Country Report: Urban Climate Research in Spain

Felipe Fernández García
Grupo GEOCLIMA
Geography Department
Universidad Autonoma de Madrid

Alberto Martilli
Department of Environment
CIEMAT, Madrid

Introduction

Of the 46 million people that live in Spain, 76% are in cities of more than 10,000 inhabitants and 50% are in cities with more than 50,000. This urbanization process received a strong boost between 1987 and 2000, when the artificial land cover in the country increased by 29.5%. Such an increase was localised mainly along the Mediterranean coast (within the first kilometre inland, more than the 20% of the land is urbanized), and around the biggest city of the country, Madrid, in the interior (Fig 1). Other large cities are Barcelona (1.5 million), Valencia, Sevilla, Malaga and Zaragoza (all with more than 500,000 inhabitants).

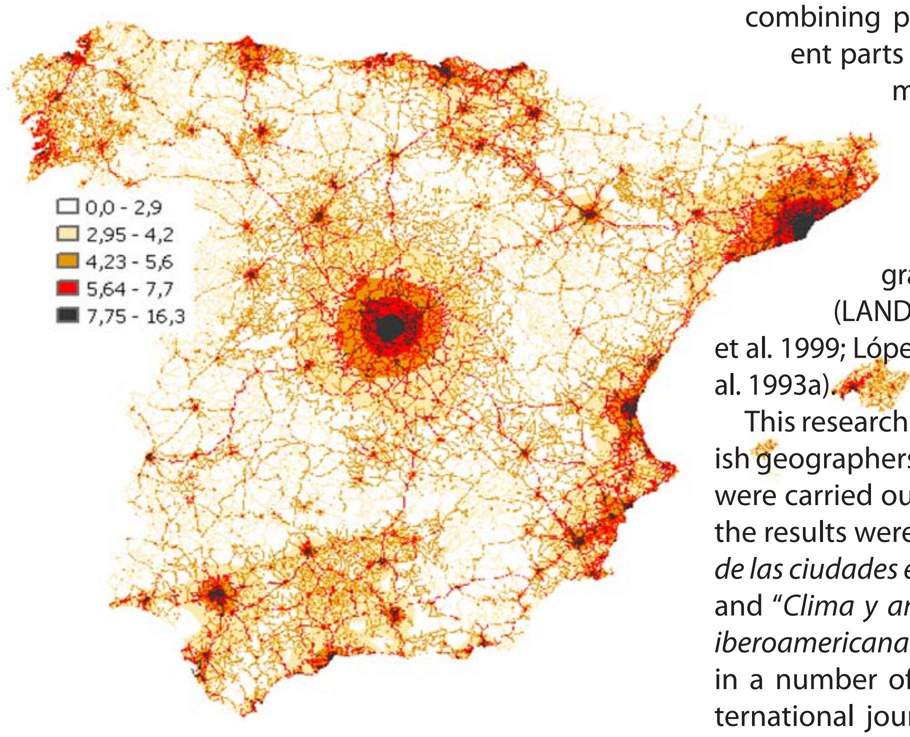


Figure 1. Percentage of artificial land cover (*Source*: Ministry of Environment of Spain)

In Spain there is a wide variety of climates, but the predominant is the Mediterranean, with cold winters and hot and dry summers. The highly frequent stable situations, with strong solar radiation and high temperatures, are the characteristics that best define the climate of the peninsula, and those that most affect the urban climate. Summer temperatures easily reach 30ºC in the majority of the country, and days with more than 36ºC or even 40ºC in the interior are common. These very hot situations are becoming more frequent in the last decade and this tendency is forecasted to continue in the rest of the XXI century.

The first study about the urban climate of Madrid was published in 1984 by a group of researchers from the Department of Geography of the Universidad Autonoma of Madrid and the CSIC (Consejo Superior de Investigaciones Científicas) (Lòpez Gómez and Fernandez García, 1984). The aim of the study was to characterize the Madrid urban heat island (UHI) by combining point measurements, located in different parts of the city and the surroundings, with mobile measurements obtained with instruments placed over cars moving in three principle directions (NS, NE-SW, and NW-SE) (Fernández García, et al., 2003). Later, this information was integrated with images taken from satellites (LANDSAT) and airplanes (Fernández García, et al. 1999; López Gómez, et al., 1990; López Gómez, et al. 1993a).

This research line was soon followed by other Spanish geographers. During the 90s urban climate studies were carried out in several Spanish cities (Fig. 2), and the results were published in two key books: "*El clima de las ciudades españolas*" (López Gómez, et al. 1993b) and "*Clima y ambiente urbano en ciudades ibéricas e iberoamericanas*" (Fernández García, et al. 1998) and in a number of research articles in national and international journals. For example, a combination of point measurements and transects obtained with instruments mounted on cars was used to investigate the urban climate of Granada (Montavez et al., 2000a), Zaragoza (Cuadrat et al., 2005; Vicente Serrano et al., 2005), and Barcelona (Moreno, 1994; Matín Vide et al., 2003), among others.

