Assessing the effect of the urban morphology on the ambient air temperature of urban street canyons under different meteorological conditions. Application in residential areas of Thessaloniki, Greece

S Tsoka, K Tsikaloudaki, T Theodosiou and D Bikas

Civil Engineering Dep., Aristotle University of Thessaloniki, PO BOX 429, 54124 Thessaloniki

Email: stsoka@civil.auth.gr

Abstract. This study evaluates the effect of the morphological characteristics of 4 urban districts in Thessaloniki, Greece on the vertical profile of the Tair inside the various urban canyons under different meteorological conditions. ENVI-met v.4 microclimate simulations are conducted for the 4 selected case study areas, while different meteorological boundary conditions are also considered. The obtained simulation results generally suggest significant differentiations on the local climatic conditions throughout the year, due to the diverse morphological characteristics. The analysis of the vertical Tair profile, revealed low deviations during night-time and peak deviations at noon. The maximum Tair discrepancies among all areas have been mainly attributed to the different amounts of solar radiation, received by the canyons’ surfaces and the respective sensible heat release. However, in all cases, the estimated Tair differences among the study areas decreased as the distance from the ground increased.

1. Introduction

The increased urbanization process of the 20th and 21st century is strongly related to the significant changes of the microclimatic conditions of modern cities and the occurrence of high air temperature (Tair) in the urban districts compared to the surrounding rural areas [1]. The replacement of natural, permeable surfaces with mineral, rough materials resulting in large quantities of solar radiation stored and then re-emitted towards the surrounding environment, the low albedo of the urban constriction materials, contributing in larger amounts of solar radiation absorbed by building envelopes and urban surfaces, along with the progressive vegetation loss and the decrease of latent heat flux through evapotranspiration are only some of the parameters that affect the thermal environment of modern urban areas [2].

To date, the effect of the urban morphology on the local microclimate and specifically on the air temperature values (Tair) has been widely investigated [3]. Yet, most of the existing studies mainly focus at the Tair distribution at the pedestrian’s height during hot, summer conditions, while the vertical profile of the climatic variable during winter or intermediate seasons has been far less evaluated. However, the microclimatic conditions inside a study area and the respective values of the ambient Tair not only affect the pedestrians’ thermal balance (generally estimated at 1.5m height from the ground level) but also strongly influence the urban building’ units energy performance, located at various levels from the ground. Within this context, the current research aims to assess the vertical...
profile of the Tair inside the various urban canyons of 4 urban districts in Thessaloniki, Greece with regards to their diverse morphological and geometrical characteristics. More precisely, the emphasis is given on the vertical Tair distribution in the center of 4 canyons of the 4 case study areas, under different meteorological conditions (see sections 2 and 3). To perform the analysis, the ENVI-met v.4 microclimate model is applied and simulations are conducted for the 4 selected case study areas and for 3 representative days (for summer, winter and autumn conditions).

2. Case Study areas
The four case study areas in which the examined street canyons are located, are in the city of Thessaloniki, Greece, situated in the northern part of the country and characterized by a Mediterranean climate with generally dry summers, mild, wet winters and evenly distributed rainfall throughout the year [4]. The urban districts have been selected through an empirical spatial analysis of the urban tissue of Thessaloniki with consideration given on the Municipalities of Thessaloniki (i.e. the area of the city center) and Kalamaria; they are characterized by diverse geometrical and morphological characteristics (i.e. building surface density, H/W ratio of the street canyons, green coverage ratio etc.) and they have a similar size, around 40,000 m². Buildings inside the 4 case study areas are generally of residential use, whereas there are only a few commercial properties on the ground floor of some buildings. Building envelope construction materials mainly involve cement and concrete elements, while the ground surfaces comprise of impervious materials such as asphalt and concrete pavements; yet, the part of the ground surface, covered by loamy soil and other permeable materials differs from one area to the other. The Google earth images of the plan of the study areas and the cross section of the 4 examined street canyons, to which the emphasis is paid, are depicted in Figure 1, while their corresponding morphological characteristics are presented in Table 1. It has to mentioned that in Mitoudi canyon, a difference on the width of the street is noticed; thus, for a street canyon length of 85.0 m, the H/W ratio is 2.4 (narrow part) while for the rest 65.0m, the H/W ratio is 1.10 (wider part). Moreover, Vafopoulou street canyon a distinctive characteristic is noticed, involving the increased presence of vegetation; the existing deciduous mature trees (tree species of acer platanoides and platanus), reaching a height of approximately 20.0 m, form a continuous shading canopy inside street canyon. Given the increased presence of green elements, the Sky View Factor (SVF) of the street canyon varies during the year, as a function of the foliage density.
3. Methodology and simulation set-up

