EVALUATION OF URBAN HEAT ISLANDS MITIGATION STRATEGIES USING 3DIMENTIONAL URBAN MICRO-CLIMATE MODEL ENVI-MET

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ABSTRACT

Urban Heat Island (UHI) is considered as one of the major problems in the 21st century posed to human beings as a result of urbanization and industrialization of human civilization. In this study, effects of the variation of physical and geometrical properties of the urban fabric (i.e. cool roofs including green and white roofs and perviousness of paving materials) on the urban micro-climate and outdoor thermal comfort were investigated using 3dimentional urban micro-climate model, ENVI-met. Based on the predicted results, increasing the amount of vegetation and permeable pavements can cool the air temperature down by up to 3 K.

1. INTRODUCTION

According to the UN 2011 revision of world urbanization prospects the urban areas accommodate more than half of the world population and by the year 2050 this fraction will reach almost 70% of the world population [1]. The effect of increasing urbanization on the urban micro-climate has been the subject of many research projects for quite some time. Micro-climatic conditions can display a considerable variance, due to the differences in morphology and density of urban spaces as well as the thermal and radiative properties of surfaces.

Under certain weather conditions a substantial difference in the air and surface temperature may be observed between a city and its surrounding rural areas. When the isotherms are drawn for the area in request, the city is apparent as a series of concentric, closed lines of higher temperature, with the maximum values recorded at or near the dense

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part of the urban area. This condition is known as the "Urban Heat Island" [2].

Urban Heat Island (UHI) first documented for the city of London by Luke Howard in 1818. The UHI effect can raise the air temperatures in a city by 2-5 K. In the evening, the differences can be even as high as 12 K [3]. It aggravates the air pollution in the cities and impacts the local climate by altering the wind patterns over the urban area, affecting the humidity and changing the precipitation rate within the cities.

The urban heat island has been observed both in the urban surfaces and the urban atmosphere above the city. Surface heat islands mostly form in the cities which are surrounded by moist soil or vegetation, cooled by the evaporation compared to the dry and impervious urban surfaces. Several researches investigated its spatiotemporal variation in the urban surfaces [4].

Due to wide morphological and topological variation in urban spaces of Vienna, urban micro-climate in this city varies significantly [5]. Empirical measurements done by Maleki et al. [5] show about 2-3 K variance in air temperature. On the other hand recent studies show urban heat island intensity in down town of Vienna can reach up to 2.5 K.

According to Fung et al. [6] for 1 K ambient temperature rise, energy consumption would increase by 9.2% for cooling and would decrease by 2.4% for heating. Hence, 2-3 K ambient temperature variation can result in significant rise in domestic energy demand for cooling. This paper attempts to evaluate the effect of different mitigation measures on urban micro-climate in Vienna. Owing to this aim, a pilot area was selected in the city of Vienna and different mitigation scenarios were defined. Using an urban micro-climate simulation tool the influence of proposed scenarios on urban micro climate condition was computed and evaluated.

2. BACKGROUND

2.1 Climate of Vienna

Vienna, the capital of Austria, is located at 48° N, 16°E and 151-542 m above the sea level. The area of the city is 414.87 km^2 with 1.731236 population and 4173 /km^2 density. According to the Köppen classification, the climate of Vienna features a Cfb (oceanic) – climate and stands between the oceanic climate and the humid continental climate. It has relatively warm summers with average high temperatures of 22 to 26 °C, with maximums exceeding 30 °C, and minimum around 15 °C. It has relatively cold winters with average temperatures at about 0 °C. Snowfall mainly occurs from December to March. Spring and autumn are cool to mild. And the average precipitation is about 620 mm.m^{-2}, annually. According to Kiesel et al. [7] annual UHI intensity in Vienna varies from -0.5 K to 2.5 depending on the observed time and location.

2.2 Mitigation measures

Global warming, increasing urbanization and accordingly increasing UHI intensity in the cities has led to widespread researches on mitigation measures in different cities with different climates. Contributed studies have suggested and evaluated different mitigation strategies according to specific characteristics and needs of surveyed city. Some of most studied measures are increasing of vegetation, implementing cool roofs and pavements.

Vegetation: The urban green area mitigates the urban heat island by lowering the

temperature and providing shading. Several investigations show the maximum temperature difference between the inside and outside of the small green area can be 3 K. Other studies show that in deep urban canyons the heat lowering effect of the trees decreases. Also, the position of the trees influences their moderating effect. The effect of a single tree on the air temperature can be negligible, while a row of trees affects the micro-climate of their underneath, and a cluster of trees provides even cooler temperature, compared to the linear one.