Today several groups, together with the Geography Department of the Universidad Autonoma (Madrid),

Figure 2. Spanish cities where urban climate studies have been carried out.

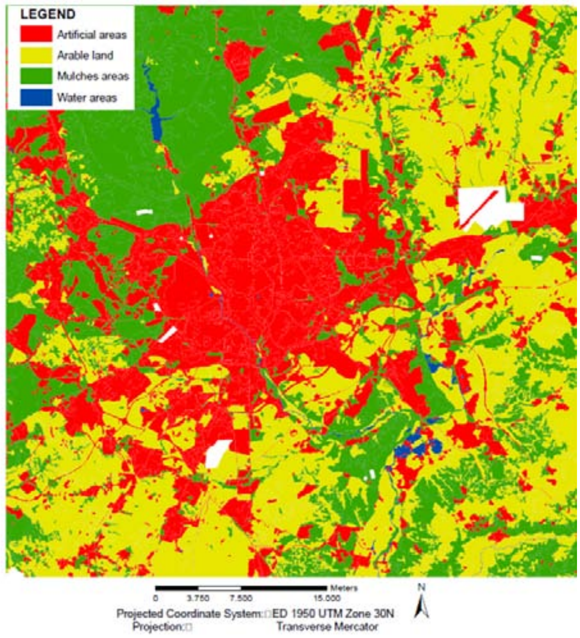


Figure 3. Land-use in the metropolitan area of Madrid. (source CORINE, 2006)

are active on urban climate – including TECNALIA-LABEIN in Bilbao (Juan Angel Acero), the University of Murcia (Juan Pedro Montavez), and CIEMAT in Madrid (Alberto Martilli). The focus of these researches is not only the urban heat island, but also thermal comfort, energy consumption and their links with air quality and health.

In this contribution we will focus mainly on studies in the region of Madrid carried out by the geographers of the Universidad Autonoma, and we will only briefly describe the main achievements of the other groups.

Relating urban morphology, UHI and thermal comfort during Heat Waves in Madrid

The metropolitan region of Madrid is an area with a high population density (more than 5 million within a radius of 50 km) that has been strongly modified by human activity (30% of the surface is artificial; see Fig. 3). It is located on a Plateau (600-700 m a.s.l.) in the middle of the Iberian Peninsula, with a mountain ridge about 40 km to the NW. Being characterized by a high percentage of anticyclonic situations, it is an ideal location to study urban climate. As mentioned previously, the first studies date back to 1984, but since then, other works on the UHI, thermal comfort, and the influence of Heat Waves on UHI have been published (Fernández García et al., 2010; Fernández García, 2001-2002; Fernández García, and Rasilla Álvarez, 2009). In 2008 the DESIREX field campaign (funded by the ESA, Sobrino et al. 2009) took place in Madrid with the aim of investigating the UHI and Urban Thermography (UT). In 2009, the GEOCLIMA group of the Universidad Autonoma started a project on *Urban climate and thermal comfort during heat wave episodes in the Madrid region*. The aim of the work is twofold: 1) to quantify the impact of urbanization on heat stress during heat waves, by means of an Accumulated Heat Index (time integral of the UHI), and 2) to establish the influence of different urban attributes like building density or green spaces on thermal stress by means of complex bioclimatic indices like PET (Physiological Equivalent Temperature). The main results can be summarized as follows:

a) UHI analysis: Madrid's UHI has been obtained by combining climatic data from different sources like point measurements, car transects, flight data from DESIREX, etc. with land-use and urban morphology data. By using the principal component analysis, a series of indices has been created starting from information on building density and green areas. The high correlation obtained between the Empirical Orthogonal Functions and these indices means that it is possible to build the spatial structure of the UHI starting from urban morphological data (Fernández-García et al, 2003). Figure 4 shows the results obtained with this methodology for 0400 LST on the 26th of June 2008 for surface temperatures (computed from the airborne data of the DESIREX campaign), and urban canopy temperatures. At this time, the surface UHI is 19.3°C, while the canopy UHI is 13.6°C. In both cases the hottest areas are those more heavily urbanized, and the coldest those with more vegetation.

b) UHI during Heat Waves. To understand if UHI exacerbates the heat waves, the intensity of the UHI for

