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COMPARISON OF MEASURED AND SIMULATED
MEAN RADIANT TEMPERATURE.
CASE STUDY IN LISBON (PORTUGAL)

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Abstract – Mean Radiant Temperature (MRT) is one of the most relevant human bioclimatic indices, particularly suitable for assessing the influence of climatic parameters on thermal comfort outdoors. MRT can be calculated either from physical measurements, carried out using a globe thermometer or a pyranometer and a pyrgeometer, in order to quantify short and long wave radiation fluxes, or through computer simulation. The first method, although accurate, entails the measurement of radiant fluxes from six directions, therefore it is time consuming, complex and it requires the use of expensive equipment. The second method is based on RayMan, ENVI-met and SOLWEIG computational models, often employed in urban climatological research. The present research deals with the comparison of MRT data obtained by measurement and computational simulation in Campo de Ourique, a densely populated city quarter of Lisbon. The measurements were carried out in a park and in the surrounding canyon streets during four summer days in 2006. The three computational models present some differences regarding their viability in estimating MRT compared to measurement: in case of direct solar exposure RayMan and SOLWEIG provided particularly good approximation (with an average difference of 6 and 9%, respectively), whereas the average overestimation of MRT obtained by ENVI-met is around 20%. However, in shaded locations ENVI-met provided the most acceptable agreement between measured and simulated MRT; in contrast RayMan and SOLWEIG overestimated MRT by 15% on average.

Keywords: Mean Radiant Temperature, measurement, simulation, RayMan, ENVI-met, SOLWEIG, Lisbon (Portugal).

Resumo – Simulação e medidas in-situ da Temperatura Radiativa Média. Exemplo em Lisboa (Portugal). A Temperatura Radiativa M*édia* (MRT) é um dos índices

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bioclimáticos melhor adaptados para a apreciação da influência dos parâmetros climáticos no conforto térmico em espaços exteriores. Pode ser determinada a partir de medições com um termómetro-globo ou com piranómetro e pirgeómetro para quantificar os diversos fluxos de radiação, ou por simulação numérica. O primeiro método dá resultados precisos, mas exige a medição dos fluxos de radiação em seis direcções e os aparelhos são caros. O segundo método utiliza os modelos RayMan, ENVI-met e SOLWEIG, frequentemente usados em climatologia urbana. Os resultados obtidos por medição e simulação foram comparados no caso de um bairro urbano denso de Lisboa (Campo de Ourique). As medições foram efectuadas durante quatro dias, no Verão de 2006, num espaço verde e ruas vizinhas. O cálculo de MRT pelos modelos numéricos dá resultados algo diferentes. Nos locais ao Sol, os valores obtidos por RayMan e SOLWEIG são os que mais se aproximam dos valores medidos (diferenças médias de 6% e 9%, respectivamente), ao passo que ENVI-met os sobrestima em 20%. Nos locais à sombra, ENVI-met fornece o melhor resultado, ao passo que RayMan e SOLWEIG sobrestimam os valores em 15%.

Palavras-chave: Temperatura Radiativa M*édia, medição, simulação numérica*, RayMan, ENVI-met, SOLWEIG, Lisboa (Portugal).

Résumé – SIMULATION ET MESURE IN-SITU DE LA TEMPÉRATURE RADIANTE MOYENNE. UN EXEMPLE À LISBONNE (PORTUGAL). La Température Radiante Moyenne (MRT) est un des indices bioclimatiques le plus adapté pour apprécier l'influence des paramètres climatiques sur le confort thermique en espace extérieur. Elle peut être calculée soit à partir des mesures physiques effectuées par un thermomètre dit "globe" ou avec un pyranomètre et un pyrgéomètre pour quantifier les flux de radiation, soit par simulation numérique. La première méthode donne des résultats précis, mais exige la mesure des flux selon six directions. Elle est longue et compliquée à mettre en œuvre, en plus l'appareil de mesure est coûteux. La seconde méthode utilise les modèles RayMan, ENVI-met et SOLWEIG, couramment employés dans les recherches de climatologie urbaine. Les résultats obtenus par ces deux méthodes ont été comparées dans le cas d'un quartier urbain dense situé à Lisbonne: Campo de Ourique. Les mesures ont été effectuées pendant 4 jours, en été 2006, dans un parc et dans des rues environnantes. Les modèles numériques utilisés montrent quelques différences en ce qui concerne leur validité pour calculer la MRT. Pour les endroits ensoleillés, les valeurs obtenues par RayMan et SOLWEIG correspondent le plus aux valeurs mesurées (la différence moyenne étant respectivement de 6 et 9 %), cependant ENVI-met les surestime de 20% en moyenne. Dans le cas des endroits ombragés, ENVI-met fourni l'approximation la plus pertinente, alors que RayMan et SOLWEIG présentent une surestimation de 15%, en moyenne.