Hamada and Ohta [8] show that in summer temperature, the difference between urban and green areas is larger than in winter. Also during the day it was larger than night time, whereas in the winter months the relationship was opposite. Oliveira et al. [9] show the difference is higher in hot and sunny days.

Green shades (trees, vines, etc.) reduce the incident solar radiation and accordingly, the surface temperature. Studies report that the shaded surfaces with green canopies are 5-20 K cooler than the sunlit surfaces [10].

Green area reduces the run-off water (after rain) compared with the impervious surfaces of the urban areas or the bare ground. The run-off water drains quickly and in the long run, the less surface water remains available for the evapotranspiration. The lower evapotranspiration rate in the urban areas is the major effective factor in increasing the daytime temperatures. The evapotranspiration from the vegetation system is another effective moderator of the near surface climates, particularly in the warm and dry mid and low latitude [11].

The urban vegetation influences the urban micro-climate and consequently the outdoor pedestrian comfort levels along with the indoor ones [12]. The effect of the urban climate improvement on the indoor environment is, potentially, reducing the heat gains and the energy demands of the buildings [13]. The urban trees not only help control the heat gain and mitigate the urban heat islands [4], but also reduce noise levels [14].

Planting trees has the direct effect on reducing atmospheric CO_2 because; each individual tree sequesters carbon directly from the atmosphere through photosynthesis. However, planting trees in the cities has also an indirect effect on CO_2 by reducing the demand for cooling energy, thereby indirectly reducing the emission of CO_2 from the power plants [15].

2.3 Cool roofs

Cool roofs technology is an economic and ecological solution for mitigating the heat island effect [16], which results in part from the combined heat of numerous individual hot roofs in a city or suburb. Cool roofs are made of highly reflective and emissive materials, which are referred to as a high-albedo or high thermal reflectance surface [17].

In contrast to the dark roof systems, cool roofs reflect unwanted summer heat and can also radiate away thermal energy after being absorbed in the roofs. Cool roofs consist of a highly reflective roofing surface that can remain approximately 28-33 ° C cooler than traditional dark materials during peak summer days.

Studies show cooling energy savings varied from 2% to 44% and averaged about 20%. for radiant barrier systems Heating energy savings of 11% through 19% were reported, which can reduce heat fluxes and, as a result, can reduce heat loss to the attic and to the outside of a building in the winter weather condition.

2.4 Cool pavements

Urban surfaces are usually paved by dark and impermeable materials. Such pavements contribute to the heat island effect by warming up in the sun and releasing this stored energy to their surroundings during the evening and overnight. Cool pavements, using water-holding materials, decrease the ambient air temperature about 1–2 K comparing with the lawn and 3–5 K lower than air temperature above the building rooftop [18].

2.5 Parameters

In this project four parameters were calculated to evaluate the effect of proposed scenarios i.e. air temperature and specific humidity as well as Mean Radiant Temperature (MRT) and Physiological Equivalent Temperature (PET) as indicators for the outdoor thermal comfort assessment.

2.6 Mean radiant temperature (MRT)

The mean radiant temperature (T_{mrt}), which sums up all global short and long wave radiation fluxes, to which the human body is exposed. It is one of the meteorological parameters governing human energy balance and the thermal comfort [19]. The T_{mrt} is defined as the 'uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure' [20].

2.7 Physiological equivalent temperature (PET)

PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed. This way PET enables a layperson to compare the integral effects of complex thermal conditions outside with his or her own experience indoors [21]. In this study the calculation of PET was based on the Gagge-2-node mode. Defined body and clothing parameters in this model is shown in Table 1:

Table 1: defined body and clothing parameters for simulating PET by ENVI-met

Age	Gender	Weight (kg)	Height (m)	Static Clothing Insulation (clo)	Metabolic rate
35	**Male**	**75**	**1.75**	**0.60**	**164.49**

3. IMPLEMENTING THE MITIGATION MEASURES

As it mentioned before, several solutions has been proposed to mitigate the UHI effect in the cities. The optimum solution can differ between the cities according their morphological and geographical characteristics. In this project, regarding to capabilities of selected area five scenarios pertaining to change in vegetation density and materials properties were defined:

• Increasing in the amount of vegetation:

– **V1:** Trees;

In this scenario to increase the amount of the vegetation (with reference to the base case) 100 trees were added to the domain. Most of them were distributed within the streets and a few in the courtyards (courtyards already had some trees). The type of the used trees was Robinia with 12 m height and 7 m crown diameter, with LAD= 2 . The density of trees in

the area has been increased in this way from 21 trees/hectare to 50 trees/hectare.