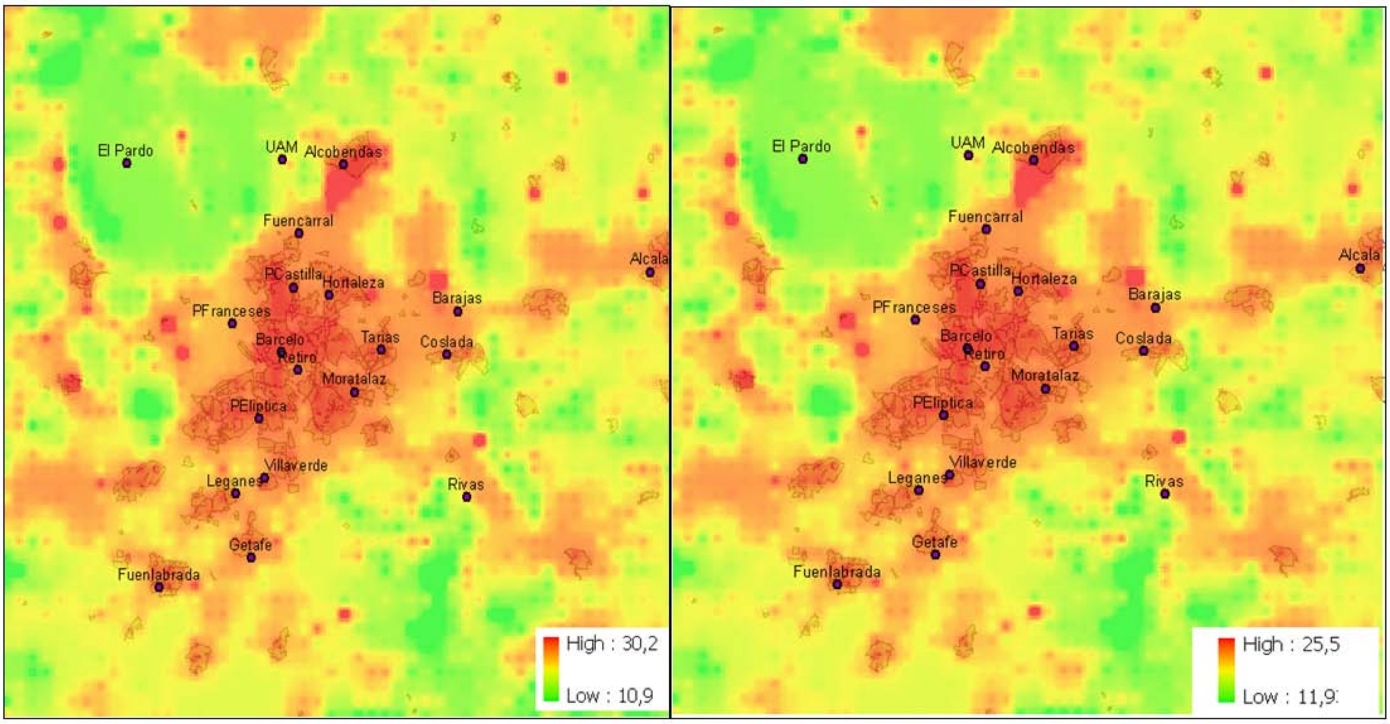
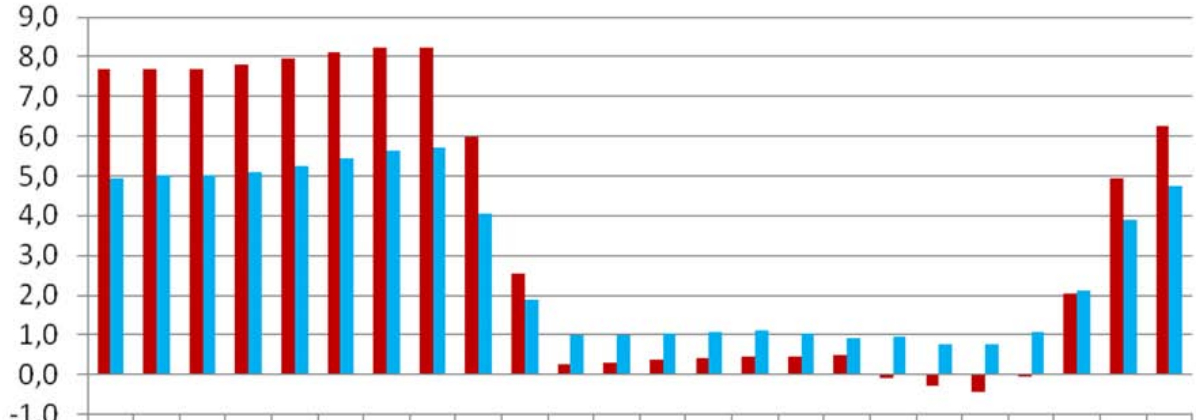


Figure 4. Soil Surface Temperature (left) and air temperature (right) in the metropolitan area of Madrid at 0400 LST for the 26-06-2008 (Fernández García, 2010).



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
UHI_Hw	7,7	7,7	7,7	7,8	8,0	8,1	8,2	8,2	6,0	2,5	0,3	0,3	0,4	0,4	0,4	0,5	0,5	-0,	-0,	-0,	-0,	2,0	5,0	6,2
UHI_summer	4,9	5,0	5,0	5,1	5,3	5,5	5,6	5,7	4,1	1,9	1,0	1,0	1,0	1,1	1,1	1,0	0,9	0,9	0,8	0,8	1,1	2,1	3,9	4,8

Figure 5. Average UHI intensity time evolution during all the summer days (blue) and the heat wave days (red) (2004-2007).

days with maximum temperature of more than 36.5ºC was analyzed and compared against the rest of the summer days. Results show that during heat wave periods, the strength of the daytime UHI is slightly reduced compared to normal summer days, but the nighttime UHI is significantly stronger (Fig. 5, Table 1).

c) Characterization of the thermal comfort regimes in Madrid. The PET has been computed with RAYMAN (Matzarakis et al. 2000; Matzarakis et al. 2007) for the metropolitan area of Madrid, based on meteorological data (maximum and minimum temperature, wind

Table 1. UHI intensity during all summer days, and during heat wave days (maximum temperature at Barajas Airport higher than 36.5ºC).

