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Microclimatic variation of thermal comfort in a district of Lisbon (Telheiras) at night

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With 5 Figures

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Summary

The microclimatic spatial variation of air temperature, wind speed, radiative fluxes and Physiological Equivalent Temperature (PET) was studied in Telheiras, a northern district of the city of Lisbon. The main goal was to assess how to improve outdoor thermal conditions based on research results. An empirical model was developed to estimate PET in Telheiras under different weather types; the model allows the continuous spatial representation of PET, using a Geographical Information System (GIS) and can be used in other areas of Lisbon. Although there is a small microclimatic variation in air temperature, the PET presents a much stronger variation, due to the influence of wind and radiative fluxes. Urban geometry, expressed by the Sky View Factor (SVF), is the main factor controlling the microclimatic diversity of the neighbourhood. The coolest conditions occur in open areas (centre of large courtyards and marginal areas) and the warmest in streets with low SVF that are sheltered from the wind.

1. Introduction

Much urban climate research has been focussed on the urban heat island, the typical pattern of temperature variation in urban areas at local and mesoclimatic scales (Oke, 1987, 1997, 2004). However, within the same local climate, there is a great variety of microclimates (Oke, 1997, 2004). Microclimatic differentiation is mainly observed in the urban canopy layer (UCL) which shows the direct influence of basic urban features (buildings, streets, trees) at scales of only a few hundred metres.

Urban spaces modify all atmospheric variables that influence the body's energy balance, viz: air temperature (T_a), mean radiant temperature (T_{mrt}), wind speed (v) and vapour pressure (e_a), which belong to what is called the urban "thermal complex" (Matzarakis et al., 1998; VDI, 1998; Jendritzky et al., 2003). The thermal complex affects human comfort and health as well as energy consumption in urban areas.

A main goal of human bioclimatology has been to produce indices that express the combined influence of thermal complex factors on the human body (Parsons, 1993; Auliciems and DeDear, 1997). Increasingly complex models of the body's energy balance have been developed since the mid-20th century (Fanger, 1972; Gagge et al., 1986; Parsons, 1993; Auliciems and DeDear, 1997). MEMI (Munich Energy – Balance Model for Individuals; Höppe, 1999) is one such model that simulates physiological processes of thermoregulation based on six basic thermal environment parameters (T_a, T_{mrt}, v, e_a, activity level and clothing). The Physiological Equivalent Temperature (PET; Mayer and Höppe, 1987; Höppe, 1999; Matzarakis et al., 1999) can be obtained from MEMI and expresses a person's thermal state on a centigrade scale taking into account fixed values of internal heat production and thermal resistance of clothing (80 W m^{-2} and 0.9 Clo for a 35 year old man, 1.75 m tall and weighing 75 kg). PET is equivalent to the air temperature of a place with a "standard environment" of $T_a = T_{mrt}$; $v = 0.1$ m s^{-1} and $e_a = 12$ hPa, which requires the same thermophysiological response as the real environment. For example, a combination of $T_a = 30.0$ °C, $T_{mrt} = 45.0$ °C, $e_a = 22$ hPa and $v = 2$ m s^{-1} corresponds to the PET value of 34.1 °C, which means that this real environment causes the same thermophysiological response as a "standard environment" of $T_a = 34.1$ °C (Andrade, 2003).

PET is sometimes referred to as an index that has low sensitivity to variations in humidity. Humidity is important to human thermal comfort in hot conditions, but not with temperatures below the comfort zone (Berglund and Cunningham, 1986; Gagge et al., 1986; Parsons, 1993; Auliciems and DeDear, 1997). A simulation of the variation of the total evaporative heat loss from the skin (E_{sk}) with air humidity, following the equations of ASHRAE (1989, cited by Parsons, 1993), under a set of constant conditions ($T_a = T_{mrt} =$ 35 °C; $v = 0.3$ m s^{-1}; $I_{cl}{}^1 = 0.5$; $M = 80$ W m^{-2}), is shown in Fig. 1. It can be seen that E_{sk} has weak variation with increasing air relative humidity (RH), until RH reaches 66% ($e_a = 37.1$ hPa at 35 °C); above this value, body capacity to generate evaporative loss falls, with a negative consequence for human thermal comfort.

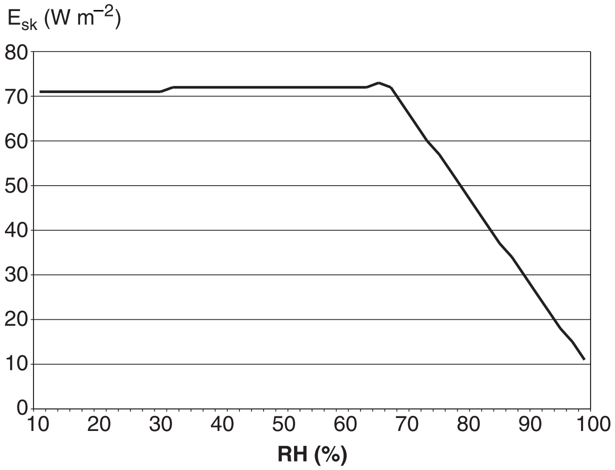

Fig. 1. Variation of evaporative heat loss from the skin (E_{sk}) with humidity, with $T_a = T_{mrt} = 32$ °C, $v = 0.1$ m s^{-1}; $I_{cl} = 0.5$; $M = 80$ W m^{-2}

Below the humidity threshold (66%), the values of E_{sk} and PET are strongly correlated ($r = 0.85$); E_{sk} is also strongly correlated to the Standard Effective Temperature (SET – Gagge et al., 1986; Parsons, 1993). SET is frequently referred to as an index with high sensitivity to humidity variations (Gagge et al., 1986; DeDear and Leow, 1990; Parsons, 1993; Chen et al., 2004). Above the boundary of $RH = 66\%$, SET clearly has a better relation with E_{sk} than PET ($r = 0.96$ with SET; 0.88 with PET) and, above RH = 88%, PET does not change with humidity.

Under the climate of Lisbon, the low sensitivity of PET to high humidity is not very important, because the coincidence of high temperatures and high humidity occurs seldomly. Temperatures above 32 °C at the Airport (Lisboa/GC), between 1990 and 2005, correspond, in 80% of the cases, to a RH between 20% and 39%; the average value of RH was 28% and the maximum was only 51%.

