Investigation of the effect of different sealed surfaces on local climate and thermal stress

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dated : 1 July 2015

1. Introduction

Local climate is driven by the interaction between energy balance and energy transported by advected air. Short-wave and long-wave radiation are major components in this interaction. Huge differences in temperature (~10°C) between sunlit and shadowed surfaces may result from the radiation balance. Hence adjusting the grade of reflection of surfaces is an efficient way to influence this range of temperature. While reflectivity is growing with the amount of reflected radiation the absorbed radiation is transformed into thermal energy heating the affected body and giving off heat to the air.

In urban areas the specific geometry of the building structure leads to a larger surface area, thus the absorbable amount of solar radiation is higher. On the contrary undeveloped areas do not heat up like urban areas because of the higher amount of shadow and the higher capacity of evapotranspiration from vegetation. On hot summer days when the heat exchange is on a low level, buildings begin to heat up and act as a thermal storage system, leading to the well-known "heat island" effect.

Climate warming at global- and urban-scale enhance this effect, therefore using different materials for buildings or streets can be considered as an effective method to influence urban microclimate. Santamouris et al.(2012) investigated the influence of albedo of asphalt materials on air temperature. They found a decrease of surface temperature of 12 °C and of air temperature of 1.9°C - compared to a conventional asphalt surface - above an asphalt surface with a reflection of 47% in the visible and 71% in the infrared spectral range. Using results of various studies dealing with the influence of the albedo of a city on the urban heat island, Santamouris (2014) found a relationship between increase of albedo (ALBIN) and decrease in temperature (ATD) of the form:

$$ATD = 3.11\ ALBIN$$

As an example a rise in albedo of 0.05 would lead to a decrease in average temperature of the city of 0.15.
Lot of studies have dealt with the contribution of white roofs to the average albedo of a city and with the reduction on air temperature. Though an increase in albedo may lead to a decrease in surface and air temperature, several investigations (e.g. Gomez et al., 2013; Lee et al, 2014) showed that an increase in surface albedo or in the albedo of buildings may lead to a higher thermal stress for humans because of the higher reflected shortwave radiation, which has a large impact on human energy balance.
The goal of the present study is first a study of the accuracy of one chosen urban energy balance model, which consists of a simulation of the effect of a change in albedo of sealed surfaces on surface temperature and radiation balance and the comparison of these simulations with measurements. In a second step comparison of two urban energy balance models (TEB and Envi-met) and their output with respect to different building and road surfaces are made. In a third step the thermal stress issue is adressed. The universal thermal stress index (UTCI) is calculated based on the simulations. Possible ways to use high reflecting road surfaces in order to increase the average albedo of a city, however keeping the thermal stress to the pedestrians at the same level, are investigated. First preliminary results are presented in the present paper.

2. Methods

2.1. Experimental investigations

Routine measurements of the radiation balance (Fig. 1a), of the ground and of the air temperature and humidity at different heights above the ground and measurements of the shortwave and longwave optical properties (albedo, emissivity) from/above 6 different types of sealed surfaces were performed over a duration of 4 months. During this measurement campaign the above mentioned components were measured above 2 conventional asphalt surfaces, one conventional concrete and three newly developed concrete surfaces with increased reflectances (Fig. 1b). Measured albedo values amounted to 0.12±0.02 for the asphalt surfaces and to maximum values of 0.57 for concrete (Table 1).

Figure 1a (left panel) shows the instrumentation used for the measurements of radiation balance (Kipp and Zonen 4 component radiometer), for temperature (pt 100 sensor) and for wind (2 –D ultra sound anemometer)
Figure 1b (right panel) shows the 6 different types of sealed surfaces: asphalt (2x left in front), conventional concrete (left in the back) and the three new high reflecting concrete surfaces (right row).

