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PEDESTRIAN THERMAL COMFORT IN RELATION TO STREET ZONES WITH DIFFERENT ORIENTATIONS

A pilot-study of Rotterdam

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Abstract. This paper presents the impacts of different street orientations and street zones of a typical Dutch residential area on micro-scale human thermal comfort. The spatial and temporal variation of mean radiant temperature (T_{mrt}) of a typical summer day in Rotterdam, The Netherlands, is simulated by using an established long- and short-wave 3D radiation fluxes model (*SOLWEIG*). This model calculates human radiation load and expresses this as a T_{mrt}. Hereby we simulate and analyse the T_{mrt} variations for three zones of a street consisting of a centre area for cars and the adjacent pedestrian zones for pedestrians and bicycles. The streets are azimuth rotated. The simulation and analysis results show various T_{mrt} patterns of the three zones in the different orientations at different periods during daytime. We show that the spatial distribution of T_{mrt} at street level strongly depends on street orientation and street zone. This is crucial since optimizing street configuration will directly influence the human thermal comfort in relation to street orientation and street zone. Finally we present a time adjusted framework of thermal comfort and classify the various T_{mrt} for each zone and orientation.

Keywords. Thermal comfort; street orientation; street zone; mean radiant temperature (T_{mrt}); *SOLWEIG*.

1. Introduction

An increase of extreme summer heat waves around the globe is arising, which has a strong impact on thermal comfort of people (AR4 IPCC, 2007; National Assessment Synthesis Team, 2000). Urban design affects microclimates as well as the energy consumption of buildings. Thus the orientation of streets and their zones in their relationship to the sun is a key issue not only in design but also in biometeorology. Outdoor and micro climate become increasingly popular issues and generates new collaboration between different fields of research (Brager and de Dear, 1998). However urban design knowledge on outdoor thermal comfort for pedestrians remains limited.

The mean radiant temperature (T_{mrt}) is an important thermo-physiologically relevant assessment index. Several European studies show that the perceived temperature during hot summer days directly relates to T_{mrt} (Mayer et al., 2008). T_{mrt} represents the human radiation exposure to all short and long wave radiation fluxes by weighting the directional components in all six directions (front, back, left, right, top and bottom) to represent the radiation load on a standardized human being (Matzarakis et al., 2007). Thorsson et al. (2011) have showed that the *Solar Long Wave Environmental Irradiance Geometry Model* (*SOLWEIG*) presents reasonable T_{mrt} simulation results for the urban canyon micro climate in Goteborg, which has a similar maritime climate as the Netherlands (Kottek et al., 2006). We selected for our simulation a typical summer day such as August 6th, 2009 (Figure 2) akin to Heusinkveld et al. (2010) urban heat stress assessment in Rotterdam via a mobile platform. Dai et al. (2012) shows that the SOLWEIG model compares well with Heusinkveld et al. (2010)'s survey results. We constructed a street model with variable building width and variable orientation and selected the same meteorological data set for our simulation and used SOLWEIG (Figure 3) as a model to simulate T_{mrt} in various urban settings, in order to get an overview of spatio-temporal distribution of T_{mrt} within different zones of a street with different orientations (Figure 4).

Some studies have showed that there is a relationship between urban form and human thermal comfort. For instance, Herrmann and Matzarakis (2012) conducted an analysis on T_{mrt} in idealised urban canyons using another radiation fluxes model called *RayMan* (Matzarakis et al., 2007), which is a point simulation model for modelling radiation in a complex 3D environment. They also considered the street orientation impact on T_{mrt} in idealised urban canyons; however they simulated the T_{mrt} along the centre line of the street only. Typically however, people are staying in pedestrian-zones which are usually located at the street side. Hence the mean or centre point's simulation result can't differentiate between different zones of street's T_{mrt} in detail. In our research we simulate T_{mrt} for three zones, namely the centre and two adjacent pedestrian zones to the left and right side of a street. While Thorsson et al. (2009) showed the spatial variations of T_{mrt} with four types of urban forms using SOLWEIG, our research focuses on the various street orientations and the impact of T_{mrt} on three zones of a typical street. Dai et al. (2012) also considered impact of street orientations, but they just considered North-South and East-West orientations. Bourbia and Awbi (2004) analysed six street orientations but limited their analysis to shading patterns instead of a T_{mrt}

spatial distribution which is more closely related to the human thermal energy balance or comfort. Ali-Toudert and Mayer (2007) considered E-W, N-S, NE-SW and NW-SE street orientations by a 3D non-hydrostatic model, called *ENVI-met* (Bruse and Fleer, 1998) in a subtropical location. However, in our study we focus on the spatial-temporal distributions of the three zones of a street in relation to their orientations in a temperate climate zone.

