A multiscale analysis of the urban heat island effect
From city averaged temperatures to the energy demand of individual buildings
Yasin Toparlar

How can we as engineers prepare buildings and their users for a warmer future? Today, buildings are responsible for approximately 40% of the global energy demand. Among this demand, the share of space heating is typically larger than the share of space cooling or lighting. However, considering the global climate change and rapid urbanization, this relative dominance of space heating may not last much longer. Within the second half of the 21st century, global energy demand for space cooling is probably going to be higher than the energy demand for space heating.

To counter the increasing cooling demand, much has been achieved in the past with more efficient cooling systems and better building designs. An alternative way to reduce the energy demand for space cooling would be to obtain better microclimatic conditions under which buildings operate. This design option can be suitable especially for cities since cities are commonly warmer than their rural surroundings (Urban Heat Island effect), with higher cooling demands. If the envelope of a building and its HVAC (heating, ventilation, air-conditioning, cooling) installations are designed computationally with the goal of reducing the building’s cooling demand, can we also design urban microclimates with the same goal in mind? This question has been the primary motivation for this research project.

Assessing and potentially altering the urban microclimate with the aim of lowering building energy demand requires linking two computational fields: 1) urban microclimate modeling and 2) building energy modeling. Urban climate modeling has grown in popularity since the 1950s and it used to be conducted at the meteorological mesoscale, where the focus is on horizontal distances of a few to several hundred kilometers. Although studies at this scale are capable of including atmospheric phenomena, such as cloud formations, they cannot provide information specifically at the spatial scale around individual buildings (i.e. the meteorological microscale) due to modeling constraints. Meteorological microscale studies, conducted by numerical simulation with Computational Fluid Dynamics (CFD), therefore focus on domains with horizontal distances in the range of 0.1 – 5 km. At this scale, wind flow and the associated heat and mass transfer occurring at spatial grid resolutions in the range of 0.1 to 100 m can be modeled. Thus, building specific microclimatic information can be extracted. This information can be used in Building Energy Simulations (BES) as a boundary condition and different microclimate scenarios can be tested to investigate the effect of the urban microclimate on the building energy demand.

In CFD urban microclimate simulations, one should be able to combine wind flow and heat transfer aspects in a time-dependent manner. Even though CFD has been employed almost exponentially in various fields since the 1960s, it is only in the past 20 years that its application for urban microclimate studies has come to flourish. In a review study conducted by the present author and his supervisors as part of this research, studies focusing on the CFD analysis of urban microclimate published from 1998 till the end of 2015 were investigated. Among the 183 studies investigated in the review, more than half were published in the last three years of the investigated period (Figure 1), which testifies to the rapidly increasing popularity of this research field combined with this specific assessment method.

Figure 1: The yearly distribution of published peer-reviewed journal papers on CFD analysis of urban microclimate. In total, 183 studies, published from 1998 till the end of 2015, were included in the investigation.
In the present research project, a CFD methodology was developed towards a sufficiently accurate representation of urban microclimate. The methodology was built upon the CFD best practice guidelines previously established within the urban physics and wind engineering research communities. The methodology was based on the 3D Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations together with the realizable k-epsilon turbulence model for closure. The developed methodology was first employed in a case study of the Bergpolder Zuid district in Rotterdam. CFD simulations considering both wind flow and heat transfer were performed and resulting wind velocity and surface temperatures in the area of interest were investigated (Figure 2). The resulting surface temperatures were compared with the surface temperatures obtained via satellite imagery. The CFD methodology was shown to provide a fairly good performance in predicting the surface temperatures with an average absolute temperature difference of 2.2°C.