– **V2:** Green roofs;

In the Base Case, there is no green roof in the model area and most of the roofs are pitched. For this scenario just the capable roofs (flat roofs and the roofs with low slope) were converted to green roof. The roofs were identified using the " Grun dachpotenzial ketoster". At the end, green roof was implemented on 60% of the roof areas within the model. By doing this, the selected vegetation type was grass with a height of 18 cm and an albedo of about 0.2. The humidity of the soil is in its maximum possible condition and plants never reach to the stress condition during the simulation interval.

– **V3:** Combination of trees and green roof;

In previous scenarios, V1 and V2, the effect of increase in amount of the vegetation within the canopy layer (V1) and above it (V2) was surveyed, separately. This scenario, V3, was defined to evaluate the effect of combining the two aforementioned scenarios, V1 and V2, on the urban micro-climate within the model area. To do so, 100 trees with the same pattern as V1 were added to the area, and the green roofs were implemented on the entire possible roof like as V2.

• Changing the materials properties:

– **M1:** Permeable pavements;

In the main model (in the base case), 18% of the inbuilt area comprises of natural soil, mostly placed inside the courtyards as a constituent of the gardens; and the rest of the surface (i.e. 82%) is sealed (asphalt, stone). In scenario M1 the existing pavements of the narrow streets, all the existing sealed surfaces of the courtyards and the sidewalks of the wide streets have been replaced with a permeable material. For this purpose, pervious concrete, with less water content capacity and more hydraulic conductivity than loamy soil (for more details see [22]) was used. Through this implemented modification the fraction of the permeable surfaces increased to 53% (of the inbuilt space).

– **M2:** White roofs;

The aim of defining scenario M2 was to evaluate the influence of increasing the reflectivity of the urban surfaces. Since increasing the reflectivity of pavements can result in entrapping the solar radiation inside the urban canopy in this scenario changes were applied just to the roof surface. In the main model (in the base case) around 60% of the model area was occupied by buildings, whose roofs were in dark colors with a reflectivity of about 0.3 (i.e. the selected reflectivity in ENVI-met for the roof material in the base case was 0.3). To match the above-mentioned goal in this scenario all roof materials were replaced with a material having a reflectivity of 0.8.

• Combination of change in materials properties and vegetation density:

– **VM:** trees and green roofs with permeable pavement;

Scenario VM was defined to evaluate the interaction between all the changes modifying the urban micro-climate through evaporation. In order to do so, scenarios V3 and M1 were combined together to form VM. For this purpose, trees and green roofs were added to the model area in the same pattern as V3 and the existing pavements of the narrow streets, courtyards and the sidewalk of the wide streets were replaced with permeable pavements as like as M1.

In this way, the simulation results concerning each of the above mentioned scenarios were compared with those of obtained for the base case to depict the effect of each.

4. METHODOLOGY

The uncontrollable and the unpredictable weather conditions and the wide variances in the urban geometry impose significant limitations to the empirical studies concerning the micro-climatic conditions. As a substitute, Numerical simulation perfectly fits to deal with the complexities and nonlinearities of the urban climate systems. This method progressively is improving with computing power and sophisticated meteorological models that can integrate the effects of the urban configuration. Owing to this fact, in this project a computational approach was employed to evaluate the affectivity of recommended mitigation measures for the city of Vienna.

In this regard, an urban area, shown in Figure *1* including a part of VUT complex with several courtyards, wide North-South oriented streets, narrow North-South and East-West oriented streets was selected as case study. The domain boundaries were defined in a way to include the two available stationary weather stations within the area as well. These weather stations are the BPI weather station and Vienna inner city weather station named "Wien Innere Stadt" (WIS). These two weather stations were used to adjust and calibrate the simulation model as well as for providing the input weather data.

The simulation model of selected area was generated and calibrated using ENVI-met, a 3-dimentional urban microclimate simulation model. Afterward, suggested mitigation measures, defined in 5 scenarios, were implemented to the model. Simulated air temperature, MRT, PET and specific humidity for each scenario were compared with base case to evaluate the impact of every changed (contributed) parameter.

4.1 Overview of deployed modeling tool
The tool ENVI-met was selected as it has the capability to simulate the urban microclimate while considering a relatively comprehensive range of factors (complex building shapes, vegetation and different types of pavements, etc.). The high-resolution output generated by this tool includes air, soil and surface temperature, air and soil humidity, wind speed and direction, short wave and long wave radiation fluxes, gas particles and many other important metrological factors.

