Potential contribution of urban developments to outdoor thermal comfort conditions: The influence of urban geometry and form in Worcester, Massachusetts, USA

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Abstract

Urban development projects have an immense impact on local microclimates which in turn affect the thermal comfort and space quality within a city. Thermally comfort outdoor spaces will encourage walkability in cities and improve public health and air quality. To design better urban environments it is necessary to measure and analyze outdoor thermal comfort in various climatic conditions, not only in warm but also in temperate and cold climates. Quantitative information helps us to adopt effective urban design solutions for existing and future urban environments. The overall objective of this research is to explore the variation of outdoor thermal comfort conditions affected by urban features. Therefore, the main aim of this paper is to discuss and assess the impact of urban geometry and form on microclimates of open spaces.

Urban geometry and form will be investigated using field measurements and simulations in a developing urban environment. The measurements and simulations of climatic conditions will be executed in summer during the months of June and July, representing the hottest time of the year in downtown area of Worcester, Massachusetts, USA (humid continental, Dfb in Köppen climate classification).

Keywords: Urban microclimate; Thermal comfort; Urban geometry and form; ENVI-met simulation; RayMan; UMI

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1. Introduction

1.1. UHI phenomenon

Urban Heat Island (UHI) is a phenomenon which occurs in dense urban areas and contributes to a difference in air and surface temperature during day and night from rural areas. For instance, a city with a million or more population can be 1 to 3 °C warmer than its surrounding areas [1]. This phenomenon has been studied in several urban areas worldwide and it varies based on the morphology, location and climatic zone of each site [2]. From the historic point of view, according to Garland, first documentation of UHI has been done in 1818 by Luke Howard [3]. Howard, was an amateur meteorologist who found an artificial excess of heat in the city in comparison to the country [3].

UHIs form in urban areas mainly due to the characteristics of urban materials. In comparison to natural materials in suburban areas, construction materials can absorb and hold more of the sun’s heat and gradually release it back into the environment. This occurs because of two main reasons: 1- most urban construction materials are impervious and watertight, and 2- these materials are usually darker than natural ones and therefore they collect more of the sun’s energy [3]. On a hot sunny summer day, surface temperature of urban areas can reach up to 27 to 50 °C hotter than the air [4], while vegetated surfaces remain significantly cooler. Characteristics of urban surfaces can be defined by surface reflectivity, availability of moisture and thermal mass of construction materials [5].

In addition to characteristics of materials, urban form and configuration of buildings play an important role in intensifying this phenomenon. Urban form and geometry can considerably change wind patterns and the amount of insolation urban surfaces receive. There is a correlation between physical configuration of an urban setting with the microclimate surrounding it. Urban configuration can ease wind velocity penetration within the city and increase or decrease temperature subsequently. Single high rise buildings for example, divert the wind in different directions and this helps adjacent street become ventilated [6]. Building’s form also affect the levels of shading achieved on the ground. A study in Dubai done by Thapar et al, shows that in hot-arid climate courtyard block form and denser developments can provide well shaded streets for pedestrians [7]. Urban geometry and form is characterized by Sky View Factor (SVF), height to width ratio (H/W) of urban canyons, and orientation of streets regarding sun and prevailing wind.

In addition, anthropogenic heat which refers to heat produced by human activities such as heating, cooling, running appliances, transportation and industrial processes, can also contribute to the formation of UHI [8]. Intensity of human activities within the city can create pockets of urban microclimates. Consequently, as Golany mentions, each part of the city has its unique thermal performance and therefore a different design consideration is needed for each site [6]. UHIs can be problematic and contribute to health issues and human discomfort, higher energy use of buildings, and air pollution.

