ESTUDOS SOBRE CIDADES E ALTERAÇÕES CLIMÁTICAS

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THERMAL BIOCLIMATIC MAPS FOR PORTUGAL

Andreas Matzarakis, Henrique Andrade, Maria João Alcoforado

Abstract - Thermal bioclimatic indexes can be used for several purposes in applied climatology and biometeorology, since they allow the assessment of the combined effect of all the atmospheric variables significant to the human energy balance. In the present study, thermal comfort and heat stress (using the thermal index physiologically equivalent temperature - PET) are analysed in order to quantify the monthly bioclimatic conditions in Portugal. The maps produced can be used as a basis to assess suitability to tourism activity throughout the year in different regions. Furthermore, the analysis of the PET can deliver information which can assist decision making on various levels, including health and regional planning.

Resumo – Mapas bioclimáticos de portugal continental.
Os índices referentes ao bioclima térmico podem ser utilizados para diversos fins em climatologia aplicada e biometeorologia, uma vez que permitem a avaliação dos efeitos combinados de todas as variáveis atmosféricas significativas para o balanço energético do ser humano. No presente estudo, o conforto térmico e o stress devido ao calor são analisados (utilizando o índice "temperatura fisiológica equivalente", PET) para quantificar as condições bioclimáticas médias mensais em Portugal. Os mapas produzidos podem ser utilizados como base para a avaliação das potencialidades para a actividade turística em diferentes regiões, ao longo do ano e pode apoiar a tomada de decisão a vários níveis, incluindo na saúde e no planeamento regional.

1. Introduction

For the bioclimatic evaluation of a specific location or area, several meteorological parameters are required since a complex evaluation of the effects of climate conditions and thermo-physiological values is needed, in order to describe the effects of the thermal environment on humans. Several models and indices were developed to calculate the extent of thermal stress during the last decades. The earlier bioclimatic indices (Discomfort Index, Windchill, thermohygrometric index-THI) consider only some and simple meteorological parameters (Thom, 1959; Steadman, 1971; Unger, 1999; Matzarakis *et al*., 2004). New models, based on the human energy balance equation, produced the so-called comfort indices - for example Predicted Mean Vote (PMV), Physiological Equivalent Temperature (PET), Outdoor Standard Effective Temperature (OUT_SET*) to evaluate the thermal stress on the human body (Fanger, 1972; Jendritzky *et al*., 1990; Höppe, 1993, 1999; VDI, 1998; Matzarakis *et al*., 1999; Spagnolo and de Dear, 2003). These indices can be applied in different time and spatial resolutions (Jendritzky *et al*., 1990; Matzarakis *et al*., 1999; Koch *et al*., 2005). For example, describing a small area (e.g. surroundings of a building, part of a street), with fine resolution can be useful for architects and urban designers (Matzarakis, 2001; Mayer and

Matzarakis, 1998; Andrade and Alcoforado, 2007). Micro-scale studies (e.g. bioclimatological description of a town) provide data for urban planning (Unger *et al*., 2005). Examining even larger areas (e.g. a whole region or country) has not only scientific value: the results of these studies can be the basis of planning regional recreation and tourism development (Mayer and Matzarakis, 1997; Matzarakis *et al*., 1999; Matzarakis *et al*., 2004).

The aim of this study is to present a bioclimatic analysis of Portugal by means of bioclimatic mapping with the aid of geo-statistical methods. At this scale, application to tourism is particularly useful, considering that tourism is a very important activity in Portugal and that there is a lack of climatic information for that purpose (Alcoforado and Andrade, 2004; Andrade *et al*., 2008).

The present study links geographical information (Hastings *et al*., 1999) with climatological data (New *et al*., 1999, 2000, 2002) in order to generate a spatial distribution of PET values of a region. The calculation of PET is performed with the aid of the RayMan Model, which calculates the thermal indices mentioned above (Matzarakis *et al*., 2000, 2007).

2. Study area and methods

2.1. Study Area

Portugal is located in the western part of the Iberian Peninsula, between 37 º and 42º09’ latitude N and 9º30 and 6º11’ longitude W. Maximum altitude reaches circa 2000 m, in Serra da Estrela (fig. 1); main mountainous areas are in the Northern part of the country and in the inner centre.

