



Research on ecological design to enhance comfort in open spaces of a city (Valencia, Spain). Utility of the physiological equivalent temperature (PET)



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ABSTRACT

For many years now, research has focused on issues concerning making cities easier to live in and some of the most important of these concern climatology and thermal comfort issues. There is also a growing awareness of the importance of open spaces and green areas, as key elements in providing opportunities for human interaction, leisure and physical exercise. They are important for all inhabitants, but particularly so for children and the elderly population. Of especial interest are the studies which have examined the interaction of comfort with the urban climate. This issue was studied throughout the twentieth century, but recently the role which can be played by biometeorological indices has come to be recognized, especially because of the better understanding them for those responsible for the design of these urban spaces. This study explores the application of the PET index to urban micro-spaces (urban structures), where general values for cities are not valid and where there is a need to know the PET values in order to measure the impact of all items of the urban environment which can provide an increase in comfort. The study was carried out in Valencia (Spain) with the aim of discovering, through these indices, the natural and ecological effects of urban design which can improve comfort. The study focused on: the role of water features, streets with and without trees, squares with hard and soft street surfaces, the effect of different street orientations and the impact of breezes on the city. We have found that the sheets of water, or ponds, provide a cooling effect for the space in which they are located because they have a lower albedo than its surrounding area. In narrow streets, the trees may have a blanket effect and prevent the passage of breezes. Water jets of the fountains should be designed to take advantage of the effect of the breeze to improve the thermal comfort in the surrounding area. The use of hard surfaces and light colors causes a great thermal stress in summer due to higher solar reflexivity that involves higher heat load.

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1. Introduction

From the many different possibilities of offers in the city, open spaces are key elements in providing opportunities for human interaction, leisure and physical exercise, both for children and the elderly population. The levels of interaction and thermal comfort which these spaces ultimately provide depend on the use which is actually made of them.

Western countries, where there is perhaps greater concern for the quality of these spaces, are aware of how important the existence of healthy environments near one's place of work, residential area, or town will be a few years from now for an aged population. Quiet green areas are needed, where the sounds of birds and bees can be enjoyed – something which the EU is pushing for through the [European Environmental Agency \(2012\)](#). However, there are some real problems facing the design of these spaces with regard to the search for human thermal comfort.

There are two particularly challenging issues. The first of these is (a) the difficulty inherent in the very nature of cities for the accurate recording of the meteorological parameters required for biometeorological studies. In cities, a phenomenon is present which must necessarily be taken into account: the conglomeration of buildings and their positioning affect those same climatic and environmental

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conditions, raising the temperature and affecting the precipitation and wind patterns.

This has been known for some time and has provided the motivation for various studies – Chandler (1976), Landsberg (1981), Oke (1984, 2006), López (1985), Eliasson (2000), Alcoforado et al. (2009), etc. – which allow us to speak of the existence of urban climatological conditions which are affected by both the physical climate and the human environment. Heat absorption by the mass of buildings during the day and the slow irradiation loss of this heat during the night leads to the formation of a “heat island” which is surrounded by a cooler rural area.

Besides temperatures, modifications are also made to the direction and intensity of winds, as they are obstructed by built-up areas, causing their trajectory and turbulence to be affected.

Landsberg (1981) demonstrated that cities significantly modify the meteorological conditions of the surrounding area: overall radiation is higher, except ultraviolet radiation; the mean annual temperature is higher in cities than in the surrounding areas; wind speed is considerably lower in cities, being slowed by the buildings. As a consequence, relative humidity in cities is lower.

The albedo measured in the cities allow us to confirm that tar-covered or paved surfaces accumulate much more heat than natural ground. This heat is re-radiated to the atmosphere, and that is the reason why it is important to shade the streets and sidewalks, in addition to creating a microclimate of shade for pedestrians to walk in (Tan and Fwa, 1992; Akbari et al., 2001; Lin et al., 2007; Akbari et al., 2009).

Secondly (b), the other factor which stands in the way of finding sound solutions for these spaces is inherent to the nature of urban planning: those responsible for the design of such spaces are architects, urban planners or engineers – i.e. professionals who are unfamiliar with the problems arising from the interference of urban dynamics with local climatological conditions.

In our view, the only way to remove this barrier is to communicate those components of urban comfort studies which are comprehensible and easily applied to the urban design that these spaces require.

2. Comfort in open urban spaces.

2.1. Heat balance studies

Heat balance establishes that on the human body heat gains must be equal to the losses. If the external environment does not allow for a balance to be established, then thermoregulation mechanisms are activated. The human body secretes sweat, so that this may evaporate, taking heat away from the body and restoring the balance (Höppe, 1993). Although the balance can be maintained in this way, excessive sweating is an uncomfortable situation, as, besides the organic effort involved in the secretion of sweat, it also leads to the undesirable effect of leaving the skin and clothes wet (Alvarez et al., 1991) (Fig. 1).

In summer conditions, ideal thermal comfort is achieved when different energy/heat flows are balanced so that heat loss through sweating is negligible. When one of the sources of heat gain increases, sweating is required in order to lose heat and to get thermal comfort. For this heat balance equation and for the specific situation of a single person, it is possible to calculate all the parameters and to quantify the different gains and the possible losses (Fig. 1).

In order to improve the thermal comfort situation, it is necessary to increase the favorable heat flows (losses) and reduce the unfavorable ones (gains), by eliminating these wherever possible and even transforming them into losses if reversal is feasible (Table 1).

This table is logically based on a prior analysis of the parameters in the “heat balance” equation while defining whether each

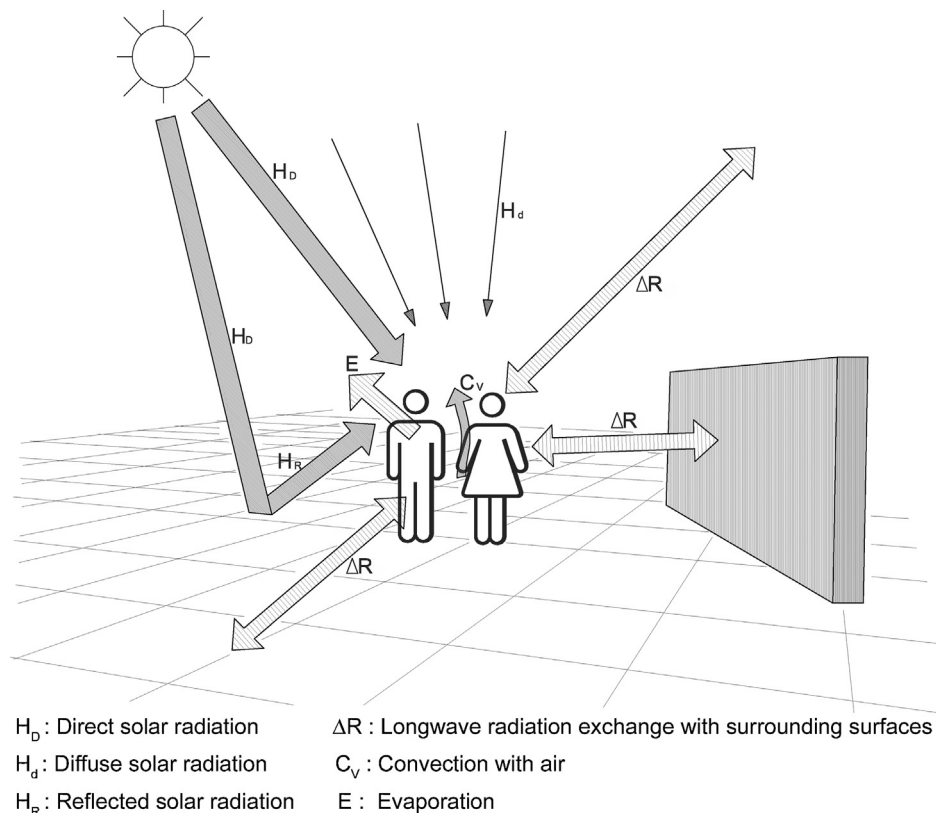


Fig. 1. Diagram of the heat flow around people in an open space.