UHI intensity	Max. temp		Min. temp	
	summer	>36.5	summer	>36.5
<2ºC	99	100	34.7	11.0
2-4ºC	0	0	44.9	47.0
4-6ºC	1	0	19.7	40.2
>6ºC	0	0	0.7	1.8

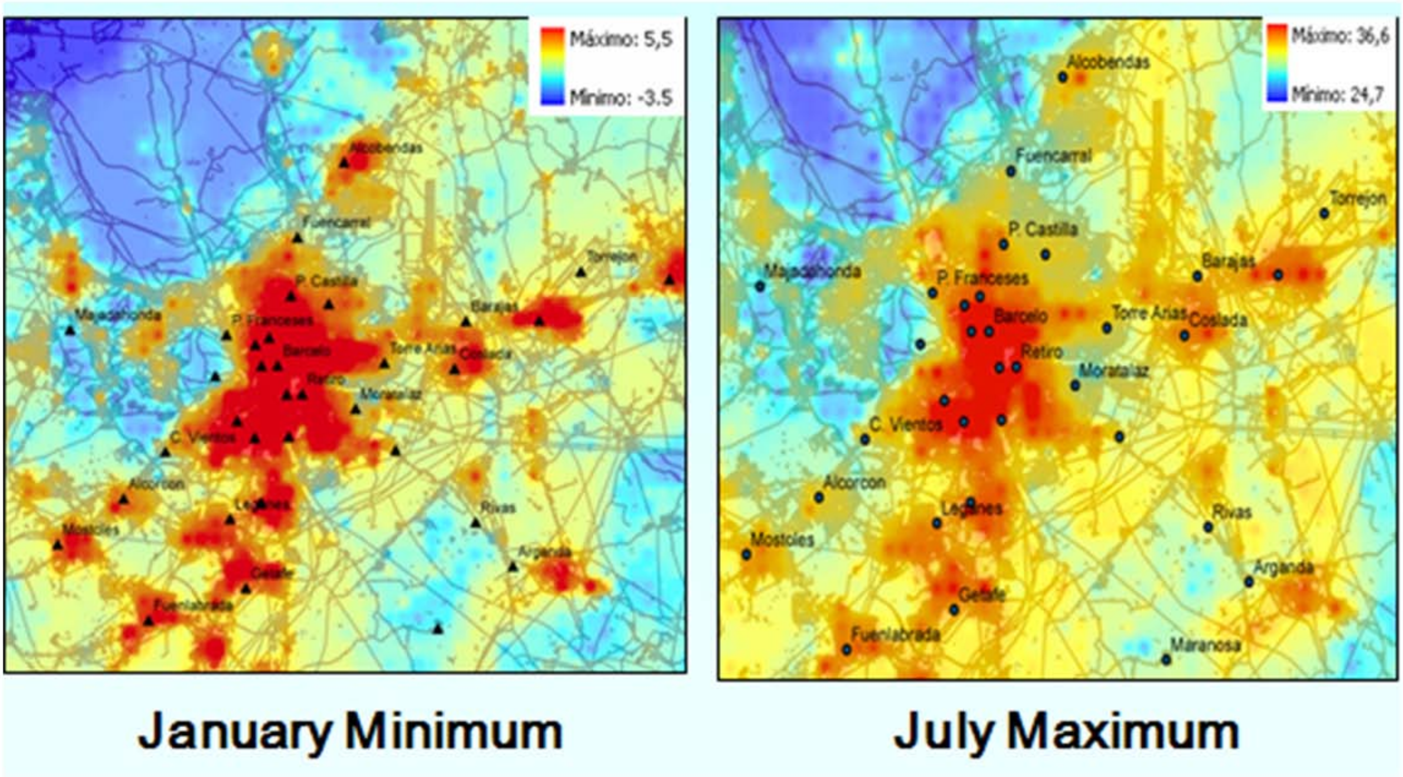


Figure 6. Minimum PET in the metropolitan area of Madrid during January (left) and Maximum PET during July (right), for the period 2002-2004 (Fernández-García, F. 2009)