Mots-clés: Température Radiante Moyenne, mesure, simulation numérique, RayMan, ENVI-met et SOLWEIG, Lisbonne (Portugal).

ملخص: محاكاة وقياس الحرارة المشعة المتوسطة في الموقع. مثال لشبونة (البرتغال). إن الحرارة المشعة المتوسطة من بين المؤشرات المناخية البيولوجية الأكثر ملاءمة لتقييم تأثير المتغيرات المناخية على الراحة الحرارية في الفضاء الخارجي. ويمكن أن تحسب إما عن طريق القياسات الفيزيائية بواسطة محرار و بالبيرومتر و البيروجيمتر لقياس تدفق الإشعاع أو عن طريق المحاكاة العددية. وتعطي الطريقة الأولى نتائج دقيقة ولكن تتطلب قياس التدفقات في ستة اتجاهات. وتكون طويلة ومعقدة التنفيذ بالإضافة لكون جهاز القياس مكلفا. ويستخدم الأسلوب الثاني نماذج رايمن، إنفيمت وسولفيغ التي يشيع استخدامها في أبحاث المناخ الحضري. وتمت مقارنة النتائج المحصل عليها من خلال هاتين الطريقتين في حي بالمناطق الحضرية الكثيفة في لشبونة: كامبو دي أوريك. أجريت القياسات لمدة 4 أيام في صيف عام 2006، في حديقة وفي الشوارع المحيطة بها. وتشير النماذج العددية إلى بعض الخلافات بشأن صلاحيتها لقياس الحرارة المشعة المتوسطة. وبالنسبة للمناطق المشمسة، فالقيم التي تم الحصول عليها بواسطة رايمن وسولفيغ أكثر ملاءمة (الفرق متوسط ما بين 6 و 9%)، أما عبر إنفيمت ، فإن الفرق يبلغ نسبة 20% في المتوسط. و بالنسبة للمناطق الظليلة، كانت إنفيمت الأكثر ملاءمة ، في حين رايمن وسولفيغ قدمت فرقا متوسطا بنسبة 15%.

كلمات البحث: درجة الحرارة المشعة المتوسطة ، قياس ، المحاكاة العددية، رايمن، إنفيمت، سولفيغ ، لشبونة (البرتغال).

I. RESEARCH CONTEXT

Natural and artificial surfaces can be found in urban environments where more than half of the Earth's population lives. The former surfaces can be mineral or contain vegetation whereas the latter can be dense or porous and made of metal, glass etc. The atmospheric variables in urban areas, and therefore human thermal comfort outdoors, are significantly affected by the geometry of the convoluted urban environment and by the physical characteristics of the materials.

Nowadays, public awareness has been raised towards the various consequences of urbanisation and, among them, the urban heat island phenomena (UHI).

The UHI is a result of a combination of factors affecting the local energy balance, such as the building geometry, surface roughness, physical properties of building materials, anthropogenic heat sources etc. (Oke, 1982, *in* Yow, 2007). According to Oke (1982) and Arnfield (2003) seasonal climatic and daily synoptic conditions, such as diurnal cycle, play an important role in determining UHI characteristics. Therefore, each urban area has a specific UHI uniqueness due to the circumstances at a given location.