Table 1
Strategies for the conditioning of open spaces (Guerra et al., 1991).

Criteria	Generic action	Reduction of gains (W)	Specific techniques
Reduction of solar radiation	Obstruct direct and diffuse radiation	40–70	Provision of shade
	Obstruct reflected radiation	25–50	Confinement Treatment of nearby surfaces
Reduction or reversal of the exchange of long wavelength radiation	Reduce temperature of surrounding surfaces	20–50	Cool road surfacing Water features provision devices Waterfalls Water curtains
Reduction or inversion of convective exchange	Reduce air temperature	15–50	Confinement
	Facilitate movement of cool air		Sensible cooling Latent cooling Channeling of breezes Jets of water

parameter is externally controllable and whether it is possible to reverse the direction in which heat transfer takes place. In some cases, a balance can be achieved by means of natural techniques: for example, the shade provided naturally by trees or via specific cultivation. In other circumstances, artificial shade must be provided or a combination of techniques employed (Fig. 2).

In practice, taking these issues into account enables urban planning professionals to design urban spaces in which variables such as solar radiation, one of the biggest sources of heat gain, can be

controlled, or in which excessive heat can be eliminated through convection by using fountains or bodies of water.

So, there are two problems for those who are to design such spaces: a) the meteorological parameters which enable thermal comfort to be known cannot be deduced from the general parameters for the city, which are measured by the meteorological services, because, as we have said, the urban structures modify those parameters in the micro-spaces which are surrounded by buildings; (b) if they are measured *in situ*, human-biometeorological indices become necessary, for which the balance equations have been modeled and which are easy to use with the values obtained.



Fig. 2. Calle Sierpes (Seville). Device for the limitation of solar radiation reaching the road surface.

2.2. Background to the most widely used thermal indices at the present time

Recent studies on bioclimatic comfort continue to follow the two basic approaches described by Morgan and Baskett (1974): an analytical or rational approach, based on the human energy balance, and a synthetic or empirical approach, based on combinations of various meteorological variables. Empirical indices, such as those referred to earlier, do not take into account the decisive role played by thermal physiology, activity, clothes and other personal data (height, weight, age, sex, etc.). Rational indices are newer, they tend to be created using computing techniques, and they correspond to the human energy balance (Höppe, 1993).

Currently, rational indices are more closely linked to the interests of urban planning and they have a significant international profile. Examples include: the studies carried out for the Universal Exposition of Seville (Alvarez et al., 1991); the RUROS project, carried out for the European Union, which is especially interesting (Nikolopoulou et al., 2004); the RayMan Model, designed by meteorologists at the University of Freiburg (Matzarakis et al., 2007, 2010) has had a great impact, with the model being based on VDI Guideline 3787 (1998), published by the Association of German Engineers; and the workgroup of the University of Sonora (Ochoa and Serra, 1998), based on the research of Brown and Gillespie (1995).

A key contribution to such research has been made by the International Society of Biometeorology, both through its publications and via the creation of a Special Commission (1999) for the study of the Universal Thermal Climate Index (UTCI) (<http://www.utci.org/index.php>).

Recently, research has been undertaken into the evidence for the important role played by psychological factors on the perception of individual comfort, especially with regard to a city's open spaces – it is therefore important to bear these factors in mind when designing open air spaces (Nikolopoulou and Steemers, 2003; Nikolopoulou and Lykoudis, 2006, 2007; Sanesi et al., 2007; Van

den Berg et al., 2007; Lin, 2009; Lin et al., 2011; Lin and Matzarakis, 2011; Kántor and Unger, 2010; Lin et al., 2012, 2013). These surveys of the opinions of city-dwellers, the ultimate users of these spaces, have also confirmed the results achieved using empirical indices (Gómez et al., 2004; Oliveira and Andrade, 2007).

Studies have also been undertaken with regard to the variation, development and applicability of these indices (Tornero et al., 2006) and a more recent, very detailed and interesting study compared the UTCI with a selection of the most widely used indices of the last 10 years (Jendritzky et al., 2012). The authors of the latter study highlighted the PET and UTCI indices for their ease of use.

The first of these, the PET (Physiologically Equivalent Temperature), is based on a physiological heat-balance model: the MEMI heat-balance model for the human body (Höppe, 1984, 1994). The latter author defines this as “the Physiologically Equivalent Temperature of a given place (indoors or outdoors) is equivalent to the air temperature at which, in a typical indoor setting, the heat budget of the body (80 W activity, in addition to the basic metabolism: thermal resistance of clothing of 0.9 clo) is balanced with the same core and skin temperature as under the outdoor conditions to be assessed”.

As an example, a person in a hot and sunny outdoor location with a PET value of 43 °C would experience the same sensation of heat as if they were inside a room in which the temperature was 43 °C. If the person were to move from the sunlit area to the shade, this would lead to a reduction of the PET of around 14 K to 29 °C. The thermal stress which the PET measures is the same as the temperatures which are measured outdoors.

The assumption of constant values for clothing and activity for this index is carried out in order to be able to establish an index which is independent of individual behavior. This does not limit the scope for its application, as any variations in clothing or activity, if they vary equally outdoors and in the standard indoor situation, do not significantly affect the PET values.

PET (Matzarakis et al., 1999) has also been well-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”.

Finally, we have already referred to the difficulty which some models present with regard to both the calculation and application of data. With the PET, these issues are straightforward, through the use of the RayMan model (Matzarakis et al., 2007, 2010).

This model enables the estimation of the mean radiant temperature (MRT), one of the most difficult parameters to calculate, based on the overall radiation. This means that urban planning professionals, who are not experts in climatology, have a tool available to them which is not overly complicated.

The PET index has been successfully used in bioclimatic studies in cities with different types of climate (Matzarakis et al., 1999), to study urban bioclimates (Matzarakis and Endler, 2010), to analyze urban bioclimatic events, such as for example heat waves (Matzarakis et al., 2009), to study the influence of sea breeze on human comfort during hot periods (Lopes et al., 2011) and to draw bioclimatic maps of different geographic zones (Matuschek and Matzarakis, 2011). The physiological importance of the PET in outdoor thermal comfort has been given special attention (Chirag and Ramachandraiah, 2010). Gulyas et al. (2006) also used PET in a study of the structure of complex surfaces in urban areas. Ali-Toudert and Mayer (2006) analyzed the contribution of street design in the development of a pedestrian-friendly microclimate, and Johansson (2006) researched the influence of urban geometry on outdoor

Table 2

Parameters introduced into RayMan, for the PET calculation.

Parameters	PET
Clo (for all seasons)	0.9
Activity (for all seasons)	80 W
Wind speed (height)	1.1 m

thermal comfort. Lin (2009) used the PET to examine thermal comfort in a public square in the hot and wet Taiwan climate. Knez and Thorsson (2008) examined the influence of culture (Sweden vs. Japan) and environmental attitude (urban vs. open-air person) on participants' thermal, emotional and perceptual assessments of a park, within the PET comfortable interval of 18–23 °C. Its correlation with perception has recently been examined in thermal comfort studies (Kántor et al., 2012a, 2012b) in Hungary, Sweden, Portugal, Canada and Taiwan.

The other index which is also of wide potential application and is a member of the “rational” group is UTCI, which is expressed as the equivalent ambient temperature (°C) of a reference environment which produces the same physiological response as the actual environment in a particular person. In this case, the calculation of the physiological response to the meteorological contribution is based on the “multi-node” model (Fiala et al., 2012), taking into account the clothing that people wear. The passive system of this multi-node model consists of 12 bodily compartments composed of a total of 187 tissue nodes. The active system can be adjusted to take into account the static insulation provided by clothing to the ambient temperature, in accordance with the seasonal clothing habits of Europeans (Blazejczyk et al., 2012).