Figure 1 – Location map

Although it lies near the Atlantic, its climate is considered “Mediterranean”, as the dry season occurs in the warm half year. This feature is a stress factor for vegetation, but it is regarded as an advantage by tourists, particularly by those seeking seaside leisure activities. Tourism activity represents 4.6 % of Portuguese GDP and 7.8 % of employment (INE, 2007).

Although the dimensions of the country are limited, there are very large climate variations due to latitude, and, to a greater extent, to altitude and distance from the Ocean (Ribeiro *et al*., 1987; Alcoforado and Dias, 2002).

Total annual rainfall exceeds 2500mm on the NW Sierras and the "Cordilheira Central", where frontal activity is increased by altitude. In most of southern Portugal, annual precipitation is comprised between 500 and 700 mm, with minimum values in the Algarve and inner southern Alentejo (fig. 1). Although southern Portugal is dry, very heavy showers can occur, mostly due to deep surface depressions and altitude cut-off lows and cold air advections.

The limit between the more humid and drier areas follows roughly the Portuguese course of the Tagus River. Global radiation decreases gradually from the NW to the SE. There are great thermal contrasts in Portugal, due to the distance from the western coast and the altitude. In the summer, average maximum temperature ranges from circa 20ºC (near the western coast to the North of Lisbon and on the main mountain ranges) to more than 32ºC in the inner parts of the country, exacerbated in valley floors, such as the Douro valley. On the contrary, average minimum winter temperature is highest (circa 6ºC; Ribeiro *et al*., 1987) at the Atlantic shore from the Algarve to circa 39º latitude North and it decreases to the East and on the Mountains (reaching values under 1ºC).

Wind direction varies a lot along the year. In winter, the main wind directions are W, SW and NE, while in the summer wind blows mostly from the N and the NW, being particularly strong and constant on the coastal areas.

2.2. Applied bioclimatic index

In this study one of the most widely used bioclimatic indexes, the PET, is used as an indicator of thermal stress and thermal comfort. PET evaluates the thermal conditions in a physiologically significant manner (Höppe, 1999; Matzarakis *et al*., 1999). It is defined as the air temperature at which the human energy budget for the assumed indoor conditions is balanced by the same skin temperature and sweat rate as under complex outdoor conditions to be assessed. PET enables various users to compare the integral effects of complex thermal conditions outside with their own experience indoors (Table 1). In addition, PET can be used for the whole year and in different climates (e.g. Höppe, 1999; Mayer and Matzarakis, 1997). Meteorological parameters influencing the human energy balance, such as air temperature, air humidity, wind speed and short- and longwave radiation, are also represented in PET values. P*Et al*so considers the heat transfer resistance of clothing and the internal heat production. As it is expressed in a widely known unit (ºC), the results are easily understandable and comprehensible for potential users. This is especially the case for planners, decision-makers, and even the public who might be not familiar with modern human-biometeorological terminology.

Table 1 - Physiologically Equivalent Temperature (PET) for different grades of thermal sensation and physiological stress on human beings (during standard conditions: heat transfer resistance of clothing: 0.9 clo; internal heat production: 80 W) (Matzarakis and Mayer, 1996)

PET (°C)	Thermal sensation	Physiological stress level
	very cold	extreme cold stress
4	……………	………………
	cold	strong cold stress
8	……………	………………
	cool	moderate cold stress
13	……………	……………….
	slightly cool	slight cold stress
18	…………….	……………….
	comfortable	no thermal stress
23	…………….	………………..
	slightly warm	slight heat stress
29	…………….	………………..
	warm	moderate heat stress
35	…………….	………………..
	hot	strong heat stress
41	…………….	………………..
	very hot	extreme heat stress

2.3. RayMan model

RayMan, one of the recently used models of radiation and bioclimate, is well-suited to calculate radiation fluxes (e.g. Mayer and Höppe, 1987; Matzarakis, 2002; VDI, 1998), and thus, all our calculations for T_{mrt} and PET were performed using this model. The RayMan model, developed according to the Guideline 3787 of the German Engineering Society (VDI, 1998) calculates the radiation flux in simple and complex environments on the basis of various parameters, such as air temperature, air humidity, degree of cloud cover, time of the day and year, albedo of the surrounding surfaces and their solid-angle proportions.

2.4. Data

The climatic data used for this analysis was provided by the data collection program at the Climatic Research Unit (UK, New *et al.*, 1999, 2000, 2002). The required data for the thermal bioclimatic analysis, namely air temperature, relative humidity, sunshine and wind speed, are available on a monthly resolution for the climate period 1961 to 1990 and on a ten minute resolution for the specific area. The calculated PET grid values have been used as dependent variable. They have been recalculated into a higher spatial resolution (1 km) through the use of geo-statistical methods (independent variables were latitude, longitude and elevation). For this purpose the digital elevation data of the GLOBE data set (Hastings *et al.*, 1999) was used.