To assess the effect of urban morphology on the Tair values under different meteorological conditions, microclimate simulations are performed for all 4 study areas for 24 hours diurnal cycles for representative days in July, October and January. As suggested by Tirabassi [5], the definition of representative days would require the statistical analysis of long-term climatic records. In this study, a long-term database of climatic variables over the 1958-2000, recorded at a meteorological station inside the University Campus has been applied and the selected representative days are (a) the 22th of July 2015 for the summer period, (b) the 4th of January 2016 for the winter period and (c) the 1st of October 2015 for the autumn, intermediate period; the detailed procedure is described in a previous study of Tsoka et al. [6].

In terms of the ENVI-met microclimate model, it is a prognostic, three-dimensional, grid-based microclimate model, designed to simulate complex surface-vegetation-air interactions in the urban environment. Based on the fundamental laws of fluid dynamics and thermodynamics, it can simulate the diurnal cycle of major climatic variables, such as air and soil temperature and humidity, wind speed and direction, radiative fluxes etc., with a typical horizontal resolution from 0.5 m to 5.0 m and a time step of 1 to 5 seconds, while the simulated time period usually varies between 24 hours and 5 days ([7-9]). The required input parameters for the microclimate simulations with the ENVI-met model involve the area input file, representing the geometry of the studied site and the configuration file, containing the meteorological boundary conditions of the simulations. The 3D area input files of the 4 case study areas are shown in Figure 2. For the generation of all model’s geometry, a set of 134 x 134 grids has been adopted for the x and y axis with a resolution of 1.5 m, while in the z axis, the number of cells was set to 20 with a 3.0 m resolution. Seven nesting grids have been also placed around the main domain area, to minimize the boundary effects. The geometry and the foliage characteristics of the modeled plants have been designed in the ‘Albero’ tool of the ENVI-met model, whereas special care has been also given to the modeling of the temporal differentiation of the trees’ foliage density.

Table 2. Thermal and optical properties of the building envelope materials ([10, 11])

| Material          | Plaster | Brick | Concrete | Roof Tiles |
|-------------------|---------|-------|----------|------------|
| Thickness (m)     | 0.02    | 0.19  | 0.20     | 0.03       |
| Therm. conductivity (W/mK) | 0.87    | 0.51  | 2.5      | 1.50       |
| Density (kg/m³)   | 1800    | 1500  | 2400     | 2100       |
| Specific heat (J/kg.K) | 1000   | 1000  | 1000     | 1000       |
| Solar reflectance*| 0.40    | -     | -        | 0.30       |
| Emissivity*       | 0.90    | -     | -        | 0.90       |
The thermal properties of the building envelope materials and the physical properties of the ground surface materials are based on the ISO 10456 and ISO 13370 and they are given in Tables 2 and 3 respectively. In terms of the meteorological boundary conditions, wind speed, wind direction, hourly values of Tair and RH, used for the forcing along with the mean monthly value of soil temperature for all simulation days have been obtained from the meteo station of the Aristotle University.

Finally, the evaluation of the performance of the ENVI-met microclimate model has been conducted using onsite measurement results of Tair and RH, for all the selected simulation days. More precisely, high accuracy weatherproof Hobo-data loggers, suitable for outdoor environment, have been used at the 4 case study areas. All loggers have been placed inside suitable radiation shields to ensure the accuracy of the climatic records; they were then mounted on tripods and positioned at 1st floor balconies of building in the examined street canyons (i.e at Pittakou, Mitoudi, Vafopoulou and Gavriilidou Streets, at 4.5 m from the ground level).

### Table 3: The physical properties of the ground surface material ([10, 11])

| Material       | Asphalt | Concrete Tiles | Soil |
|----------------|---------|---------------|------|
| Volumetric heat capacity Cp (J/m³K) | 2.1x10⁶ | 2.1x10⁶ | 3.0x10⁶ |
| Therm. conductivity (W/mK) | 0.70 | 1.50 | 1.50 |
| Solar reflectance | 0.12 | 0.30 | 0.20 |
| Emissivity | 0.90 | 0.90 | 0.95 |

![Figure 2](image-url)

**Figure 2:** Area input files for the 4 case study areas, introduced in ENVI-met

4. **Results and discussion**

At a first step and in order to assure the ENVI-met model’s performance, the obtained simulation results for the Tair values inside the examined street canyons have been compared with the corresponding observed values, for all the selected representative days. To this aim, the commonly
applied statistical index Root Mean Square Error (RMSE), has been calculated for all sites and for all simulation days. The estimated values are shown in Table 4. The estimated values have been compared with the corresponding ones reported in the existing literature [12] and it can be concluded that the model can accurately simulate the diurnal evolution of the Tair parameter inside the 4 study areas, under different meteorological conditions.