2.3. Conditions of use of the PET index

The particular meteorological variables and the physiological parameters used will vary according to the model employed. However, as the modeling of this index is well explained in the cited bibliography, here we will only refer to the variations with regard to the entry data (Table 2). There are data regarding the location and day: for example, longitude, latitude, altitude and time zone, and, for the date, the year, month and day.

Another issue to take into account is the ranges to be used. For the PET thermal index, we follow the use of Matzarakis et al. (1999) (Table 3).

3. Bioclimatic characterization of the city of Valencia

The city of Valencia (Fig. 3) and its surrounding area possess all of the typical characteristics of the climate of the north-western

Table 3

Ranges for the PET.

Thermal Perception	PET
Very hot	> 41
Hot	35–41
Warm	29–35
Slightly warm	23–29
Comfortable	18–23
Slightly cool	13–18
Cool	8–13
Cold	4–8
Very cold	< 4

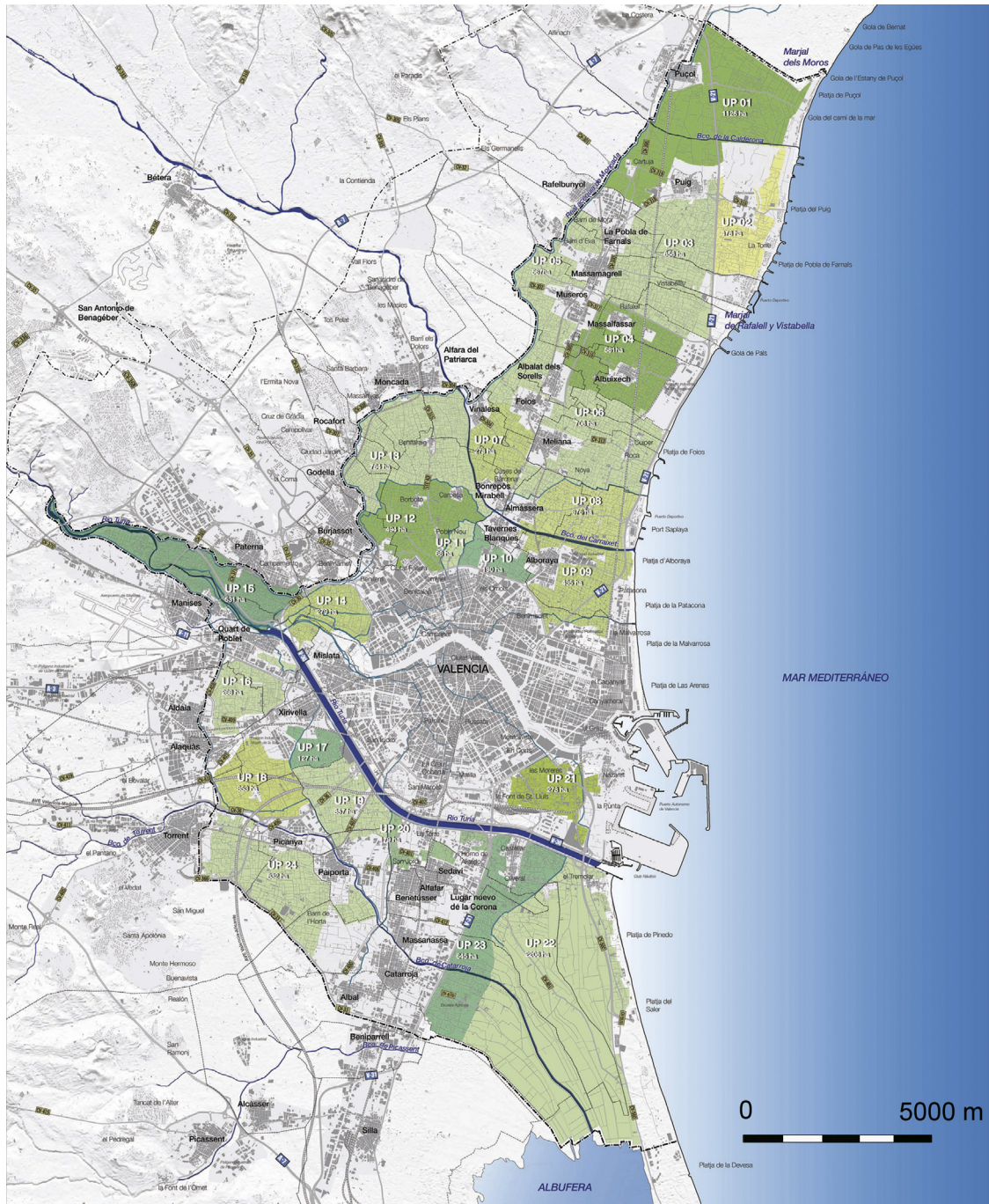


Fig. 3. Overview of the metropolitan area of Valencia.

Mediterranean, although it receives less rainfall due to its position on the eastern seaboard, being sheltered from the storms of the Atlantic and even from those of the Gulf of Genoa. This climate typically has a very mild winter (around 10–12 °C) and a summer with moderately high daytime temperatures, which do not fall significantly at night: in general, they remain at approximately 20 °C. The autumn sees a high concentration of the relatively scarce rainfall.

With regard to aspects of climatic comfort, the mild temperatures stand out, being very close to the thermal limits of the comfort zone defined by Olgay (1963) and frequently within them (most days in spring and autumn and at night during the four to five hottest months).

One element of discomfort is the high environmental humidity, which increases the sensation of cold in winter and, more especially, causes a great deal of discomfort in summer due to the combination with the heat. The high relative humidity (around 70–75% in winter and 65–79% in summer, with vapor pressures around 24 hPa) is directly linked to the proximity of the Mediterranean Sea and is possibly increased by the huge tracts of land under intensive irrigation surrounding the city, which is located in the area known internationally as the *Huerta de Valencia*.

The sea breeze regime of certain Mediterranean cities has been studied in detail (Azorin-Molina et al., 2011). In the particular case of Valencia (Fig. 4), the breezes pattern and, in general,

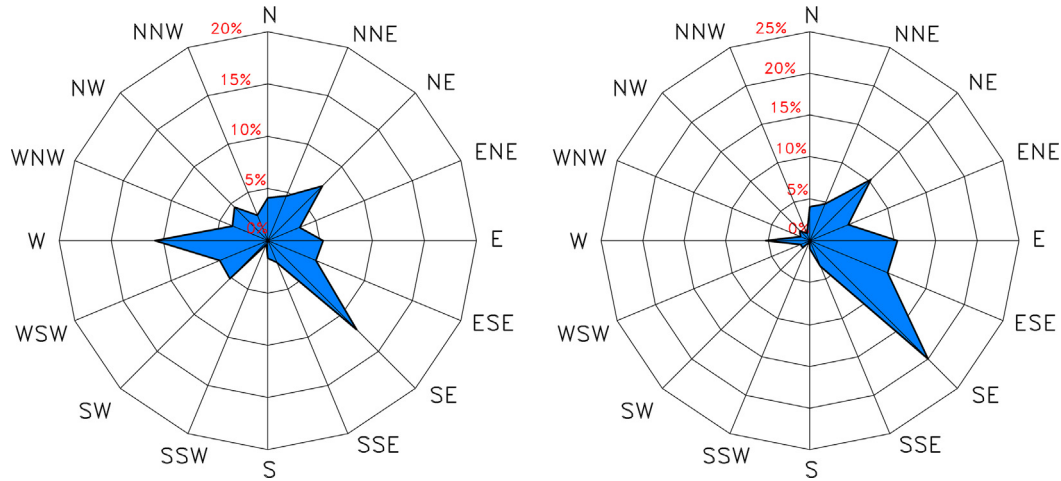


Fig. 4. Annual (left) and summer (right) Valencia wind rose.

all advections coming from the east bring high environmental humidity indices. The breezes which to start to make themselves felt in March and continue to blow through to November occur on more than 80% of the days in the spring months and early summer.

