditions in outdoor spaces, emphasizing the need to investigate the different ways to quantify the outdoor comfort conditions.

Previous studies in Mendoza Metropolitan Area (AMM), inserted oasis town in an arid area, showed that none of the indices analyzed efficiently shows what the locals feel. Given these limitations, we developed a new model: the "thermal comfort Index for cities Dry Areas (IZA)." The formula considers the four microclimatic variables commonly used in studies of thermal comfort and allows for general situations, within the given limits, predicting thermal sensations for a population adapted to the climatic conditions of the city of study.

This model is the result of multi-model inference of a set of confidently with an accumulated Akaike weight of 0.9465. This means the approximate probability that this is the best model of the set of models considered is of the order of 95%.

In subsequent studies, it is estimated that nonlinear regressions can provide significant results according to the type of data, the type of response variable and taking into account that some independent variables exhibit multicollinearity among themselves. However, IZA has the great advantage over the models developed elsewhere that it presents a high percentage of hits that exceeds 85%.

Also suggests the use of the new model IZA during winter and COMFA model during summer, due to the adjustment having each in respective seasons.

The IZA model will be useful for designers and urban planners as a careful design of open spaces can provide protection against the negative aspects and adequate exposure to the positive aspects of climate, therefore, increase the use of outdoor space for throughout the year.

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