ENVI-met is a 3-dimensional non-hydrostatic model fit for the simulation of surface-plant-air interactions within urban environments. It is a micro-scale model with a time step between 1 to 10 seconds and resolution that ranges from 0.5 to 10 m, for the grid length (x) and the width (y). Height of the grids (z) can be more than 10 m. ENVI-met calculates the dynamics of microclimate during a diurnal cycle (24 to 48 hours) using the fundamental laws of fluid dynamics and thermodynamics. An overview of the data flow within the ENVI-met is given in Fig. 1.
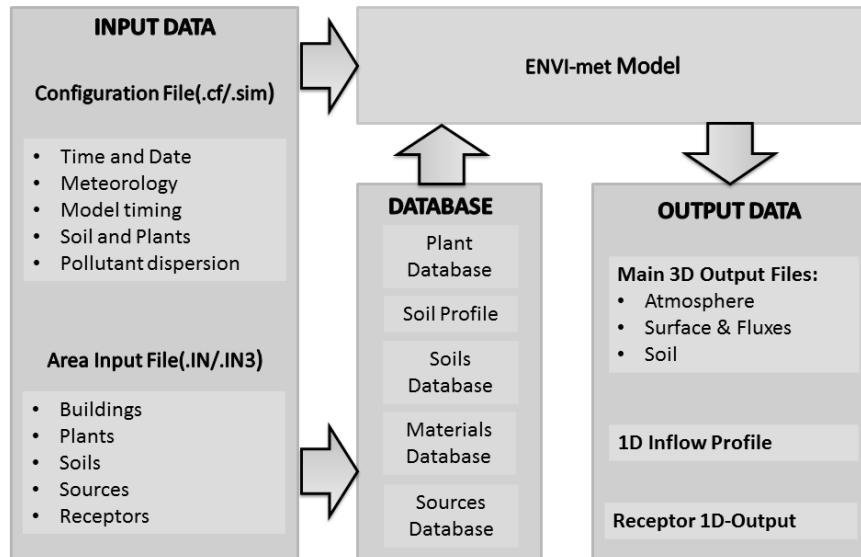
Figure 1. The overview over the data flow within the ENVI-met

4.2 Generating the model

The size of the model domain is about 76960 m² (296 m×260 m), out of which around 42544 m² (55%) is occupied by buildings. The mean value of the model buildings compactness (building volume/area) is around 4.85 m. Most of the buildings are considered as old buildings with light colored walls and dark roofs. Pitched roofs comprise 60% of the roof areas. Ground surface is sealed by either asphalt or single stones except for green areas, which consist of soil, and cover 18% of the surface area. There is no vegetation in the streets. Green areas and trees (total number of trees is 71) are mostly inside the courtyards. There is no green roof in the area. Most part of the buildings is either allocated to academic affairs or commercial use. The existing narrow streets within the domain are not supposed to suffer a heavy traffic load. The above mentioned domain, selected as the simulation model, is mapped in Fig.s Figure *1* and Figure *3*.
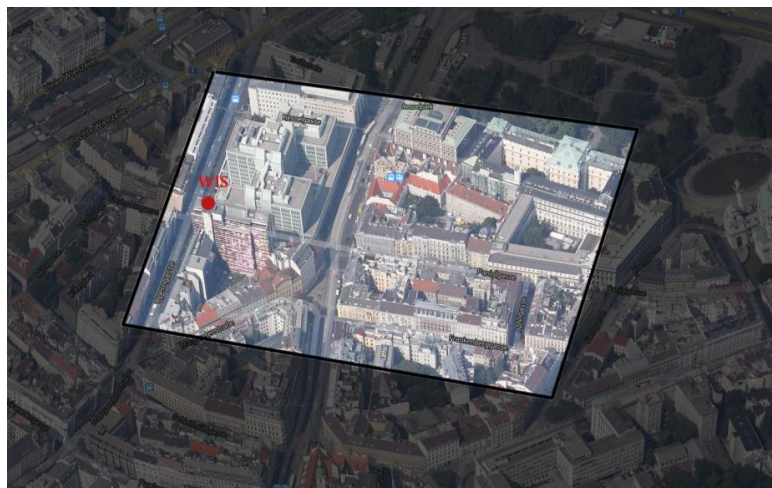

Figure 1. Arial picture from the simulated area (Google. Map)

4.3 Simulation assumptions

The described model, which was made and set based on the real geometrical and material properties of the urban area, is used as the "Base Case" for the parametric analysis. Simulations were performed for a time period starting of 5:00 h on July 13th to 4:00 h on July 14th 2011. Sky was considered clear during the simulation and associated weather data obtained from the WIS were used for forcing. Air temperature during this day was fluctuating between 21.5°C and 33.5°C. The average relative humidity was around 52% and the specific humidity was fluctuating between 10.5 to 12 g.kg^{-1}. For this day the average wind speed above the canopy was around 2.5 m.s^{-1} and the prevailing wind direction was from South-East to North-West (for further information about input data see [23]).

