Nuevos aires en la Geografía Española del siglo XXI

New trends in the XXI century Spanish Geography

Contribución Española al 32º Congreso de Colonia 2012

Comité Español de la Unión Geográfica Internacional

Spanish contribution to 32nd Congress Cologne 2012

AGE Asociación de Geógrafos Españoles
CSIC Consejo Superior de Investigaciones Científicas
Instituto Geográfico Nacional cnig
Gobierno de España Ministerio de Fomento

Este libro constituye la Aportación Española al 32º Congreso de la Unión Geográfica Internacional, Colonia 2012

Traducción: Martín M. Barillas
Producción General y Edición: Teresa Albert (IGN) y Laura Carrasco (IGN)
Equipo de Diseño (IGN): Diego Gómez, Laura Carrasco, David Tapiador, Manuel Avendaño y Fernando González
ISBN-13: 978-84-615-8004-0

Thermal stress and urban influence in the Metropolitan Area of Madrid

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Abstract

This contribution evaluates the influence of a large city, Madrid, and their different land uses and urban structures on the regional bioclimatic conditions through the analysis of the spatial patterns of the Physiological Equivalent Temperature (PET).

A clear climatic contrast exists between the urbanized areas and the regional rural background, being PET values of 0ºC (winter) and 34ºC (summer) the boundary between both areas. Within the city, significant differences between three areas have been found: the coolest corresponds to the green areas (PET lower than -2ºC in winter and 30ºC in summer); the central built-up areas, densely urbanized, are the warmest (January PET values are above 0ºC, while summer values increase to 35ºC); finally, an intermediate area, whose boundaries are PET values of 0/-2ºC (January) and 30/35ºC (July), coincides with a less compact urban structure, characterized by wide streets and avenues, small gardens and a significant forestry cover between the buildings and the recreation surfaces.

Key words

Urban Bioclimatology, Physiological Equivalent Temperature (PET), Madrid (Spain).

Introduction

1. Cities constitute the most radical example of man's capabilities of landscape transformation, genesis of a human-made space in which the combination of new materials and large built-up areas modify the radiation balance between the Earth surface and the lower levels of the troposphere. In such an environment, evaporation diminishes, surface runoff decreases and roughness limits the horizontal air exchanges but enhances turbulence. All those modifications become the fundamentals of a specific "urban climate", whose more prominent features are the increase in temperatures in relation to the cooler neighbouring areas and the reduction of wind speed and relative humidity.

2. The Urban Heat Island (UHI) is the phenomenon which better characterizes the urban climate and its interaction with the regional climate and geographical background. Most of their main features, such as its extension and magnitude, varies as a consequence of the meteorological conditions, the density of the urban fabric and the variety of materials and surfaces (Voogt and Oke, 2003; Runnalls and Oke, 2000; Morris *et al.*, 2001; Tomlinson *et al.*, 2010).

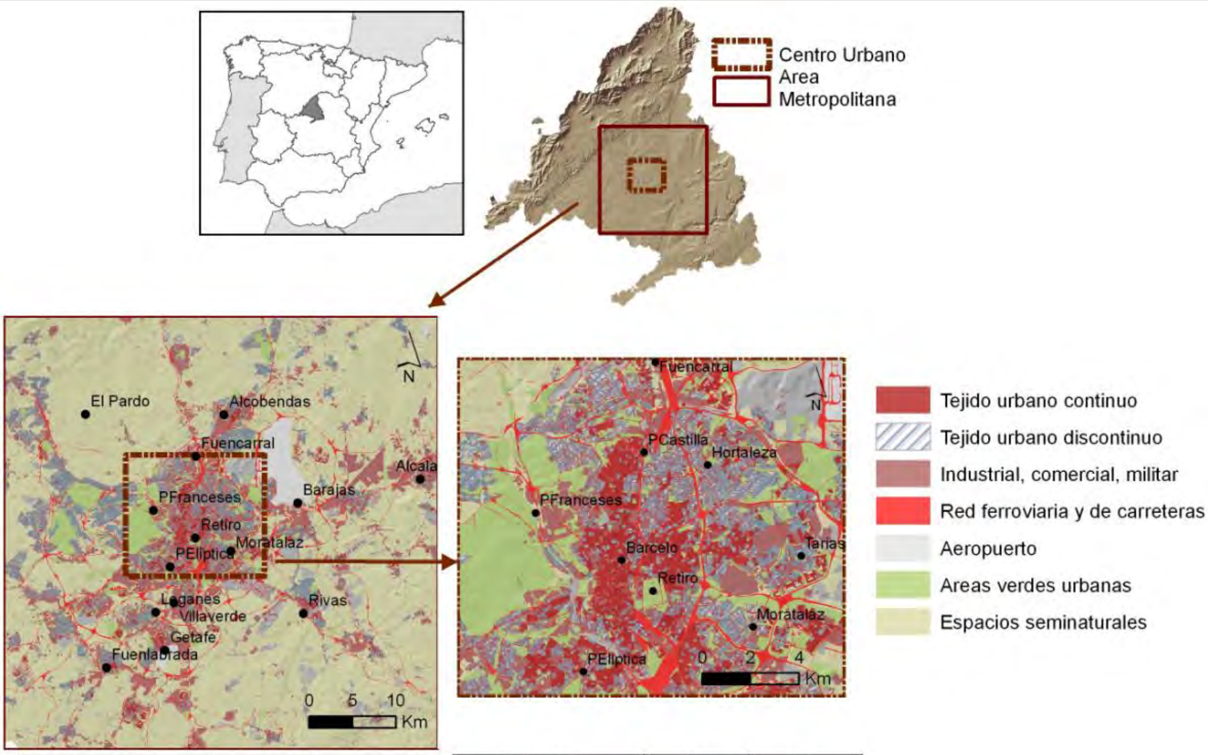
3. The negative impacts of this differential warming manifests especially in summer, when the UHI worsens the thermal stress experienced by the population, which results on an increase of the mortality rates, as the 2003 and 2007 heat waves clearly induced in many European countries (Haines *et al.*, 2006; Vandentorren *et al.*, 2004; EEA, 2008). As an example, mortality rates were 40 % greater during the 2003 heat wave with regard to normal conditions in Madrid, and most of the deaths occurred in neighbourhoods where the intensity of the UHI was maximum (Alberdi *et al.*, 1998; García and Alberdi, 2004; Fernández García, 2009). Another remarkable negative impact is the increase of power consumption for the air conditioning, and the abnormal levels of ozone (Giannakopoulous, 2006; Knowlton *et al.*, 2004). All those impacts are expected to intensify

as a consequence of the ongoing global warming which, according to the projections provided by various institutions and climate models, will continue throughout the 21st century. Simultaneously, the urban population, accounting for slightly more than 50% of the global population at the beginning of the current century, will represent approximately 70% in 2050. Today, urban spaces, occupying less than 2% of the planet's surface, consume more than 75% of the natural resources and expelled more than 80 % of the total emissions of greenhouse gases. Cities, therefore, do not only become areas of maximum risk during extreme climate events, but also the main contributors to CO_2 emissions, partly derived from the high energy consumption rates needed to mitigate the UHI consequences (UN-Habitat, 2011).