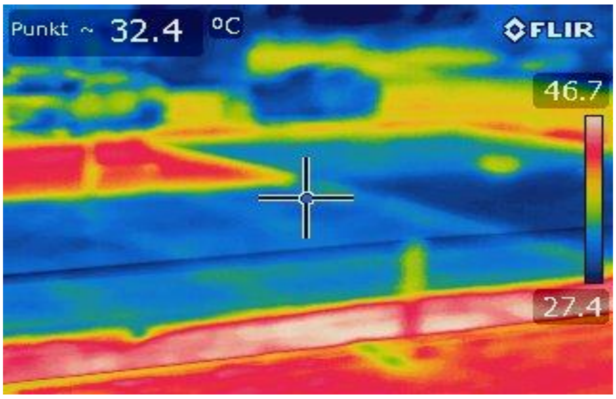


Fig 2a (left panel) shows surface temperature measurements performed with a thermal camera. The figure corresponds only to a smaller section of the visible photograph (right pannel) and shows the surface temperature of one asphalt surface (left in the second row) of conventional concrete surface (right in the second row) and of high reflecting concrete surfaces (first row). Fig 2b (right panel) shows the visible photograph of the surfaces which includes a wider area than Fig. 2a. Measurements and photographs were performed on 17. Juli 2014, 1114 MET.

The surface temperature is clearly anticorrelated with the albedo (Fig. 2). The measured surface temperature of asphalt was on 17. Juli 2014 with temperatures around 42 °C approximately up to 15°C hotter than the concrete surfaces. Table 1 gives an overview of the measured albedo of the surfaces and of the corresponding maximum surface temperatures on 17. Juli 2014. In addition the emissivity was determined by obtaining a fit of the calculated emitted longwave radiation (using Stefan Boltzman law and the measured surface temperature) with the measured upward longwave radiation. The accuracy of this method is being under investigation. In addition the specific heat capacity was determined in the lab, using two buckets filled with water and a cube of the respective material. One PT100 sensor was introduced inside the cube to measure the change in temperature of the cube. By measuring the change in time of the water temperature of the bucket which contains the cube, by comparing it to the water temperature of the other bucket (without cube inside) and by measuring the change in temperature of the cube with time it is possible to determine the heat capacity (Table 1).

Table 1: Measurements of the albedo of the 6 sealed surfaces and of the corresponding surface temperature performed on 17. July 2014. The two right columns show the emissivity obtained by comparing measured ground temperature (PT100) and measured longwave radiation (Kipp and Zonen 4 component radiometer) and specific heat capacity. The specific heat capacity was determined in the lab using two buckets filled with water and with a cube of the respective material in one of the buckets.

Surface	*Albedo*	*Surface temperature [°C]*	*Emissivity*	*Specific heat capacity [J/(kg.K])*
Asphalt 1	*0.12*	*40 ± 1°C*	*0.95 ± 0.02*	*901*
Asphalt 2	*0.13*	*42± 1°C*	*0.98 ± 0.02*	*901*
Conventional concrete	*0.43*	*34 ± 1°C*	*0.99 ± 0.02*	*721*
High reflecting concrete 1	*0.57*	*27 ± 1°C*	*0.99 ± 0.02*	*891*
High reflecting concrete 2	*0.47*	*30 ± 1°C*	*0.99 ± 0.02*	*891*
High reflecting concrete 3	*0.48*	*29 ± 1°C*	*0.99 ± 0.02*	*891*

2.2. Model simulations

Simulations of the surface temperature, of radiation balance and of the thermal stress were first performed with the model Envi-met version 3.99 Beta version (Bruse et al http://www.envi-met.com/documents/onlinehelpv3/helpindex.htm) and will only be performed in a later stage with the Meteo France Town Energy Balance (TEB) model (Masson, 2000). Envi-met is a microscale climate model which takes energy balance, wind circulation, and all meteorological components such as air temperature, solar radiation, air humidity into account. The model includes building elevation map and for each pixel the characteristics of the sealed surfaces (among others heat capacity, albedo, emissivity). Vegetation may also be included. Since the dimensions of the areas are rather small, air temperature is strongly affected by advected air. In the following section only surface temperature, radiation balance and mean radiant temperature will therefore be shown.