The main objective of this study is to investigate the relationship between street orientations and thermal comfort (characterised by T_{mrt}) of different zones of a street using the SOLWEIG model developed by the Göteborg Urban Climate Group (Lindberg and Grimmond, 2010; Lindberg et al., 2008; Lindberg and Thorsson, 2009). Hereby we simulate T_{mrt} for a typical Dutch residential suburb area with fixed height/width-ratio (h/w) of 1:1 in six azimuth orientations in 30° steps using the SOLWEIG model.

2. Method

A typical height (h) of 15m is selected for idealised urban buildings in Rotterdam and 15m is chosen for street' width (w) (akin to Herrmann and Matzarakis' model (2012) (h/w=1:1). Rotterdam (approximate Longitude 4°28' and Latitude 51°55') is a harbour city characterized by a temperate maritime climate influenced by the North Sea and Atlantic Ocean. We build a computer model of an artificial street by constructing a *Digital Elevation Model* (DEM). A DEM is a digital 3D model to present a terrain's surface (Holmes et al., 2000). Next, six urban canyon versions were constructed by rotating the DEM in 30° steps, namely 0°, 30°, 60°, 90°, 120° and 150° (Figure 1), hereby the situation in 0° is the same as that in 180°, and 30° is the same as 210° etc. In the third step, we simulate the streets in their different orientations in SOLWEIG using nearby weather station data and generate their T_{mrt} values for the two pedestrians and the centre zones (Figure 1). 3m is set as the width of pavements and 9m for the centre zone of the street. Finally we classify the simulation results into three T_{mrt} categories and relate them to the duration of exposure. Left and right is defined based on the orientation of the street starting from 0° and rotating to 150° as shown in Figure 1.

3. Simulation of T_{mrt} for different scenarios

The profile of August 6th, 2009 (Figure 2) matches best a diurnal distribution of temperature and global radiation (smoother diurnal distribution suggests less wind) which we select for our simulation from each profile of global radiation and temperature (temperature was almost 24 °C) of each day in summer 2009.

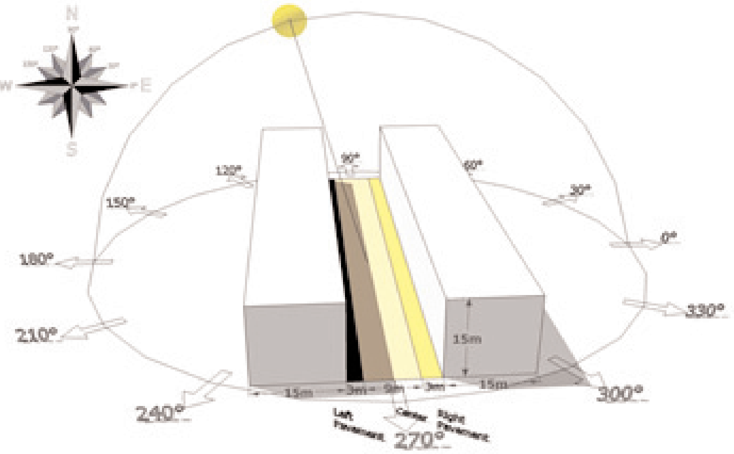

Figure 1. The idealized urban street scenario (h/w =1:1): showing the study areas of left and right pavements (each 3m) and the centre zone (9m) of a street and the six orientations.