This study was carried on the city district of Telheiras, in northern Lisbon (Fig. 2). Telheiras is a residential neighbourhood built in the early 1980s and developed according to relatively demanding quality patterns. The initial plan was that 37% of the area would be occupied by greenspace and equipped with recreational areas and 13.5% by housing and services. The study area covers 14 ha and has a population of 1800. Altitude varies between 100 and 110 m and gently slopes to the south.

There is a predominance of apartment buildings that form blocks in lines along the side of the streets; there are also some single family buildings, others taken up by social facilities and, to the west, a strip of "tower-like" buildings (Fig. 2b). The main road axes are oriented in either the north–south or the east–west directions and vary between 18 and 25 m in width. The height of the buildings also varies considerably: the tallest are around 25 m (32 m in the case of the towers). The H/W ratio[2] varies between 0.5

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[1] I_{cl} = Intrinsic Clothing Insulation is the property of clothing that "...represents the resistance to heat transfer between the skin and the clothing surface..." (Parsons, 1993, p. 105).

[2] The canyon aspect ratio between the height of the buildings (*H*) and the width of the streets (*W*) is a useful parameter to describe the urban geometry (Oke, 1981, 1987).

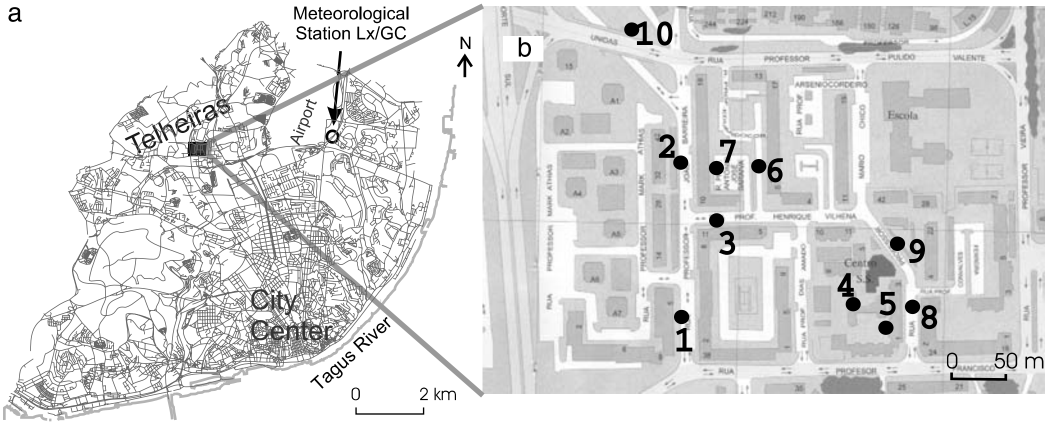


Fig. 2. The location of the city district of Telheiras in Lisbon (**a**) and of the sites in the measurement network (**b**)

and 1.1. The courtyards are taken up by parking spaces, social facilities and small garden areas.

The reasons for choosing this neighbourhood for study were two fold: first, there was interest in understanding the climatic behaviour of an area that can be considered a positive example of urban planning; second, this neighbourhood has a relatively uniform character, particularly in terms of altitude, which makes it more likely that the results can be applied to other similar areas.

The main goals of the project were 1) to analyse the variation of PET and of the variables that make up the thermal complex in characteristic urban micro-environments; 2) to model the variation in spatial terms and map them using a Geographical Information System (GIS) and 3) to decide how to improve the outdoor thermal conditions using the research results. The study was carried out both at night and during the day; however, only the night-time results are presented here. Two sets of results are presented: in Sect. 2, the calculation of PET was made for 10 measurement points in Telheiras, based on measurements of T_a, the radiative fluxes and estimated wind speed and T_{mrt}. Measurement and estimation methods are presented and discussed, namely the main factors that control the spatial variation of the base parameters measured within the Telheiras neighbourhood (T_a and radiative fluxes). In Sect. 3, an empirical model to estimate PET is presented, based on the results obtained in the previous section. This is done using a GIS and hence allowing the computation of the continuous spatial variation of the thermophysiological index. The main objective was to obtain a model that can be applied to other districts of Lisbon that have similar mesoclimatic conditions. PET could then be estimated without direct measurements of climatic parameters.

2. PET calculation and spatial variation within Telheiras

2.1 Data acquisition

PET was calculated based on data obtained in three different ways: measurements of the air temperature (T_a) using fixed devices, measurements of long (L) and short (K) wave radiation from mobile surveys, and estimations of the wind speed (v), and the mean radiant temperature (T_{mrt}) using numeric models. The vapour pressure was not measured directly, rather the value for Telheiras was equated to that at the Lisboa/GC weather station (in the Lisbon Airport – Fig. 1a). In the present study this weather station was used as the reference with regard to the analysis of the regional conditions.

2.1.1 Measuring the air temperature using fixed devices

Two air temperature measurement campaigns were carried out using 10 fixed measurement devices (Fig. 2b) between June 10 and 22, 2001 and between February 16 and 26, 2002; both periods had cloudless sky conditions.

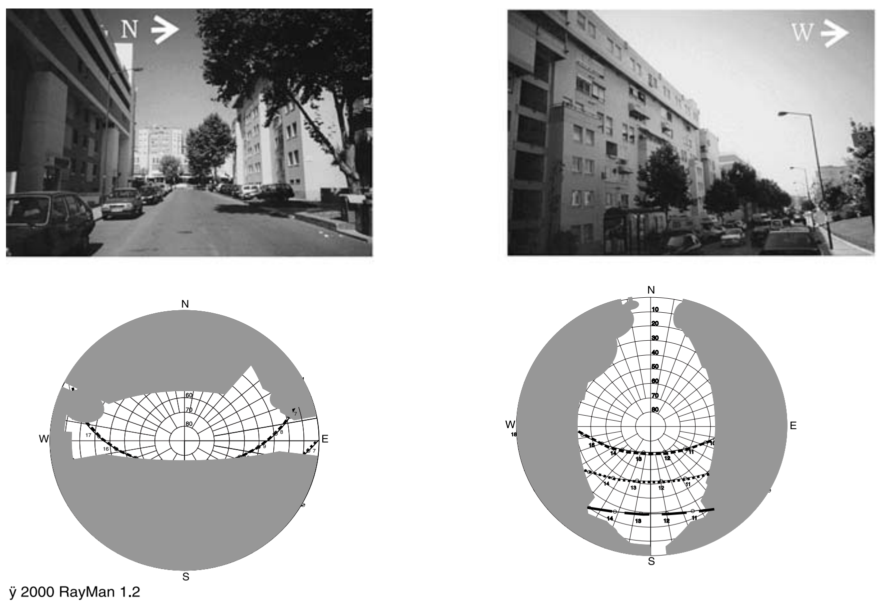
Air temperature was recorded using Gemini Data Loggers' Tiny Talk devices (Vieira et al., 2000), placed at a height of about 3.5 m on public lamp posts. The height was chosen to avoid vandalism and robbery. Air temperature measure-