The model was adjusted and calibrated using the monitored data at BPI and WIS, two stationary weather station located inside the domain. As it is illustrated in Fig. Figure *2* the simulated data showed a good agreement with the observed data (for further information about calibration method see [22]).

Due to variation in characteristics of the locations air temperature as well as the specific humidity varies within the model.
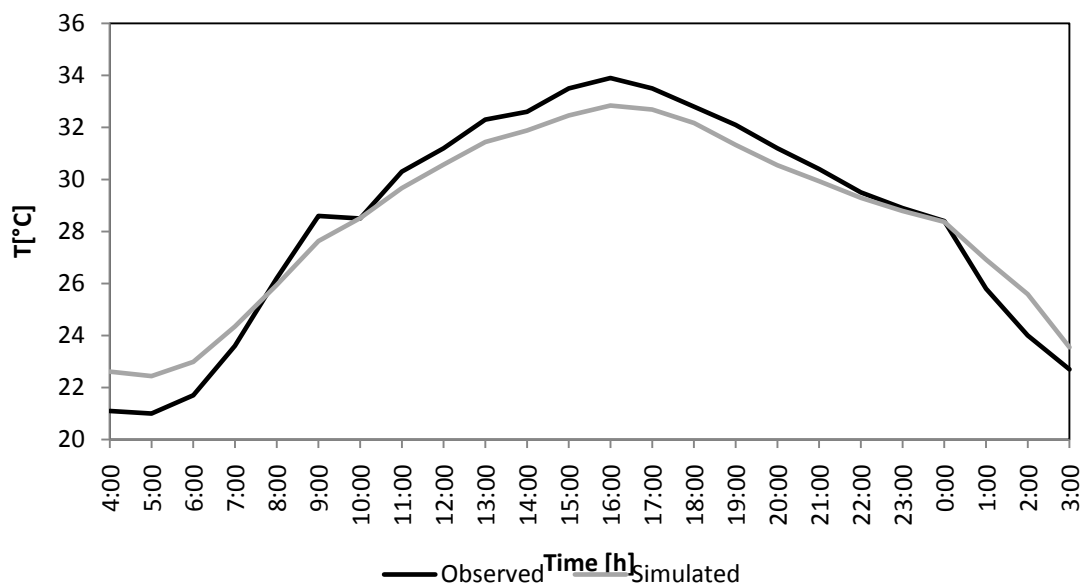

Figure 2. Observed and predicted air temperature at WIS, (simulated day: 13.07.2011)

To evaluate the results of modifications and study of their general effects on micro-climate of the defined area, mean value of the outputs of all the grids inside the streets within the defined borders of the model except the plants (yellow area in Fig. 4) was calculated as represented value for the whole area. Then the result of every scenario was subtracted from the result of base case (current condition), shown in Fig. 5, to show the magnitude of modification done.
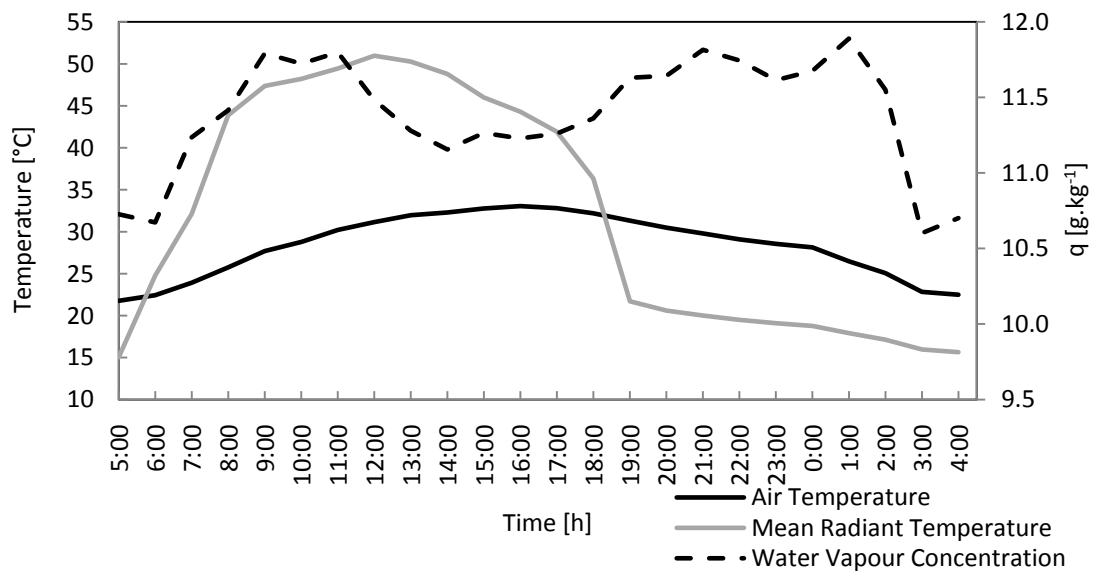
Figure 3. Plan of generated model by ENVI-met