4. Bioclimatology, a branch of climatology focusing on the study of the relationship between living organisms and atmospheric phenomena, is currently experiencing relevant methodological changes to face those challenges. One of its high-priority objectives is not only the analysis and characterization of the Urban Heat Island, but also the evaluation of their impacts on human health and comfort, as well as in the search for strategies intended to prevent and subdue such impacts.

Area of study: characteristics and interest

The metropolitan area of Madrid includes a central nuclei, the city of Madrid, with a population well above three million people (3,255,944, in 2009), and several periphery nuclei, ranging from several thousand inhabitants to more than 300,000 people. Altogether, more than five million people are concentrated within an area no longer than 50 km around Madrid, and approximately one million people (roughly 20%) belong to an at-risk population (younger than 5 years or older than 65). The regional climate is Mediterranean (Csa), characterized by scarce precipitation (450 mm) and an intense summer dryness (AEMET– IMP, 2011).



Urban Atlas	Ha	%
Tejido Urbano Continuo	6345,11	2,66
Tejido Urbano Discontinuo	18296,43	7,66
Industrial, comercial, militar	18920,44	7,92
Red ferroviaria y de carreteras	14938,87	6,25
Aeropuerto	3907,37	1,63
Areas Verdes Urbanas	13144,98	5,50
Espacios Seminaturales	163430,74	68,39

Urban Atlas	Ha	%
Tejido Urbano Continuo	2718,40	12,98
Tejido Urbano Discontinuo	4314,98	20,60
Industrial, comercial, militar	2663,35	12,71
Red ferroviaria y de carreteras	3404,34	16,25
Aeropuerto	197,56	0,94
Areas Verdes Urbanas	5263,89	25,13
Espacios Seminaturales	2384,80	11,38

Figure 1. Localization and characteristic of the study area

Nevertheless, the isolation and high altitude (~600 m) of the Southern Spanish Meseta extreme thermal regime, also experiences cold winters (minimum temperatures frequently drop below 0ºC) and hot summers. Moreover, an increasing trend in the frequency and length of the heat waves has been detected (Fernández García and Rasilla Álvarez, 2008). Large sunshine values and low cloud cover and wind speeds, resulting from a dominance of stable conditions, make an ideal scenario for the development of a clearly defined UHI.

Previous studies regarding Madrid`s urban climate go back to the 1980´s, progressing during recent decades to include not only several aspects of the UHI, but also the thermal comfort, atmospheric pollution (López Gómez and Fernández García, 1984; López Gómez *et al.*, 1993; Fernández García *et al.*, 2003; Fernández García, 2001, 2002 and 2005), heat waves (Fernández García and Rasilla Álvarez, 2008; Rasilla Álvarez and Fernández García, 2005; Sobrino *et al.*, 2009) and diverse relating human comfort aspects (Fernández García and Rasilla Álvarez 2009).

Our paper's main objective is to evaluate how the urban spaces in Madrid modifye regional bioclimatic conditions. The bioclimatic conditions are quantified by the Physiological Equivalent Temperature (PET). Consequently, the paper is organized as follows: the first section analyzes the spatial differences in the mean values of PET during the year extreme seasons, at both metropolitan and urban scales; the second section presents the main features of the different bioclimatic regimes obtained from the analysis of the daily thermal sensations; while a focus on the effect of heat waves is the main topic of third section, which ends with a summary of the main findings.