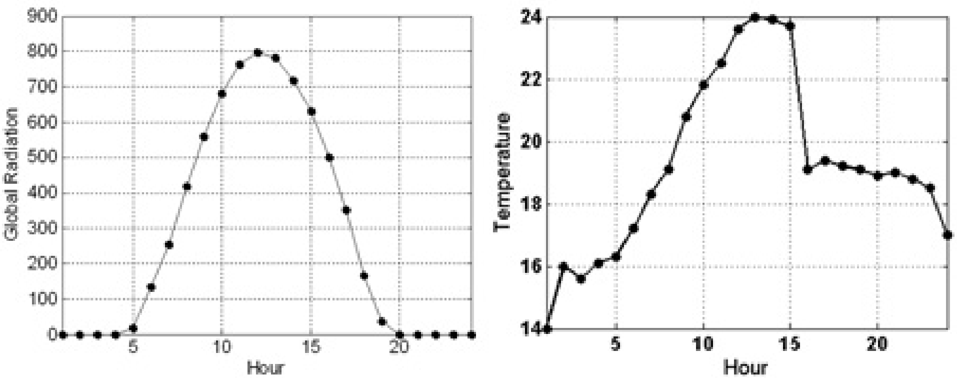

Figure 2. Profile of Global Radiation (left) in W/m² and Temperature (right) in °C of Rotterdam on 6th August, 2009.

Figure 3 shows the workflow for the SOLWEIG model. The Digital Elevation Model (DEM) (Step 1) is a digital 3D model to present a terrain's surface information (Holmes et al., 2000) to get the matching appropriate Sky View Factor (SVF) (Step 2). DEM first calculates SVF and it is the fraction of the sky visible from an observer' point of view within the street canyon. Then SOLWEIG uses the SVF to calculate solar radiation (direct and diffuse) for a given longitude, latitude, date and time. We use the default model parameters (Step 3), which

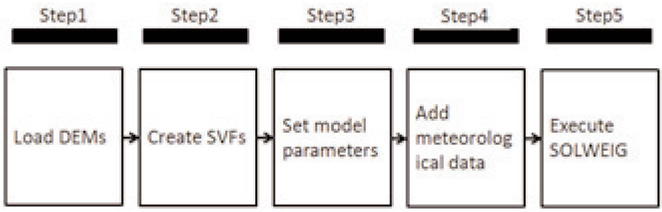

Figure 3. The five steps to simulate T_{mrt} *using the SOLWEIG model.*

appeared to simulate correctly for T_{mrt} within 60°C (Dai et al., 2012). Albedo (0.15), emissivity for surface (0.95) and emissivity for buildings (0.90) are given for this study, which are the same setting as Thorsson et al. (2011).

Then we synchronize August 6th, 2009, Rotterdam's meteorological data (Rotterdam WMO weather station Zestienhoven, source: KNMI, The Netherlands, 2012), which includes temperature, relative humidity and global radiation for the simulation day (Step 4) and finally we execute the software to simulate the T_{mrt} variation (Step 5).

4. Simulation Results

Figure 4 below shows the T_{mrt} simulation results in their six orientations. The simulation results allow us to study the impact of T_{mrt} in each street orientation for the three zones of the street. We focus on the daytime from 5:00 to 19:00.

Figure 4 also shows the diurnal profiles of T_{mrt} distributions in six street orientations during daytime (5:00-19:00, Coordinated Universal Time: UTC). The graphs show that the range of T_{mrt} of all orientations is between 16°C and 56°C.

We can see clearly the T_{mrt} differences in the 0° and 150° orientations and similar T_{mrt} patterns in 90° and 120° orientations. In the 0° orientation, the T_{mrt} of the left pavement is the highest reaching 56°C at around 11:00h, while the T_{mrt} of the centre zone is highest with 45°C at around 8:00h and the right pavement 43° at around 7:00h respectively. In the 150° orientation, T_{mrt} of the right pavement is the highest of 51° at around 12:00h, while T_{mrt} of the centre zone is the highest of 44°C at around 14:00 and the left pavement 34°C at around 15:00h.

In the 90° orientation, the three profiles are close to a Standard Normal Distribution (SND). T_{mrt} of the right pavement is highest (56°C) at 11:00h, while T_{mrt} of the centre is highest (50°C) at 12:00h and T_{mrt} of the left pavement is highest (48°C) at 13:00h respectively.