The thermal impact of the breezes falls off relatively quickly as they move inland: their refreshing effect is felt to the maximum along the shoreline, with it being quite high in the *Huerta* and city, with the effect falling away in the dry region to the west of the city.

There is a moderately high level of insolation in Valencia, with an annual average of 2631 h (59% of the theoretical maximum). Over the course of the year, the summer maximum is very high – 329 h in July – with the minimum in winter being 142 h in December.

With regard to cloud cover, there is an average of 81.8 days with clear skies per year, 218.2 cloudy days and 62.5 overcast days. The maximum number of days with clear skies falls in July, with 11.8, and the minimum of 5.0 days occurs in May and October. There is a maximum number of 7.9 overcast days in March and a minimum of 1.2 in July.

4. Research objectives and methodology

The following three conditioning factors had to be taken into account:

1. The human-biometeorology and geographical location of the city of Valencia;
2. The specific conditioning factors of the urban environment, affecting and distorting some meteorological components;
3. The characteristics of each index, with regard to their components and modeling.

The use of the PET index appeared to be appropriate for those open spaces of the city of Valencia where, due to their use, it was desirable to discover the level of comfort which can be obtained by employing natural techniques, using the features of the urban environment which are already present in these open spaces.

Once the appropriate locations had been chosen for the study of the different situations described for each of the objectives, the methodology was to measure the precise meteorological variables for their input into the RayMan model. These objectives are:

1. Establish the behavior of the water features
2. Establish the role played by the wind in streets of different orientations

3. Establish the level of comfort of streets with and without tree cover
4. Squares with hard and soft surfaces

With regard to the sampling points, 23 of these were chosen across the city of Valencia (Fig. 5). These locations had to be appropriate to the nature of the objectives.

A prior statistical analysis was carried out, according to which at least 9 measurements at each sampling point would be necessary (to calculate the size of the sample, a stratified sampling was carried out at a 95% confidence level; an estimation of $P=Q=0.5$ and a sampling error of 2.5% were used). As has been mentioned above, in each of the 23 spaces studied, two or three portable Hobo H21-00 weather stations were placed in different positions. Each of the stations issued data every hour from sun-rise to sunset (in order to obtain direct solar radiation values). The highest number of values was of course obtained in summer, with fewer in spring and autumn and fewest of all in winter.

Data was collected for three consecutive years (2007–2009), in each of which measurements were made on three different days in the middle month of each of the four seasons (spring, summer, autumn and winter); in other words, the value of the weather parameter assessed for each position and season of the year was the mean of the nine values obtained.

The definitive values obtained were compared to the mean values for each season of the year recorded by the Valencia Meteorological Service. It should be borne in mind that in each of the spaces studied we looked for contrasts between sunshine and shade, zones with and without a breeze, hard and soft ground, wet and dry surfaces, etc., when choosing sites for the three weather stations.

In order to measure the meteorological parameters in this study, Hobo H21-00 weather stations were used. These possess sensors for overall radiation, albedo, air temperature, relative humidity, wind speed, and surface (soil) temperature, which were all connected to a data logger, enabling the data to be processed electronically (Fig. 6).

5. Results and discussion

5.1. Ponds and their surrounding area

Firstly, we tackled objective number 1, regarding the role played by ponds of water and water features. We focused on a fountain



Fig. 5. Sample points.

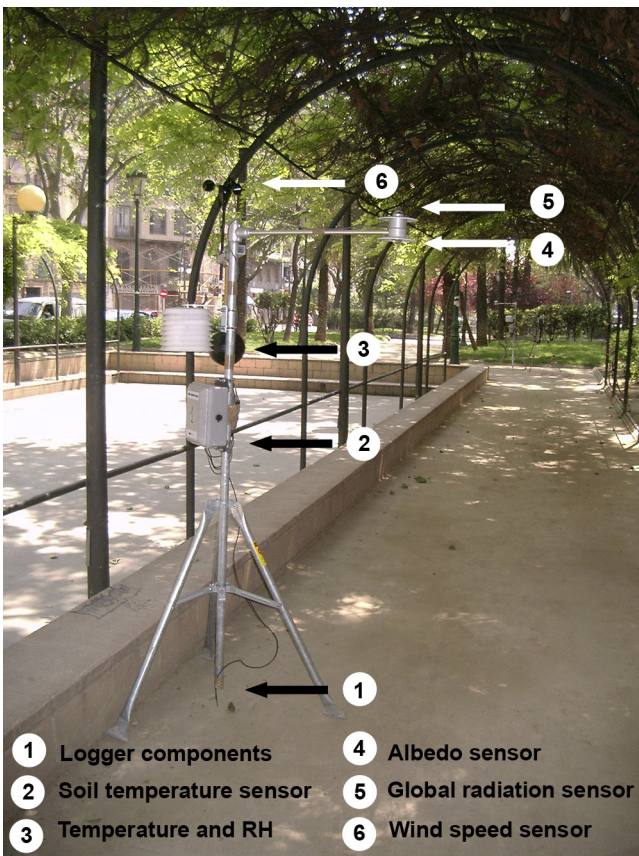


Fig. 6. Hobo weather station and its different components.

located in the former river bed of the River Turia, behind the Palau de la Música concert hall.

Although the values recorded at the stations on either side of the fountain were of greater interest, a third station was placed near the edge of the fountain (Fig. 7).

Now, looking only at the values from stations (1) and (2) (Fig. 8), it can be seen that, although high values were recorded in the middle of the day, the values are not as high as those seen in other locations, e.g. in the Plaza del Ayuntamiento (Fig. 12) and Plaza de la Virgen (Fig. 13). It is particularly important to note that there is no sudden jump in the values from the morning to those of the time at which the breeze begins to blow.

We believe that the reason for this is that at this fountain there was another parameter, the pond of water, which has a very different albedo from the other ground surfaces seen during the course of the research. It is our understanding that this difference in the albedo was sufficient to modify the temperature measured by the station and cause this lowering of the PET values. The PET values can be seen in Fig. 8. It should be recalled that the albedo is defined as the ratio of reflected flux density to incident flux density, referenced to the some surface.

The weather station we used possessed a self-contained LP PYRA 05 sensor, on which two LP PYRA 02 pyranometers were placed. One of these measured the radiation striking the water and the other measured the radiation reflected by the water, but the two sensors were linked in such a way as to ensure that they had the same sensitivity. The cable then transmitted the signals from the two pyranometers, which could then be processed to obtain the physical measurements sought (ISO and WMO, 1990).

This hypothesis has support from different authors who have studied the albedo of the different materials with which cities are normally built (Robitu et al., 2006), especially with regard to cities in the USA (Akbari et al., 2001). The angle of incidence of sunlight varies and when the sun shines down vertically, water reflects a