Table 4: Estimated RMSE for the Tair in all study areas and for all examined days (°C)

|          | Summer | Autumn | Winter |
|----------|--------|--------|--------|
| Pittakou | 1.02   | 1.55   | 0.85   |
| Mitoudi  | 1.35   | 1.15   | 1.30   |
| Vafopoulou | 0.95 | 1.35   | 1.11   |
| Gavriilidou | 0.89 | 1.27   | 0.91   |

To continue, the simulation results concerning Tair, will be discussed for different heights, varying from 0.0 m till 18.0 m, reflecting the higher building levels inside the examined street canyon. Previous scientific studies have highlighted the differentiation of microclimatic parameters as a function of height, suggesting higher Tair values in the lower half of the canyon and reduced Tair values in the higher parts of the canyon where the ambient wind speed is also increased ([13, 14], [15]). On the other hand, Tair measurements in deep canyons in Athens revealed lower Tair at the ground level and increase of Tair with height, following the distribution of the surface temperatures of the building walls [16]. In the same context, other experimental studies have revealed significant Tair differences near opposite building facades, or facades at different heights, due to the impact of solar exposure and the respective convention phenomena from the neighboring building walls [16].

In the current section, emphasis is mainly paid on the vertical Tair distribution in the center of the 4 main canyons of the 4 case study areas (i.e. Pittakou, Mitoudi, Vafopoulou and Gavriilidou). The simulation results of 3 representative days are presented and discussed; Air temperature simulation results, are given for all 4 case study areas, starting from the ground level till 60.0 m height, which is the upper limit of the model domain. The respective data are derived from the Y-Z cross diagrams, indicated in Figure 2.

4.1. Air temperature simulation results for a representative summer day

Figure 3 shows the thermal stratification inside the three E-W canyons (i.e. Pittakou, Mitoudi and Vafopoulou) and the NE-SW Gavriilidou canyon, at 9:00 a.m., 12:00 and 16:00 p.m., during the representative day of July. The Tair stratification inside the 4 street canyons, for the heights between 0.0 m and 13.50 m, is found to be rather minor, with values ranging between 1.0%-3.0% for every 3.0 m (i.e. per building-floor height) and with the maximum corresponding values being reported in Gavriilidou street canyon. Low variations of Tair as a function of height have been also reported in previous experimental campaigns in street canyons in the city of Athens ([14, 16]). Yet, important deviations on the hourly Tair values among the 4 street canyons have been observed during daytime, due to their diverse geometrical and morphological characteristics. Air temperature is always higher in the midpoint of Gavriilidou street compared with the other three canyons, mainly due to the greater contribution of the direct solar radiation since early in the morning, because of the low H/W ratio and the lack of shading. Comparing Mitoudi and Gavriilidou canyons, higher amounts of direct solar radiation will reach the ground and building surfaces of the latter one, leading to increased solar absorption and finally warming of the air volume through sensible heat transfer. More precisely, at 9:00 a.m., the estimated Tair in the middle of Mitoudi street, at 4.50 m and 7.50 m from the ground, is 25.7 °C and 25.5 °C correspondingly, 1.0 °C and 0.7 °C lower than the respective values in
Figure 3.: Street canyons cross sections showing the vertical profile of Tair in the four case study areas at 9:00 a.m., 12:00 and 16:00 p.m. for the representative day of July.

Gaviılidou street canyon; the equivalent deviations at noon reach 1.5 °C and 1.0 °C (i.e. at 4.50 m and 7.50 m height respectively). On the other hand, the daytime Tair differences between the 2 sites are found to be less important at 13.50 m and this is mainly attributed to the similar solar access of both canyons, at an intermediate floor level. In parallel, the lowest Tair discrepancies have been reported between Mitoudi and Vafopoulou study areas, indicating the significant contribution of the solar shading on the reduction of summer Tair values; in the first canyon, the ground surfaces and the lower parts of the South building walls are mainly kept in shadow during daytime, due to the high aspect
ratio while in the second canyon, the dense foliage of the high *acer* trees, blocks the direct shortwave radiation from reaching the canyon’s surfaces. Indicatively, at 16:00 p.m., the Tair difference between the midpoints of Mitoudi and Vafopoulou canyons at 4.50 m and 7.50 m only reach 0.20°C and 0.25°C respectively, while a peak difference of 1.0°C has been noticed at the height of 13.50 m. This is because at this time step, the middle height surfaces of the Mitoudi canyon are exposed to solar radiation, while on the other hand, the whole Vafopoulou canyon is continuously kept in shadow (the height of planted trees approximates the canyon height.) Finally, at 16:00, the Tair in the center of Pittakou canyon, being fully exposed to shortwave radiation is estimated close to 29.9°C and 29.7°C at 4.50m and 7.50m respectively, 0.60°C and 0.70°C higher than the respective Tair values in the midpoint of Vafopoulou street.