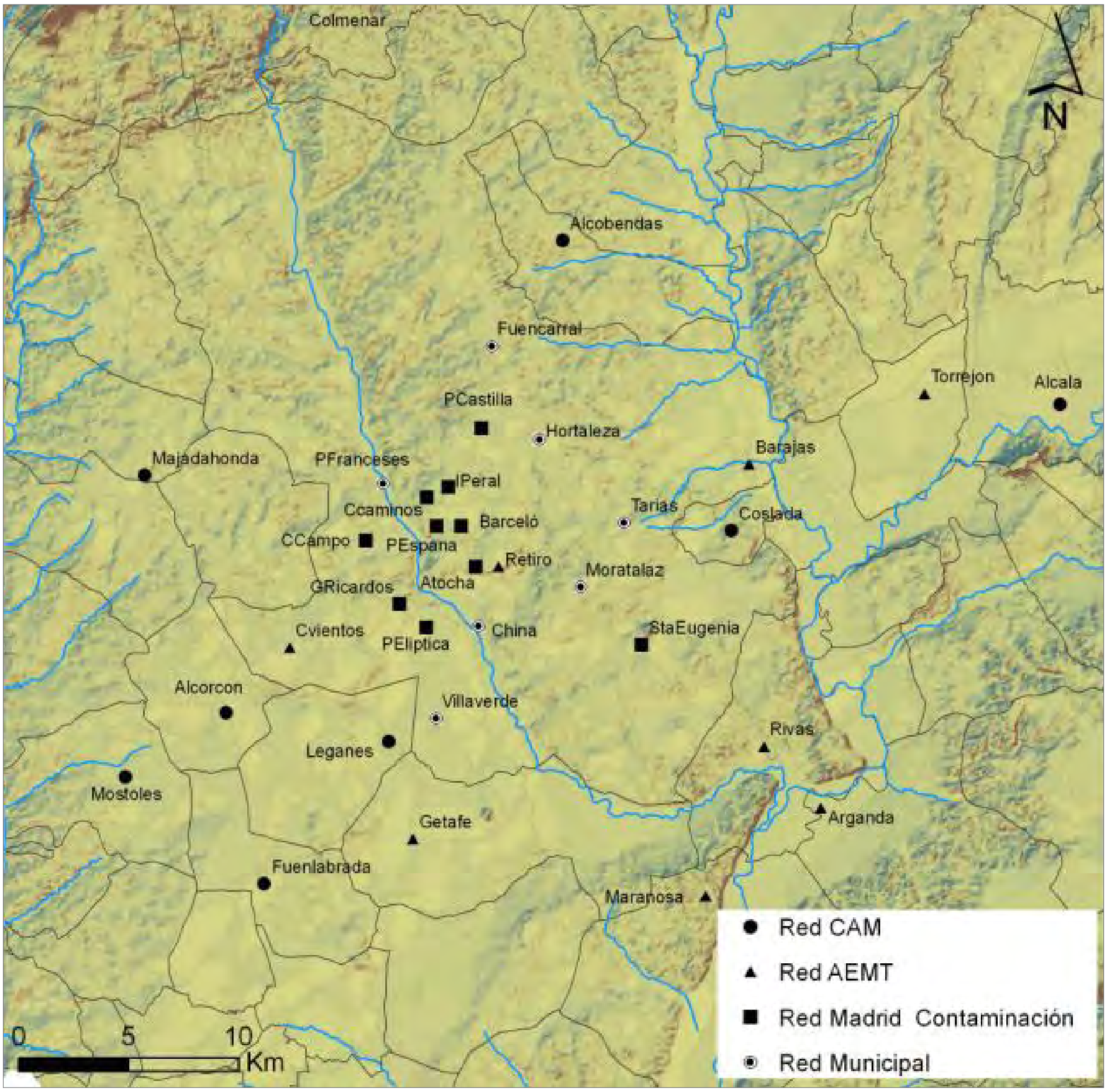


Figure 2. Location of the meteorological stations

Data sources

Our study area comprises the Metropolitan Area of Madrid, which spans over 2,500 km^2, corresponding approximately to the central section of the province of Madrid (Figure 1). Two different databases have been used.

Meteorological databases

The meteorological information was provided by several sources (Figure 2):

- The synoptic network installed by the Spanish meteorological authorities (AeMet), composed by 5 stations: Torrejón and Barajas are two airfields located outside the city, in a almost rural environment, Cuatro Vientos and Getafe can be classified as suburban airfields, while Retiro is not purely urban, since it is located in a relatively large urban park in the core of the city of Madrid. Additionally, three 2nd order stations (only maximum and minimum daily temperatures) have been used (Arganda, La Marañosa and Rivas de Vaciamadrid).

- The networks installed by the Town Council of Madrid (Red de Vigilancia de la Calidad del Aire and Red Meteorológica Municipal) comprises 17 stations in various emplacements which can be considered urban or suburban.

- The network supported by the Regional Authorities of Madrid (Red de Calidad del Aire, Comunidad Autónoma de Madrid), whose 8 stations are located in towns of different sizes.

The data retrieved consisted in daily maximum and minimum values of dry-bulb temperature, relative humidity, wind speed, average cloud cover and radiation, during the period 2002-2004. These data were submitted to a prior homogenisation and validation procedure, following the methodology proposed by Kreienkamp and Spekat (2010), using as reference the observatories from AeMet.

Geographic database

It consists of several layers, in both raster and vectorial format, incorporating a Digital Terrain Model (DTM) and a land use layer provided by the URBAN ATLAS project (European Agency of Environment; GMES, 2010). Compared with previous databases (Corine Land Cover 2006; project AUDIT, carried out by the Area of Urbanism of the Town Council of Madrid, 2008), the URBAN ATLAS provides higher resolution cartography of more than 300 large cities of the European Union. The 19 original land uses categories were regrouped in five groups:

1. Built-up urban spaces, split in three subcategories (urban continuous, urban discontinuous with middle height buildings and urban discontinuous with low buildings).
2. Urban green areas, including the sport and recreational areas.
3. Non- or slightly anthropic (agricultural) surfaces.
4. Road network and associated uses.
5. Industrial and services areas.

Methodology

The studies of the urban climate following a bioclimatic approach are relatively recent because of the lack of representativeness of the traditional comfort indices, devised for in-door spaces (Fernández García, 2003). This drawback has promoted a growing research line looking for new indices able to integrate the complex relationships between human beings and the atmospheric environment in out-door spaces (Pickup and Dear, 1999; Álvarez *et al.*, 1992; Jendritzky and Grätz, 1998), linking those indices with human health and environmental quality in urban areas (Höppe, 1999; Kalstein and Green, 1997; Blazejczyk, 1994 and 1996). The World Meteorological Organisation (WMO) and the International Biometeorological Society (IBS) have joint efforts to design a universal index, easily adapted to different environmental conditions, climate type. etc (Jendritzky *et al.*, 2001, 2002). Additionally, they pursue the establishment of methodological rules to integrate bioclimate-oriented research into the Urban Climatology field, adapting it to new social demands, such as the prevention, at short temporal scales, of the risk conditions associated with extreme climate events, and at longer time scales, for the improvement and adaptation of urbanization processes to environmental conditions.

We adopted the Physiological Equivalent Temperature (PET; Matzarakis *et al.*, 1999) as a comfort index, which is derived from the combination of several meteorological input variables (air temperature, relative humidity, wind speed, radiation). The inclusion of additional variables, such as mean radiant temperature, and the capability of discriminating between the roles of various land uses, especially under very warm conditions, as to thermal comfort, makes PET one of the most appropriate indexes for urban bioclimatic research (Svenson *et al.*, 2002; Andrade, 2003). Human comfort in several cities has

PET (°C)	Thermal sensation	Stress level	January	July
> 41	Sultry	Extreme	> 35.8	> 42.7
35 - 41	Very hot	Strong	29.8 - 35.7	36.7 - 42.6
29 - 35	Hot	Moderate	23.8 - 29.7	30.7 - 36.6
23 - 29	Warm	Light	17.8 - 23.7	24.7 - 30.6
18 - 23	Comfortable	Null	11.6 - 17.7	16.8 - 24.6
13 - 18	Fresh	Light	6.6 - 11.5	11.8 - 16.7
8 - 13	Cool	Moderate	1.6 - 6.5	6.8 - 11.7
4 - 8	Cold	Strong	-2.4 - 1.5	2.8 - 6.7
< 4	Very cold	Extreme	< -2.4	< 2.8

Table 1. Thresholds of the thermal sensations based on PET values (ºC)

Source: (Matzarakis, 1999; Fernández García et al. 2010)

been analyzed using PET as a comfort index (Höppe, 1999; Jendritzky *et al.*, 2002; Gratz *et al.*, 1992; Friedrich *et al.*, 2001; Matzarakis and Rutz, 2005; Gulyas *et al.*, 2003; Fernández *et al.*, 2010). Daily and hourly PET values have been calculated using the RAYMAN software (Matzarakis and Rutz, 2005).

Finally, a set of comfort thresholds were calculated from the Barajas daily time series of PET, taking into account the adaptation to the "normal" climate conditions and the human response in terms of clothing (Table 1); Fernández García *et al.*, 2010). The absolute scale, without adaptation, appears in the first column (Matzarakis *et al.*, 1999).