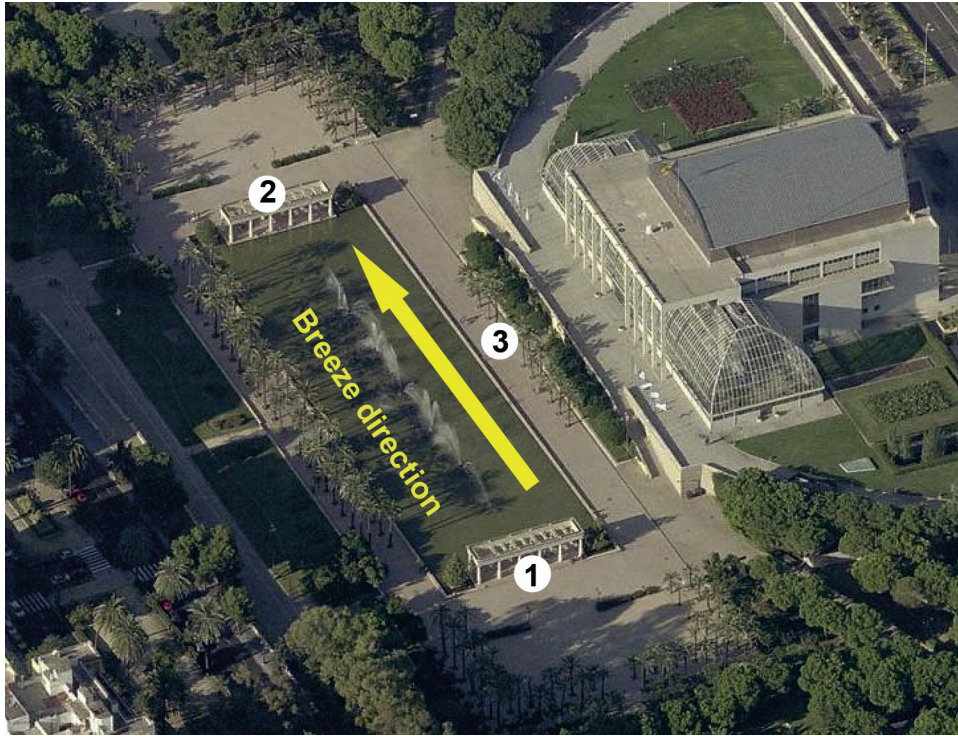


Fig. 7. Aerial view of the fountain behind the Palau de la Música. Breeze direction and weather station positions.

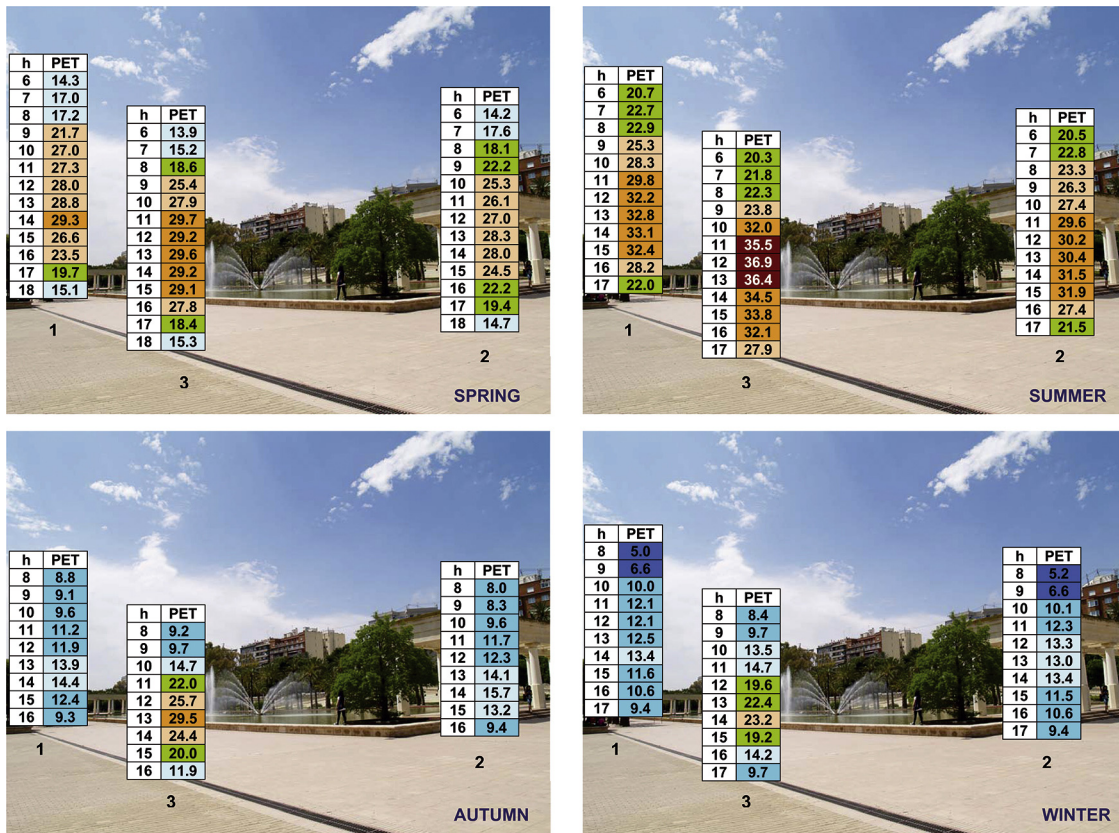


Fig. 8. PET values obtained at different times of the day (h) at the three meteorological stations (shown by points 1, 2 and 3) placed around the fountain at the Palau de la Música.

Table 4

Albedo values obtained from the three meteorological stations around the fountain at the Palau de la Música.

Albedo (%)		
Station 1	Station 2	Station 3
34.2	26.8	57.5
15.0	13.4	46.8
14.5	3.3	41.1
11.9	6.8	41.3
9.1	9.4	41.1
9.2	11.4	40.8
19.1	10.7	41.2
21.3	9.3	41.3
24.0	20.4	45.2
33.1	19.9	55.3

very low percentage of the total radiation it receives, i.e. it retains it without reflecting it back out into the environment. Both the effect of the breezes in the former riverbed of the River Turia and the albedo measurements taken at the three weather stations can be seen in Fig. 7 and Table 4.

The albedo values in Table 4 confirm the hypothesis that for the stations placed over the water, (1) and (2), the albedo was rather lower than was the case for point (3) placed over the paved ground.

The values obtained at points (1) and (2) were not as low as those obtained previously of around 4% (Bretz and Akbari, 1998). We assume that this is due to the currents created by the jets of water of the fountains. They were also found to be lower during the middle of the day due to the more vertical angle of incidence of the sunlight.

We have only compared the values of the stations located in positions (1) and (3) due to the similarity between those of (1) and (2), for the reasons explained with regard to the PET.

However, notwithstanding the foregoing, and given the PET values, the middle of the day in spring and summer should be hotter. The fact that this does not occur is due, we believe, to the presence of the wind, which is channeled right along the course of the old riverbed, where this space is located, encountering fewer obstacles on its way through than it does in other parts of the city. This is

the reason why the hotter values are similar for stations 1 and 3 (in spring and in summer).

5.2. The incidence of trees and orientation on the comfort level of the streets.

The next objective was to establish how the PET index performed in two streets of different orientations, one which has trees and another which does not. The streets in question are Cirilo Amorós and Grabador Esteve, which are part of in a grid pattern of streets dating from the early twentieth century and are located in close proximity to the former riverbed of the River Turia (Fig. 9).

On the one hand, Grabador Esteve street, which does not have trees, has less protection from the accumulation of radiation, in contrast with Cirilo Amorós street which has trees on both sidewalks. On the other hand, as we can see in Fig. 9, Cirilo Amorós street is more open to the wind due to it directly leading away from the former riverbed of the River Turia (which now contains giant gardens), one of the major entry points into the city of the wind. The PET results for both streets, in summer and winter are shown in Figs. 10 and 11.

As we had foreseen, the PET values from Grabador Esteve street are higher in summer and winter. Our interpretation of this is that there is greater capacity for heat accumulation (in the ambient and in the surface) in Grabador Esteve street, which does not have the benefit of the winds which are distorted by the grid-like street network and do not refresh this street. In contrast, Cirilo Amorós street enjoys tree cover, giving rise to a lower radiation value.

However, an important point to note is that the trees benefit Amorós street in one sense, but they are a disadvantage in another, because, as Fig. 10 shows, the foliage is rather thick and low, providing an obstacle to the normal passage of the wind and its cooling power into this street. This is also the case in other streets in Valencia and we believe that this is an important point to take into account: on the one hand, the tree cover is needed to attenuate the solar radiation in summer, but on the other, the wind must be allowed to come into the street and the trees make this more difficult. The only reasonable solution that we can see is for large



Fig. 9. Aerial view of the streets Cirilo Amorós (with trees) and Grabador Esteve (without). Their proximity to the riverbed can be also be seen, where the breezes generally originate from. The figure shows the passage of the breezes, with these being more significant in Cirilo Amorós street and very slight in Grabador Esteve street. This was demonstrated by the wind measurements taken at the time of entry of the breezes.