1.2. UHI in cold climate cities

UHI has different impacts on different climates. It can be harmful or beneficial to urban dwellers and energy users according to the geographic location and prevailing weather conditions [9]. Generally speaking, in hot and arid climates this phenomenon should be mitigated, while in cold climates UHI could be less of a problem or beneficial because it reduces heating loads during cold seasons. However this is not applicable to all situations, each site should be studied independently and according to its local climate and use. A study of outdoor thermal comfort conditions conducted by Thorsson et al in Gothenburg, Sweden (as a high latitude city) shows a thermal stress during summer and how a densely built structure could mitigate extreme swings in mean radiant temperature (T_{mrt}). This study demonstrates direct impact of urban geometry and its potential to mitigate daytime thermal stress in cities [10]. Considering future climate change and increase of air temperature (T_a) and accordingly T_{mrt}, by the end of this century, increase in the number of heat-related deaths is expected. Thorsson mentions that, in the case of Stockholm, Sweden, if the mean air temperature rises up to 4 °C during summer, we could face a rise by 5% in heat-related deaths [10]. Although milder winter seasons are expected due to UHI effect, on the other hand heat waves in summer seem more problematic for dwellers of cold climate cities simply because they are not yet adapted to heat and extreme weather conditions in summer [11]. This shows the significance of the subject in cities with high latitude.
1.3. Thermal comfort and walkability in cities

The fact that almost 50 per cent of the world’s population lives in urban areas, demonstrates how consequential is the UHI impacts on people’s comfort and health. Therefore, the outdoor urban space needs more attention in terms of design with consideration of thermal comfort. A thermally comfortable urban space with higher air quality can facilitate walkability of communities. A walkable urban environment can contribute to a livable community which is less dependent on motor vehicles. Walkability can improve public health by encouraging daily physical activity associated with different modes of transportation [12]. In addition, mitigation strategies such as using cool roofs, cool pavements, and planting vegetation and trees can bring such benefits to the neighborhood: 1- temperature reductions, 2- energy savings, 3- air quality improvements, 4- human comfort and health improvements, 5- stormwater run-off reductions, 6- maintenance and waste reduction, and 7- aesthetic benefits [3]. Consequently, this study intends to evaluate the diurnal thermal comfort at pedestrian level in the city center of Worcester, MA in order to provide design consideration regarding outdoor thermal comfort.

2. Heat mitigation strategies

Considering causes of UHI formation, there are several mitigation strategies. One of the strategies is associated with the use of vegetation in urban areas. Vegetation can contribute to park cool island (PCI) effect and consequently can reduce air temperature up to 3 to 4 °C in summer [13]. Vegetation makes this heat reduction possible through four mechanisms: 1- with a higher albedo compared with construction materials like concrete or asphalt, 2- through evaporation and transpiration (the sum of these two processes together called evapotranspiration), 3- with lower specific heat capacity greenery stores less heat, and 4- with shading, leaves and branches reduce the amount of solar radiation that reaches the urban surfaces below canopy layer [2,13,14,15,16,17]. Use of vegetation as a mitigation strategy can be applied as extensive and intensive green roofs. A study in New York City shows the heat mitigation potential of green roofs. The researchers have modeled air temperature reductions 2 m above the roof surface of the city, with assumption of changing all roofs to green ones. The results show an average 0.2 °C temperature reduction for the whole city in the day [18].

Cool pavements and cool roofs are also applicable as effective heat reduction strategies. Technologies in pavement and roof materials results in less heat accumulation and consequently lower surface temperatures in comparison to conventional materials. Cool materials’ performance is associated with properties such as solar reflectance, heat capacity, permeability, surface roughness, heat transfer rates, and thermal emittance. As an example, researchers in Lawrence Berkeley National Laboratory have estimated that every 10% increase in albedo of surfaces could decrease surface temperatures up to 4 °C [19].

Some studies on the thermal performance of urban spaces are only focused on air temperature while the others consider mean radiant temperature as well. These strategies are applicable in existing retrofitting urban projects and they are factors which communities are focusing on, while strategies related to urban geometry and anthropogenic activities can be considered in future urban developments. This study is mainly focused on the role of urban geometry and form as a potential mitigation strategy. According to Golany, in cold-humid climates urban design solutions for a better thermal performance in outdoor spaces are based on heating (passive and active) and are as following: 1- mixture of open and enclosure forms, 2- protected edges at winter windward side (with structures or trees), 3- uniformed building heights, 4-medium dispersed open space, and 5- circumferential and intersecting tree strips [6]. Golany also suggests a mixed of open and controlled enclosure forms in cold-humid climates.