There are various types of UHI and several methods of observing and studying them. UHI occurs at ground level, at different heights and as surface heat islands. Atmospheric UHI may be measured within the planetary boundary layer (above the city) and in the urban canopy (up to the top of the buildings of the urban zone). The surface UHI occurs at the level of the various urban surfaces and Yow (2007) refers to it as skin surface temperature. Surface UHI has a particularly strong effect on radiative environment and therefore on thermal comfort of humans in outdoor urban environments, especially in case of strong solar radiation exposure. It can exacerbate thermal discomfort, in particular during warm summer periods: the artificial surfaces, such as asphalt and concrete absorb heat during daytime, warm up the air by convection and release heat into the atmosphere during the night (Oke, 1982; Kuttler, 2008; Armson *et al.,* 2012). The reduction of vegetation and the increase of artificial surfaces lead to lower albedo (and the decrease of reflected short-wave radiation) and to the reduction of evapotranspiration (in other words, the decrease of cooling due to latent heat transfer).

Atmospheric and surface UHI represent an important problem during hot summer periods that occur regularly in southern Europe. The increased use of air conditioning during these periods releases more heat into the outside air which adds to the high short and long wave radiation fluxes in the urban environment resulting in extended and more frequent thermally uncomfortable periods. These in turn give rise to health problems especially among children and the elderly.

The UHI phenomenon is predicted to increase with climate change, since mean temperatures, the frequency of heat waves and their duration are forecasted to rise (Vanos *et al.,* 2010).

The present study aims to evaluate the computationally simulated MRT values against *in-situ* measured MRT values. MRT was measured and evaluated in an urban garden and also in surrounding streets − both on shaded and sun-exposed sides.

II.   THERMAL COMFORT IN OUTDOOR ENVIRONMENTS

The human body exchanges energy with its environment through convection, conduction and radiation. In an outdoor environment the climatic parameters vary to a substantially larger extent than in an indoor environment: in particular, long-, and shortwave radiation, air movement, surface and air temperatures. As a consequence, the human body needs to adapt to the extended range of environmental outdoor conditions through its thermoregulation system, in order to maintain a constant deep body temperature. Thermal comfort signifies a state where the constant deep body temperature can be maintained by the least energy exchange occurring at the body's surface. Discomfort describes the departure from comfort.

In terms of human thermal comfort, outdoors thermal conditions are strongly influenced by temperature and even more so by radiation, whose variable pattern induce large differences between sun-exposed and shaded zones (Égerházi *et al.,* 2013; Kántor *et al.,* 2012).

The Mean Radiant Temperature (MRT) is one of the indices that takes into account all short and long-wave radiative flux reaching the individual and is applicable in complex outdoor environments. It integrates the incoming and reflected direct and diffuse short wave radiation, as well as long wave radiation from the surrounding surfaces, the ground and from the sky.

In what concerns the human thermal comfort outdoors, conductive heat fluxes can be neglected. On the contrary, radiative and convective fluxes play an important role in the heat balance of the human body. Convective fluxes of latent and sensible heat are modified mainly by air humidity and air temperature, respectively, while both are influenced by wind speed (Kántor *et al.,* 2012). However, the MRT is the key factor affecting thermal comfort in case of strong direct solar radiation.

MRT can be measured with a globe thermometer − a tool used originally in indoor environmental conditions and later adapted for outdoor settings. The standard globe thermometer is a hollow sphere of copper, painted black and containing a thermometer in its centre. The wall thickness is 0.4mm and the sphere diameter is 150mm. The temperature measured in the centre of the globe thermometer results from radiative and convective fluxes. Indoors, where air movement is restricted, the globe temperature gives a good approximation of MRT, whereas in outdoor locations its reading is significantly influenced by convection and is closer to air temperature. Therefore it is not an ideal tool to measure MRT outdoors.

MRT can also be measured using a pyrgeometer and a pyranometer, proposed by Höppe and also suggested by VDI 3789 Guideline (Höppe, 1992; VDI, 1998). It requires costly equipment and the measurement procedure is tedious and time-consuming. Terrestrial and solar radiation fluxes that fall on a person are measured separately: a pyranometer is used to measure radiative fluxes within the short wave domain and a pyrgeometer is used to record radiative fluxes situated in the long-wave domain. The 3D space is divided into six parts: upper and lower directions, and the four cardinal directions. The different directions have different weighting factors according to the body's position (seating down or standing) (Kántor *et al.,* 2012)