A basic drawback of the urban climate studies is the lack of appropriate meteorological information inside the cities. The synoptic networks, whose basic objective is the characterization of the regional climate, are designed to ovoid local influences as much as possible, precisely those caused by the urbanization. On the other hand, the *ad-hoc* installation of a network inside a city faces a multitude of problems stemming from the complexity of the urban space (Oke, 2006), which compromises the validity of the observed records. GIS resources have been used lately to transform the specific information provided for a few controlled stations into a continuous meteorological field, balancing at the same time the influence of surrounding surface and land-use characteristics on their spatial variability.

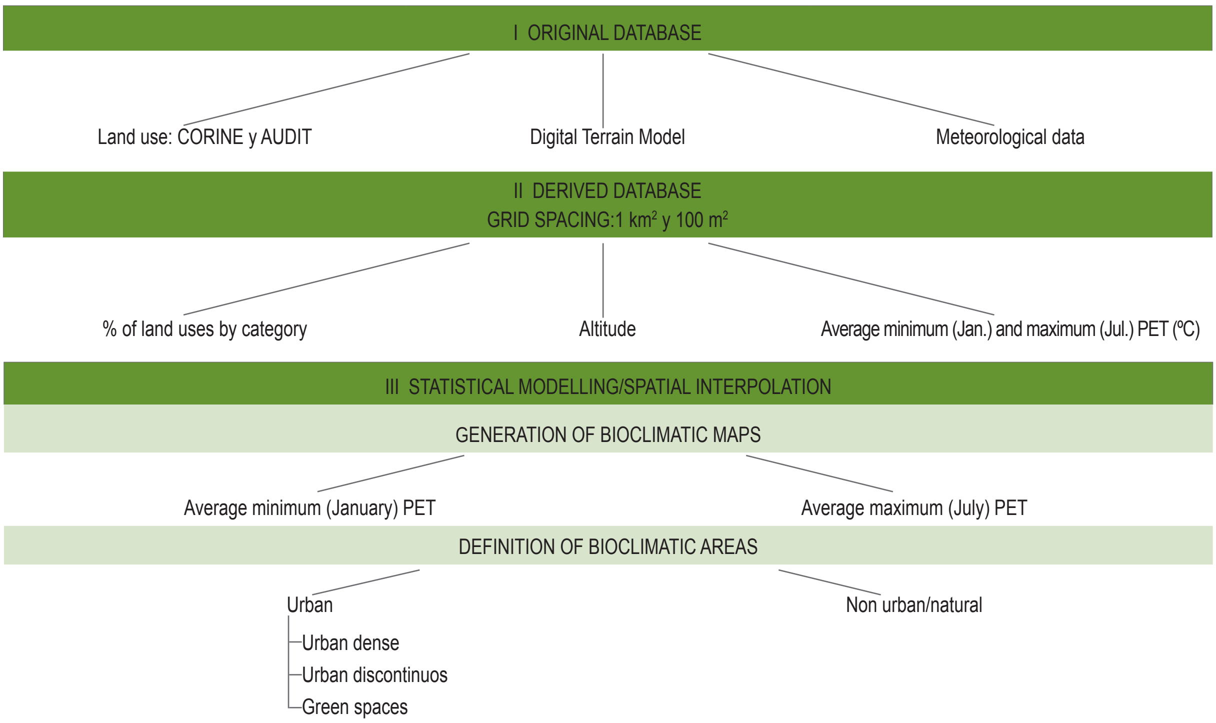


Table 2. Summary

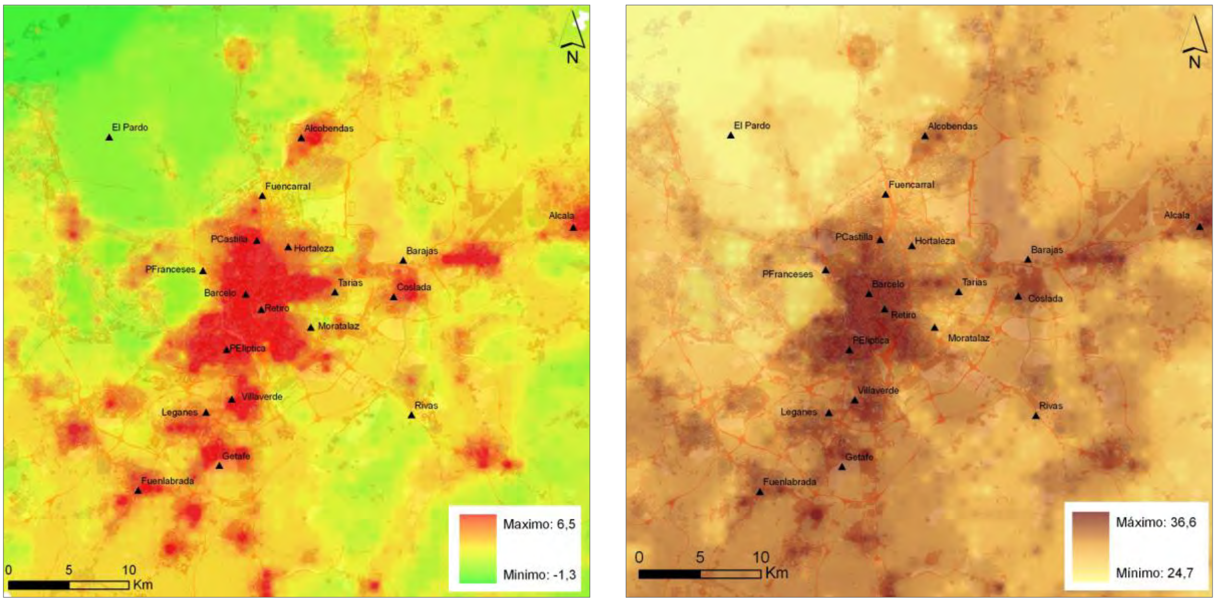


Figure 3. Minimum (January, left) and maximum (July, right) values of PET (ºC) across the Metropolitan area of Madrid

According the objectives of the research, the original databases have been integrated into two reticular grids with different spatial amplitude and grid density: a larger window, with a spatial resolution of 1 km^2 for the whole Metropolitan Area, and another smaller window with a 100 m resolution, restricted to the area of maximum urban density (approximately 240 km^2), using a ArcGis 9.3 Geographic Information System. A stepwise multiple regression technique (Wilks, 1995; Storch and Zwiers, 2002) was used to establish the numerical relations between PET values (dependent variable) and the geographical factors (independent variables), extracting the best group of predictors. The derivation of the models was carried out with the statistical package SPSS.14, following the procedure summarized in Table 2.