3. Context

This study was conducted in the city of Worcester, Massachusetts (42.27°N, 71.87°W). The altitude is about 308 m above sea level. The city is named after Worcester, England and it is located 64 km west of Boston. It is incorporated as a city in 1848 and today, according to 2010 Census with population of almost 181 000 inhabitants, is the second largest city in New England after Boston (Fig. 1). Based on the Köppen-Geiger climate classification, Worcester is characterized by a humid continental climate or Dfb in the classification. This climatic region typified by warm to hot summers and cold winters [20]. Prevailing wind in Worcester is west-east and the mean annual dry bulb temperature is 8.75 °C. All these contribute to severe
climate in winter and a short period of hot summer. According to Golany, major problems of cold-humid climates are low temperature, winter and summer high precipitation, and windy weather conditions [6] (Fig. 2).

4. Methodology

In this study the existence of UHI is tested in four locations. First, a total of four measuring stations, representing different forms and geometries were chosen and were investigated in terms of climatic parameters in order to demonstrate the existence of Urban Heat Island (UHI). The magnitude of spatial and temporal variations of mean radiant temperature, outdoor air temperature, wind speed and relative humidity were quantified using ENVI-met model and thermal comfort was assessed using Physiologically Equivalent Temperature (PET) index via RayMan. Secondly, the thermal comfort level of one of the locations will be measured after applying mitigation strategies and results will be compared. Thirdly, the performance of downtown Worcester in terms of walkability will be examined using Urban Modelling Interface (UMI). Any kind of intervention in urban settings can change the outdoor thermal conditions. This study intends to measure the impact of new developments on existing urban areas via comparing thermal condition in two scenarios, before and after development. Figure 2 illustrates this concept.

4.1. Study area

The study area is located in downtown Worcester. The urban fabric is relatively dense and average height of buildings is five-story. The street canyons are mostly in N-S and W-E direction with a slight clock-wise rotation.
Vegetation is rare in this part of the city, except an urban square adjacent to City Hall building which is rich in greenery and is considered as an important urban park. Streets are paved with asphalt and there are concrete and brick paths on sides. Building facades are made of brick and stone in variety of colors and with 33 to 75% window to wall ratio [21]. Masonry material with individual windows characterizes the buildings in western side of Main Street and the Canal District as Historic District while in Innovation District, including Washington Square, precast concrete, glass, and metal panels are preferred [21]. Downtown Worcester is characterized by municipal buildings and it is the site of important business, cultural and civic activities [21]. Diverse uses in addition to historic identity of this area make it a potentially livable and walkable urban community. Considering relatively high level of pedestrian users in downtown Worcester, it is necessary to study thermal comfort at pedestrian level in this area. The study area represents different forms and geometric configurations of open spaces and streets. Study locations were chosen based on variation of the Sky View Factor (SVF), height to width (H/W) ratio and orientation and listed as following: 1- east-west canyon (Mechanic Street), 2- north-south canyon (Main Street), 3- urban square (City Common), and 4- surface parking (Fig. 2). Detailed description of study locations including major surface material, SVF, and H/W ratio are illustrated in Table 1.

| Study area            | SVF  | H/W  | Major surface material                      |
|-----------------------|------|------|--------------------------------------------|
| Location 1 (E-W canyon) | 0.34 | 2.00 | Pavement: asphalt  
Building facades: glass and brick |
| Location 2 (N-S canyon) | 0.52 | 1.75 | Pavement: asphalt  
Building facades: light grey stone, brick |
| Location 3 (urban square) | 0.75 | 0.5  | Pavement: asphalt and grass  
Building facades: light grey stone, brick |
| Location 4 (surface parking) | 0.68 | 0.16 | Pavement: asphalt  
Building facades: brick |

4.2. Meteorological data

In order to examine the existence of UHI in downtown Worcester, several climatic datasets have been used. For this purpose, results from computer simulations were compared to data coming from weather station in airports or suburban areas.
4.3. Computer simulations