3. Results and discussion

The monthly spatial distribution of PET in Portugal is shown on figures 2 to 13. On the coldest month (most frequently January – fig. 2) PET values ranges from -6 to + 12°C in the investigated area, being very dependent from latitude and altitude. The lower values (under -6ºC) were found on the mountains of the North and Centre. Milder winter conditions (mean January PET near 11ºC) occurs in the southern coast (Algarve, fig.1). The mean PET in January remains above 8ºC also along the central Western coast of the country (from the Algarve to the north of Lisbon), as a result of the effect of the Atlantic Ocean on the attenuation of extremes values, not only of temperature (Daveau *et al*., 1985) but also of PET.

However, patterns of PET are greatly different from these of air temperature (Ta). Winter PET values are usually lower than Ta. The differences are very strong on the mountains, where PET values go down to under -6ºC, while mean Ta values never drop below 0ºC. For example, in the 1510 m high meteorological station of Penhas da Saúde (Serra da Estrela, fig.1), the mean air temperature in January is 1.3ºC (average 1975/85; Mora, 2006). These strong differences in mountainous areas are due to strong wind speed and low solar radiation. In low altitude areas, differences between PET and Ta are usually weaker, with PET 1ºC to 2ºC below the air temperature values; in Algarve, sunny and partly sheltered from the prevailing North winds, mean PET and Ta are very similar. This region concentrates the larger part of the tourist activity of Portugal during winter time, mainly with British tourists.

During springtime, the first area reaching PET values above 18ºC is the eastern Algarve, in May; during this month, PET values varied between 15ºC and 18ºC in southern Portugal and on the central and northern coastal areas; lower values were observed on the mountainous areas (under 7ºC). In June, PET values above 18ºC were generalized to almost the entire country, with the exception of the highlands of northern and central Portugal.

The summer is the main tourist period, all over the country. The hottest months are July and August (figures 7 and 8), with PET values ranging between circa 18ºC and 30ºC. During this season, the main geographical controls are proximity from the ocean and altitude. Along the western coast, PET values range between 22ºC and 26ºC, with a slight increase to the south. In Algarve, values are higher (26ºC to 30ºC) mainly in August and in the eastern part of the region, because of the shelter from the prevailing N and NW winds, that cools the western coast (Alcoforado and Dias, 2002). The inner south has usually very hot days, but relatively cool nights. The resultant mean PET values (26ºC to 28ºC) are therefore lower than in Algarve, where night time is usually hotter and day time cooler. As referred before, altitude is an important climatic factor, with lower PET values (under 20ºC) being recorded in the northern and central mountains.

Autumn cooling is fast: in October (fig. 11), almost the whole southern Portugal still registers PET values above 18ºC (20ºC in the Algarve), while in the highlands of the north and centre of the country the values have already dropped below 15ºC. However, in November, in all the territory but the Algarve (where PET reaches 15ºC), values were below 14ºC, dropping to near 0ºC in the mountains.

Figures 2 to 13 - Mean monthly spatial distribution of PET (period: 1961-1990)