Results

Definition of bioclimatic areas

The analysis of the main bioclimatic types was carried out starting from four maps (two corresponding to larger window –Figure 3–, and other two for the city of Madrid –Figure 4–), displaying the spatial patterns of average daily minimum PET (January) and maximum PET (July), derived from the statistical multiple regression model

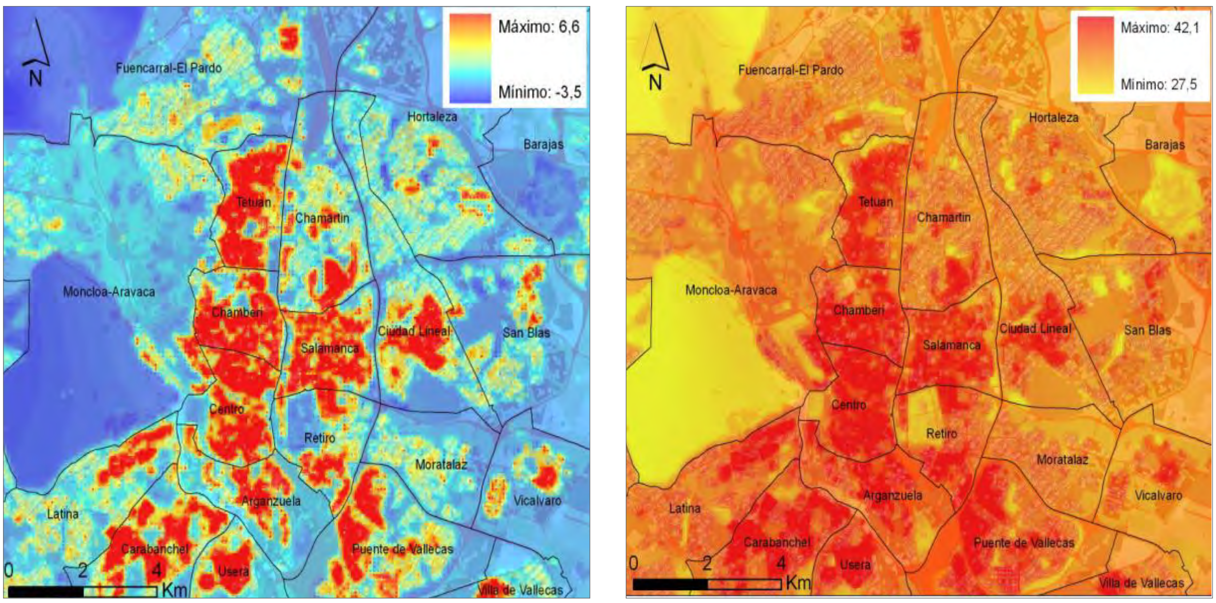


Figure 4. Minimum (January, left) and maximum (July, right) values of PET in Madrid

Average minimum PET January		Average maximum PET July	
Land uses	R^2	Land uses	R^2
Semi-natural	0.695	Urban dense	0.405
Urban discontinuous	0.745	Urban green	0.506
Urban dense	0.773	Seminatural	0.606
Road network	0.780	Urban discontinuous (medium height)	0.619
		Urban discontinuous (low height)	0.624
		Industrial	0.637

Table 3. Partial explained variance (R^2) between PET values and land use by season ($p < 0.05$)

(Table 3). As an example, the model for the largest window explains 78% of the variance in January, loading heavily the fraction of semi-natural and urban surfaces. The determination coefficient is lower in July, although sufficient to explain 63% of the spatial variability of PET, acquiring more importance the density of the buildings and the fraction of urban green areas

Focusing on the largest window, the comparison between PET values of January and July reflects the clear thermal seasonality which characterizes the aforementioned continental nature of the regional climate: a winter season with prevalence of very cold sensations (January PET values oscillate between a minimum of -3.5ºC and a maximum of 5ºC) and a summer with warm sensations (lowest maximum PET is 24.7ºC and the highest 36.6ºC) is the most remarkable feature of the regional bioclimate.

Regardless of the spatial scale displayed, the PET values in both seasons also presents a clear spatial differentiation, feature resulting from the different degrees of built-up density and land uses. Taking a closer look at the Metropolitan Area plots, a warmer archipelago of urban nuclei (highest PET values) corresponds to the most densely urbanized areas, as a consequence of the largest thermal inertia of the buildings and asphalted surfaces, the smallest evaporation and reduced wind speed. The modified thermal balance contributes to increase the long wave emission, represented by radiant temperature. Non-urbanized areas become “cold spots”, a consequence of a reduced radiant temperature and an increased relative humidity, factors enhancing the latent heat consumption.

Besides, it is worth pointing out that, contrary to the classical UHI, whose maximum intensity is usually reached during the night, the “Physiologic UHI” is stronger during the summer daytime hours; for example, the difference between the coldest and the warmest points corresponding to the minimum PET is 8ºC (from -3.5ºC and 5.5ºC), while in summer the maximum PET difference is 11.9ºC (from 24.7ºC and 36.6ºC).

The spatial patterns of PET derived from the smaller window exhibits another typical feature of the urban climates, such as the complexity of the urban space (Figure 4). The most striking element is the noticeable influence of green areas like El Retiro or Paseo del Prado, being drawn as cold spots in winter and cool ones in summer. Equally, some neighbourhoods located at NE (Viso, Arganzuela, Moratalaz y Hortaleza), characterized by extensive vegetation patches among the buildings and streets, break up the continuity of the warmer patch extending throughout the more densely built-up neighbourhoods located between La Castellana Avenue (to the east), and the Manzanares River to the west. The role of the topographically-channelled cold flows in