4.2. *Air temperature simulation results for a representative autumn day*

The vertical profile of the Tair inside the three E-W canyons (i.e. Pittakou, Mitoudi and Vafopoulou) and the NE-SW Gavriilidou canyon, at three different time steps, during the representative day of October is depicted in Figure 4. As with the spring and summer results, minor Tair variations as a function of height are found in the center of the examined canyons; a marginal reduction of Tair up to 1.0%-3.0% per building floor (i.e. per 3.0 m height) is noticed. Still, the deviations on the hourly Tair values among the 4 street canyons during daytime are rather important, especially for the lower part of the street canyons. More specifically, among the 4 canyons, the highest Tair values at 4.5 m and 7.5 m are always reported in the center of Gavriilidou street; the estimated morning Tair in the midpoint of the latter canyon, at 4.50 m and 7.50 m from the ground, is 17.70 °C and 17.50 °C correspondingly, 0.50 °C and 0.36 °C higher than the respective values in Mitoudi street canyon. The Tair deviations between Gavriilidou and Vafopoulou canyon reach 0.45 °C and 0.29 °C, at 4.5 m and 7.5 m height respectively, at 9:00 a.m.

Again, the higher Tair values are attributed to the more important amounts of direct solar radiation reaching the ground and building surfaces of the Gavriilidou canyon since early in the morning, contributing to increased solar absorption and warming of the air volume through convection phenomena. Nevertheless, minor differences are found for the Tair values at 13.5 m at 9:00, since at this level, all areas receive similar amounts of solar radiation and the effect of shading by the surrounding obstructions is minor.

At noon, the peak difference on the hourly Tair values has been observed between Mitoudi and Gavriilidou canyons, reaching 0.82 °C and 0.50 °C at 4.5 m and 7.5 m correspondingly. On the other hand, the lowest Tair discrepancies at this timestep are found between Mitoudi and Vafopoulou canyons and they are close to 0.10 °C, both at 4.5 m and 7.5 m, suggesting the effect of the solar shading on the reduction of Tair values; even if the examined representative day belongs to the defoliation period, still the high acer trees keep almost 50% of their foliage density, blocking thus an important part of the direct shortwave radiation from reaching the canyon’s surfaces. Finally, at 16:00, the Tair in the center of Pittakou, Gavriilidou and Vafopoulou canyons, at 4.5 m reaches 18.45 °C, 18.50 °C and 18.30°C, suggesting minor discrepancies that become even more negligible for a distance of 7.5 m and 13.5 m from the ground level.

4.3. *Air temperature simulation results for a representative winter day*

The Tair distribution inside the three E-W canyons (i.e. Pittakou, Mitoudi and Vafopoulou) and the NE-SW Gavriilidou canyon, during the representative day of January is given in Figure 5. In all study areas and for all time steps, no significant Tair variations as a function of height were found near the midpoint of the street canyons whereas the deviations on the hourly Tair values among the 4 street canyons during daytime are also of minor importance; at 9:00 a.m. the estimated morning Tair in the midpoint of the Gavriilidou canyon, at 4.5 m from the ground, is 5.55 °C, marginally higher than the respective values in Mitoudi and Pittakou street canyon, while at 7.5 and 13.5 m, the differences
between the 4 case study area are again low with peak deviations reported between Gavrilidou and Vafopoulou, without however exceeding 0.20 °C.

At noon, the maximum difference on the hourly Tair values has been observed between Mitoudi and Gavrilidou canyons, reaching 0.15 °C at 4.5 m, while at 7.5 m and 13.5 m, the differences on the hourly Tair in the midpoint of the 4 street canyons are negligible and lower than 0.10 °C. Similarly, at 16:00 p.m., minor Tair discrepancies are found among the 4 street canyons at 4.5 m, while they are even lower for 7.5 m and 13.5 m from the ground level. The minor Tair differences are attributed to the low solar heights and the low solar radiation intensity during the specific simulation day; in

**Figure 4.:** Street canyons cross sections showing the vertical profile of Tair in the four case study areas at 9:00 a.m., 12:00 and 16:00 p.m. for the representative day of October.
Thessaloniki, the solar altitude in this day of January is rather low, close to 26 °C at midday, suggesting low amounts of direct solar radiation on the lower and middle parts of the E-W canyons, that could finally contribute to the higher surfaces and air temperatures.

Figure 5: Street canyons cross sections showing the vertical profile of Tair in the four case study areas at 9:00 a.m., 12:00 and 16:00 p.m. for the representative day of January.

5. Conclusions
This study evaluated the vertical profile of the Tair, estimated inside urban canyons of Thessaloniki, with different morphological characteristics and under various meteorological boundary conditions. The analysis of the vertical Tair profile, estimated inside all canyons during the representative days of
all seasons, revealed peak deviations at noon. The maximum Tair discrepancies among all areas have been mainly attributed to the different amounts of solar radiation, received by the canyons’ surfaces and the respective sensible heat release. Yet, the effect of the solar radiation access has been proven more prominent in summer. Indicatively, during the representative autumn day, peak hourly differences, reached 1.20 °C at 4.50 m height, while in summer, the respective peak hourly deviations among the examined canyons reached 2.60 °C. However, in all cases, the estimated Tair differences among the study areas decreased as the distance from the ground increased. The only exception is noticed in the case Vafopoulou canyon in summer, in which the denser trees’ foliage contributed to lower Tair values near the examined building units, due to the increased shading and the evapotranspiration effect.

References
[1] S. Grimmond, Urbanization and global environmental change: local effects of urban warming, The Geographical Journal, 173 (1) (2007) 83-88.
[2] M. Santamouris, C. Cartalis, A. Symneta, D. Kolokotsa, On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review, Energy and Buildings, 98 (2015) 119-124.
[3] A.M. Rizwan, L.Y. Dennis, L. Chunho, A review on the generation, determination and mitigation of Urban Heat Island, Journal of Environmental Sciences, 20 (1) (2008) 120-128.
[4] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World map of the Köppen-Geiger climate classification updated, Meteorologische Zeitschrift, 15 (3) (2006) 259-263.
[5] T. Tirabassi, S. Nasetti, The representative day, Atmospheric environment, 33 (15) (1999) 2427-2434.
[6] S. Tsoka, K. Tolika, T. Theodosiou, K. Tsikaloudaki, D. Bikas, A method to account for the urban microclimate on the creation of ‘typical weather year’ datasets for building energy simulation, using stochastically generated data, Energy and Buildings, 165 (2018) 270-283.
[7] M. Bruse, H. Fleer, Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model, Environmental Modelling & Software, 13 (3) (1998) 373-384.
[8] S. Huttner, Further development and application of the 3D microclimate simulation ENVI-met, Mainz University, Germany, (2012).
[9] Envi-met, Basics of Envi-met model in, http://www.envi-met.com/.
[10] E. ISO, 10456: Building materials and products-Hygrothermal properties-Tabulated design values and procedures for determining declared and design thermal values (ISO 10456: 2007), in, CEN, 2007.
[11] E. ISO, 13370: Thermal performance of buildings-Heat transfer via the ground-Calculation methods (ISO 13370: 2007), in, CEN, 2007.
[12] S. Tsoka, A. Tsikaloudaki, T. Theodosiou, Analyzing the ENVI-met microclimate model’s performance and assessing cool materials and urban vegetation applications-a review, Sustainable Cities and Society, 43 (2018) 55-76.
[13] R.A. Memon, D.Y. Leung, C.-H. Liu, Effects of building aspect ratio and wind speed on air temperatures in urban-like street canyons, Building and Environment, 45 (1) (2010) 176-188.
[14] K. Niachou, I. Livada, M. Santamouris, Experimental study of temperature and airflow distribution inside an urban street canyon during hot summer weather conditions—Part I: Air and surface temperatures, Building and Environment, 43 (8) (2008) 1383-1392.
[15] K. Niachou, I. Livada, M. Santamouris, Experimental study of temperature and airflow distribution inside an urban street canyon during hot summer weather conditions. Part II: Airflow analysis, Building and Environment, 43 (8) (2008) 1393-1403.
[16] M. Santamouris, N. Papanikolaou, I. Koronakis, I. Livada, D. Asimakopoulos, Thermal and air flow characteristics in a deep pedestrian canyon under hot weather conditions, Atmospheric Environment, 33 (27) (1999) 4503-4521.