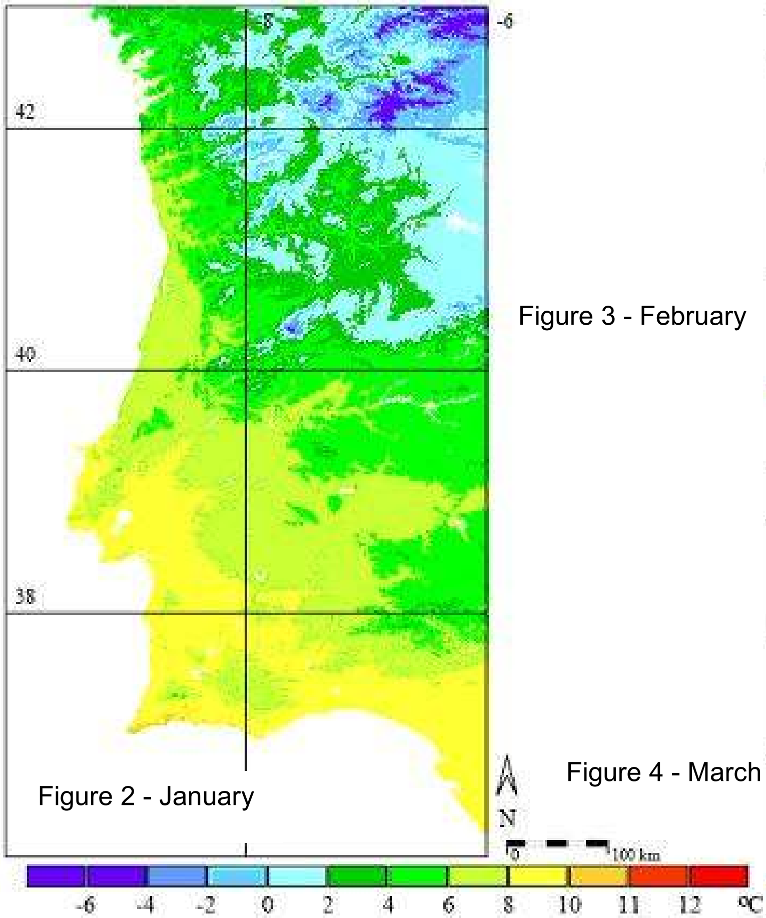

Figure 2 - January

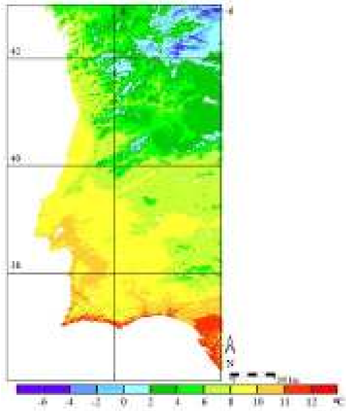

Figure 3 - February

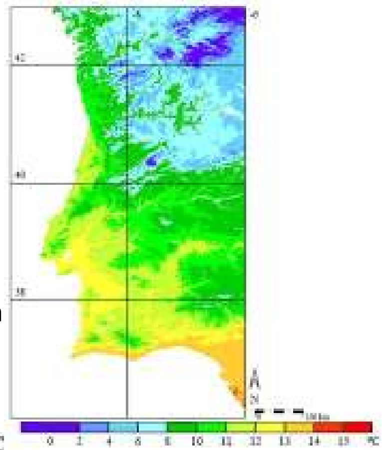

Figure 4 - March

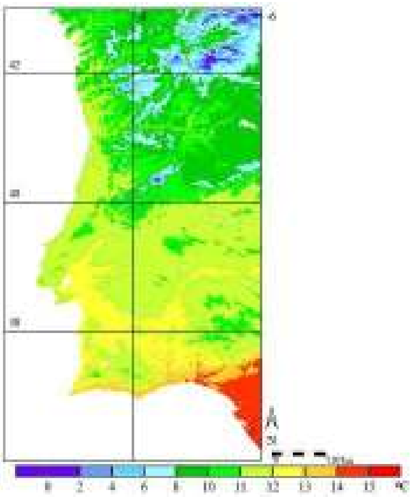

Figure 5 - April

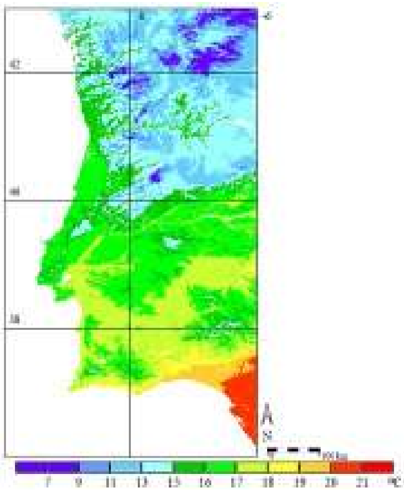

Figure 6 - May

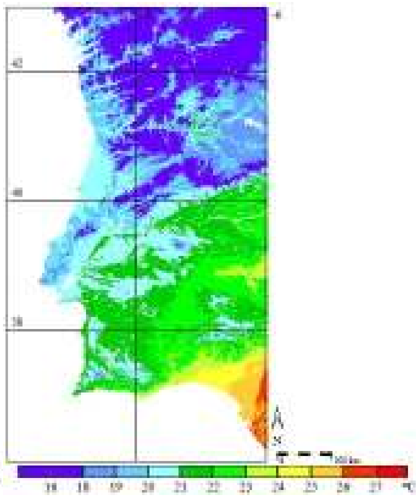

Figure 7- June

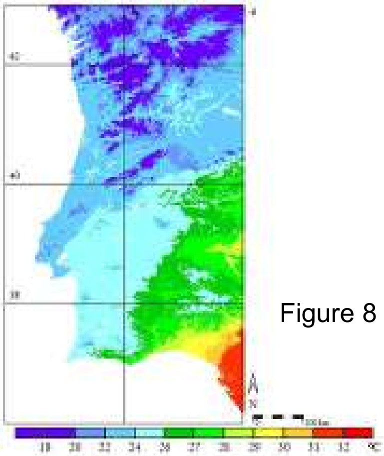

Figure 8 - July

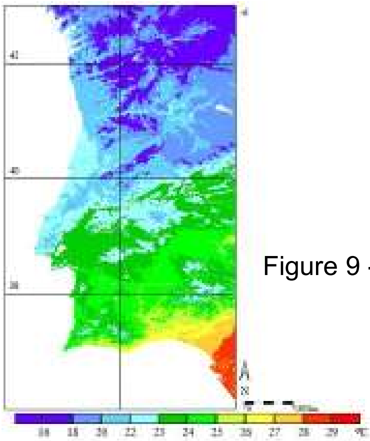

Figure 9 - September

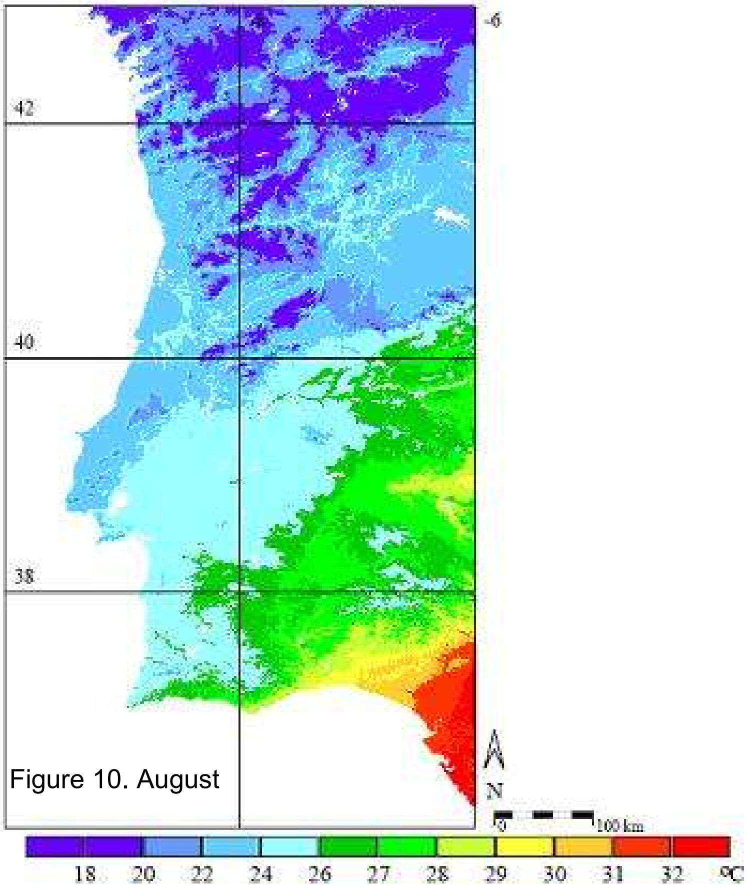

Figure 10. August

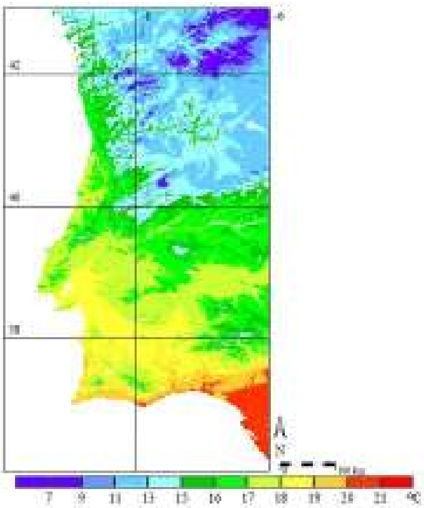

Figure 11 - October

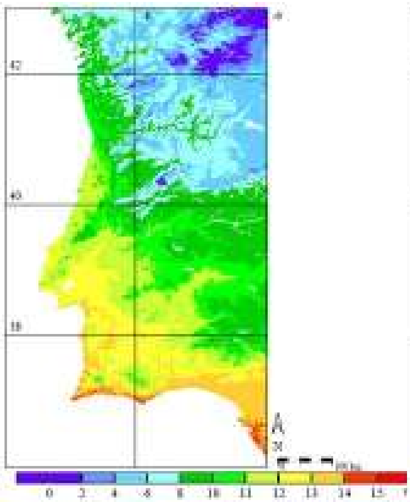

Figure11 - November

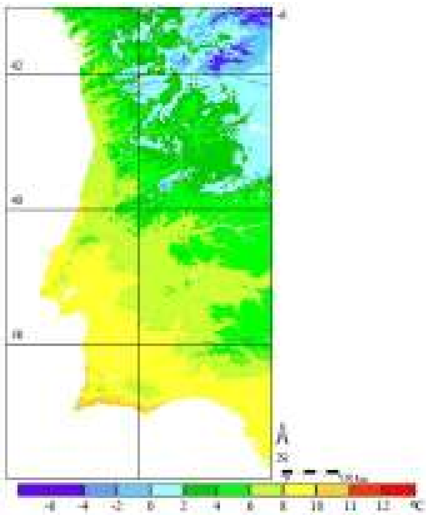

Figure 12 - December

Conclusions

The analysis of the PET, when applied to the present climate conditions, can deliver information which can assist decision making on various levels, including health, tourism and regional planning.

The results presented in this paper have to be considered as preliminary. Additional analyses, based on daily data from other regional models, will permit to describe with greater detail the climate conditions and predict extreme events. Sensible