Table 1. Sites of Telheiras'city district where the temperature recording devices were placed

Site no.	Characterisation	SVF of the measuring point
1	Commercial/residential street with a north–south orientation	0.35
2	Commercial/residential street with a north–south orientation	0.50
3	Residential street with an east–west orientation	0.29
4	Closed inner courtyard with garden areas and a parking lot	0.65
5	Closed inner courtyard with garden areas and a parking lot	0.25
6	Semi-open courtyard with garden areas and a parking lot	0.46
7	Semi-open courtyard with garden areas and a parking lot	0.38
8	Commercial/residential street with a north–south orientation	0.31
9	Open courtyard with garden areas	0.73
10	Open area	0.74

Spot 3

Spot 2



Spot 4

Spot 10

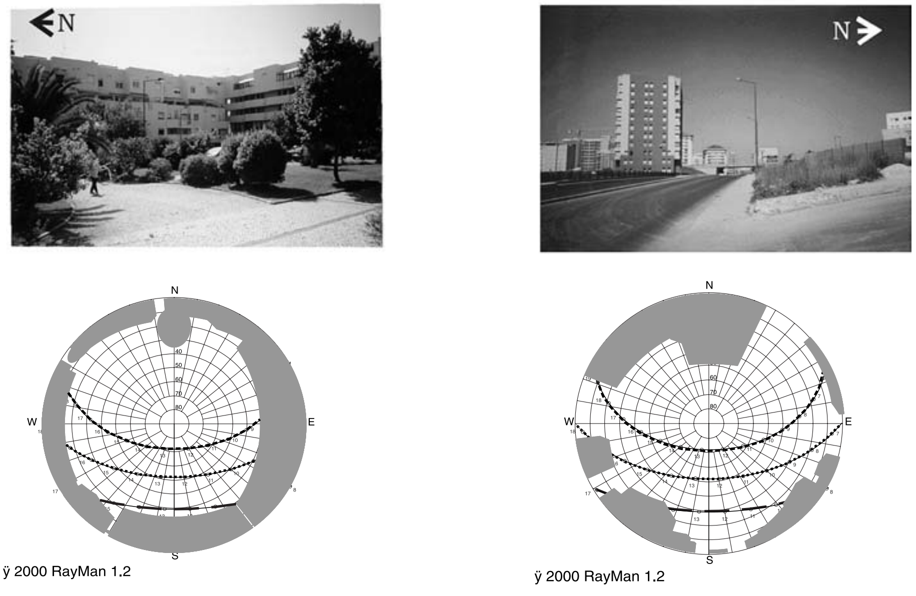


Fig. 3. Some of the measurement sites and their respective solar diagrams, with Sun Paths at the time of the solstices and equinoxes

ments in the UCL may be carried out above the standard height (1.25 m to 2 m), because air temperature gradients in the UCL are very slight (Nakamura and Oke, 1988; Oke, 2004). According to Oke (2004, p. 17) "...measurements at heights of 3 to 5 m are little different from those at the standard height, have slightly greater source areas and place the sensor beyond easy reach or damage...".

The measurement sensors were insulated from the posts using cork sheets and were protected from solar radiation by a home-made shelter made of a 15 cm wide cardboard tube with Styrofoam and tinfoil coating and openings at both ends. The loggers were programmed to record air temperature at 10 min intervals and results were averaged over 30 min periods. Both before and after each campaign the devices were tested under experimental conditions and calibrations were applied when necessary. The sites where the sensors were placed ensured they represented the various micro-environments in the neighbourhood. Table 1 provides a description of the physical and functional characteristics of the sites (see also Figs. 2b and 3).

The most satisfactory way to calculate the SVF involves the use of "fish-eye" lenses, however, these are expensive. An alternative is the RayMan program (Matzarakis et al., 2000) which can be used to represent both the celestial hemisphere and horizon obstructions (trees and buildings) at a specific site. In order to assess the accuracy of the SVF calculations using the RayMan model, values using the method were compared with the actual SVF measured from 23 photographs using a Canon fish-eye lens at different sites in Lisbon. After digitising the photographs the visible fraction of the sky was computed by counting the number of pixels. The values from the fish-eye photos and RayMan model were not statistically different using variance analysis ($F = 0.006$, with a critical value of 4.05, for 0.95 probability). The maximum difference between the values estimated by the model and those calculated using the photographs was 0.03 (the average difference was 0.016).

The SVF is strongly related to H/W in urban canyons with a regular form, but SVF is considered the better descriptor of urban geometry in irregular canyons, courtyards and open spaces, such as some of the locations in the present study.

2.1.2 Estimating T_{mrt}

a. Radiation measurements. Measurements of both the short and the long-wave radiation was made during mobile surveys. Solar radiation was measured with a Kipp & Zonen CM 21 pyranometer with 95% precision in the spectral band between 0.335 and 2.2 μm, and its field of view was 180°. Long-wave radiation (5 to 25 μm) was measured using a Kipp & Zonen CG1 pyrgeometer with a field of view of 150°. The values recorded by both the pyranometer and the pyrgeometer were displayed on a digital multimeter.

The recordings were made under clear skies and various wind speed conditions. The measurement of the radiation fluxes, needed to compute T_{mrt}, was made using the procedure described in Jendritzky and Nübler (1981) and VDI (1998). The pyranometer and the pyrgeometer were placed on a portable and rotating tripod. For both the solar and thermal infrared measurements, four observations were taken towards the cardinal directions of the horizon, spinning around the vertical axis, plus two additional readings, one upwards and one downwards, by spinning the system around its horizontal axis.

b. Calculating the mean radiant temperature. The radiation observations provide only discrete information in time and space. In order to permit the continuous spatial calculation of the T_{mrt}, the RayMan model was used (Matzarakis et al., 2000), based on modelling the energy balance in accordance with VDI (1994, 1998). For this purpose microscale quantitative information concerning each site was obtained either by field work or by map analysis. Furthermore, a T_{mrt} estimate also depends on the position (siting, standing) of the individual. The observed values made it possible to validate and calibrate the T_{mrt} estimates.