speed, maximum and minimum relative humidity, radiation, cloud cover), and type of clothing. The PET map (Figure 6) shows an archipelago of hot spots associated with the urban areas. In winter, values oscillate between -3.5ºC and 5ºC, while in summer the lowest maximum PET is 24.7ºC and the highest 36.6ºC. One of the most remarkable features that can be seen in the map is the difference between the very hot SW part of the city, very dense and with little vegetation, and the relatively cooler N and NE parts, which are residential and with a larger percentage of green areas. The importance of vegetation can be seen even more clearly in the spatial distribution of the extremely hot days (Figure 7), where the cool footprint of the *Parque del Retiro* (a large urban park with an extension of 118 acres) is prominent. Based on this study three urban bioclimatic zones can be established based on the urban morphology: 1) very hot for the very dense urban areas with scarce vegetation, 2) hot for the low density residential areas with some vegetation, and 3) relatively cool for the urban parks. The differences between these three zones are exacerbated during the heat waves. For example, during the heat wave of 2003 (Figure 8) the maximum PET computed for the dense urban area was above the extreme heat threshold (*umbral extremo*) nearly for the whole period studied (July and August). On the contrary, in the residential neighborhood of Barajas only occasionally the PET exceeded the extreme threshold, and finally in the urban park of Retiro, the maximum PET never exceeded the extreme value, and only on a few occasions the very hot value (*umbral muy cálido*). Based on this, we can conclude that the urban impact on climate in Madrid increases during the heat waves.

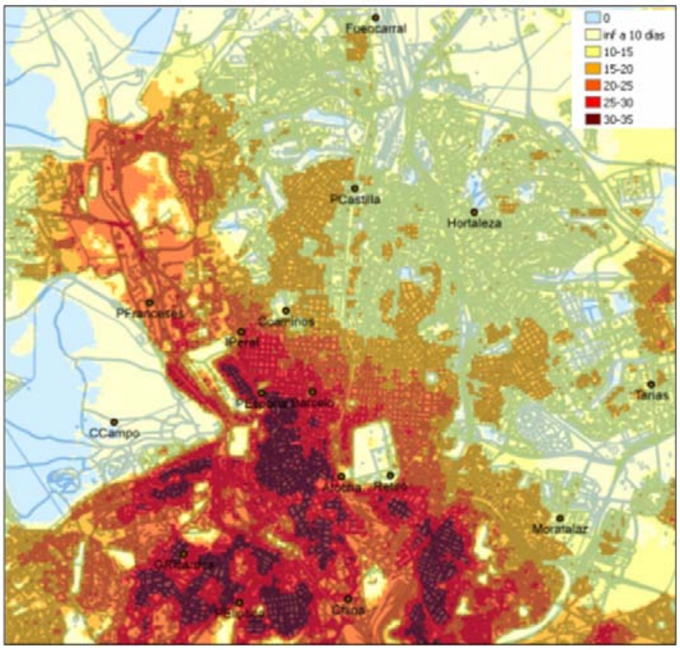


Figure 7. Spatial distribution of the extremely hot days in Madrid (2002-2004) (Fernández-García, 2009).

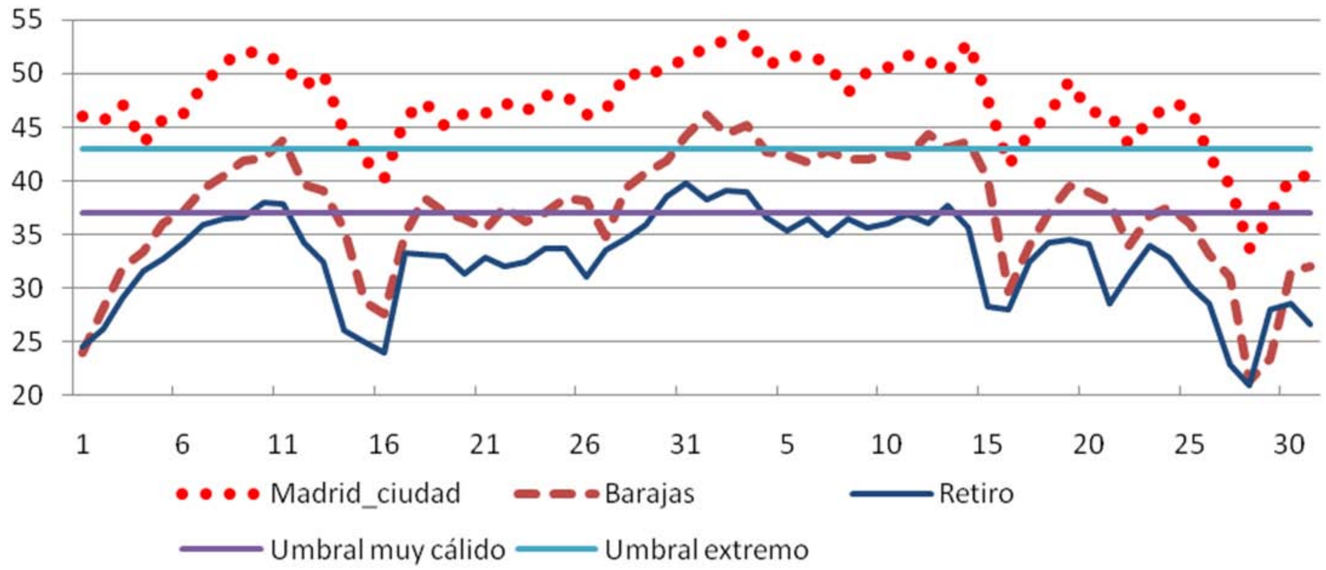


Figure 8. Maximum daily PET for an urban station (red dots), a residential station (brown dashed), and an urban park (solid blue) for the heat wave of July and August 2003. (Fernández-García, 2009).