and vulnerable areas can be detected and mapped. This cartography may be helpful in the development of adaptation strategies for tourism planning and protection of tourism facilities in relation to climate change issues. Additional information can be strategic to the detection of spatial development of extreme events, i.e., heat waves in order to develop adaptation strategies to tackle climate change at the regional and urban planning level.

References

Alcoforado, M. J.; Dias, M. H. (2002) – *Climatic maps from Lisbon's region and enquadramento in the climatic diversity of Continental Portugal*. (Coloured maps and a short text in Portuguese) Centro de Estudos Geográficos, Lisboa (CD edition).

Alcoforado, M. J.; Andrade, H.; Paulo, M. J. (2004) - Weather and recreation at the Atlantic shore near Lisbon, Portugal. A study on applied climatology. *In* A. Matzarakis, DeFreitas, C.R. e Scott, D. (ed), *Advances in Tourism Climatology*, Número especial de *Berichte des Meteorologishen Institutes der Universitaet Freiburg*, 12: 38-48.

Andrade, H.; Alcoforado, M.J. (2007) – Microclimatic variation of thermal comfort in a city-district of Lisbon (Telheiras). Night-time period. *Theoretical and Applied Climatology, on line first*.

Daveau, S. *et al.* (1985) – *Climatic Maps from Portugal: Thermal contrasts and Fog and Nebulosity* (in Portuguese, with an extended English Summary). Memórias do Centro de Estudos Geográficos, vol. 7; CEG, Lisboa (+ two coloured maps, 1: 250 000).

Fanger P. O. (1972) *Thermal comfort*. New York, Mc Graw–Hill.

Hastings, D. A.; Dunbar, P. K.; Elphingstone, G. M.; Bootz, M.; Murakami, H.; Maruyama, H.; Masaharu, H.; Holland, P.: Payne, J.; Bryant, N. A.; Logan, T.; Muller, J.-P.; Schreier, G.; MacDonald, J. S., (eds.), (1999) - *The Global Land One-kilometer Base Elevation (GLOBE) Digital Elevation Model, Version 1.0*. National Oceanic and Atmospheric Administration, National Geophysical Data Center, 325 Broadway, Boulder, Colorado 80303, U.S.A. Digital data base on the World Wide Web (URL: http://www.ngdc.noaa.gov/mgg/topo/globe.html).

Höppe, P. R. (1993) - Heat balance modelling. *Experientia*, 49: 741-745.

Höppe P. R. (1999) - The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. *Int J Biometeorol,* 43: 71–75.

INE (Instituto Nacional de Estatística) (2007) *Estatísticas do turismo 2006*, INE, Lisboa.