2.1.3 Modelling wind speed

Understanding wind speed variation in the area under scrutiny was more difficult than for air temperature and T_{mrt} because it proved impossible to carry out useful recordings. It was decided to rely on a simulation of the average wind speed, by way of the Envi-Met model (Brüse and Fleer, 1998). Simulations were made using the wind speed and direction as recorded at the Airport at a height of 10 m as the input base. Telheiras was represented on a three-dimensional grid created using the program interface, upon which the buildings and the vegetation were drawn. Each pixel was $5 \times 5\,\mathrm{m}^2$, which was considered sufficient to represent the main features of the area.

2.2 Spatial variation of different temperature parameters (T_a, T_{mrt} and PET)

In order to analyse the spatial variation of air temperature, the maximum spatial difference (MSD) in terms of temperature between any two points (T_a, PET or T_{mrt}) at a given moment was calculated:

$$\mathrm{MSD} = T_{max} - T_{min},$$

where T_{max} is the highest and T_{min} the lowest temperature at a given moment within the study area. The largest values of MSD in the study area were for T_{mrt} and PET, whose variations far exceeded that of T_a. In summer, 25% of the values for the MSD were in excess of 5.2 °C for T_{mrt}, 3.5 °C for PET and just 0.9 °C for T_a. In winter, the 75th percentile were 5.5 °C, 3.9 °C and 0.8 °C, respectively. The absolute maximum value for MSD_{T_a} (2.1 °C) was reached at dawn of February 20th 2002, under a clear sky and with weak wind from the north; the highest T_a (9.9 °C) was recorded at site No. 3 (Figs. 2b and 3) and the lowest at site No. 10 (7.8 °C). At the same time, $\mathrm{MSD}_{T_{mrt}}$ was 7.0 °C and MSD_{PET} was 4.4 °C.

On summer nights, MSD_{PET} decreases as the wind speed coming from the north increases. The correlation coefficient between the two variables is −0.79 (significant at the 0.99 level of probability). The MSD_{T_a} also had a significant linear relation with the wind from the north, though weaker than the case of MSD_{PET} ($r = -0.40$). The average behaviour of the MSD_{PET} in the summer was characterised by low values in the early evening with strong winds from the north, gradually increasing until dawn as the wind speed decreases.

The correlation coefficient between MSD_{PET} on winter nights and wind speed is also statistically significant ($r = -0.65$), as is the relation between air temperature and wind speed, although this latter association is much weaker ($r = -0.34$). Most of the time the highest values for both air temperature and PET were recorded at sites Nos. 3, 7 and 5, which have relatively low SVF and a higher degree of shelter from the wind (Table 1). The lowest temperatures were recorded, on most occasions at sites No. 9 and 10, which are open and exposed to the wind from almost every direction. In summer, at sites that have a SVF lower than 0.40, more than 21% of the values for the night-time PET were higher than 20 °C. At those places where the SVF is higher than 0.70, less than 3.5% of the observations exceeded 20 °C.

2.3 Discussion

2.3.1 Factors affecting radiation fluxes and T_{mrt}

a. Effect of SVF on radiation and T_{mrt}. Analysis of the relation between the measured parameters and a series of factors, particularly those related to urban geometry, show that those related to radiation (fluxes from the different directions and the T_{mrt}) were highly correlated with SVF (Table 2). Of the measured radiation fluxes the one that exhibits the strongest association with regard to SVF is incoming long-wave (L↓), due to the partial replacement of atmospheric radiation by radiation from the (warmer) walls. The association between the outgoing long-wave (L↑) and SVF is weaker, because SVF has only an indirect effect upon the temperature of the lower walls and the road, by modifying the radiation balance. In the relation between T_{mrt} (which synthesises the different radiation fluxes) and SVF lateral fluxes must be taken into account.

The residuals of the regression of SVF against T_{mrt} (Table 3) reflect the influence of other factors. The greatest positive residuals were recorded in sites No. 1 and 2, in a street that includes commercial functions on the west side (P. J. Barreira Street); the average values of long-wave radiation

Table 2. Results of the regression of SVF against the long wave fluxes and the T_{mrt} (all values are statistically significant for a 0.95 degree of probability)

Dependent variable (y)	r^2	Regression equation
L↓	0.78	$y = -109.93\ \mathrm{SVF} + 49.225$
L↑	0.52	$y = 3342.3\ \mathrm{SVF}^4 - 5537\ \mathrm{SVF}^3 + 3037.7\ \mathrm{SVF}^2 - 634.81\ \mathrm{SVF} + 42.312$
L average	0.63	$y = -51.387\ \mathrm{SVF} + 23.595$
T_{mrt}	0.67	$y = -10.927\ \mathrm{SVF} + 4.9993$

Table 3. Average residuals of estimation of T_{mrt} with SVF to different measurement points

Sites (Fig. 2b)	Residuals
1	**1.4**
2	**2.4**
3	−0.3
4	−0.6
6	−0.4
8	−0.7
9	0.3

from the wall on that side of the street are systematically higher than from the opposite side. These higher surface emissions on the west side of the street are probably related to the higher level of energy consumption (the Q_{F} term, after Oke, 1987, 1988, 1991) for lighting and air conditioning purposes, etc.

b. T_{mrt} estimates. The linear correlation coefficient between the recorded values of T_{mrt} and those estimated using the RayMan model was 0.96 (Fig. 4). As mentioned with regard to SVF, the T_{mrt} values estimated for sites Nos. 1 and 2 were systematically below those actually recorded. Consequently, an additional variable was introduced into the regression analysis to differentiate sites Nos. 1 and 2 from the rest. It took the form of a dummy variable (Wilks, 1995), which assumed the value 1 in the case of the observations recorded in the commercial street and the value 0 for other streets. This improved the quality of the fit between the recorded values and those estimated by the model to $r = 0.98$.

Thus, the best-fit estimation of the night-time T_{mrt} [$T_{\mathrm{mrt(night)}}$] was found to be computed as follows:

$$T_{\mathrm{mrt(night)}} = 2.16 + (1.768X_1) + (0.914X_2)$$

where X_1 is the dummy variable to differentiate P. J. Barreira Street (or another with similar functional characteristics), and $X_2 = T_{\mathrm{mrt}}$ estimated by the RayMan model.