Figure 4. simulated air temperature, MRT and water vapor concentration for the base case

5. RESULTS AND DISCUSSION

The simulation model was performed to predict air temperature, MRT, PET and specific humidity to evaluate the effect of defined mitigation scenarios. Therefore, the results of every parameter for all scenarios were compared together and discussed.

   Air temperature:

   The results of simulation V1, shown in Figure 5, show adding trees has caused an air temperature decrease of about 0.7 K in the streets. While a slight cooling in the air temperature, about 0.3 K, is seen for implementing green roofs in the model area. Green

roofs alter the urban micro-climate via decreasing the surface temperature, by shading the roof surface and using the solar energy for evapotranspiration. Thus, the lower surface temperature leads to the lower air temperature. The slight cooling effect of green roofs in this scenario may have been caused by the uniformity of buildings height. The uniform building height decreases the possibility of mixing the air above the canopy with the air inside the canopy. Consequently, in such urban configuration, green roof, which influences the air layer above the roof surface, can hardly affect the pedestrian level.

The results predicted in scenario V3 show the air temperature of all the streets has decreased almost equally, about 1 K. Comparison among the results of V1, V2 and V3 showed, as expected, a somehow cumulative effect of V1 and V2 can be considered in scenario V3. This may especially be traced back to the fact that in case of the scenario V3 the cooling down mechanism in each of the scenarios V1 and V2 are acting independent from each other in affecting the air temperature in the model domain. But to come up with a certain conclusion on the interactive influence of these two modifications more measurements and investigations are needed.

Scenario M1 depicts how the change in the perviousness of the pavements can influence the air temperature of the area. As it can be seen, replacing sealing of walk sides and narrow streets by pervious material dropped the average air temperature in all streets 0.3 K to 1.4 K during the simulated time.

Studying of the air temperature changes caused by scenario VM, as shown in Figure *5*, revealed the fact that although the observed air temperature difference between VM and the Base Case is the largest among other scenarios, i.e. V1, V2, V3 and M1; while matching the expectations, it did not show a cumulative effect of the mentioned scenarios. The reason could be traced back to the fact that, unlike scenario V3, in this scenario, two types of modifications, i.e. increasing the extent of vegetation (adding trees) and that of permeable pavements, were applied to the canopy layer (within the canopy). Hence it may be concluded, the shades of the added trees has weakened the cooling effect of the additionally embedded permeable pavements.

The results of the performed simulation as scenario M2, revealed a slight effect in terms of cooling down the ambient air temperature, i.e. the implemented modification has just caused a slight decrease in the air temperature at the pedestrian level. The observed reduction in the air temperature seemed to be somehow identical in the streets (max. cool down of about 0.5 K).

The graph showed that the scenario VM, which is about the combination of adding more trees and green roof as well as changing the ground surface sealing to the permeable pavement, has affected the air temperature at most, comparing to the other scenarios.

The scenarios M1 and V3 caused approximately equal reduction in the air temperature, but in different hours. The cooling effect of M1 was more during the day, while V3 showed more cool-down in the area during the evening and the night

By the scenarios V2 and M2 it was about changes applied on the surface of the roofs, hence their effect on the air temperature within the canopy layer was almost equal and in the same pattern.
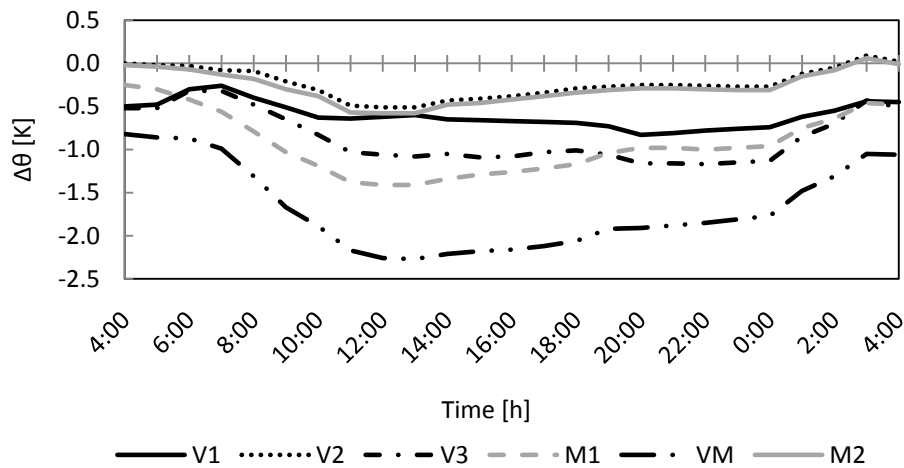
Figure 5. Average air temperature differences between scenarios and the base case within the model domain (Scenario -Base)