3. First preliminary results

3.1 Simulations for the test surfaces

Before comparing simulated with measured surface temperature, the main energy component, the solar global radiation was first compared with the measurements and tuned to obtain a perfect fit. This was done for 20. July 2014. In addition all the properties of the surfaces (heat capacity, density, emissivity) were precisely adjusted to the real determined properties of the materials. Meteorological data (air temperature, air humidity, wind) were precisely set up. 20. July was during the whole day almost cloudless. Fig. 3 compares the simulated with the measured surface temperature. During the night the simulated surface temperatures of asphalt and concrete are respectively around 5 and 2 degrees lower than the measured. During the day the simulated surface temperatures of asphalt and concrete are around 2 –3 degrees lower.

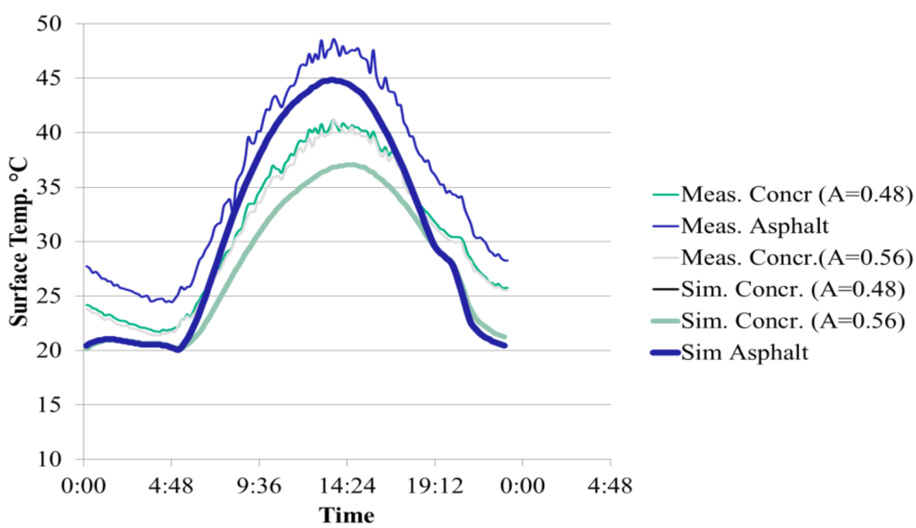


Fig. 3: Comparison of the simulated (Sim) surface temperature of Asphalt and concrete (Concr) with the measured (Meas) surface temperatures

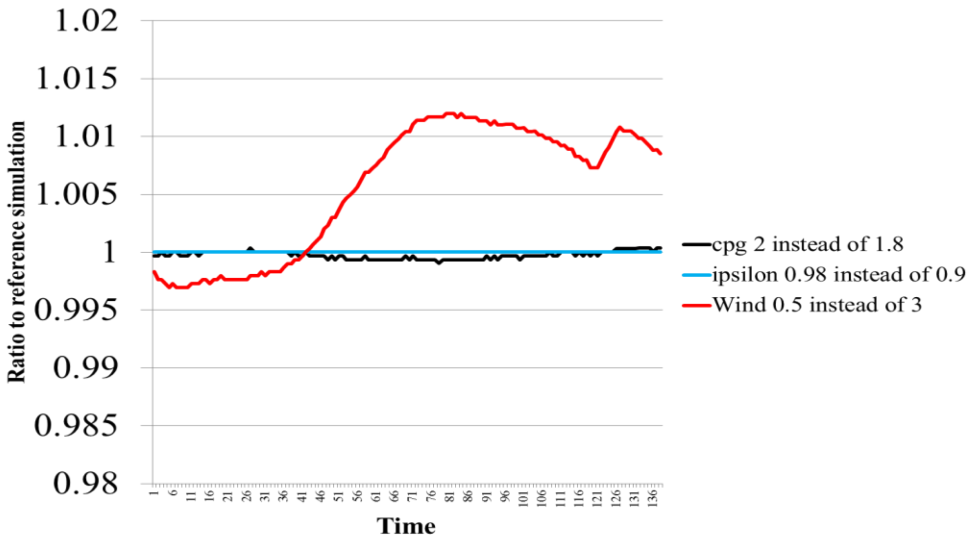


Fig. 4: Sensitivity study showing the influence of uncertainties of specific heat capacity (cpg), emissivity (ipsilon) and wind on the surface temperature. Shown is the ratio to the reference simulation. cpg was changed from 1.8 to 2, ipsilon from 0.99 to 0.98 and the wind from 3 to 0.5 m/s. The x axis is in relative unit but extends over 24h.