2.3.2 Factors affecting the air temperature

The relation between T_{a} and SVF has been the object of several studies, whose results are not always comparable (Svensson, 2002). The scale at which the studies were carried out seems to be an important factor. According to Oke (1981), empirical and experimental research conducted in European, North American and Australian cities points to the conclusion that urban geometry is a basic physical determinant of the night-time urban heat island, within the UCL, under clear sky and weak wind conditions and in situations in which the urban heat emissions do not significantly affect the energy balance. Ezpeleta and Veras (1998) studied the relation between urban geometry and night-time air temperature in Santiago de Compostela, at 14 different sites. The correlation coefficient between the SVF and the T_{a} in that study, under clear weather conditions, was −0.80 and −0.82 in the summer and winter, respectively. Goh and Chang (1999) analysed the relation between the intensity of $\Delta T_{\mathrm{u-r\ (max)}}$ (which corresponds to the largest temperature difference recorded in a measurement

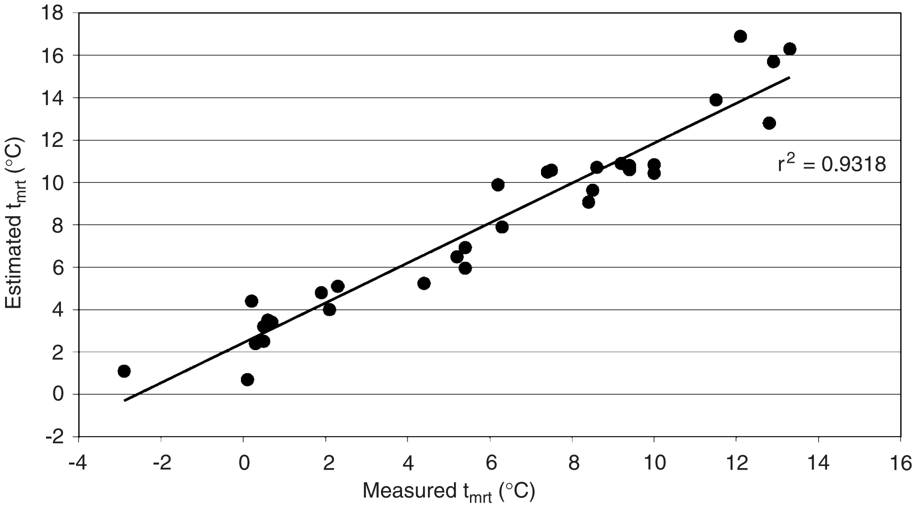


Fig. 4. Relation between the T_{mrt} estimated with RayMan and that calculated from radiation field measurements

traverse in a given neighbourhood) at 10 pm and the urban geometry, as represented by the H/W ratio, in the city of Singapore. The authors were able to find a statistically significant association (though not a particularly strong one: $r^2 = 0.28$) between the $\Delta T_{u-r(\max)}$ and the median value of the H/W ratio in each neighbourhood. Svensson et al. (2002) found a strong relation between air temperature and SVF in Göteborg, subject to categorising sites according to their land use.

In the present work, the relation between SVF and T_a was analysed. The regression coefficient indicates that this relationship is statistically significant, and more strongly so in summer than winter: $r = 0.79$ in June 2001 ($n = 2460$); $r = 0.69$ in February 2002 ($n = 2160$).

In order to further explain the spatial variation in T_a, other independent variables were included: wind speed at each site and the functional characteristics of the streets (commercial/residential function), using the same process used in the survey measurement of T_{mrt}. The best-fit model estimated using the stepwise regression explains between 60% (in the winter) and 63% (in the summer) of the variance (Table 4). Bearing in mind the size of the sample, this can be considered highly significant. The greatest controlling factor is always the SVF, especially in the summer. In winter, the commercial/non-commercial nature of the street also contributes considerably to explaining the spatial variance of air temperature. Wind speed plays a larger role in summer.

To summarise, values of T_a are clearly the highest in places with low SVF and low wind speeds. In winter, the temperature also tends to be higher in the case of the P. J. Barreira Street, which includes commercial functions.

Table 4. Results of the regression between the night-time air temperature and the independent variables

	Summer	Winter	Total
n	2460	2160	4620
r^2	0.63	0.60	0.59
β of the independent variables			
SVF	−0.79	−0.62	−0.71
Commercial/residential street	–	0.33	0.16
LN v(t)	−0.15	−0.10	−0.06

The conclusions reached in the case of Telheiras are consistent with those in the literature: a significant (though not particularly strong) negative relation exists between night-time T_a and SVF, by way of the influence of the urban geometry upon the long-wave radiation balance. This relation is weakened by the influence of wind speed, while functional factors also seem to interfere, most likely due to the anthropogenic heat emissions that are associated with commercial functions.

On the other hand, given that SVF determines both T_{mrt} and the air temperature (and also exhibits a statistically significant relation with the wind speed), it is no surprise that the night-time PET is also strongly influenced by urban geometry. Thus, on warmer summer nights, sites with a higher degree of exposure are considerably more favourable in terms of thermal comfort. In winter, in contrast, PET under 4 °C accounted for more than 20% of the observations in open areas, but under 8% in those places that had a SVF lower than or equal to 0.5.

3. Modelling the night-time PET in Telheiras

An empirical model was developed to estimate PET for Telheiras and to allow its continuous cartographic representation without direct meteorological measurements. Empirical modelling of the relation between various geographical factors and air temperature has already been conducted by Alcoforado (1994), Andrade and Lopes (1998), Andrade (2003) and Alcoforado and Andrade (2005). Several models have been produced which permit the reconstruction of the thermal field from the spatial variation of the input factors. Eliasson and Svensson (2002) used a similar process in order to model the variation of air temperature for the city of Göteborg. The use of a GIS allowed for the continuous spatial representation of the information and had the additional advantage of being easily updateable (Svensson et al., 2002).

3.1 Method

PET modelling was a two-step process:

– A multiple regression model enabled the estimation of PET for each measurement site in Telheiras (PET(t)) at any given moment, based on the weather conditions recorded at the Airport at the same time and parameters to describe local conditions.

- **Spatial interpolation** of PET for other locations using the regression equation determined in the previous stage. In this process, a **GIS** with a $5 \times 5\,\mathrm{m}^2$ pixel grid was used. Each independent variable was depicted in a different layer.