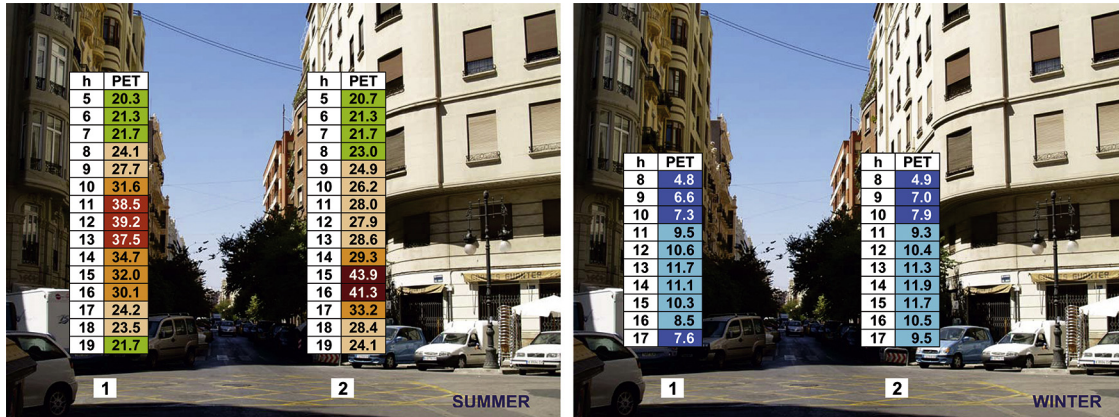


Fig. 10. PET values obtained at different times of the day (h) at the two meteorological stations (shown by points 1 and 2) placed in Cirilo Amorós street.

trees to be planted in these streets whose foliage is further from the ground, some 8 or 9 m, enabling the wind to enter the street lower down and exert its cooling power in summer. If the trees are deciduous, they would not pose a problem in the winter.

This also illustrates the complexity, which we referred to at the beginning of this paper, arising from the urban layout and the distortion of the wind and the subsequent accumulation of heat in other streets.

5.3. Fountains and their surrounding area

Lastly, we turn to our final objective: the effect of the hard or soft ground surfaces on PET values. To this end, the PET index was calculated using meteorological values obtained in two squares in Valencia: the Plaza del Ayuntamiento and the Plaza de la Virgen. Both have a fountain with jets of water, but the former is surrounded by soft ground and the second by a hard surface. The values obtained are shown in Figs. 12 and 13.

The effect of the breeze was noted at both stations, from mid-day onwards. This led to a cooling effect in the area on the right of the Figs. 12 and 13, with the breezes moving from left to right (of these figures). This effect is more pronounced in spring and summer, when these sea breezes are common. In this square, the stations were placed on the lawn surrounding the fountain, i.e. on soft ground with a relatively low albedo, leading to greater absorption of the solar radiation.

In the Plaza de la Virgen, the measurement locations were very similar to those at the Plaza del Ayuntamiento: the stations were placed to the east and west of the fountains and in very similar weather. The difference was that in this square the ground surface is made up of cement tiles: a hard material which is able to withstand the friction and weight of the countless people who come to this square for the different events held there throughout the year. However, these cement tiles have an albedo which is significantly higher ($\pm 32\%$) than the lawn in the other square ($\pm 24\%$): it therefore absorbs less solar radiation.

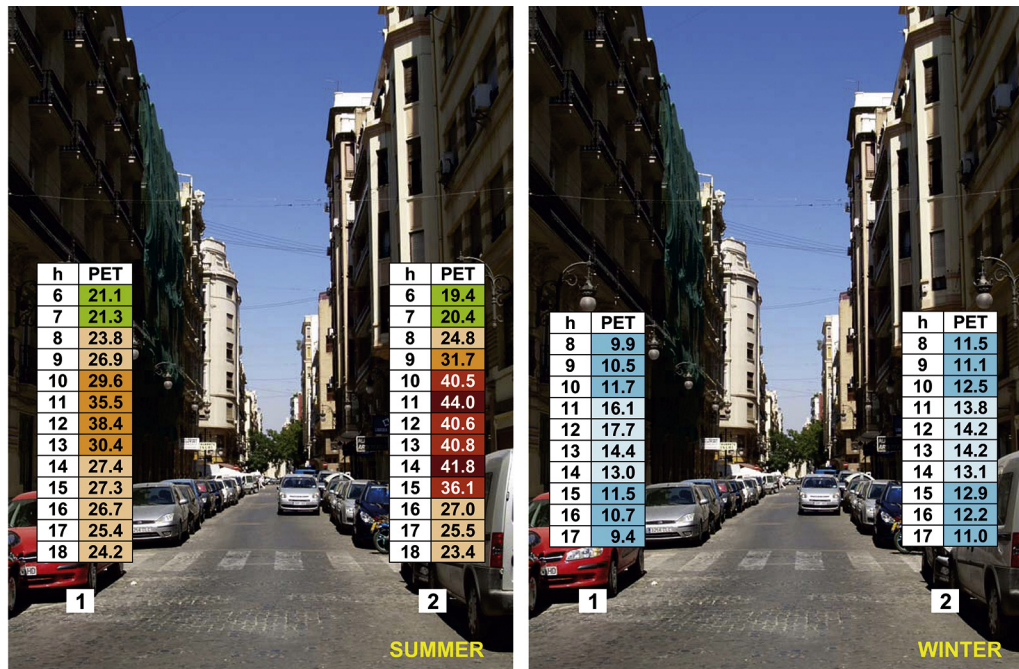


Fig. 11. PET values obtained at different times of the day (h) at the two meteorological stations (shown by points 1 and 2) placed in Grabador Esteve street.



Fig. 12. PET values obtained at different times of the day (h) at the two meteorological stations (shown by points 1 and 2) placed around the fountain at the Plaza del Ayuntamiento.

There is no doubt that the greater albedo of the Plaza de la Virgen leads to the presence of more environmental heat, due to this greater level of reflection. In fact, during the middle of the day in summer, the terraces of the bars which can be seen in Figs. 12 and 13 are frequently empty, despite the fact this is one of the city’s most iconic squares, whereas, in winter, they are often busy with people on sunny days. This is one of the clearest pieces of evidence for the level of comfort provided by an open space in a city: the use made of it.

After checking the results from the sampling sites, this would be a good point to insert a comparative analysis and discussion to clarify the data obtained.

In the Plaza del Ayuntamiento (Fig. 12) it can be clearly seen that the breeze, blowing from left to right after about 12 o’clock in the morning, has a cooling effect on the right-hand side of the fountain, where the temperatures are seen to drop. For example, at different times the temperature from left to right is in summer, respectively (Fig. 12, left): at 12.00 it is 40.8 °C and 39.3 °C, at 13.00 it is 41.4 °C and 38.0 °C, at 14.00 it is 40.8 °C and 37.3 °C, etc. This is confirmed by the increase in relative humidity to the right of the fountain, with RH on both sides as follows: at 12.00 – 58% on the left and 64% on the right, at 13.00 – 56% on the left and 65% on the right, at 14.00 – 58% on the left and 66% on the right, etc.

In the Plaza de la Virgen (Fig. 13) the same effects can be noted, but with two differences: the temperatures are higher (this square is more enclosed) and the type of pavement is different, which influences the albedo) and the differences in air humidity between the

two sides of the fountain are lower, due to the smaller size and dispersion of the water jets. For example, the temperature values on both sides of the fountain (Fig. 13, left) are as follows: at 12.00 – 46.3 °C and 41.3 °C, at 13.00 – 44.1 °C and 41.3 °C, at 14.00 – 43.2 °C and 39.2 °C. As far as humidity is concerned, this is seen to rise on the right-hand side of the fountain, but at a lower rate than in the Plaza del Ayuntamiento, even so, the combination of the breeze and the rise in humidity manages to lower the PET value. The air humidity values on both sides are, respectively: at 12.00 – 51% and 51%, at 13.00 – 51% and 53%, at 14.00 – 51% and 54%, etc.