The mean radiant flux density (S_{Str} in W/m^2) absorbed by the individual is calculated from the measured terrestrial (L_i in W/m^2) and solar (K_i in W/m^2) fluxes in the above mentioned six directions, multiplied by the weighting factors (W_i) according to the body shape corresponding to each direction ($i = 1$ to 6), and by the absorption coefficients of the clothed body from short− (a_k), and longwave radiation (a_l) − as equation 1 illustrates (Höppe, 1992, in Kántor *et al.,* 2012).

$$S_{Str} = \sum_{i=1}^{6} W_i \cdot \left(a_k \cdot K_i + a_l \cdot L_i \right)$$

Eq. 1

The MRT can be calculated from S_{Str} according to the Stephan –Boltzmann law, using equation 2 (*Kántor et al., 2012)*:

$$MRT = \left(\frac{S_{Str}}{\varepsilon_p \cdot \sigma} - 273.15 \right)^{1/4}$$

Eq. 2

where
σ is the Stefan-Boltzmann constant and
ε_p is the emissivity of the clothed human body which is equal to a_l according to Krichhoff's law (Kántor *et al.,* 2012).

In order to avoid difficult and lengthy measurements, various computational models can be used to estimate MRT: RayMan (Matzarakis *et al.,* 2000; Matzarakis *et al.,* 2007), ENVI-met (Bruse, 1999 and 2006) and SOLWEIG (Lindberg *et al.,* 2008; Lindberg and Grimmond, 2011).

The present research provides a detailed comparison of computer simulated MRT values with measured MRT at Campo de Ourique, a densely populated city quarter of Lisbon, Portugal. It is the extension of a previous research project carried out by Oliveira *et al.* (2011), which focused on the assessment of the thermal performance of an urban garden and its influence on the atmospheric parameters in the neighbouring area.

III.   STUDY AREA

The chosen study area is situated in Lisbon, a city located near the western coast of Portugal, at 38°43' latitude N and 9°9' longitude W, lying 30km to the east of the Atlantic shore, on the Tagus river estuary (Alcoforado *et al.,* 2009). Lisbon's climate is ''Mediterranean'' with mild winters and hot, dry summers. The hottest month is August (average temperature: 23°C), followed by July (22.7°C) and September (21.8°C) (Alcoforado *et al.,* 2009). The prevailing wind in summer blows from N and NW during the whole day (40% of the time) and during late afternoon (30% of the time) (Alcoforado *et al.,* 2006). Total average precipitation is less than 7mm in July and August, while it increases to 28mm in September.

The studied urban quarter is situated in a densely built-up zone in the western part of Lisbon, close to the Monsanto hill forest park. The study area is relatively flat with an altitude of approximately 90m above sea level. It has a garden, the Garden *Teófilo de Braga,* surrounded by 15-25m high buildings along a N-S and E-W oriented network of approximately15 m wide streets (Oliveira *et al.*, 2011). The average sky view factor of the streets calculated by RayMan is 0.28, which leads to pronounced differences regarding duration of insolation along the longitudinal axis of the N-S and the E-W oriented streets: 3.5 hours for the former and 11 hours for the latter (Oliveira *et al.*, 2011).

The garden has a rectangular shape and occupies 0.58ha. It is a pleasant place for rest, contemplation of nature and recreation. It has a small lake in its centre and a dense plant community consisting mostly of deciduous trees (Oliveira *et al.*, 2011).

IV.   METHODOLOGY: MEASUREMENT AND COMPUTER SIMULATION

Itinerant measurement campaigns were carried out in 2006 during four summer days, at 2 locations in the garden (points 1 and 2) and at 4 locations in the neighbouring streets (points A, C, D, E), as shown in figure 1, in order to measure air temperature, relative humidity, wind speed, short and long wave radiation. The measurement points were chosen so that they could provide some information on the influence of the garden on microclimatic parameters in different street orientations and in streets with and without trees. Points A, C and D are situated in streets with no trees and a N-S, NW-SE and E-W direction respectively. Point E is located in a N-S direction street lined with dense rows of mature trees. Point 1 is situated within the garden, in a location where people enjoy sitting at tables, and is exposed to sun during the entire afternoon, while point 2 is constantly under shade projected by the tree crowns.
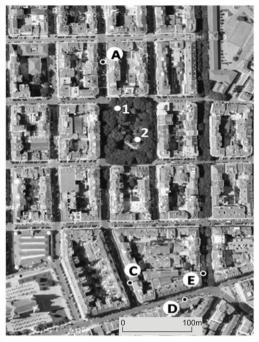
Fig. 1 – Location of observation points (www.googlemaps.com), redrawn from Oliveira et al. (2011).
Fig. 1 – Localização dos pontos de observação (www.googlemaps.com), redesenhada a partir de Oliveira et al. (2011).