The independent variables were selected by stepwise multiple regression. The best-fit equation was:

$$\begin{aligned}\mathrm{PET(t)} = {} & -1.46184 + 1.07735\,T_{\mathrm{a\ Airp}} \\ & - (3.07473\ \mathrm{SVF}) \\ & - (2.77031 \ln \mathrm{V(t)} + 1)\end{aligned}$$

where PET(t) is the value for a given site in Telheiras (°C), $T_{\mathrm{a\ Airp}}$ is the air temperature recorded at the Airport, SVF is the sky view factor of the location and V(t) is the wind speed, as computed for that particular pixel using the Envi-Met model, based in the measured wind at the Airport (ln V(t) stands for its natural logarithm).

The quality of the fit can be judged by the fact that $r^2 = 0.98$ and only 10% of the residuals are greater than 1 °C and only 0.1% are greater than 2 °C. The β coefficients allow for an assessment of the relative weights of the independent variables in explaining the spatial variation of PET. The main independent variable is $T_{\mathrm{a\ Airp}}$ ($\beta = 0.94$), followed by wind speed and SVF (β respectively -0.22 and -0.096).

The air temperature recorded at the Airport is the main independent variable, followed by wind speed and SVF. The weight of air temperature in this regression is due to the fact that the regression is valid for the full year and for different weather types. One can therefore consider that $T_{\mathrm{a(Lx/GC)}}$ represents the mesoscale thermal conditions, to which the variations in wind speed and SVF introduce microclimatic modifications.

This model allows the estimation of PET for any location in Telheiras. Such estimates were made for various types of weather conditions in both summer and winter. Test cases were selected because of their relative frequency or because they were extremely cold or hot (see Table 5).

3.2 Weather and PET in Telheiras

In simulations with summer weather conditions and the wind coming from the north, the level of thermal comfort differed substantially between examples **a** and **b** (Table 5). On a very warm night, such as a (Fig. 5a), PET exceeded 22 °C in places that are more sheltered and are less exposed to the sky. In the streets with a north–south orientation and in the central part of the courtyards, values were between 18 and 19 °C and only on their west and north-east peripheries was PET less than 18 °C (with a minimum of 17.5 °C). Thus, PET values between 18 and 22 °C were predominant and are considered comfortable according to Matzarakis et al. (1998). It is worth recalling that the PET modelling assumed a level of clothing equivalent to 0.9 Clo. Under summer conditions, clothing can be considerably reduced: at 20 °C, a 0.5 Clo level of thermal isolation by clothing brings about a decrease in the PET of around 3.3 °C, which amounts to extending the conditions of moderate discomfort due to the cool conditions. On nights with characteristics such as these, staying out in the open is clearly an enticing idea, because the sensation of slight thermal discomfort is easily compensated by small clothing adjustments.

The analysis so far only concerns outdoor thermal conditions. The assessment of night-time bioclimatic needs must also consider indoor conditions, which are strongly dependent upon heat transfers from the outside (Taesler, 1990, 1991). During nights when T_{a} is close to 20 °C, thermal conditions may be comfortable outside, but not

Table 5. Weather conditions selected to the PET simulations

Season	Characteristics	Relative frequency (%)	Figure showing the pattern
Summer weather types	Temperature above the average, clear sky and weak North wind	11	5a
	Relatively fresh weather conditions, clear sky and strong North wind	17	5b
Winter weather types	Cold weather, clear sky and weak East wind	15	5c
	Cool weather, overcast sky and moderate to strong Northwest wind	12	5d

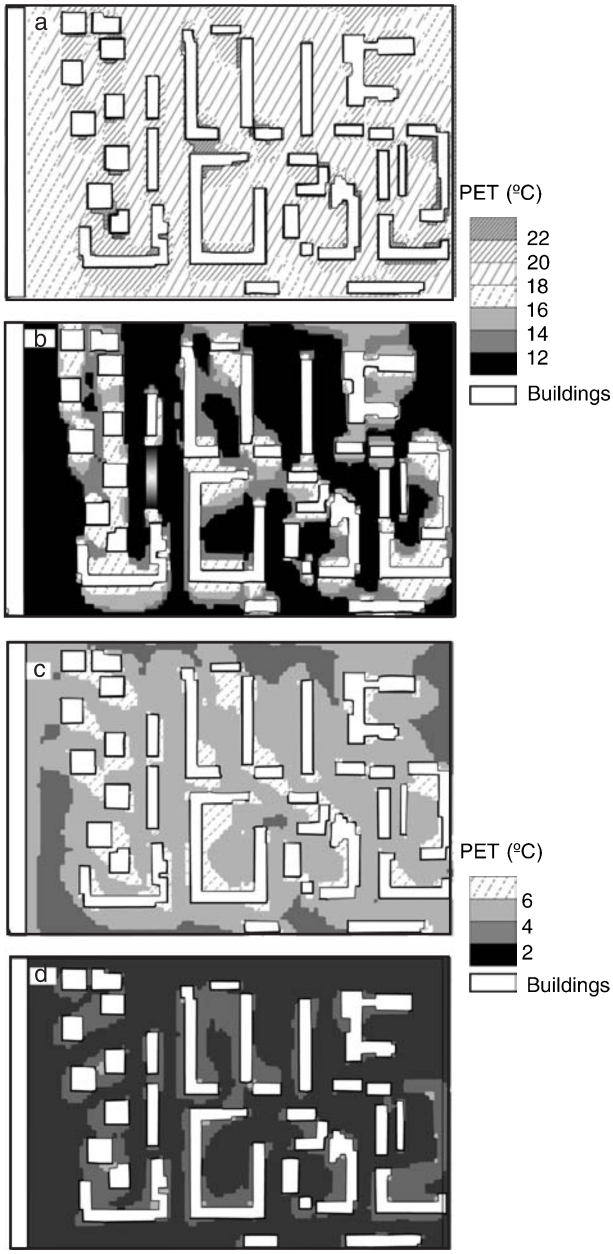


Fig. 5. Night-time PET estimates for different weather types

inside houses. According to Müller-Limmroth (1977, cit. in Höppe, 1991), there is significant negative impact upon night-time rest when the T_a is between 18 and 28 °C. Höppe (1991) indicates maximum values of 18 to 21 °C for proper night-time rest.