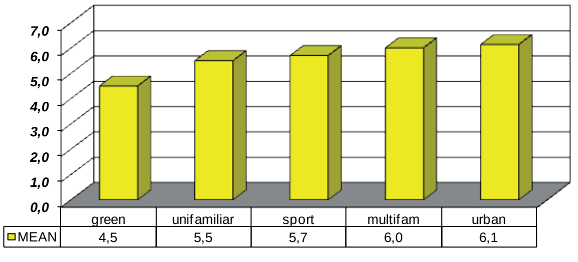


Figure 5. Average values of maximum PET (January) by categories of land uses

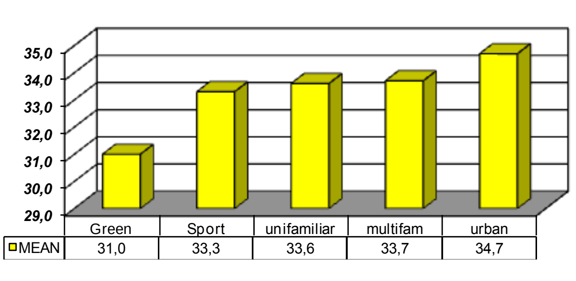


Figure 6. Average values of maximum PET (July) by categories of land uses

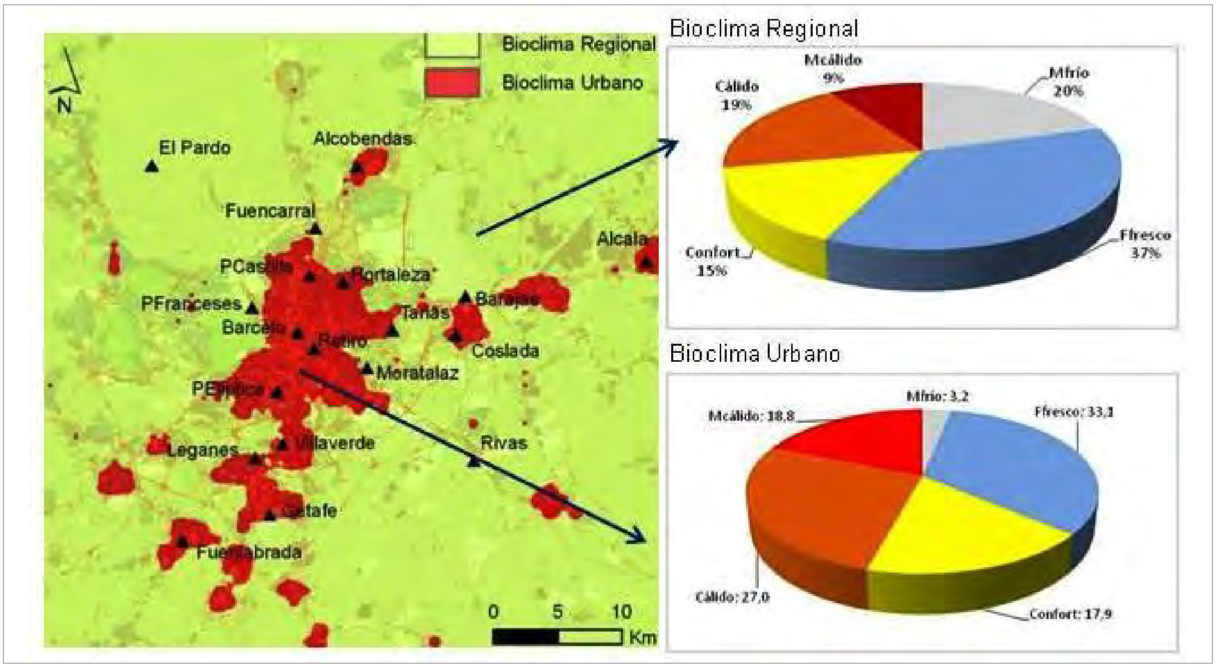


Figure 7. Delimitation and characteristics of the main bioclimatic zones of Madrid´s Metropolitan Area

winter, flowing through the river stream beds southwards, converts the River Manzanares and the Abroñigal Creek into the coldest places in winter, an effect which rapidly vanishes in summer.

Figures 5 and 6 summarize the average values of PET calculated from each category of the main urban land uses. It must be highlighted the relevant role carried out by green surfaces minimizing the summer thermal stress: if the PET calculated for this area is, on average, 1.6ºC lower than the calculated for the urban are in winter, this difference rises up to 3ºC in summer. These results are quite promising, having in mind that our model derives the results from the relative surface occupied by each main land use category. We estimate that better results will be obtained at a higher spatial resolution when additional information is included in the model, such as the height and volume of the buildings, the width and orientation of the streets, or the type and density of the forestry canopy.

Main bioclimate regimes

The spatial distribution of PET during the extreme months of the year allows defining two main bioclimate regimes in the metropolitan area: one corresponding to the areas with weak or even null urban influence, and other typically urban. But inside the latter, a differentiation exist between the more densely urbanized areas, whose PET values are higher, a transition neighbourhoods corresponding to a less dense urban fabric, and finally, a third environment, cooler than the others because of the presence of green surfaces.

Bioclimatic regimes in the metropolitan area

As stated previously, the most relevant feature from the bioclimatic point of view at regional scale is the urban-rural contrast (Figure 7). Conversely, decrease of the cold and remarkable increment of the heat is the distinctive feature of the city: broadly speaking winters can be classified as cool in the urban areas, while summers become warm. In contrast, winters are cold or very cold outside the city, but summers are cooler. As first consequence, the city is confirmed as an area of special vulnerability, because of the high percentage of exposed population (Table 4). Not less important it is the incidence of this thermal increase on energy consumption, especially for the air conditioning during the summer season.

The regional bioclimatic regime, elaborated from the meteorological information available from Madrid-Barajas airport, displays the typical features of a Mediterranean

Bioclimate environment	Very cold	Cold-cool	Comfortable	Warm	Very warm
Airport	20	37	15	19	9
City	3	33	18	27	19

Table 4. Frequency of days by thermal sensation in urban (Madrid) and non-urban (Madrid-Barajas airport) areas

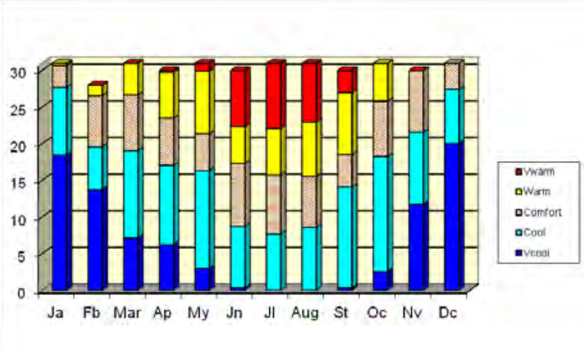


Figure 8. Average bioclimatic regional (Madrid-Barajas airport) regime (frequency of days by month)

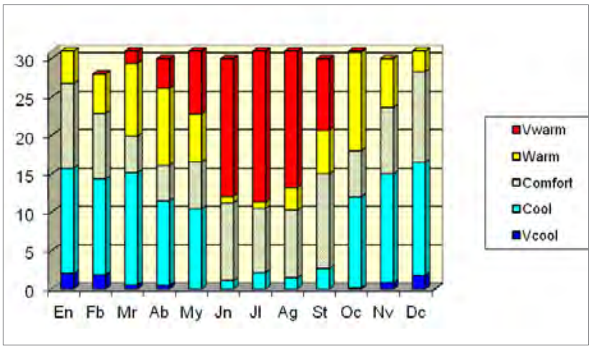


Figure 9. Average bioclimatic urban regime (frequency of days by month)