Fig. 2 – Observation points: street views. Photos from Oliveira et al. (2011).
Fig. 2 – Pontos de observação. Fotografias de Oliveira et al. 2011.

Air temperature, relative humidity and wind speed were recorded at all sites, at a height of 1.5 m, using Testo probes, while incident short-, and longwave radiation from six directions were measured at a height of 1.1m, using CM21 Kipp & Zonen pyranometer and a CG1 Kipp & Zonen pyrgeometer, respectively. The measurements were performed according to the integral measurement method developed initially by Jendriztky and Nübler (Jendriztky and Nübler, 1981; VDI, 1988; Oliveira *et al.,* 2011; Kántor and Unger, 2011) during the early afternoon hours when most people visit the garden to find shelter from the summer heat. The pyranometer measures the short wave radiation (K), and the pyrgeometer the long wave radiation fluxes (L). K and L have been recorded for the four cardinal directions, as well as downwards and upwards. The mean radiation flux intensity absorbed by the human body was calculated using the terrestrial and the solar radiation fluxes, weighted according to the direction and the absorption coefficient of the body for short and longwave radiation. The MRT was calculated according to the Stefan-Boltzmann law (Oliveira *et al.*, 2011) taking into account the direction of the solar and thermal infrared radiative fluxes. The MRT can be considered as an indicator of all surface temperatures combined and as an overall descriptor of perception regarding the radiative environment surrounding the human body, and therefore is a biometeorological indicator.

Two sets of *in-situ* measurement were carried out consecutively at each street point, one in the shade and the other under direct solar radiation (the instrument was moved from the shade to the sun), in order to detect the impact of solar radiation. The measurement equipment stayed in place for 10-15 minutes during each measurement at the sun exposed and at the shaded locations.

Table I – Observation points, equipment used and measured parameters.
Measurements were carried out between 13:00 and 15:00 on 07/08/2006, 09/08/2006,
10/08/2006 and 05/09/2006.
Quadro I – Pontos de observação, equipamento usado e parâmetros meteorológicos medidos
entre as 13:00 e as 15:00 em 07/08/2006, 09/08/2006, 10/08/2006 e 05/09/2006.

Observation Points	Location	Equipment (parameters measured)
1	Garden (sun)	Hot wire anemometer (v)
2	Garden (shade)	CM21 Kipp & Zonen
A	Street – orientation: N S	pyranometer (K)
C	Street – orientation: NW - SE	CG1 Kipp & Zonen
D	Street – orientation: E W	pyrgeometer (L)
E	Street – orientation: N S	Testo probes (v, t, RH)

The general atmospheric conditions during the experiment were relatively hot, cloudless with maximum and minimum temperatures above the average monthly values measured at the airport: Tmax - 31.8°C (07/08/2006), 35.6°C (09/08/2006), 33.3°C (10/08/2006) and 31.0°C (05/09/2006), Tmin – 22.0°C (07/08/2006), 26.4°C (09/08/2006), 22.9°C (10/08/2006) and 21.1°C (05/09/2006) (Oliveira *et al.*, 2011). The temperature threshold above which the impact of high temperatures can be observed on mortality rates in Lisbon is 32°C (Nogueira and Paixão, 2008); the temperature measured was above this threshold at two experiment sites. The wind conditions were highly variable with very low speeds: between 1.6 m/s and 0.4 m/s.