Urban climate map reconstruction

The studies carried out by Tecnalia (in Bilbao, in particular by Juan Angel Acero) in collaboration with Kassel University (Germany) focus on a new method to develop Urban Climate Maps (UC-Map). These maps aim to translate urban climate information into urban planning recommendations. The method is easy to apply and is based on GIS calculations. It requires urban climate expert knowledge to evaluate ventilation issues, and also measurement campaigns inside the Urban Canopy Layer to validate/calibrate the GIS calculations. Finally, the UC-Map shows different climatopes (i.e. areas with relatively homogeneous climatic variables) and presents urban planning recommendations in order to improve actual thermal comfort and prevent future problems. The concept of UC-Map was firstly developed in Germany and is now applied also in other countries (Ren et al., 2010). In Spain this mapping has firstly been carried out in Bilbao where the influence of sea breezes and complex terrain, together with cold air drainage flows, have shown an interesting case study. In this case three measurement campaigns were carried out along the urban area combining stationary with mobile devices. Considering spatial scale limitations of the UC-Map, additional microscale studies have been done to evaluate the influence of vegetation, shadowing, building orientation etc. This is an important aspect, since the inclusion of urban climate in urban planning requires a muti-scale spatial approach.

Urban climate modelling studies

The impact of cities on local climate has been also studied in several Spanish institutions by using mesoscale atmospheric models. For example, researchers from the Universities of Murcia, Granada and Madrid have used MM5 (Montavez et al., 2003) to simulate the Madrid region, and found that the Katabatic winds induced by the mountain ridge NW of the city extend the urban temperature perturbation several kilometers downwind of the city itself.

In CIEMAT (Madrid), urban climate research is carried out by using the Weather and Research Forecast model (WRF) adapted for urban areas (Chen et al. 2010). The main contribution of CIEMAT to this model is the implementation of a multilayer urban canopy parameterization (Martilli et al., 2002) linked to a simple Building Energy Model (Salamanca et al., 2010). Thanks to this module, key features that characterize urban climate can be simulated: shadowing and radiation trapping in the street canyon, heat storage in the buildings, and exchanges of heat between the interior and exterior of buildings, including heat flux due to air conditioning. Moreover, the BEM module can provide the electric consumption due to space cooling. The WRF-urban model has been applied to study the Madrid metropolitan area during a few days of the DESIREX campaign in summer 2008 (Salamanca, et al. 2011). Results show that the model is able to capture the UHI correctly as compared with available measurements, and that the impact of the heat ejected by the air conditioning systems on the atmosphere can reach up to 1.5-2^{o}C in some parts of the city in late afternoon (Fig. 9). These results open the door to future studies of the interactions between urban climate, energy consumption and air quality.