In the 120° orientation, the T_{mrt} of the right pavement is close to a SND and reaches the highest value (52°C) at 11:00h, while the T_{mrt} of the centre zone is

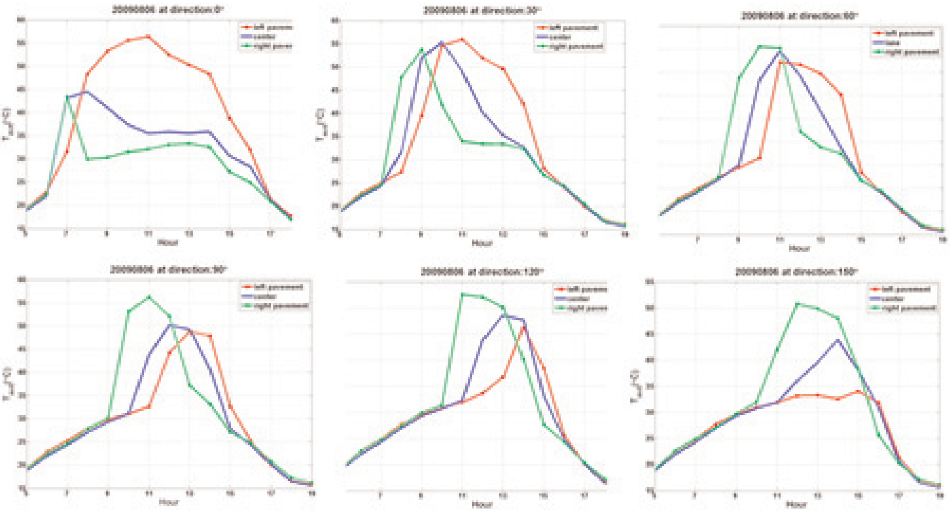

Figure 4. The profile of T_{mrt} *with six street orientations from 5:00 to 19:00 for left, right pavement and centre of street on August 6*th*, 2009 in Rotterdam.*

highest (48°C) at 13:00h and the T_{mrt} of the left pavement is highest (46°C) at 14:00.

Finally in 30° and 60° orientations, the highest T_{mrt} of the three zones are all well above 50°C from 9:00h to 13:00h during the simulation day.

In general, the right pavement is the first area to become warmer, centre is the second area to get the sunshine and the left pavement is the last zone. For the left pavement the T_{mrt} values are higher than that of the other zones in 0° and 30° street orientations. At the same time, T_{mrt} value of the left pavement becomes smaller for the other orientations. Due to the path of the sun and its subsequent exposure, the right pavement' T_{mrt} is higher in the 90°, 120° and 150° orientations. These would be used to translate to moderate heat stress as we can build buildings in a better orientation on a better part of street.

Mean, Standard Deviation, Maximum and Minimum of T_{mrt} are shown in Table 1. Based on our results, we use the statistical distribution (Mean plus or minus Standard Deviation) as a method to classify the thermal comfort into three levels: Normal (Level I), Warm (Level II) and Hot (Level III). The T_{mrt} of Level I are all below 20°C, Level II ranges between 20°C and 49°C and Level III has T_{mrt} values above 49°C. The three classifications are shown in Table 2.

Generally the T_{mrt} of Level I is considered as a comfortable normal temperature (note that T_{mrt} is different from air-temperature: it sums all short and long wave radiation fluxes and weights the directional components for each up or

Table 1. Mean, Standard Deviation, Max and Min of T_{mrt}

	***Tmrt* (°C)**
Mean	*34.2*
Standard Deviation	*14.2*
Max	*61.0*
Min	*15.3*

Table 2. The classification of Tmrt: three levels of thermal comfort: Level I: Normal, Level II: Warm, Level III: Hot.

Classification of thermal comfort	***Tmrt***
Level I: Normal	$T_{mrt} <= 20°C$
Level II: Warm	$20° < T_{mrt} <= 49°C$
Level III: Hot	$T_{mrt} > 49°C$

down), Level II is considered as warm – not hot, yet a longer time of exposure will make people feel uncomfortably warm; and Level III is considered as hot to extreme hot. Matzarakis et al. (1999) links Physiologically Equivalent Temperature (PET) to human thermal comfort. They consider "PET > 35" as "Hot, strong heat stress", and "PET around 23" as "Comfortable, no thermal stress". Mayer et al. (2008) find the relationship between T_{mrt} and PET according to their European study results using linear regression. Our classification method aligns with the results of both Matzarakis et al. and Mayer et al.