The measured MRT values were compared with computationally simulated ones obtained using three different models: Rayman, ENVI-met *3.1* and SOLWEIG*2*. These computational models calculate the radiative environment within the studied city district at pedestrian level. The various models require different data inputs as described below."ENVI-met is a raster-based 3D microclimate model, designed to simulate surface-vegetation atmosphere processes in urban areas, with a typical grid resolution from 0.5 m to 10 m in space and 10 seconds in time" (Bruse, 1999 and 2006). It simulates the dynamics of microclimate during a diurnal cycle using fundamental laws of thermodynamics and fluid mechanics. The model requires input data regarding buildings, vegetation and meteorological conditions. The atmospheric parameters used are from *Lisboa/Geofísico* Meteorological Station (MS), 1 km SE of the study site. The prognostic variables of ENVI-met includes, among others, temperature, wind speed and direction, radiative fluxes, humidity and particle dispersion.

RayMan is a bioclimate and radiation model that facilitates the calculation of radiation flux densities based on building, vegetation and meteorological data. The 3D environment is divided into an upper and a lower hemisphere separated by a plane surface 1.1 m above the ground (Matzarakis *et al.,* 2000, Matzarakis *et al.,* 2007). RayMan requires input data on building geometry, surface characteristics (albedo, emissivity), geographical location, date, time, meteorological variables and vegetation.

SOLWEIG – SOlar and Long Wave Environmental Irradiance Geometry model, developed by Lindberg *et al.* (2008) simulates spatial and temporal variation of radiation fluxes, shadow patterns in urban environments, based on the geographical location, the urban morphology (buildings, plants) and meteorological parameters (temperature, humidity, direct and diffuse components of short wave radiation). SOLWEIG is a raster-based model and uses Digital Elevation Models to represent the convoluted urban morphology including buildings and vegetation. It requires data on building geometry, surface characteristics (emissivity for vertical surfaces and for the ground, albedo, transmissivity of shortwave radiation for the vegetation), meteorological data (short, and longwave radiation, temperature, relative humidity, wind speed), date and time in order to calculate MRT at a point of interest.

The simulated MRT and shadow patterns have hourly temporal resolution, and the spatial resolution of the 3D geometrical model is 2.5 m. The cell sizes used to model the Campo de Ourique area by ENVI-met and SOLWEIG are 2m x 2m, and 2.5 x 2.5 m, respectively.

V.   RESULTS

The observed MRT values recorded during the *in-situ* measurement campaigns were compared with computer simulation results obtained using SOLWEIG, RayMan and ENVI-met models. The analysis is concentrated on the effect of solar radiation; therefore the data were divided into two groups: those recorded at sun-exposed locations, and those recorded in shaded areas.

The observed and simulated datasets – recorded and calculated both under shade and sun – were compared through regression analysis, statistical similarity test of series (using F test, calculated with ANOVA method), and calculation of differences for each point analysing the mean and the extreme differences. The computationally simulated and the measured data have a very strong correlation for all models used: The highest correlation was found for the ENVI-met model (0.96), and a slightly lower one for SOLWEIG and RayMan models (0.87 for both), meaning that the covariance between the measured and the simulated values is strong, but they are not necessarily identical (table II and fig. 3). The F test revealed, under the null hypothesis that values of the two datasets are similar, that measured and simulated values are not significantly different when MRT was calculated using ENVI-met and SOLWEIG (F =1.07 and 0.47 respectively); however the null hypothesis was rejected (F=6.43) when RayMan model was used (table II).

Regarding the median value of the absolute temperature difference for the observation points, the ENVI-met and SOLWEIG models once again yield better results (3.7 and 7.7°C respectively), while the result is less favourable when the RayMan model is used: 13.5°C.
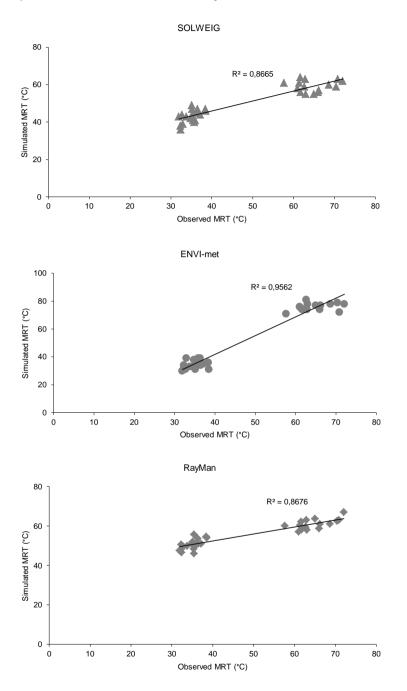
Fig. 3 – Correlation of observed and simulated MRT data by SOLWEIG, ENVI-met
and RayMan models.
*Fig. 3 – Correlação de temperatura radiativa média (MRT) observada e simulada pelos modelos
SOLWEIG, ENVI-met e RayMan.*