MRT and PET

As it is illustrated in Figure *6* andFigure *7* the effect of suggested scenarios on MRT and PET, outdoor thermal comfort indicators, didn't follow the same pattern as air temperature.

Scenarios V2 and M2, green and white roof respectively, didn't have considerable influence on improving thermal comfort in pedestrian level. Even a slit increase, about 0.5 K, in PET is seen during the morning.

But scenarios V1, V3 and VM which influenced the radiation budget within the urban canopy by additional trees and consequently more shading, improved the thermal comfort significantly. The most effective scenario, VM, decreased the MRT up to 10 K and PET up to 5.5 K. V1 and V3 with almost similar effect decreased the MRT and PET up to 6 K and 3 K respectively. Although in case of air temperature M1 had better performance than V1 and V3 but it in case of MRT and PET, M1 had less influence. It points that shading has more important role in improving outdoor thermal comfort than absolute air temperature. That is why during the day the effect of implementations on thermal comfort is more intensive than during the night and dark hours.
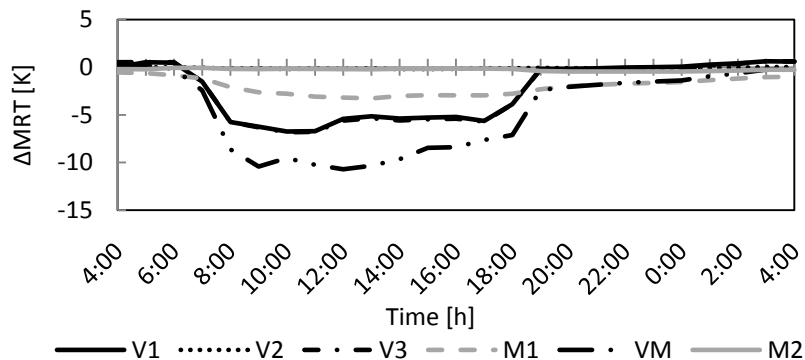

Figure 6. Average mean radiant temperature (MRT) differences between scenarios and the base case within the model domain (Scenario -Base)
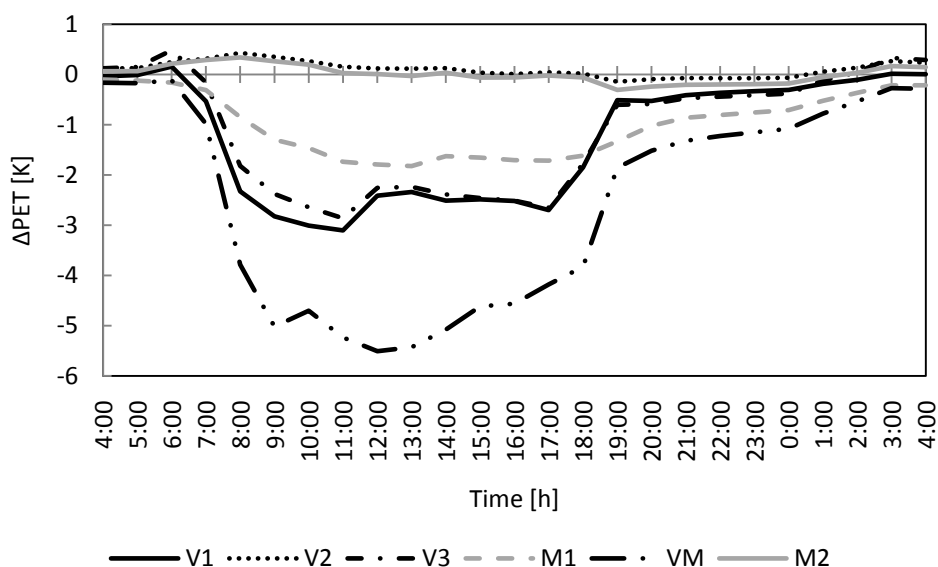
Figure 7. physiological equivalent temperature (PET) differences between scenarios and the base case within the model domain (Scenario -Base)

Water vapor pressure

One of the cooling mechanisms in urban spaces is converting the sensible heat to latent heat. This can be done by evaporation of existing water or moisture in the environment or plants evapotranspiration. The evapotranspiration via trees has a strong correlation with the solar radiation. Thus it can be seen in Figure *8*, that additional trees caused an increase in the air specific humidity after sunrise. After the sunset the humidity differences in the whole model area has dropped and stayed steady during the evening and the night.