Jendritzky, G.; Menz, H.; Schirmer, H.; Schmidt-Kessen W, (1990) - Methodik zur raumbezogenen Bewertung der thermischen Komponente im Bioklima des Menschen (Fortgeschriebenes Klima-Michel-Modell). Beitr. Akad. Raumforsch. Landesplan. No. 114.

Koch, E.; Marktl, W.; Matzarakis, A.; Nefzger, H.; Rudel, E.; Schunder-Tatzber, S.; Zygmuntowski, M. (2005) - Klimatherapie in Österreich. Broschüre zu den Potentialen der Klimatherapie in Österreich. Bundesministerium für Wirtschaft und Arbeit.

Matzarakis, A. (2001) - Die thermische Komponente des Stadtklimas. *Ber. Meteorol. Inst. Univ. Freiburg*, Nr. 6.

Matzarakis, A. (2002) - Validation of modelled mean radiant temperature within urban stuctures. *AMS Symposium on Urban Environment*, Norfolk, 7.3.

Matzarakis, A.; de Freitas, C.; Scott, D., (eds.) (2004) - *Advances in tourism climatology.* Ber. Meteorol. Inst. Univ. Freiburg Nr. 12.

Matzarakis, A.; Mayer, H. (1996) - Another kind of environmental stress: Thermal stress *NEWSLETTERS* No. 18, WHO Collaborating Centre for Air Quality Management and Air Pollution Control: 7-10.

Matzarakis, A.; Mayer, H.; Iziomon, M. (1999) - Applications of a universal thermal index: physiological equivalent temperature. *International Journal of Biometeorology*, 43: 76-84.

Matzarakis, A.; Rutz, F.; Mayer, H. (2000) - Estimation and calculation of the mean radiant temperature within urban structures. In de Dear RJ, Kalma JD, Oke TR, Auliciems A.eds. *Biometeorology and Urban Climatology at the Turn of the Millenium.* Selected Papers from the Conference ICB-ICUC'99, WCASP-50, WMO/TD No. 1026, Sydney 2000: 273-278.

Matzarakis, A.; Rutz, F.; Mayer, H. (2007) - Modelling Radiation fluxes in easy and complex environments – Application of the RayMan model. *International Journal of Biometeorology*, 51: 323-334.

Mayer, H.; Höppe, P., (1987) - Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology*, 38: 43-49.

Mayer, H.; Matzarakis, A. (1997) - The urban heat island seen from the angle of human-biometeorology. *Proceed. Int. Symposium on Monitoring and Management of Urban Heat Island*, Fujisawa, Japan: 84-95.

Mayer, H.; Matzarakis, A., (1998) - Human-biometeorological assessment of urban microclimates' thermal component. *Proceedings of the Int. Symposium on Monitoring and Management of Urban Heat Island*. Fujisawa, Japan: 155-168.

New, M.; Hulme, M.; Jones, P. (1999) - Representing twentiethcentury space-time climate variability. Part I: Development of a 1961–90 mean monthly terrestrial climatology. *J Climate*, 12: 829-856.

New, M.; Hulme, M.; Jones, P. (2000) - Representing twentiethcentury space-time climate variability. Part II: Development of 1901-1996 monthly grids of terrestrial surface climate. *J Climate*, 13: 2217-2238.

New, M.; Lister, D.; Hulme, M.; Makin, I. (2002) - A high-resolution data set of surface climate over global land areas. *Climate Research,* 21: 1-25.

Ribeiro, O.; Lautensach, H.; Daveau, S. (1988) – *Geografia de Portugal, vol.II – O ritmo climático e a paisagem*. João Sá da Costa, Lisboa.

Spagnolo, J.; de Dear, R. (2003) - A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. *Building and Environment*, 38: 721-738.

Steadman, R. G., (1971) - Indices of windchill of clothed person. *J. Appl. Meteorology*, 10: 674-683.

Thom, E. C., (1959) - The Discomfort Index. *Weatherwise,* 12: 57-60.

Unger, J. (1999) - Comparisons of urban and rural bioclimatological conditions in the case of a Central-European city. *International Journal of Biometeorology*, 43: 139-144.

VDI (1998) - *Methods for the human-biometeorological assessment of climate and air hygiene for urban and regional planning.* − Part I: Climate. VDI guidline 3787. Beuth, Berlin.

WMO (1996) *Climatological normals (CLINO) for the period 1961-1990*. WMO/OMM-No. 847, Geneva.