The maximal absolute differences obtained with all models are high: 18°C for ENVI-met, 14°C for SOLWEIG and 20°C for RayMan (Andrade and Szűcs, 2012).
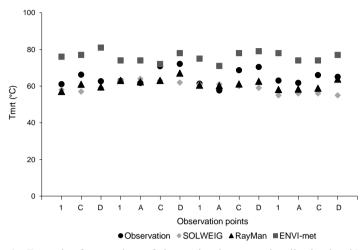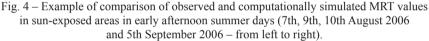
Table II – Statistical characteristics of observational and simulated datasets.
Quadro II – Características estatísticas de dados observados e simulados

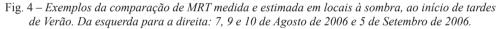|	SOLWEIG	ENVI - met	RayMan
Correlation coefficient (R^2) both sun and shade	0.86	0.96	0.87
Standard deviation (δ) both sun and shade	1.37	1.40	2.10
Standard deviation (δ) sun	1.88	3.27	1.25
Standard deviation (δ) shade	1.95	0.71	3.62
F test – ANOVA (F) both sun and shade	0.47	1.07	6.43

The shaded and the sun-exposed zones show significant differences regarding MRT. The highest value, 72°C, was observed at point D that was exposed to direct solar radiation and situated in an E-W orientated street on the south part of the selected zone, while the lowest, 58°C, was obtained at point A (fig. 4). It may be surprising that the lowest MRT was not observed in the garden, but instead at point A in the northern part of the study area. The explanation is that point A receives direct solar radiation during a short period of 2 hours whereas point 2 has 3.5 hours of solar exposure (Oliveira and Andrade, 2007) – which is intense enough to counterbalance temperature reduction due to evapotranspiration.

It should be noted that point 1 was exposed to solar radiation during the measurement period and has no MRT values measured in the shade. On the contrary, point 2 has no MRT data recorded under direct solar exposure, since it is shaded during the afternoon. Furthermore, the MRT data for August 7th are not available for point A due to a data handling error.

The observed difference between minimum and maximum MRT values in shaded areas is substantially smaller: 6ºC, resulting from a minimum value of 32°C recorded in the garden (point 2) and a maximum value of 38°C occurring at point E (fig. 5).

Fig. 4 – Example of comparison of observed and computationally simulated MRT values
in sun-exposed areas in early afternoon summer days (7th, 9th, 10th August 2006
and 5th September 2006 – from left to right).
Fig. 4 – *Exemplos da comparação de MRT medida e estimada em locais à sombra, ao início de tardes
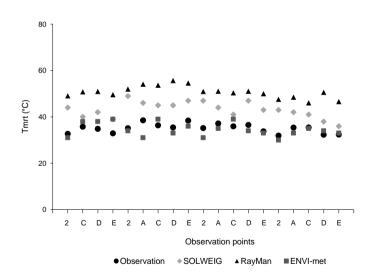de Verão. Da esquerda para a direita: 7, 9 e 10 de Agosto de 2006 e 5 de Setembro de 2006.*

Fig. 5 – Example of comparison of observed and computationally simulated MRT values
at shaded locations in early afternoon summer days (7th, 9th, 10th August 2006
and 5th September 2006 – from left to right).
Fig. 5 – *Exemplos da comparação de MRT medida e estimada em locais à sombra, ao início de tardes
de Verão. Da esquerda para a direita: 7, 9 e 10 de Agosto de 2006 e 5 de Setembro de 2006.*

The MRT estimations, calculated by the 3 computational models used for the study, provide a relatively satisfying fit with measured MRT values, both in shaded and in sun-exposed areas.