The same CFD approach was employed to assess the effect of an urban park on the microclimate in its vicinity. The focus area was the Stadspark in Antwerp, Belgium and its surroundings up to a distance of 850 m away from the park. This park was specifically chosen as the focus area to investigate the so-called park cooling effect (PCE). The PCE occurs due to the shading and evapotranspiration caused by the park trees and the cooling effect is convected further downstream of the park. The PCE was investigated by focusing on two parameters: 1) the intensity of the cooling effect, designating the maximum reduction in air temperature outside of the park and 2) the range of the cooling effect, designating the maximum horizontal distance where a minimum of 0.1˚C cooling effect is present (Figure 3). To calculate the PCE, three cases are compared: (1) reference case with the park; (2) a case with an open square instead of the park; and (3) a case with representative buildings instead of the park. The differences in air temperature resulting from individual cases (Figure 4) are then compared to calculate the PCE. The maximum intensity and range of the cooling effect for the investigated date (30 June 2012) were calculated to be 3.4˚C and 498 m, respectively, occurring at 15:00 hours. The maximum PCE was calculated when the results from the reference case with the park were compared to the case with representative buildings instead of the park. Further research is recommended to provide insights on how the urban form can be modified to increase the range of the cooling effect to the benefit of more buildings.
Incited by the cooling effect caused by the Stadspark, a next step was to analyze the relationship between the PCE and the building energy demand. For this analysis, the same computational grid and domain used as in the previous study were utilized (Figure 5). On-site measurements and CFD simulations were conducted to evaluate the performance of CFD simulations and to generate location-specific microclimatic conditions. The CFD simulations were found to be able to reproduce the measured air temperatures at the corresponding urban measurement point (Figure 5) with an average absolute temperature difference of 0.88°C.

With the fairly good predictive capability of CFD simulations, location specific microclimatic conditions (MCs) were generated at three locations: (1) a rural location outside Antwerp; (2) an urban location inside central Antwerp, away from the Stadspark; (3) another urban location, close to the Stadspark. Later, these three MCs were used in the BES of a building with the same form and orientation but with different construction characteristics and building use types. BES were performed to compare the resulting cooling demands for July 2013. It was shown that buildings subjected to an urban MC had up to 90% more cooling demand than buildings subjected to a rural MC. In addition, buildings close to Stadspark were found to have (on average) 13.9% less cooling demand than buildings away from the urban park of interest. The results from this particular study are significant as they document the importance of meteorological wind direction and local cooling sources (i.e. the urban park investigated) on the estimated summertime building cooling demand.

Within the scope of this project, a fundamental limitation of the CFD simulations performed in this research and in the worldwide ongoing urban microclimate research was tackled. This limitation entails the assumption of uniform vertical temperature inlet profiles for CFD urban microclimate studies. As these profiles are not only unrealistic but also mathematically inconsistent, this leads to horizontally inhomogeneous flow fields. We analytically derived a new temperature inlet profile to address this limitation. This profile is consistent with the vertical mean velocity and turbulence profiles, the turbulence model, the wall functions and the grid resolution adopted. It was shown that this newly developed profile can assure the simulation of horizontally homogeneous Atmospheric Boundary Layer (ABL) flow not only in terms of mean velocity and turbulence characteristics, but also in terms of temperature.

The hypotheses underlying this research project were: 1) urban microclimates can affect building energy demand; 2) urban microclimates can significantly be altered by urban (design) features, such as vegetation and urban morphology; 3) these effects can be assessed computationally by a combination of CFD and BES. All three hypotheses were confirmed. The multiscale approach presented in this thesis can be utilized for different cities to assess and ultimately modify urban microclimates within which people can live with improved health, comfort and productivity and buildings can operate in a more energy-efficient way.
Figure 5: Computational domain. a) View of the complete domain; b) View of the explicitly modeled part of the domain with buildings, trees and streets. c) Aerial view of the area of interest from south (source: Google Maps) d) Corresponding computational grid on buildings, street and tree surfaces (total cell count: 9,078,916 cells).

This thesis is the result of a collaboration between Eindhoven University of Technology (TU/e) and the Flemish Institute for Technological Research (VITO). The thesis was supervised by prof. dr. ir. Bert Blocken (TU/e – KU Leuven), prof. dr. ir. Gert-Jan van Heijst (TU/e) and dr. Bino Maiheu (VITO).

Parts of this thesis were published in international peer-reviewed journal papers as:


One chapter of this thesis is under preparation for publication as a journal paper:
