



# Street canyon design and improvement potential for urban open spaces; the influence of canyon aspect ratio and orientation on microclimate and outdoor comfort



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## ABSTRACT

Urban morphology and material properties are critical parameters in the formation of outdoor microclimates and their effects on the thermal comfort of pedestrians. Despite considerable amounts of previous and ongoing research the scientific research results have not yet been fully adopted on urban projects. The present paper aims to contribute empirical and analytical results that highlight potential improvements that can be achieved through urban design. The paper draws upon environmental measurements, taken in both winter and summer periods, in 18 street canyons located in a dense central area of the city of Thessaloniki in northern Greece. The measurements are complemented by microclimate simulation studies involving modelling of the 18 street canyons as well as a number of generic cases. The results of these studies suggest the most favourable canyon geometries in terms of pedestrian thermal comfort and support the incorporation of basic climatic parameters into urban design.

## 1. Introduction

Over the last few decades several attempts have been made to link urban microclimate research with urban design in different climates. Oke (1988) investigated optimum street canyon geometric proportions based on diverse climate related criteria in mid latitude cities. Nikolopoulou et al. (2004) presented an extended study on microclimate and outdoor comfort in multiple open urban spaces across Europe to examine assessment methods and design potential. Ng (2009) reported on the development of urban planning guidelines based on air ventilation assessment in Hong Kong. Moreover, several studies focus on specific urban configurations such as courtyards, streets or urban blocks and discuss design implications and general recommendations based on case studies or simulation results. Martinelli and Matzarakis (2017) examined courtyard typology in different climate zones of Italy in relation to thermal comfort. Lindberg, Thorson, Rayner, and Lau (2016) used the mean radiant temperature  $T_{mrt}$  as a measure of heat stress in their study of the likely effects of density and vegetation cover for present and future climate scenarios on a redevelopment area in Gothenborg. Similarly, Chen, Yu, and Yang (2016) used  $T_{mrt}$  to investigate the effect of urban geometry on the radiant environment and pedestrian heat stress in different urban settings in Shanghai. Duarte,

Shinzato, dos Santos Gusson, and Abrahao Alves (2015) assessed the role of vegetation in high density urban environments in Brazil and its potential for outdoor comfort amelioration. Ali Toudert and Mayer (2006) studied thermal comfort conditions in the street canyons of an arid climate focusing on the effects of orientation and aspect ratio (height to width ratio, H/W) on the radiant environment. Johansson (2006) and Emmanuel, Rosenlund, and Johansson (2007) looked at these factors and at material properties in tropical climates. Pearlmutter, Berliner, and Shaviv (2007) also investigated street geometry effects on radiative and convective exchanges influencing thermal stress in a hot arid region. Santamouris et al. (2012) examined the thermal and airflow conditions forming in a deep street canyon in Athens. Kantzioura, Kosmopoulos, Dimoudi, and Zoras (2015) reported on a case study from the north of Greece. Yuan and Ng (2014) examined architectural design options in relation to wind field at pedestrian level, based on CFD simulations and a case study in Hong Kong.

Despite the knowledge acquired from all these studies, there still seems to be a gap between research and its application to urban design. In Greece, only recently has microclimate begun to be taken into account in urban design projects, most of which focus on refurbishment of existing. Tsitoura, Michailidou, and Toutsos (2016) present a study on a renovation project for an urban area in Crete with bioclimatic criteria,

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and discuss the effects of design parameters on microclimate and comfort. Santamouris (2000) reports on a microclimate improvement project for a large urban park in Athens focusing on the replacement of pavement materials. Altinisik, Klemm, Peretti, and Bruse (2014) presented an architectural competition project for the redevelopment of an urban area in central Athens, offering a climate-responsive design to fulfill specific microclimate and comfort criteria. Urban morphology potential is hardly considered in redevelopment projects where the existing urban configuration cannot be altered. Tsitoura et al. (2016) categorise the H/W ratios and orientations of existing street canyons as ‘permanent parameters’.

Acknowledging that street canyon geometry, in terms of aspect ratio and orientation, is a key factor affecting exposure to sun and wind, and thus the formation of different street canyon microclimates, the present paper assesses the resulting microclimates highlighting favourable and unfavourable conditions and potential design interventions that can help ameliorate pedestrian thermal comfort and reduce building energy loads in existing or future urban configurations.

To this aim measurements of environmental variables were taken over selected summer and winter periods in 18 centrally located street canyons of different geometric characteristics in the city of Thessaloniki, Greece. The measurements were complemented by simulation studies aimed at pinpointing the effects of individual variables as well as characterising generic configurations for the suggestion of urban design guidelines. The suggestions are aimed at providing solar access and wind shelter in winter and offering solar protection and airflow in summer.