Fig. 4 shows that especially uncertainties in wind speed may lead to larger simulation uncertainties whereas the influence of specific heat capacity and emissivity on surface temperature seems to be much lower.

3.2 Simulations of thermal stress on humans

Fig. 5 a and b and 6 a and 6 b show simulations performed for a chosen district of Vienna using a low albedo of 0.12 (asphalt) (Fig.5a) and a high reflecting concrete material (albedo of 0.57) (Fig. 5b) for the road surfaces. Fig 5 a and b show that the surface temperature of the asphalt surface is much higher as compared to the concrete surfaces.

The comparison of the mean radiant temperature shows however a higher mean radiant temperature(MRT) above the concrete surface than above the asphalt surface (Fig. 6 a and b). This confirms other findings from literature (e.g. Hui Li, 2012) which mentioned that lower surface albedo not automatically leads to lower stress on humans since the reflected shortwave radiation has a strong influence on MRT and human body energy balance. The universal thermal climate index is with 43.9 °C approximately 2 °C higher above the concrete surface than above the asphalt surface.

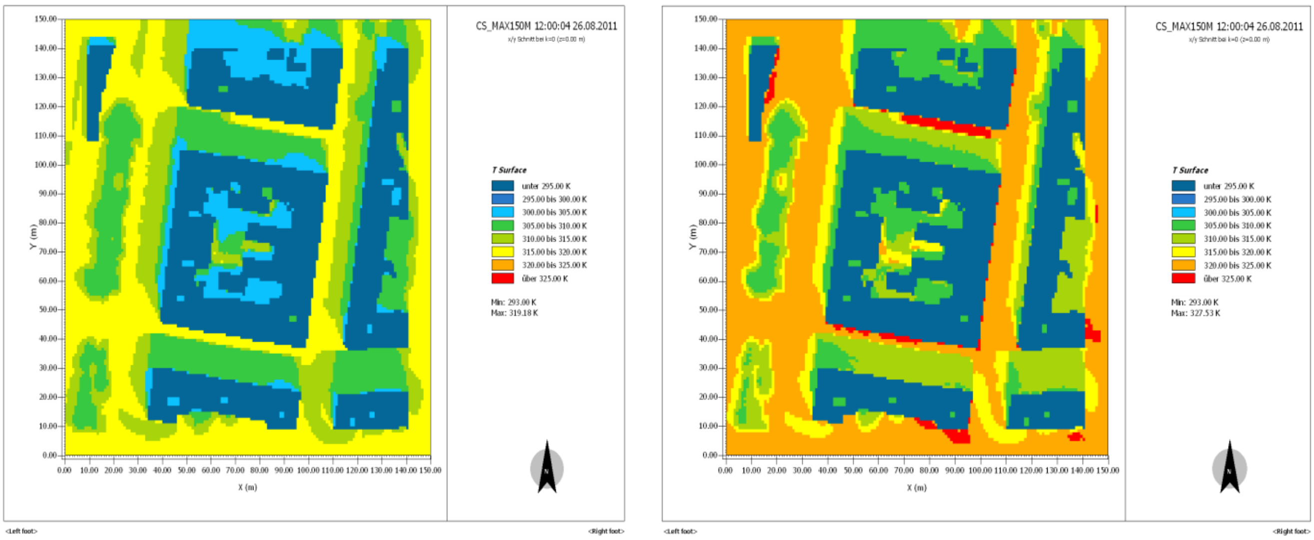


Fig 5 a and b) surface temperature of concrete roads (left fig) and of asphalt roads (right fig.) The orange color corresponds to a surface temperature between 320 and 325 K whereas the yellow color corresponds to 315 to 320K.