There is another option with water jets behind the Palau de la Música (Fig. 8). For the two positions on the left and right of the fountain we can see that summer temperatures are as follows: at 12.00 – 32.2 °C and 30.2 °C, at 13.00 – 32.8 °C and 30.4 °C, at 14.00 – 33.1 °C and 31.5 °C, etc. At these same times the air humidity on both sides of the fountain was, respectively: at 12.00 – 65% and 68%, at 13.00 – 66% and 69%, and at 14.00 – 65% and 68%. There is a considerable rise in humidity (possibly due to the size of the water jets) but this does not have much effect on the temperatures because this fountain is situated on the old river bed of the Turia, nowadays the Turia Gardens, and is one of the main entry channels for breezes into the city. Since this is an open space, these breezes are somewhat turbulent and thus do not continuously blow on the water jets in a single direction, as happens in some of the other squares. The micro droplets are dispersed in all directions from the Palau fountain, though predominantly from east to west.

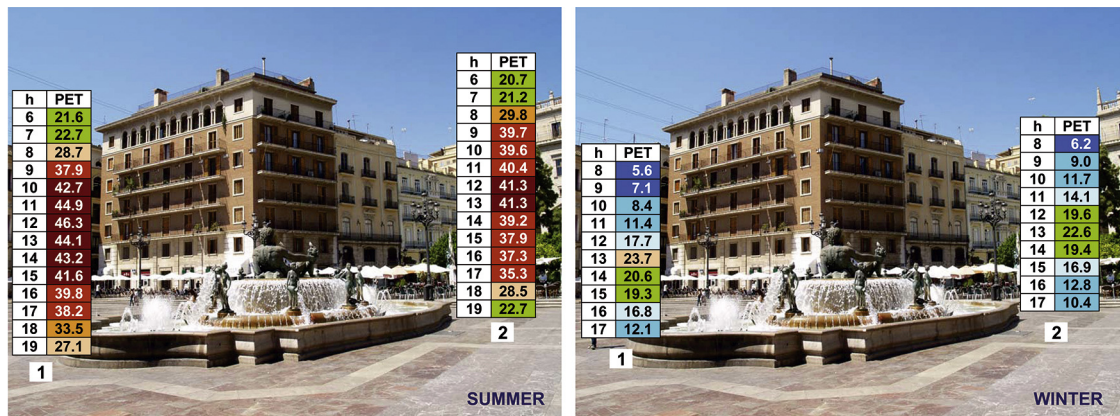


Fig. 13. PET values obtained at different times of the day (h) at the two meteorological stations (shown by points 1 and 2) placed around the fountain at the Plaza de la Virgen.

In all these cases only the midday hours (12.00, 13.00 and 14.00) were taken as examples in summer, since they were the most important locations within the time-range studied.

In the present study we used the PET to determine bioclimatic behavior in different situations within the same urban space with the aim of finding possible urban solutions that help to improve these situations when they are adverse. The PET results serve as indicators for the general public, who can obtain a clear idea of the thermo-physiological conditions that can be expected in a certain place at a certain time and in a certain season of the year.

6. Conclusions

Ponds of water act as cooling elements to their own microspaces, primarily due to evaporation, which is important in spring and summer, as it lowers the temperature. In addition, in the course of our research we found that the water albedo, which is lower than that of the materials surrounding the ponds, helps to keep the temperature down and thus improves the comfort in this area. This is important as such areas are often used as play areas for children and for walks by the elderly.

Streets with trees can be considered to provide greater thermal comfort in spring and summer than those which do not possess this natural barrier to solar radiation. However, in narrow streets, the trees may have a blanket effect and prevent the passage of breezes in those cities where such breezes are frequent. It is important to know the exact, on-the-ground situation of the street with regard to these breezes in order to be able to select the appropriate type and size of tree.

Fountains with water jets, which are very common in the open spaces of the city of Valencia, are not merely decorative. This study, undertaken using PET values taken from either side of the fountains, indicates the importance of ensuring that the design of the water jets takes advantage of the spring and summer breezes, leading to an improvement in thermal comfort in the surrounding area, which is affected by these environmental data.

Architects and urban planners often design squares with innovative decorative elements and hard surfaces. In hot areas, such as in southern Spain and the Mediterranean area, this can lead to places of great heat stress, due to the low albedo of these materials, leading to great solar reflectivity and higher heat load. It is often the case that such squares see little use, especially in summer, due to the enormous amount of heat accumulated by the surface elements. The color of surfaces determines the absorption capacity of the material and this creates an opportunity to make a selection which can create specific conditions in outdoor spaces.

By studying these three objectives, it has been demonstrated that the PET index is mostly appropriate, because it clearly shows great sensitivity to variation in the human-biometeorological parameters, as can be seen in the different figures for Mediterranean climates.

This greater clarity it provides is very important for geographers, urban planners and architects, who are involved in and concerned with finding better designs for the open spaces of our cities, even if they cannot attain specialized knowledge of urban climatology.