In this study all the simulations were conducted using ENVI-met 3.1 [22], RayMan 1.2 [23] and UMI [24]. ENVI-met 3.1 is a three-dimensional non-hydrostatic microclimate model designed to simulate the surface, plant and air interactions in an urban environment with a typical spatial resolution of 0.5-10 m in space and 10 s in time. This program uses soil, radiative transfer, and vegetation models based on fundamental laws of fluid dynamics and thermodynamics that can simulate exchange processes of heat and vapor at horizontal and vertical surfaces around and between buildings. This program is capable of calculating meteorological parameters such as air temperature (°C), relative humidity (%), wind velocity (m/s), vapor pressure (hPa), and mean radiant temperature (°C) of the center of models. This program has been extensively used in order to study the effect of natural and built elements on urban microclimates in addition to the impacts of climate change[25].

RayMan 1.2 is a model which simulates the short- and long-wave radiation flux densities from the three-dimensional surroundings in simple and complex environments. RayMan model is based on radiation and human-bioclimatic model. The aim of the RayMan model is to calculate radiation flux densities, sunshine duration, shadow spaces and thermo-physiologically relevant assessment indices using only a limited number of meteorological and other input data. Field measurements show the validity of simulation values for global radiation and mean radiant temperature conducted via RayMan [26]. In this study RayMan has been used for PET index calculations.

Urban Modelling Interface (UMI) is a Rhino-based integrated urban modeling and design environment which is helpful for urban planners, architects to improve the performance of their designs at the building and street scale. UMI provides operational and embodied energy use, walkability and daylighting potential of neighborhoods and cities. UMI is being developed by the Sustainable Design Lab at the Massachusetts Institute of Technology. Version 2.0 of the software was released on November 7th, 2014 [24,27]. In future steps of this study UMI will be utilized to simulate the walkability potential of downtown Worcester.

4.4. Field measurements

During June and July 2015 field measurements will be conducted using a FLIR infrared camera to measure surface temperature and a HOBO weather station to measure air temperature, globe temperature and wind speed. In further studies of urban materials’ characteristics, a spectrophotometer will be used to measure albedo of surfaces. Field measurements results will be used to verify results from simulations.

5. Results and conclusion

ENVI-met simulations were done on July 2nd, 2014, representing hottest day of the year according to data gathered from Worcester regional airport weather station. These simulations show thermal comfort condition at pedestrian height (around 1.6m). Figures 3 and 4 demonstrate simulated hourly T_{met} and PET index at specific points (1 to 4) for four study locations. The temporal variation is from 8am to 8pm, representing daytime hours when people are willing to walk in downtown area. In figure 3, it can be seen that from 8am to 12pm the level of T_{met} is almost equal in all four locations, while at 12pm all locations except N-S canyon start getting warmer. This condition is significant in the E-W canyon case, when the T_{met} reaches its highest (74.8 °C) at 3pm and starts cooling down after that time. E-W canyon is the only location which starts cooling down in the afternoon and it is mainly because of blocking solar radiation. On the other hand, in N-S canyon the rise in T_{met} begins at 3pm and continues till 8pm (up to 65.4 °C). This shows the importance of canyon direction and its impact on T_{met}. Urban square and surface parking show similar behaviors in T_{met} variation, considering only that surface parking becomes relatively warmer than urban square after 2pm.
Figure 4 illustrates the level of PET (°C) from 8am to 8pm in four locations. The red region shows the temperature range at which pedestrians can feel heat stress. For instance, in E-W canyon from almost 12:30pm till 8pm pedestrians feel heat stress, while this condition is different for N-S canyon. According to the graph there is in no heat stress till 5pm and it is thermally comfort before that time. For the other two locations, it can be seen that heat stress happens after 2pm. These variations in thermal comfort level show the importance of urban form and geometry in downtown Worcester.
Fig. 5. Left, ENVI-met model of study location and specific locations 1 to 4. Right, Mean Radiant Temperature (°C) in four locations from at 3pm on 2 July 2014.
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