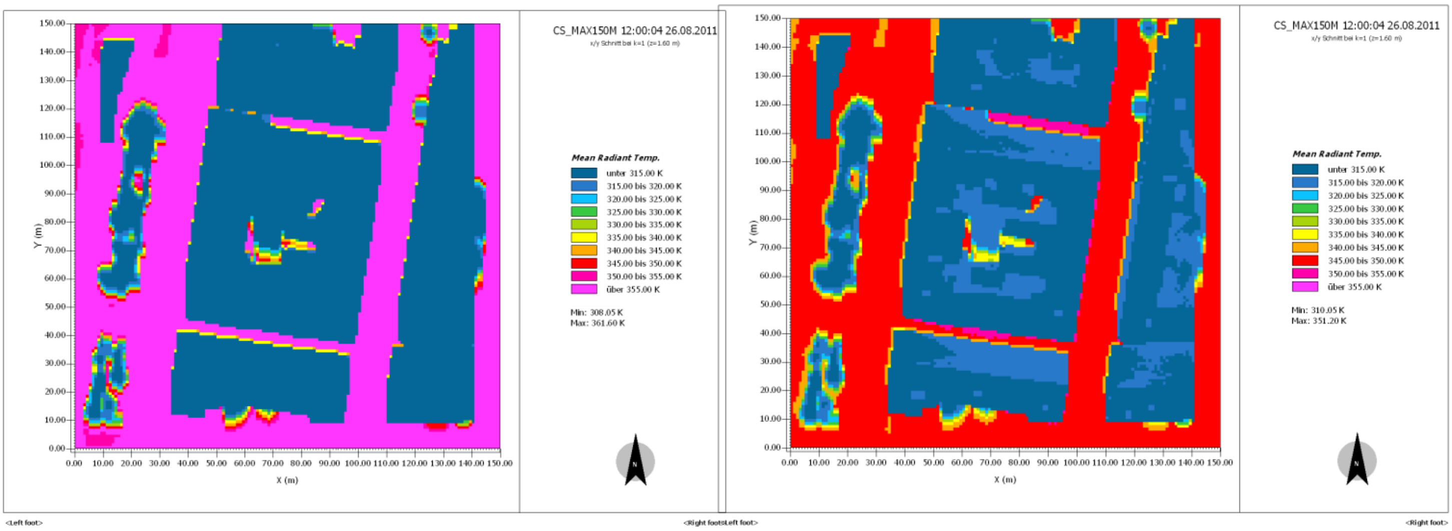
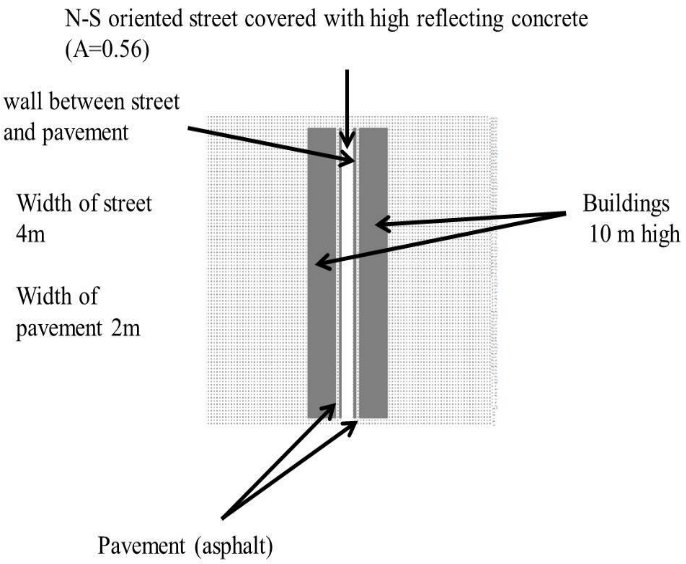
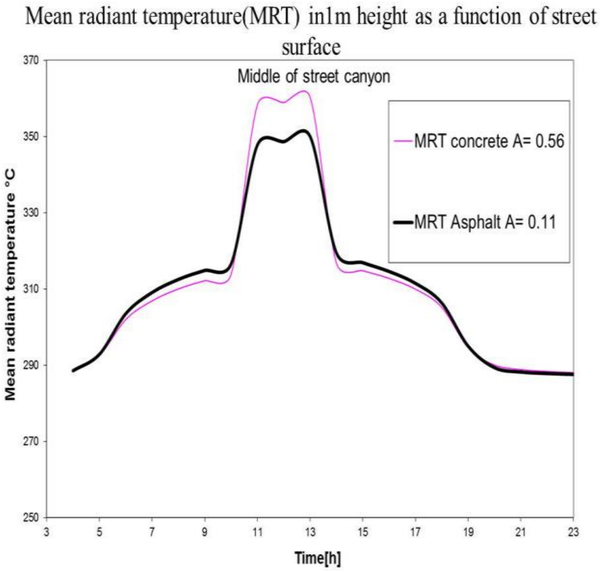