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References

- Akbari, H., Pomerantz, M., Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Sol. Energy* 70, 295–310.
- Akbari, H., Menon, S., Rosenfeld, A., 2009. Global cooling: increasing world-wide urban albedos to offset CO₂. *Clim. Change* 94, 275–286.
- Alcoforado, M.J., Andrade, H., Lopes, A., Vasconcelos, J., 2009. Application of climatic guidelines to urban planning. The example of Lisbon (Portugal). *Landsc. Urban Plan.* 90 (1–2), 56–65.
- Ali-Toudert, F., Mayer, H., 2006. Numerical study on the effects of aspect ratio and orientation of and urban street canyon on outdoor thermal comfort in hot and dry climate. *Build. Environ.* 41, 94–108.
- Alvarez, S., Guerra, J., Velázquez, R., 1991. Climatic control applications in outdoor spaces at Expo'92. In: Alvarez, et al. (Eds.), *Proceedings of the Ninth International Passive and Low Energy Architecture (PLEA)*. Architecture and Urban Space, Seville, Spain, pp. 189–194.
- Azorin-Molina, C., Chen, D., Tijn, S., Baldi, M., 2011. A multi-year study of sea breezes in a Mediterranean coastal site: Alicante (Spain). *Int. J. Climatol.* 31, 468–486.
- Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., Tinz, B., 2012. Comparison of UTCI to selected thermal indices. *Int. J. Biometeorol.* 56 (3), 515–535.
- Bretz, S.E., Akbari, H., 1998. Long-term performance of high-albedo roof coatings. *Energy Build.* 25, 159–167.
- Brown, R., Gillespie, T., 1995. *Microclimatic Landscape Design: Creating Thermal Comfort and Energy Efficiency*. John Wiley and Sons, New York.
- Chandler, T.J., 1976. *Urban climatology and its relevance to urban design*. Technical Note WMO 149. Geneva.
- Chirag, D., Ramachandriah, A., 2010. The significance of physiological equivalent temperature (PET) in outdoor thermal comfort studies. *Int. J. Eng. Sci. Technol.* 2 (7), 2825–2828.
- EEA, 2012. Report: Creating a quiet environment.
- Eliasson, I., 2000. The use of climate knowledge in urban planning. *Landsc. Urban Plan.* 48 (1–2), 31–44.
- Fiala, D., Havenith, G., Bröde, P., Kampmann, B., Jendritzky, G., 2012. UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *Int. J. Biometeorol.* 56, 429–441.
- Gómez, F., Gil, L., Jabaloyes, J., 2004. Experimental investigation on the thermal comfort in the city: relationship with the green areas, interaction with the urban microclimate. *Build. Environ.* 39, 1077–1086.
- Guerra, J., Alvarez, S., Rodríguez, E.A., Velázquez, R., 1991. Comfort issues in the outdoor spaces at Expo'92. In: Alvarez, et al. (Eds.), *Proceedings of the Ninth International Passive and Low Energy Architecture (PLEA)*. Architecture and Urban Space, Seville, Spain, pp. 179–187.
- Gulyas, A., Unger, J., Matzarakis, A., 2006. Assessment of the microclimate and human comfort conditions in a complex urban environment: Modelling and measurements. *Build. Environ.* 41, 1713–1722.
- Höppe, P., 1984. *Die energiebilanz des menschen*. Dissertation. Wiss Meteorol, Inst. Univ. München.
- Höppe, P., 1993. Heat balance modelling. *Experientia* 49 (9), 741–746.
- Höppe, P., 1994. Die wärmebilanzmodelle MEMI und IMEM zur bewertung der thermischen beanspruchung am arbeitsplatz. *Dtsch. Ges. Arbeitsmed. Umweltmed.* 34, 153–158.
- ISO, WMO, 1990. *International Standard ISO 9060, 1990(E) and the World Meteorological Organisation Guide*, 6th edition.
- Jendritzky, R., De Dear, R., Havenith, G., 2012. UTCI- Why another thermal index? *Int. J. Biometeorol.* 56 (3), 421–428.
- Johansson, E., 2006. Influence of urban geometry on outdoor thermal comfort in a hot and dry climate: A study in Fez, Morocco. *Build. Environ.* 41, 1326–1338.
- Kántor, N., Unger, J., 2010. Benefits and opportunities of adopting GIS in thermal comfort studies in resting places: An urban park as an example. *Landsc. Urban Plan.* 98, 36–46.
- Kántor, N., Egerhazi, L., Unger, J., 2012a. Subjective estimation of thermal environment in recreational urban spaces – Part 1: investigation in Szeged, Hungary. *Int. J. Meteorol.* 56 (3), 1075–1088.
- Kántor, N., Unger, J., Gulyás, A., 2012b. Subjective estimations of thermal environment in recreational urban spaces – Part 2: international comparison. *Int. J. Meteorol.* 56 (3), 1089–1101.
- Knez, I., Thorsson, S., 2008. Thermal, emotional and perceptual evaluations of a park: Cross-cultural and environmental attitude comparisons. *Build. Environ.* 43, 1483–1490.
- Landsberg, G.H., 1981. *The Urban Climate*. Academic Press, New York.
- Lin, T.P., Ho, Y.F., Huang, Y.S., 2007. Seasonal effect of pavement on outdoor thermal environments in subtropical Taiwan. *Build. Environ.* 42, 4124–4131.
- Lin, T.P., 2009. Thermal perception, adaptation and attendance in a public square in hot and humid regions. *Build. Environ.* 44, 2017–2026.
- Lin, T.P., De Dear, R., Hwang, R.L., 2011. Effect of thermal adaptation on seasonal outdoor thermal comfort. *Int. J. Climatol.* 31, 302–312.
- Lin, T.P., Matzarakis, A., 2011. Tourism climate information based on human thermal perception in Taiwan and Eastern China. *Tourism Manage.* 32, 492–500.
- Lin, T.P., Tsai, K.T., Hwang, R.L., Matzarakis, A., 2012. Quantification of the effect of thermal indices and sky view factor on park attendance. *Landsc. Urban Plan.* 107, 137–146.
- Lin, T.P., Tsai, K.T., Liao, C.C., Huang, Y.C., 2013. Effects of thermal comfort and adaptation on park attendance regarding different shading levels and activity types. *Build. Environ.* 59, 599–611.

- Lopes, A., Lopes, S., Matzarakis, A., Alcoforado, M.J., 2011. Summer sea breeze influence on human comfort during hot periods in Funchal (Madeira Island). *Meteorol. Z.* 20 (5), 553–564.
- López A., 1985. *El clima de las ciudades*. Ed. Arbor.
- Matzarakis, A., Mayer, H., Iziomon, M.G., 1999. Applications of a universal thermal index: physiological equivalent temperature. *Int. J. Biometeorol.* 43, 76–84.
- Matzarakis, A., Rutz, F., Mayer, H., 2007. Modelling radiation fluxes in simple and complex environments: application of the RayMan model. *Int. J. Biometeorol.* 51, 323–334.
- Matzarakis, A., De Rocco, M., Najjar, G., 2009. Thermal bioclimate in Strasbourg – the 2003 heat wave. *Theor. Appl. Climatol.* 98, 209–220.
- Matzarakis, A., Rutz, F., Mayer, H., 2010. Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. *Int. J. Biometeorol.* 54, 131–139.
- Matzarakis, A., Endler, C., 2010. Climate change and thermal bioclimate in cities: impacts and options for adaptation in Freiburg, Germany. *Int. J. Biometeorol.* 54, 479–483.
- Matuschek, O., Matzarakis, A., 2011. A mapping tool for climatological applications. *Meteorol. Appl.* 18 (2), 230–237.
- Morgan, D.L., Baskett, R.L., 1974. Comfort of man in the city. An energy balance model of man-environment coupling. *Int. J. Biometeorol.* 18 (3), 184–198.
- Nicolopoulou, M., Steemers, K., 2003. Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy Build.* 35 (1), 95–101.
- Nikolopoulou, M., Lykoudis, S., Kikira, M., 2004. Thermal comfort models for open urban spaces. *Designing Open Spaces in the Urban Environment: a Bioclimatic Approach, Rediscovering the Urban Realm and Open Spaces, Key Action 4 City of tomorrow and Cultural Heritage from the programme Energy, Environment and Sustainable Development*. European Union, Bruxelles.
- Nikolopoulou, M., Lykoudis, S., 2006. Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Build. Environ.* 41, 1455–1470.
- Nikolopoulou, M., Lykoudis, S., 2007. Use of outdoor spaces and microclimate in a Mediterranean urban area. *Build. Environ.* 42, 3691–3707.
- Ochoa, J.M., Serra, R., 1998. Microclimatic analysis of some urban scenarios. In: *Proceedings of PLEA'98, Lisbon*, pp. 159–162.
- Oke, T.R., 1984. Towards a prescription for the greater use of climatic principles in settlement planning. *Energy Build.* 7 (1), 1–10.
- Oke, T.R., 2006. Towards better scientific communication in urban climate. *Theor. Appl. Climatol.* 84 (1–3), 179–190.
- Olgyay, V., 1963. *Design with Climate*. Princeton Univ. Press, New Jersey.
- Oliveira, S., Andrade, H., 2007. Assessment of the climatic comfort in an outdoor public space of Lisbon. *Int. J. Biometeorol.* 52 (1), 69–84.
- Robitu, M., Musy, M., Inard, C., Groleau, D., 2006. Modelling the influence of vegetation and water pond on urban microclimate. *Sol. Energy* 80, 435–447.
- Sanesi, G., Laforteza, R., Marziliano, P., Ragazzi, A., Mariani, L., 2007. Assessing the current status of urban forest resources in the context of Parco Nord, Milan, Italy. *Landsc. Ecol. Eng.* 3 (2), 187–198.
- Tan, S.A., Fwa, T.F., 1992. Influence of pavement materials on the thermal environment of outdoor spaces. *Build. Environ.* 27, 289–295.
- Tornero, J., Pérez, A., Gómez, F., 2006. Ciudad y confort ambiental: estado de la cuestión y aportaciones recientes. *Cuad. de Geogr.* 80, 147–182.
- Van den Berg, A., Hartig, T., Staats, H., 2007. Preference for nature in urbanized societies: stress, restoration, and the pursuit of sustainability. *J. Soc. Issues* 63, 79–96.
- VDI, 1998. *Methods for the human biometeorological evaluation of climate and air quality for urban and regional planning at regional level*. VDI-Handbuch Reinhaltung der Luft, Bd. 1 b. Beuth Publishing House.