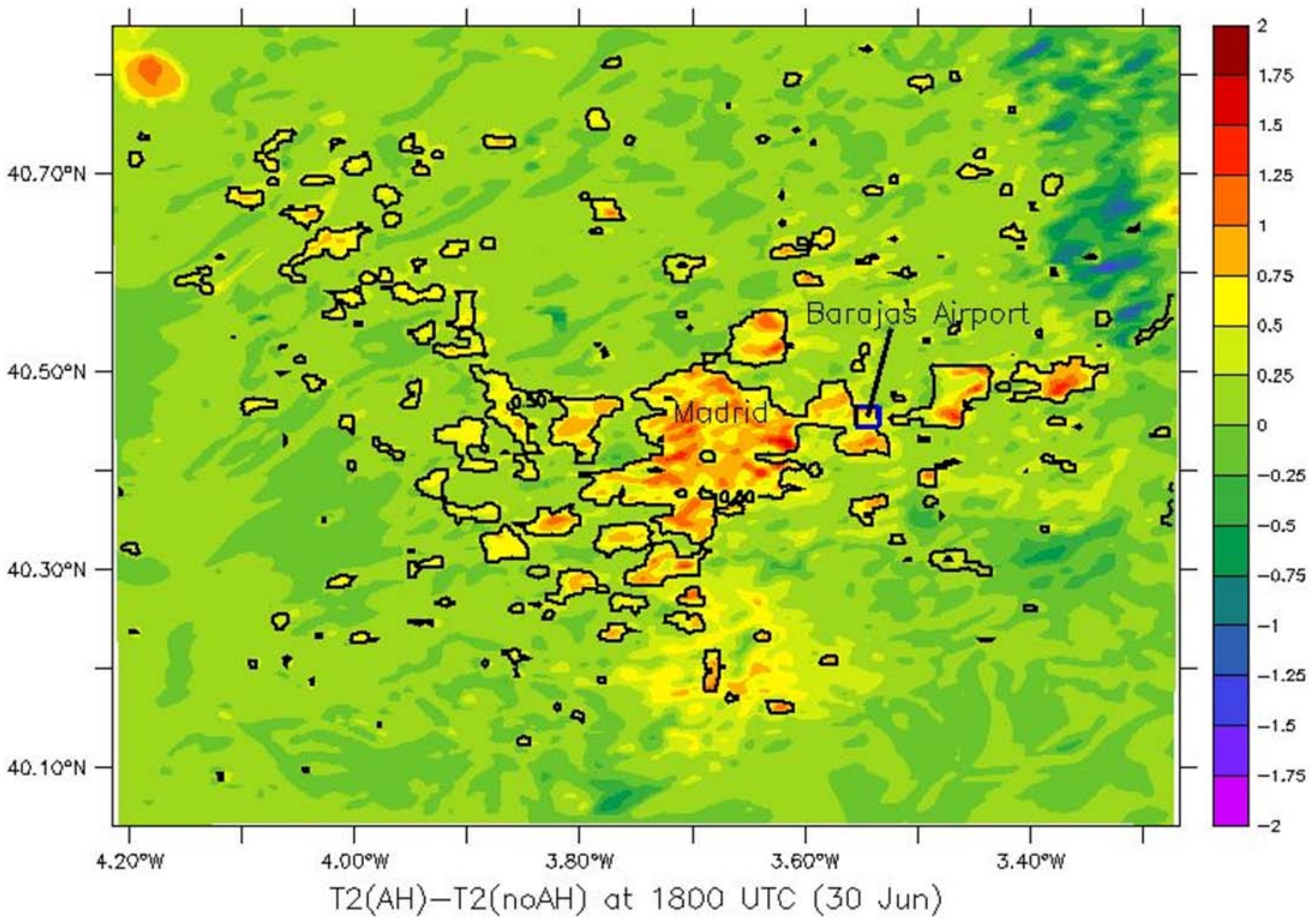


Figure 9. Differences in 2 m temperature at 1800 UTC (2000 LST) on the 30th of June, between a simulation with air conditioning systems ejecting heat to the atmosphere and not ejecting. Results obtained with WRF-urban (Salamanca et al., 2011).

Tecnalia (Bilbao in particular, Iratxe Gonzalez) in collaboration with the Danish Meteorological institute (Denmark) is using Enviro-HIRLAM (Environment – High Resolution Limited Area Model), which is an online coupled numerical weather prediction and atmospheric chemical transport modelling system. The Interaction Soil-Biosphere-Atmosphere (ISBA) land surface scheme is modified to include urban effects using the Building Effect Parameterization (Martilli et al., 2002) module and Anthropogenic Heat Fluxes (AHF) extracted from the Large-scale Urban Consumption of energY (LUCY) model of Sue Grimmond, including energy fluxes from traffic, metabolism and energy consumption. The research is focused on the impact of urban sulphate aerosols on specific climatic variables such as air temperature, wind, cloudiness, cloud liquid water content and precipitation, and the assessment of urban influence on the aerosol dispersion, transport and deposition. Air quality and meteorological scenarios at regional and urban scale are devoted to analysing the changes expected over the Basque Country (Spain) and aim to support strategies for impact assessment and adaptation to climate change.

Urban canyon modelling

A model for the urban canyon was built by Montavez et al. (2000b) at the University of Granada. Thermal radiation, conductivity and convection are simulated by means of the Monte Carlo method. The model was satisfactorily tested under ideal conditions and observational data. A strong surface temperature gradient across streets, with the canyon corners up to 4°C warmer than the canyon centre, was found for the deepest canyons.

From the results of this model (Montavez et al., 2008), a simple model for estimating the maximum intensity of the nocturnal urban heat island as a function of the thermal properties of rural and urban areas as well as urban geometry was created. This model permits an easy evaluation of the maximum UHI.

References

Chen, F., Kusaka, H., Bornstein, R., Ching, J., Grimmond, C. S. B., Grossman-Clarke, S., Loridan, T., Manning, K. W., Martilli, A., Miao, S., Sailor, D., Salamanca, F. P., Taha, H., Tewari, M., Wang, X., Wyszogrodzki, A. A. and Zhang, C. (2011), The integrated WRF/urban modelling system: development, evaluation, and applications to urban environmental problems. *International Journal of Climatology*, 31: 273–288.

Cuadrat, J.M. Saz, M.A. and Vicente, S. (2005): Los efectos de la urbanización en el clima de Zaragoza. (in Spanish) *Boletín de la Real Sociedad Geográfica*, 40:311- 328.

Fernández García, F. Galán-Gallego, E. Cañada-Torrecilla, R. editors (1998): *Clima y ambiente urbano en ciudades ibéricas e iberoamericanas*. (in Spanish) Madrid Ed.: Parteluz, 606 pp.

Fernández García, F. et al (1999) : Airborne remote sensing as a tool to study the links between land use and urban heat island, in 3rd *Historical Cities Sustainable Development: The GIS as Design and Management Support*. Siracusa, Italy, 20-21 April 1999. European Comission. Histocity Network.

Fernández García, F. (2001-2002): El clima urbano de Madrid y su influencia sobre el confort térmico. (in Spanish) *Boletín de la Real Sociedad Geográfica*, T. CXXXVII-CXXXVIII, 169-185.