Fig 6 a and b) Mean radiant temperature above concrete roads (left fig) and above asphalt roads (right fig.) The pink color corresponds to 355 to 360 K (left fig.) and a UTCI of 43.9°C whereas red corresponds to 345 to 350 K (right fig.).and a UTCI of 41.3°C

The next steps of the present study consist of possible planification techniques which could include high reflecting surfaces to contribute to a reduction of average air temperature of the city, avoiding at the same time however an increase of thermal stress on humans. Here some first preliminary resuts are shown. The simulations are made for urban canyons (Fig. 7a) and as a function of canyon orientation and width and height of the buildings. The street surface consists of high reflecting concrete material or of asphalt. Between the street and the buildings an asphalt pavement with a width of 2 m is designed. Simulations are performed a) without any protection between street and pavement, b) with a hedge between street and pavement and c) with a wall between street and pavement.First preliminary results of the simulation of the mean radiant temperature (MRT) in 1 m height are shown in Fig. 7b and 8a. Fig. 7b shows the diurnal variation of the mean radiant temperature in the middle of the canyon for a high reflecting street (albedo = 0.56) and for an asphalt street (0.11). When the middle of the street is in direct sun there is an increase of MRT above both types of surfaces. The MRT rise above the concrete surface is however much pronounced than above the asphalt surface. When the street is in the shade, the asphalt surface leads however to a slightly higher MRT than above the concrete surface. The explanation probably lies in the higher surface temperature and to a stronger longwave emission of the asphalt surface.



a)



b)

Fig 7 a) Design of urrban canyon for Envi-met model simulations. b) Envi-met simulations of the diurnal variation of mean radiant temperature in the middle of the street canyon for a high reflecting concrete surface with an albedo of 0.56 and for an asphalt surface with an albedo of 0.11. Simulations were performed for 21. June assuming clear sky conditions.