The left side of Figure 5 presents the detailed spatio-temporal distribution differences of T_{mrt} in the three zones of the street. Using the above three level classification we can re-represent our findings clearer as shown on the right scale of figure. In general, when the left pavement is hot (level III), the right one is cool (Level I), and vice versa. The hottest T_{mrt} of the day is around noon. In the 0° orientation, the left pavement sustain high T_{mrt} of above 49°C. The T_{mrt} remains in this level for ca. 6 hours, which means that it is highly uncomfortable and we subsequently reclassify it in a time-adjusted Level III.

Table 3 shows the time-adjusted classification of three zones and their orientations. From Figure 5 (right), we can see that some parts of T_{mrt} in Left 30°-, Centre 30°-, Right 90°- and Right 120°-zones are below 49°C, which is within the range of Level II. Since the T_{mrt} in these orientations remain above 49° for a longer period of time (about 3 hours), we subsequently reclassify them into category Level III. While some parts of T_{mrt} in Left 90°-, Centre 60°-, Centre 90°-, Right

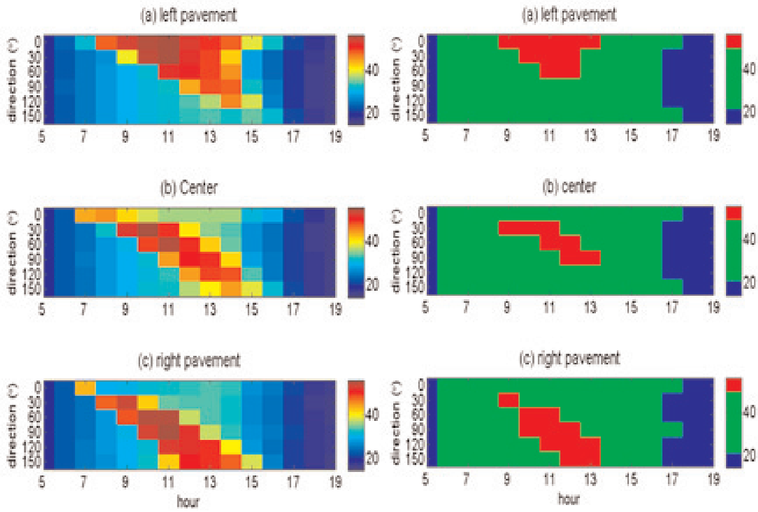

Figure 5. *Left: Average of three zones' Tmrt (°C) with the 6 street orientations from 5:00 to 19:00. Right: Our three level classification results for three zones' Tmrt (°C).*

Table 3. The time-adjusted classification of three zones and their orientations: Level I: Normal, Level II: Warm, Level III: Hot. Bold indicates the new classification.

Level III		**Level II**		**Level I**
Around 6 h	**Around 3 h**	**Around 2h**	**Around 1h**	**Around 0h**
Left 0°	**Left 30°**	**Left 90°**	Right 30°	Left 60°
	Centre 30°	**Centre 60°**		Left 120°
	Right 90°	**Centre 90°**		Left 150°
	Right 120°	**Right 60°**		Centre 0°
		Right 150°		Centre 120°
				Centre 150°
				Right 0°

60°- and Right 150°-zones are in Level III, but only for a short period of time (less than 2 hour), we assign them to Level II.

5. Conclusion and Limitation

The simulations performed in this study show that street orientation and the three different zones of a street (right-, left pavement, and centre zone) play an important role on the local T_{mrt}. We have simulated separately the three zone of a street and various orientations to distinguish T_{mrt} during typical summer day. The results show that the thermal comfort of the three zones varies: there are large T_{mrt} differences between 0° and 150° orientation, and 0° is hotter than 150°. For example, shading elements or trees can reduce the heat gain of the left pavement in the 0° orientation, the right pavement in the 90° orientation and three sides in 30° and 60° orientations; or in Rotterdam's context street orientations of 120° and 150° are better than the others orientations. As the thermal comfort for two pavements plays an important role to people's lives, the simulation results can aid in the urban design and planning in respect of micro-scale climate issues.

Further research has to be done to include elements such as monthly heat stress (different months have various sun angle) and other factors, such as vegetation, building materials, building types, shading, building/street forms, wind, anthropogenic heat, etc. In addition there are subjective factors impacting the thermal comfort of people, like personal feelings or people's activities. Next we plan to transfer this study to a variety of other climate zones to test its universal validity. Finally our research aims to combine all the said elements into a parametric model to establish and analyse spatio-temporal dependencies of urban form to thermal comfort.

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