Fernández F., Montávez J.P,. González-Rouco F.J and Valero F. (2003) : A PCA analisys of the UHI form of Madrid (Spain), in *Fifth International Conference on Urban Climate*. Lodz (Poland). 55-58.

Fernández García, F. and Rasilla, D. (2009): Urban enhancement of the heat waves in Madrid and its metropolitan area, en Geophysical Research Abstracts, Vol. 11, EGU2009-6123, 2009. EGU General Assembly 2009 6th Annual Meeting of the EMS/ 6th ECAC

Fernández García, F (2009): Ciudad y cambio climático: aspectos generales y aplicación al área metropolitana de Madrid. (in Spanish) *Investigaciones Geográficas*, 49:173-195.

Fernández-García, F. et al (2010). Caracterización del régimen bioclimático medio del área metropolitana de Madrid mediante la aplicación de la temperatura fisiológica (PET), (in Spanish) in *Clima, ciudad y ecosistemas*, Serie A, 7:505-514.

Fernández García, F. (2010): Cambio climático y espacios urbanos (in Spanish) in *Clima, ciudad y ecosistemas*, Serie A, 7:XVII-XXII. V

López Gómez, A and Fernandez García, F (1984): La isla de calor en Madrid: avance de un estudio de clima urbano. (in Spanish) *Revista de Estudios Geográficos*,174: 5-34.

López Gómez, A. Fernández García, F. et al. (1990): La temperatura diurna en la Aglomeración de Madrid, mediante imágenes remotas. (in Spanish) *Revista de Estudios Geográficos*, 201: 705 – 732.

López Gómez, A, J, Fernández- García, F and Moreno- Jiménez, A (1993a). *El clima urbano. Teledetección de la isla de calor en Madrid.* (in Spanish) Madrid, Ministerio de Obras públicas y Transportes, Serie Monografías. 230 pp.

López Gómez, A., Fernández García, F. et al. (1993b). *El clima de las ciudades españolas*. (in Spanish) Cátedra, Madrid, 268 pp.

Martilli, A., A. Clappier, M. W. Rotach, (2002). An urban surface exchange parameterisation for mesoscale models, *Boundary-Layer Meteorology* 104, 261-304.

Matzarakis, A., Rutz F., and Mayer H. (2000): Estimation and calculation of the mean radiation temperature in urban structures from the point of view of human biometeorology, in *International Congress of Biometeorology & International Conference on Urban Climatology*, Sydney - Australia, Macquarke University.

Matzarakis, A., Rutz F., and Mayer H. (2007): Modelling Radiation fluxes in simple and complex environments – Application of the RayMan model. *Int. J. Biometeorol.* 51:323-334.

Matín Vide, J., Moreno, M. C., Esteban P. (2003): Spatial differences in the urban heat island of the pre and post Olympic Barcelina (Spain). *Fifth International Conference on Urban Climate*. Vol 1, Lodz, 91-102.

Montavez J.P. Rodríguez A. and Jiménez J.I. (2000a): A study of the urban heat island of Granada. *International Journal of Climatology*, 20: 899-911.

Montávez J.P., Jiménez J.I. and Sarsa A. (2000b). A Monte Carlo model of the nocturnal surface temperatures in urban canyons. *Boundary Layer Meteorology*. 96. 433–452.

Montavez , J.P., Gonzalez-Rouco J.F and Valero F. (2003), A study of three-dimensional UHI by using a mesoscale model, *Fifth International Conference on Urban Climate*. Lodz, P2. 16.

Montávez J.P., González-Rouco J.F. and Valero F. (2008) A simple model for estimating the maximun intensity of nocturnal urban heat island. *International Journal of Climatology*. 28. 235-242.

Moreno. M.C. (1994): Intensity and form of the urban heat island in Barcelona. *International Journal of Climatology*, 14:705-710.

Moreno. M.C. (2007): Urban climatology, in: *Spanish climatology. Past, present and future* (Cuadrad and Martín Vide, ed). Prensa Universitaria de Zaragoza, pp. 191-205.

Ren, C., Ng, E., Katzschner, L. (2010). Urban climatic map studies: a review. *International journal of Climatology* 31, DOI: 10.1002/joc.2237

Salamanca F, A Krpo, A Martilli, A Clappier (2010). A new Building Energy Model coupled with an Urban Canopy Parameterization for urban climate simulations—Part I. Formulation, verification and a sensitive analysis of the model. *Theoretical and Applied Climatology* 99, 331-344.

Salamanca, F., Martilli A., Yague C. (2011). A numerical study of the urban boundary layer over Madrid during the DESIREX (2008) campaign with WRF and an evaluation of simple mitigation strategies of the Urban Heat Island. *International journal of Climatology* (accepted).

Sobrino, J. A. and Coauthors, 2009: DESIREX 2008 Final Report Contract no21717/08/I-LG (http://www.uv.es/desirex)

Vicente Serrano et al. (2005): Spatial patterns of the urban heat island in Zaragoza (Spain). *Climate Research*, 30:61-69.