MRT values calculated by SOLWEIG and RayMan for areas exposed to direct solar radiation are 9% and 6% below measured values on Celsius-scale, respectively. In contrast, ENVI-met provides an overestimation of about 20% for the same climatic conditions – that can lead to differences as high as 20°C. Figure 5 depicts the comparison between observed MRT values and those simulated computationally.

Hedquist *et al.* (2009) carried out a measurement campaign in Central Phoenix Arizona and collected surface and air temperature on the ground with mobile sampling and by helicopter in order to obtain a detailed record over a complete diurnal period; the values were then compared with those obtained by computational modelling using ENVI-met. According to their study, the model over-predicted surface radiant temperature values in the afternoon by 25-30°C compared to those measured by Hedquist *et al.* (2009). Other studies carried out by Thorsson *et al.* (2007) and Matzarakis *et al.* (2007) employed RayMan to model MRT in Göteborg in an open city square and in an urban area Freiburg Germany, respectively. The results obtained by the model were in good correlation with measurements in case of high solar elevations in Göteborg, and during the whole day of study in Freiburg.

The present study shows that the MRT values obtained by ENVI-met are in acceptable agreement with the observed data in the shade. The average and median values of the observational and simulated data sets are very close to each other, while data dispersion around a mean value (standard deviation) is slightly higher for the computationally simulated data.

In contrast, SOLWEIG and RayMan models overestimate MRT in shaded locations (by about 15%). Figure 5 shows the comparison of observed MRT values in shaded areas with the computational simulation results.

Hwang *et al.* (2009) found a good correlation ($R^2 = 0.85$) between measured and modelled MRT values, both during winter and summer seasons, when using RayMan in Taiwan in order to study outdoor thermal comfort at an university campus. Their results agree with the results of our study, in which high correlation coefficients, between computer simulated data for shade and sun, were obtained with the RayMan ($R^2 = 0.87$) the ENVI-met ($R^2 = 0.96$) and the SOLWEIG models ($R^2 = 0.87$).

It has also to be taken into account, when analysing and comparing in-situ measured data with computationally simulated results, that the measurement devices have a range of error themselves. In case of the latest generation of the Kippen & Zonen pyrgeometer the accuracy is about 3% (CG4 Handbook, 2003, in Viúdez-Mora, 2011). Moreover, the simulation is a geometrical, physical and climatological abstraction of the reality, and as a consequence the results represent an approximation of the real conditions.

VI. CONCLUSION

Modelling MRT represents a challenge for researchers in urban climatology particularly in complex environments, that include buildings from various architectural periods, constructed with different materials, as well as vegetation that has very different physical characteristics from the buildings.

The results obtained in Campo de Ourique district, through simulations and through physical measurements, highlight some differences in the viability of the three tested models to estimate MRT.

In general, it can be stated that there is always a tested computational model that provides MRT estimations with an acceptable agreement with the *in-situ* measurements, for the entire set of values. Among the three models, RayMan has provided a particularly good fit for sites exposed to direct solar radiation. ENVI-met overestimated substantially the MRT in case of direct solar exposure: the simulated values exceed those measured by 15ºC on average, and in some cases the difference reaches 20°C. SOLWEIG provided more precise results than ENVI-met for the solar exposure case, with about 4-5°C difference to the measured MRT values. The large errors occurring using ENVI-met indicate the RayMan model as the first choice for MRT estimation in sites under solar exposure and the SOLWEIG as the second choice.

At shaded locations, simulation results obtained by ENVI-met present the best fit with observed data. RayMan overestimates the MRT by 15-20°C, as does SOLWEIG, albeit to a smaller extent. As a consequence, ENVI-met is retained as the better adapted tool for MRT simulation for shaded locations, against RayMan and SOLWEIG.

The attention drawn to the quality of life in urban areas by studies of thermal comfort is of great importance when designing or renewing urban areas as the number of urban citizens is constantly increasing. Thermal ambience has to be planned concomitantly with buildings, streets, vegetation etc. An early-phase inclusion of climatic parameters into the architectural and landscape design process promotes the creation of comfortable, more pleasant and healthier open spaces.

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