## 2. Methods

### 2.1. Case study

Measurements were taken in eighteen central street canyons in the city of Thessaloniki (latitude 40.50N) during both summer and winter. The streets selected for the study included some that had their main axis parallel to the coast and others with their axis perpendicular to the coast and to prevailing winter winds (NW-SE and NE-SW). The sample also included streets that were diagonal to the normal grid of the city (N-S and E-W). The canyon aspect ratios, i.e. the ratio of building height to street width, ranged from 0.6 to 3.3 and were divided into four groups: very wide (0.6–0.7), medium wide (1.0–1.1), medium deep (1.7) and very deep (2.8–3.3). Specifically, the measurements were taken in seven canyons running NW-SE with aspect ratios ranging from very wide to very deep (0.6–3.0), seven NE-SW canyons with aspect ratios from medium wide to very deep (1.0–3.3), two deep N-S canyons with aspect ratio 1.7 and 3.0 and two deep E-W canyons with aspect ratio 1.7 and 3.2. The locations of the streets selected for the study are shown in Fig. 1 and the points where the measurements were taken are indicated in the cross sections of the canyons in Fig. 2.

### 2.2. Climate

The climate of Thessaloniki is characterized by very warm and sunny summers and by cold and humid winters. The location of the city along the coast has a large influence on daily airflow. Longterm weather data recorded at the city’s airport meteorological station are summarized in Table 1. Weather data for the dates of the measurements are listed in Table 2 and are considered representative of summer and winter conditions in the city.

### 2.3. Monitoring

The summertime monitoring took place from the 24th to the 31st of July, a period characterized by high air temperature, low wind velocity and intense solar radiation. The winter measurements took place from the 9th to the 15th of February, a cold period with partly cloudy sky

and relatively mild winds. The daily averages are summarized in Table 2 and the geometric features of the monitored street canyons are listed in Table 3.

Monitoring was conducted in 1 h or 2 h cycles with readings taken every 15 min, each day in a different group of canyons. Measurements were taken between 9:00 and 18:00 in summer and between 9:00 and 16:00 in winter. Sites 01–07 were included in the first group, sites 08–13 in the second group and sites 14–18 in the third group. Single readings at all sites were also taken consecutively with 15 min intervals on a summer and on a winter day from the morning till the afternoon and indicative spot measurements were conducted one night in summer and one in winter.

The parameters measured included the air temperature, relative humidity, wind velocity, wind direction and the globe temperature at 1.1 m above ground level. Surface temperatures were measured at each canyon on the side pavements and the centre of the canyon. Air temperature and relative humidity were measured with thermistor and capacitance sensors (Hobo H08-007-02, Hobo Pro v2 U23-002) placed within protective screens. The globe temperature was measured with an external sensor (TM C20 HD, Hobo Prov2 U23-003) placed inside a 40 mm diameter grey acrylic sphere. Surface temperatures were measured with an IR thermometer (Extech 42530). A portable 25 mm impeller anemometer (Kestrel 4600) with compass and vane was used for readings of wind direction and velocity. The instrumentation is listed in Table 4.

### 2.4. Thermal comfort indices

Measured data was used to calculate the mean radiant temperature  $T_{mrt}$  from the equation given by Thorsson, Lindberg, Eliasson, and Holmer (2007):

$$T_{mrt} = [(T_g + 273.15)^4 + (1.1 \times 10^8 \times WV^{-0.6} \times (T_g - T_{air}) / (\epsilon \times D^{0.4}))]^{-0.25} - 273.15$$

where  $T_g$  is the globe temperature,  $T_{air}$  is the air temperature,  $WV$  is wind velocity and  $\epsilon$  and  $D$  are the globe sphere’s emissivity and diameter.

The RayMan software (Matzarakis, Rutz, & Mayer, 2010) was used to calculate the thermal comfort indices with inputs from the measured weather data and the calculated values of the mean radiant temperature  $T_{mrt}$ . The thermal comfort indices derived from the software were the Physiologically Equivalent Temperature PET (Hoppe 1999) and the Universal Thermal Climate Index UTCI (Jendritzky, deDear, & Havenith, 2012). In this paper, the PET values are used to characterize thermal comfort conditions for pedestrians outdoors.

According to Matzarakis, Mayer, and Iziomon (1999) the association of PET values to grade of thermal perception and physiological stress, indicate comfortable conditions and absence of thermal stress in the PET range between 18 °C and 23 °C. Lower PET values, from 18 °C to 4 °C, correspond to conditions characterized from slightly cool to cold (and from slight to strong cold stress) while values below 4 °C indicate very cold conditions and extreme cold stress. PET values from 23 °C to 41 °C correspond to conditions from slightly warm to hot (and slight to strong heat stress) and PET above 41 °C shows very hot conditions and extreme heat stress. This association is assumed valid for pedestrians with 80W internal heat production and 0.9 clo thermal resistance of clothing. Therefore, considering lower clothing resistance in summer (0.5 clo) and higher in winter (1.5 clo) comfort range would shift to slightly higher values in summer and move to lower values in winter.

### 2.5. Simulation studies

The area of the measurements was modelled with the ENVI-met v4 software (envi\_met website, <http://www.envi-met.info/hg2e/doku>).

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