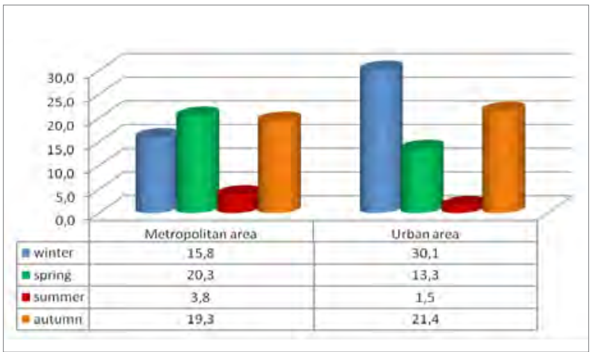


Figure 10. Frequency (%) of comfortable days in urban and suburban areas

continentalized climate: a short but very warm summer and a relatively longer colder season (Figure 8). June, July and August are the months with the maximum hot stress; warm and very warm sensations represent more than 50% of the days. Conversely, from November to March cold and very cold sensations are found more than 40% of the days, with a maximum in January (80%). April and October, May and September are the most favourable period of the year in terms of human comfort, enjoying a very similar bioclimatic rhythm: comfortable or lightly warm diurnal sensations increase, cold nights are less frequent and the number of warm and hot days is still small. Besides, also an increase in the frequency of comfortable nights is observed.

Comparatively, the number of days and the length of period experiencing very cold conditions is shorter in the urban observatories (only from November to February; Figure 9). On the contrary, very warm sensations span from March until September, accounting more than 50% of the days during the summer period (June, July and August).

Although the frequency of comfortable days is, in broad terms, similar (15% and 18%, respectively), they display different annual rhythms (Figure 10). The urban heat island effect increases the number of comfortable days in winter and the end of the autumn, disappearing practically from April until October. Comfortable sensations are more frequent in spring and autumn in Madrid-Barajas. Both areas, however, experience a considerable reduction of comfort sensations during summer.

Bioclimatic regimes within urban areas

The city, as it has been already pointed out, is not a homogeneous space, being possible to find within it important nuances related to the different degrees of built-up density, presence and size of the green areas etc. Several bioclimatic regimes can be identified inside the city (Figure 11):

Urban type: it corresponds to areas with a high density of buildings and lack of green areas. Relevant bioclimatic conditions are a reduction of cold sensations, compensated by the considerable increase of the warmer sensations, which results into an absence of comfort during the summer months.

Urban attenuate type: located in outlying neighbourhoods of lesser built-up density and important presence of tree-lined areas and small-size gardens. This type experiences a similar number of comfort conditions, but lower frequency of warm days and a higher percentage of cold nights

Bioclimate regimes	Very cold	Cold-cool	Comfortable	Warm-hot	Sultry
Urban	3	36	13	29	22
Urban attenuate	6	33	29	20	12
Green areas	13	30	32	14	11

Table 5. Annual frequency of thermal sensations by category inside Madrid

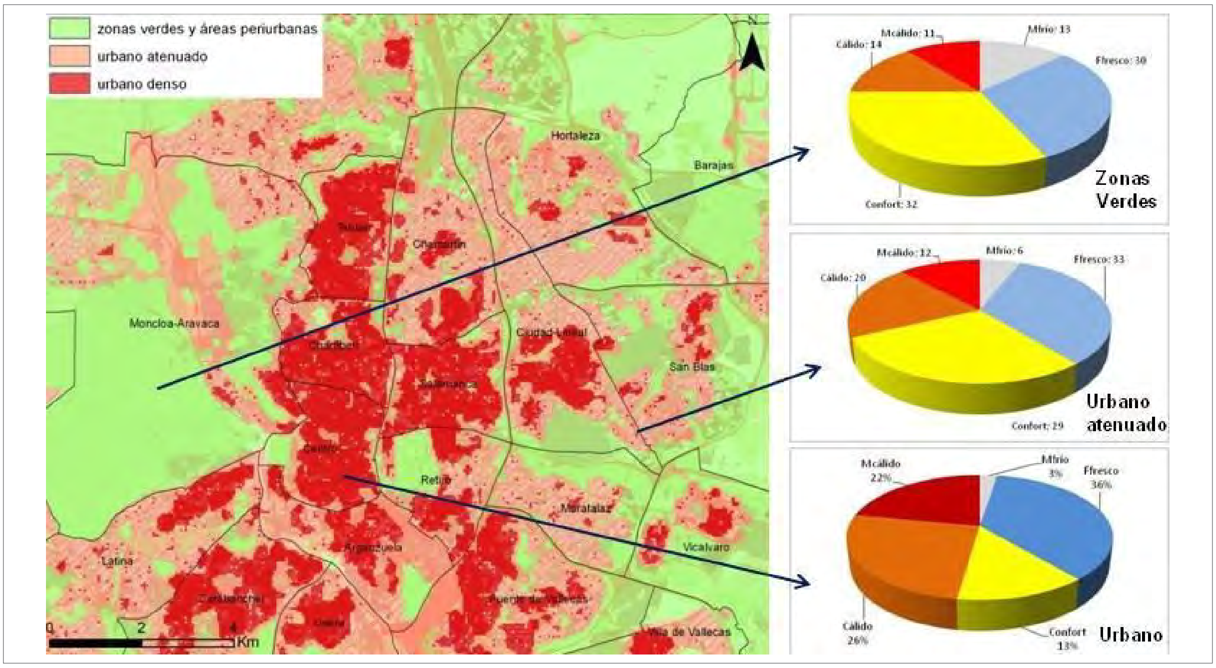
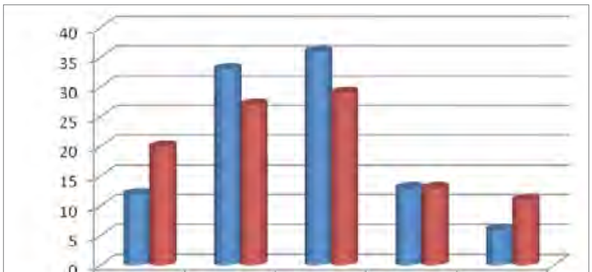


Fig. 11. Delimitation and characteristics of the main bioclimatic zones in the urban area of Madrid



	verycold	cold	Comfort	warm	very warm
Retiro	12	33	36	13	6
CCampo	20	27	29	13	11

Figure 12. Frequency (%) of thermal sensations in an urban park (El Retiro) and a suburban park (Casa de Campo)

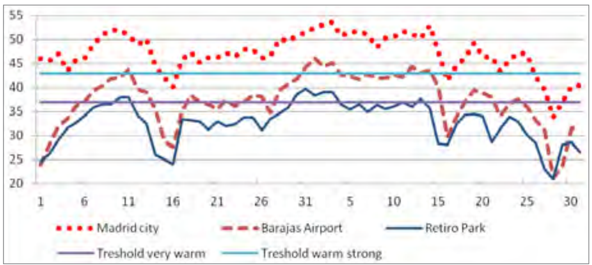


Figure 13. PET máxima diaria en tres observatorios representativos del bioclima de Madrid, durante la ola de calor de julio y agosto de 2003

Green areas (parks and forestry urban avenues): this type embraces those areas whose comfort conditions result from the abundance of trees whose shading effect is enhanced by a higher relative humidity. Cold nights are more frequent than in the previous types, but warm nights are less, as well as sultry days.