On night **b** (Fig. 5b), with strong winds from the north, the thermal conditions were either Cool or Moderately Cool (8 to 18 °C, Matzarakis et al., 1998). In the centre of courtyards, in streets with a north–south orientation and in open areas, PET was lower than 12 °C, which requires a considerable increase in the level of the thermal insulation of the clothing (close to 1.8 Clo) in order to maintain thermal balance. Obviously, these areas are not suitable for long stays without adequate protection from the wind. When there is such protection, PET increases to values that are just Slightly Cool, which can be compensated for by small adjustments in clothing.

In the case of the examples that correspond to winter night-time situations (Table 5), thermal discomfort due to the cold naturally predominates. In example **c** (Fig. 5c), under moderate wind from the north-west, PET was lower than 4 °C (with a minimum of 3.1 °C) in peripheral areas that have greater exposure and, within the neighbourhood, in corridors that cause acceleration of the north-westerly wind. The highest PET values, which occurred in sheltered areas, were seldom over 8 °C. This requires an increase in the level of thermal insulation to around 1.8 Clo in order for thermal balance to be reached.

In example **d** (Fig. 5d), temperatures were considerably lower and the wind was less intense. As a result, PET was lower than 1 °C in some large areas (with a minimum of −0.8 °C) and never exceeded 4.8 °C. Thus, there was a predominance of Very Cold conditions in accordance with Matzarakis et al. (1998). In very cold areas (where temperatures are close to or less than 2 °C), a level of thermal insulation of about 2.7 Clo is necessary for thermal comfort to be attained. It is true that these open areas consist mostly of passageways and are not meant for long stays (especially at dawn). Therefore, the level of metabolic heat production might be higher than that upon which PET calculations are based ($90\,\mathrm{W\,m^{-2}}$). At $115\,\mathrm{W\,m^{-2}}$ (which corresponds to a walking speed of $3.2\,\mathrm{km\,h^{-1}}$ – VDI, 1998), the amount of clothing necessary in order to keep the level of thermal comfort at 2 °C (with a T_{mrt} equal to the T_a and wind blowing at $0.1\,\mathrm{m\,s^{-1}}$) decreases to just 2.1 Clo. However, it may be necessary to remain out in the open on some occasions (for example at bus stops), and one must also take into account the extra vulnerability of particular groups (e.g. children and the elderly).

3.3 Discussion

The highest values of PET(t) were found in areas that are sheltered from the wind (depending on its direction) and are less exposed to the sky (Fig. 5). The thermal behaviour of the streets is found to be a function of both their orientation and the direction of the wind. In the **a** and **b** simulations (Fig. 5a and b), with winds from the north, the streets with a north–south orientation proved cooler (especially in the middle of the street) than those with an east–west orientation. In the case of Prof. Henrique Vilhena Street (site No. 3 – east–west orientation), the highest values are recorded near the west sector, where there is continuous shelter from the north. In the **c** and **d** simulations (Fig. 5c and d), PET varies in streets with both types of orientation as a result of the existence of side openings that allow the wind from the north-east and the north-west to circulate.

Thermal conditions in courtyards are more homogeneous, regardless of the direction of the wind: temperatures are lower in the centre and higher near the edges. The values of PET are lower in front of the openings, since these are sites where the wind accelerates, even when the orientation of the opening does not coincide with the direction of the wind.

In the area with tall buildings to the west (Fig. 2b), a mosaic of PET values are recorded. The warmer sectors are those sheltered by buildings. Thermal conditions are generally more moderate in such sheltered spots than in the streets or in the courtyards. This is because i) there is a low level of shelter from both the wind and the sky; and ii) because the towers are not sufficiently far apart to allow cooling to occur to the same extent as in the open areas.

With regard to winter simulations, there is little possibility of modifying the urban geometry in order to improve the level of thermal comfort. Still, it is possible to reduce discomfort due to the cold by creating more shelter from the wind, namely by adequately reinforcing those sites that are meant for long stays and by avoiding the creation of large open areas/and/or draft corridors (which do not necessarily have to be streets; a series of openings or open areas in line with each other can bring about the same effect).

4. Conclusion

In the present research, we have reached conclusions concerning the best methods of study, and the main causes of the variation of nocturnal air temperature within a neighbourhood of Lisbon and some guidelines for planning.

The research methods used in Telheiras turned out to be complementary. The measurement of climatic parameters using both fixed sensors and mobile surveys laid the basis for an understanding of the microclimatic variation of thermal conditions. They also presented some limitations when it came to generalising the results. In this respect, GIS modelling proved to be an adequate way to estimate the microclimatic conditions under different types of weather conditions. The model developed from the observations allows for such estimates, using only a small number of parameters and without requiring extra local measurement. The possibility of generalising the model to other parts of the city is envisaged as a future step of the research.

The spatial variation of the night-time air temperature within the neighbourhood is relatively small. However, T_{mrt} and PET do exhibit much greater variation, which underscores the importance of broadening the research to include other climatic elements, such as wind and radiation that significantly affect thermal comfort. The microclimatic diversity of the neighbourhood is mainly due to urban geometry. However, since the study area is relatively homogeneous in terms of construction materials, colours and presence of vegetation, it was not possible to draw conclusions on the bioclimatic importance of these factors. SVF is an important determinant of thermal conditions at night. Consequently, the existence of open areas is essential in order to moderate thermal conditions on very warm nights. A low SVF can be a positive factor on cold winter nights.

Considering the relative danger posed by the two alternatives (in a climate such as that of Lisbon), as well as the trends usually suggested in terms of global warming, one of the guidelines for urban planning should favour chilling conditions. It is worth recalling that the existence of areas with high SVF does not automatically proscribe tall buildings. Rather, it calls for an adequate balance between the height of the buildings and the density of construction.

Shelter from the wind is a consequence of urban geometry and has a large influence on the bioclimatic conditions of settlements. Besides its thermal effects, the wind influences the level of mechanical comfort and plays a key role in dispersing air pollutants. Shelter from the wind is a complex question that depends on the direction of the flux. Even when the prevailing wind directions are known, one should bear in mind that the situations that cause the most inconvenience and discomfort are not necessarily those that occur most frequently. As mentioned, changes in wind speed can have contradictory effects depending on the weather conditions. Even in summer, strong winds from the north can create (moderate) discomfort, and in cold winter conditions, the existence of a minimal level of wind circulation is necessary for air quality reasons. A ''reasonable'' guideline for urban planning might be to maintain moderate wind circulation conditions without too much obstruction whilst avoiding excessive wind speeds. The use of mobile or permeable barriers, perhaps vegetation, is a possible solution.