In scenario V3, the same discussion can be applied. Besides, a reverse relationship between the air temperature and the specific humidity could be observed, the more reduction in the air temperature the more increase in water vapor concentration in the air, verifying the role of plants in reducing the air temperature through evapotranspiration effect.

In case of scenario VM, significant rise in water vapor concentration (up to 1 g.kg^{-1}) can indicate that all the changes made in the area, mostly influence the micro-climate via evaporation and partially by shading (in case of trees) consequently, as it is shown in Figure *8* a significant water vapor concentration increase (up to 1 g.kg^{-1}) was observed in the model domain and shading the surfaces by trees does not have considerable impact on the evaporation of soil moisture.

In the contrary, in case of scenarios V2 and M2 likewise the MRT and PET, the water vapor concentration level has not been affected by the applied modifications. Probably because in streets there is no source for evaporation neither before nor after the applied modifications; so the changes in the air temperature hardly affected the water vapor concentration level at any point.
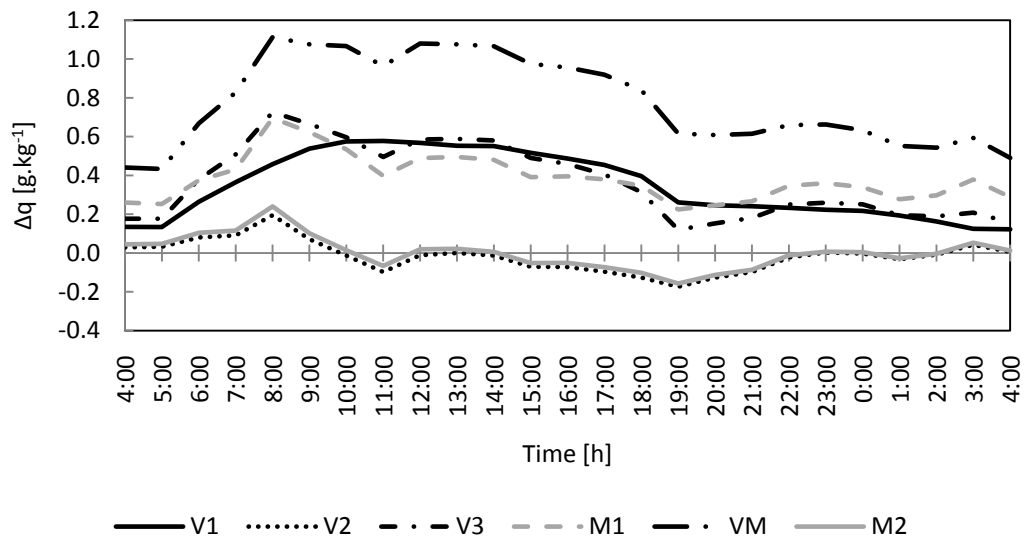
Figure 8. water vapor concentration differences between scenarios and the base case within the model domain (Scenario -Base)

6. CONCLUSION

Within the context of the computational inquiries a simulation model was generated using a three dimensional urban micro-climate simulation tool, ENVI-met 4.0. This model was used to simulate microclimatic conditions in a part of the city of Vienna.

The influence of three parameters including the density of vegetation, the extent of permeable pavements and the reflectivity of the roofs / the walls was evaluated in six scenarios. The results suggested modifications within the urban canopy were more effective in influencing the relevant microclimatic conditions than those implemented to the roof levels.

Likewise, combination of the alterations resulting in lower air temperature can enhance their cooling effect. As it was shown by the results, the maximum cooling effect, about 2.7 K in air temperature, was achieved through the scenario VM (increasing vegetation and applying permeable pavement). The numerical simulations also showed that any increase in the amount of vegetation (either within the canyon or above the roofs), the area of pervious pavements or the reflectivity of the roof material could cause a decrease in day time and night time air temperature during the hot summer period. While outdoor thermal comfort is more improved by more shading and reduction in radiative budget of the environment than increase in evaporation.

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