Built-up density and vegetation are therefore the two fundamental factors of bioclimatic differentiation inside the city (Table 5): green areas and open urbanizations increase considerably the frequency of comfortable sensations and reduce the high thermal stress sensations.

Finally, it is worth mentioning that even inside the green areas, differences are perceptible among urban parks (El Retiro) and those located in the periphery (Casa de Campo). In the latter the urban influence is weaker, corresponding to a larger frequency of cold sensations and an overall reduction of comfortable days, accounting for 5% more sultry days (Figure 12).

Heat waves and thermal stress

Heat is the dominant feature of the summer weather in Central Spain: hot days are frequent and persistent, and only two summers have not registered daily maximum temperatures equal or above 36.5ºC between 1961 and 2010. Moreover, heat waves have experienced a long-term increasing trend in their duration from 1981 onwards, although their intensity has remained stable (Fernández and Rasilla, 2008).

The impact of the different urban structures on local bioclimatic conditions is clear during those events. Figure 13 displays time series of daily maximum values of PET corresponding to the 2003 heat wave, as well as the thresholds which delimitate the extreme and very warm sensations in three distinct neighbourhoods of Madrid. Barceló is located into the most densely urbanized area, El Retiro is one of the largest urban parks of the city, and Barajas is the largest city airport, located approximately 12 km north-eastward.

Local time	Continuos Urban	Park	Discont. Urban
1	21.5	19.7	18.9
2	20.4	18.4	17.7
3	19.5	17.5	16.5
4	18.7	16.3	15.6
5	17.9	15.2	14.9
6	22.2	16.2	19.7
7	27.3	17.7	24.8
8	30.4	20.0	28.5
9	32.2	23.6	31.0
10	35.6	26.7	33.9
11	37.9	28.5	36.1
12	39.8	30.2	37.6
13	41.0	31.5	38.7
14	41.8	32.6	39.4
15	42.2	33.8	39.5
16	40.9	34.0	38.3
17	38.6	33.7	35.6
18	34.9	32.3	31.1
19	30.7	26.2	29.1
20	30.5	25.7	28.0
21	29.5	25.0	26.5
22	26.6	23.5	25.1
23	24.7	23.2	21.7
24	22.5	21.3	20.3

LEGEND

Thermal sensation	Stress level
comfortable	moderate
warm	strong
very warm	very strong

Table 6. Average daily cycle of the PET values during July 2003 by urban surface categories

PET values stayed above the extreme threshold almost consecutively from July 1st up to August 24th, when the heat wave began to remit, in the city centre. Outside the city the temporal pattern of PET is similar, but approximately 10ºC lower, only above the extreme threshold during the hottest episodes. The refreshing effect of the urban park kept temperatures almost below both thresholds, except during the two short periods when the intensity of the heat wave was in its maximum.

Summarizing, the city worsens in a remarkable way the summer heat stress in relation to the non-urban areas and such behaviour affects not only the intensity of the heat stress but also its duration: two features that contribute the most to the increase of human mortality during heat waves.

The daily cycle of the PET values also displays some differences associated to the urban space (Table 6). The duration of the worst heat stress conditions was longer in the more urbanized space, encompassing from mid-morning to the dawn (7 hours), instead of 5 hours in the less dense urban spaces, where the maximum levels of thermal stress were only reached in the central hours of the day. Remarkably, no extreme thermal conditions were experienced in the parks, where the comfort period length extended up to 13 hours.

Final remarks

The analysis of some aspects of the Madrid's urban climate through a bioclimatic approach is the main issue of this contribution, which evaluates the effect of some aspects of urbanization upon their inhabitants' well-being. The use of the Equivalent Physiologic Temperature (PET) as bioclimatic index and the integration of climatic and geographical information into a unique database allowed us to identify, at several degrees of resolution, different bioclimatic regimes and to establish their relationship with contrasted land uses. Additionally, an analysis of the frequency, at different time scales (from daily to annual), of the thermal sensations of each bioclimate is also provided.

At the regional scale, the most remarkable finding is the dramatic contrast between the urban space and the nearby rural outskirts, in the form of an archipelago of "hot spots", corresponding to the urban nuclei, in both winter (January) and summer (July). The thermal seasonality of the regional climate clearly exhibits the contrasts between cold/cool sensations during winter and warm and very warm sensations during summer. Decrease of the frequency of cold sensations in winter and increase of the heat is the most remarkable consequence of the existence of the urban areas.

A variety of bioclimatic environments is the most outstanding feature of the urban space, in relation to the heterogeneity of materials, land uses and building structures. Nevertheless, the built-up density and the size of the green spaces become relevant conditioning factors of such diversity, in such a way that an initial diversification results between: a prototypical urban bioclimate, corresponding to the most densely urbanized areas; an attenuated urban bioclimate, observed in areas of low built-up density, tree-lined streets and small gardens; and finally, the urban parks. From the standpoint of human well-being, the two latter turn out to be the most favourable types, since the summer thermal stress, the main risk factor in our area, is greatly attenuated.

As a whole, these results offer a first approach to a comprehensive analysis of Madrid's bioclimate, devoted to the implementation of a Climate-Environmental Information System which might be used as tool for prevention of the effects of heat waves and urban planning in that city.

Acknowledgements

This contribution has been supported by the research project CGL2009-10057 "Clima urbano y confort térmico durante episodios de calor extremo en el área metropolitana de Madrid", funded by the Spanish Ministry of Science and Innovation. The Spanish Meteorological Agency (AeMet), Madrid´s City Council (Red de Vigilancia de la Calidad del Aire) and Madrid's Regional Authority (Red de Calidad del Aire de la Comunidad de Madrid) are also acknowledged for providing meteorological data.

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