The difficulty of reconciling the thermal needs of the various seasons and different weather conditions reminds us of the sensible recommendation of the Expert Committee of the German Meteorological Society: ensure microclimatic variation and avoid extreme conditions. It is also worth stressing the importance of avoiding stereotypical, simplistic solutions in outdoor planning, by taking into consideration the periods and types of use (and user) of each particular space.

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References

Alcoforado MJ (1994) L'extrapolation spatiale des données thermiques en milieu urbain. Public de l'Assoc Int de Climatol 7: 493–502

Alcoforado MJ, Andrade H (2005) Nocturnal urban heat island in Lisbon (Portugal): main features and modelling attempts. Theor Appl Climatol 84: 151–159

Andrade H (2003) Human bioclimate and air temperature in Lisbon (in Portuguese). PhD Thesis, University of Lisbon

Andrade H, Lopes A (1998) A utilização de um SIG para estimação das temperaturas em Lisboa. In: Garcia FF, Gallego G, Torrecilla RC (eds) Clima y ambiente urbano en ciudades Ibéricas e IberoAmericanas. Parteluz, Madrid pp 85–91

Auliciems A, DeDear R (1997) Thermal adaptation and variable indoor climate control. In: Auliciems A (ed) Advances in bioclimatology – 5. Human Bioclimatology. Springer, pp 61–86

Berglund LG, Cunningham DJ (1986) Parameters of human discomfort in warm environments. ASHRAE Trans 92(13): 732–746

Brüse M, Fleer H (1998) On the simulation of surface plant air interactions inside urban environments. Environ Modell Softw 13: 373–384

Chen H, Ooka R, Harayama K, Kato S, Li X (2004) Study on outdoor thermal environment of apartment block in Shenzhen, China with coupled simulation of convection, radiation and conduction. Energ Build 36: 1247–1258

Clark WA, Hoskings PL (1986) Statistical methods for geographers. New York: John Wiley and Sons

DeDear R, Leow KG (1990) Indoor climate and thermal comfort in high-rise public housing in an equatorial climate: a field-study in Singapore. Atmos Environ 24: 313–320

Eliasson I, Svensson MK (2002) Spatial temperature variations and urban land use – a statistical approach. Meteorol Applic 10(2): 135–149

Ezpeleta AM, Veras AM (1998) Geometria urbana, temperatura e isla de calor en Santiago de Compostela. In: Garcia FF, Gallego G, Torrecilla RC (eds) Clima y ambiente urbano en ciudades Ibéricas e IberoAmericanas. Parteluz pp 207–218

Fanger PO (1972) Thermal comfort. New York: McGraw-Hill

Forum Ibérica (2000) Urban guide. Lisbon: Forum Ibérica

Gagge AP, Fobelets AP, Berglulg LG (1986) A standart predictive index of human response to the thermal environment. ASHRAE Trans 92(13): 709–731

Goh, KC, Chang CH (1999) The relationship between height to width ratios and the heat island intensity at 22:00 for Singapore. Int J Climatol 19: 1011–1023

Höppe P (1991) Improving indoor thermal comfort by changing outdoor conditions. Energ Build 16: 743–747

Höppe P (1999) The physiological equivalent temperature – an universal index for the biometeorological assessment of the thermal environment. Int J Biometeor 43: 71–75

Jendritzky G, Nuebler W (1981) A model analysing the urban thermal environment in physiologically significant terms. Arch Met Geoph Biokl Ser B 29(31): 313–326

Jendritzky G, Grätz A, Koppe C, Laschewski G (2003) How to deal with the urban development – urban climate – human health effect relationship, a contribution to methodology. Proc Fifth Int Conf on Urban Climate September 2003 Lodz Poland, Vol. 2, pp 47–50

Matzarakis A, Beckröge W, Mayer H (1998) Future perspectives in applied urban climatology. In Proc Second Japanese-German meeting, Report of Research Center for Urban Safety and Security, Kobe University, Special Report no 1, pp 109–122

Matzarakis A, Mayer H, Iziomom E (1999) Applications of a universal thermal index: physiological equivalent temperature. Int J Biometeor 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, Sydney, WCASP-50, WMO/TD No. 1026, pp 273–278

Mayer H, Höppe P (1987) Thermal comfort on man in different urban environments. Theor Appl Climatol 38: 43–49

Nakamura Y, Oke TR (1988) Wind, temperature and stability conditions in a east–west oriented urban canyon. Atmos Environm 22: 2691–2700

Oke TR (1981) Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations. Int J Climatol 1: 237–254

Oke TR (1987) Boundary layer climates. London: Methuen

Oke TR (1988) The urban energy balance. Progress in Phys Geog 12: 471–508

Oke TR (1997) Urban climates and global environmental change. In: Thompson RD, Perry E (eds) Applied climatology. London: Routledge, pp 273–286

Oke TR (2004) Initial guidance to obtain representative meteorological observations at urban site. IOM Report No 81, WMO/TD No 1250 Geneva: World Meteor Organiz

Oke TR, Johnson GT, Steyn DG, Watson ID (1991) Simulation of nocturnal surface urban heat island under "ideal" conditions: part 2. Diagnosis of causation. Bound-Layer Meteor 56: 339–359

Parsons KC (1993) Human thermal environments. London: Taylor & Francis

Svensson MK (2002) Urban climate in relation to land use, planning and comfort. PhD Thesis, A79 Goteborg University. Department of Earth Sciences

Svensson MK, Eliasson I, Holmer B (2002) A GIS based empirical model simulate air temperature variations in the Goteborg urban area during the night. Clim Res 22(3): 215–226

Taesler R (1990, 1991) Climate and building energy management. Energy and Build 15–16: 599–608

VDI (1994) Environmental meteorology – interactions between atmosphere and surfaces. Calculation of shortwave and long-wave radiation. VDI 3789 (2) Part 2

VDI (1998) Environmental meteorology, methods for the human-biometeorological evaluation of climate and air quality for urban and regional planning at regional level. VDI 3787 Part 2

Vieira GT, Mora C, Ramos M (2000) Registadores automáticos de baixo custo para monotorização de temperaturas do ar, da rocha e do solo. Finisterra – Revista Portuguesa de Geografia XXXV(69): 139–148

Wilks DS (1995) Statistical methods in the atmospheric sciences. San Diego: Academic Press

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