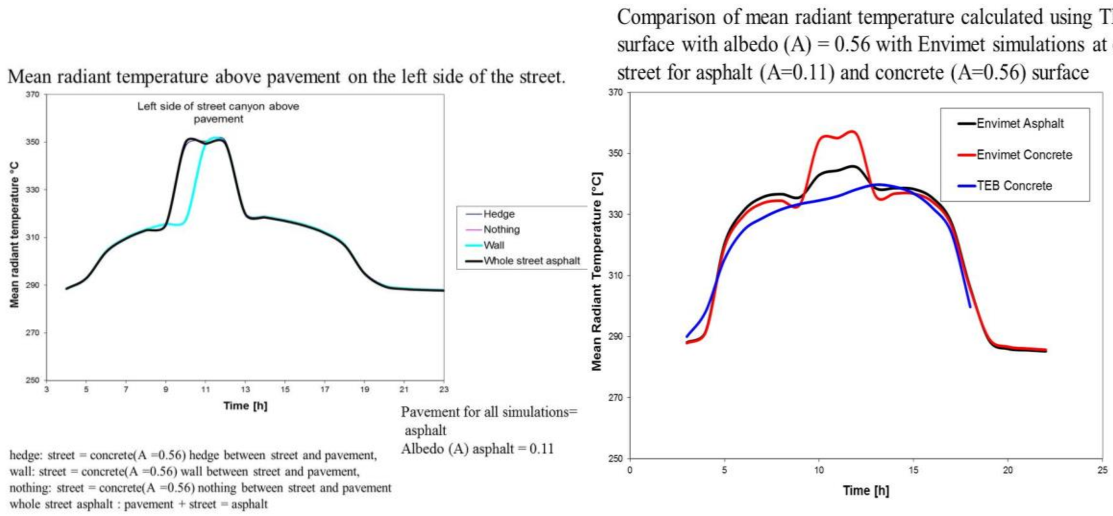


Fig 8 a) Envi-met simulations of the diurnal variation of mean radiant temperature (MRT) on the left side of the street canyon at 1 m height above the asphalt pavement (albedo of 0.11).Simulations were performed for an asphalt street (whole street asphalt) and for a concrete street with no protection between street and pavement (Nothing) and with a hedge (hedge) and a wall (wall) between street and pavement. b) Envi-Met simulations of the MRT in the middle of the street compared with the MRT calculated with TEB assuming a high reflecting concrete surface. Simulations were performed for a and b for 21. June assuming clear sky conditions.

Fig 8 a shows the MRT in 1 m height above the asphalt pavement for the left side of the canyon. According to the simulations the influence of the street surface on MRT 1 m above the pavement is not visible. The wall leads to a reduction of MRT due to a shading from direct sun. Fig. 8b shows the comparison of the simulated MRT in the middle of the canyon with the MRT simulated with the TEB model. TEB was designed to be connected with topo and macro scale models it however does not simulate micro scale features. Only an average value for the whole canyon is calculated. The average value agrees quite well with the values calculated by Envi-met when the canyon is in the shade. The reason lies in the random orientation of the canyon in TEB. Further tests with fixed canyon orientations will be however performed.

4 Conclusions and next steps

The simulations and the measurements confirmed that a higher albedo strongly reduces the surface temperature. The comparison between measurements and Envi-met model simulations still shows a discrepancy in surface temperature of 2 to 3 degrees. A first comparison of Envi-met with the urban energy model TEB was performed the agreement is reasonable but further investigation have to be performed especially by keeping the orientation of the canyon in TEB constant..

Simulations of surface temperature and MRT for chosen districts of Vienna were performed and the influence of albedo on thermal stress on humans was investigated. The results confirmed findings of other studies stating that the reflection of shortwave radiation counterbalances the reduction in surface and air temperature. Due to the increase in reflected shortwave radiation which in terms of absolute value shows a stronger increase than the reduction in longwave radiation, a higher albedo leads to a higher stress to humans. Simulations for an urban canyon seem to indicate that above the asphalt pavement a larger street reflection may not lead to such an apprehended increase in thermal stress of the pedestrians. Further simulations for 1.5 m height and for other street dimensions (width of the canyon and height of the surrounding buildings) need however to be performed.

References

Gómez,F., Pérez Cueva,A., Valcuendec, M., Matzarakis, A. 2013: Research on ecological design to enhance comfort in open spaces of a city (Valencia, Spain). Utility of the physiological equivalent temperature (PET) *Ecological Engineering* 57 27–39

Hui Li, 2012 Evaluation of Cool Pavement Strategies for Heat Island Mitigation. Phd University of California.

Lee, H,- Mayer, H., Schindler, D.Importance of 3-D radiant flux densities for outdoor human thermal comfort on clear-sky summer days in Freiburg,Southwest Germany, *Meteorologische Zeitschrift*, Vol. 23, No. 3, 315–330

Masson, V. 2000: A physically-based scheme for the urban energy budget in atmospheric models, *BLM*, **94**, 357-397.

Santamouris, M., 2014: Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy*, 103, 682-703.

Santamouris, M., Gaitani, N., Spanou, A., Saliari, M., Vassilakopoulou, K., 2012: Using cool paving materials to improve microclimate of urban areas – design realisation and results of the flisvos project. *Buidling and Environment* 53, 128-136.