7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient Buildings and Urban Environments

ibpc2018.org | #ibpc2018

Studying the impact of local urban heat islands on the space cooling demand of buildings using coupled CFD and building energy simulations

Jonas Allegrini[1,2,*] and Jan Carmeliet[1,2]

[1] Laboratory of Multiscale Studies in Building Physics, Empa, 8600 Dübendorf, Switzerland
[2] Chair of Building Physics, ETH Zurich, 8092 Zürich, Switzerland

[*]*Corresponding email: jonas.allegrini@empa.ch*

ABSTRACT
Surface as well as air temperatures are due to the urban heat island effect higher in urban compared to their surrounding rural areas. These increased temperatures have a strong impact on the building energy performance in urban environments and thermal comfort as well as health of inhabitants of these environments. At smaller scales, local heat islands are formed within urban environments, which have the same negative impacts. In this study, we investigate the influence of local heat islands on the space cooling demand of buildings. Commonly, climate information from one weather station is used for building performance simulations within a whole city. This climate information cannot take local hot spots into account, what can lead to inaccurate space cooling demand predictions. Here, we model the local urban climate with CFD (Computational Fluid Dynamics) simulations. With CFD also the local convective heat transfer coefficients (CHTC) for the building surfaces can be predicted. These local CHTC can strongly vary locally due to differences in local wind speeds. The commonly used coefficients are mostly based on measurements at facades of stand-alone buildings, where the local wind speeds are higher compared to urban areas.
This study shows a dependency of the space cooling demands on the local urban climate. Space cooling demands are higher in areas with high local temperatures, where the wind-driven ventilation is decreased. Additionally to the higher local temperatures also the local CHTC are lower leading to lower heat losses from the buildings. It can be concluded that it is important to account for the local microclimate to accurately predict the space cooling demand of buildings in urban environments.

KEYWORDS
Urban climate, CFD, Building Energy Simulations, Space Cooling Demand, Local Urban Heat Island

INTRODUCTION
In the past decades, cities have been continuously growing and today about 54% of the world population lives in urban areas, a ratio that will increase to about 66% by 2050 (United Nations, 2015). Urban areas experience the urban heat island (UHI) effect, characterized by higher air temperatures compared to the surrounding rural environment (Oke, 1987). The UHI is expected to further increase due to the continuous growth of our cities, leading to even harsher urban climates in future. In addition to the UHI effect at city scale, local hot spots can be found in cities. Certain city quarters, neighbourhoods or zones between individual buildings may show much higher air temperatures compared to neighbouring urban areas, referred to as local heat islands (Allegrini and Carmeliet, 2017). These local hot spots are mainly due to lower wind speeds caused by wind sheltering. The intensity of these local heat islands depends on factors like building density, lack of shadowing by buildings and trees, type of building materials, lack of water bodies, vegetation or parks and deficiency of wind

flows to ventilate and remove heat. The local urban climate may highly influence the energy demand for buildings, especially the space cooling demand during hot periods. Most of the building energy simulation models, which are used to predict energy demands of buildings, were originally developed for stand-alone buildings (Hensen, 2011). For buildings in urban environments the building energy demand can be quite different to buildings in rural areas. The important impact of the local urban climate on the energy demand of buildings has been shown in a number of studies (e.g. Bouyer et al. 2011) with different approaches and levels of detail.

There exist a large number of numerical urban climate models, which predict the urban climate with different spatial resolutions and levels of accuracy. In this study a detailed urban microclimate model developed by Kubilay et al. (2017) is used to simulate the local urban heat islands in a small urban neighbourhood. This is a fully-integrated urban climate model, which solves for wind flow and for the transport of heat and moisture in the air and building materials. The predicted local air temperatures and local convective heat transfer coefficients for a period of 24 hours during a generic heat-wave event are used as inputs to building energy simulations (BES), which predict the space cooling demands. This study is conducted for the climate of Zürich (Switzerland).

NUMERICAL MODEL AND SIMULATION

An offline coupling between a CFD and a BES model is used to predict the impact of the local urban climate on the space cooling demands of a building in an urban neighbourhood. First the urban climate model based on CFD is conducted to predict the local urban climate for a time period of 24 hours. In a second step the local air temperatures around the studied building is used as an input parameter for the BES. The local air temperature is determined as the mean temperature in the air volume surrounding the building with a maximum distance of 0.3 m. For the convective heat transfer coefficients (CHTC) the correlations by McAdams (1954) are used (default correlations for the used BES model). For this study, for each building surface the local wind speed (mean over the façade or roof area) is used in the CHTC correlation instead of the wind speed from the climate file. With this offline coupling approach, we can account for the local microclimate, when simulating the space cooling demand of a building.

For the microclimate simulation the urban microclimate model by Kubilay et al. (2017) is used. This model solves the steady Reynolds-averaged Navier-Stokes (RANS) equations iteratively with the unsteady heat and moisture transfer in the building materials. The model includes long and shortwave radiation exchange between the urban (building and street) surfaces. The urban climate model is implemented in OpenFOAM 2.4 and a standard k-ε turbulence model is used. The building materials are modelled as porous domains and the heat and moisture transport equations are solved. The long and shortwave radiation is modelled based on a radiosity approach. For more details on the urban climate model, we refer to Kubilay et al. (2017).

For the Building Energy Simulation (BES), the program CitySim (Kämpf, 2009) is used. CitySim is a simulation tool which models the energy fluxes in a city, with a size ranging from a small neighbourhood to an entire city. In CitySim detailed radiation models for solar and longwave radiation are implemented that can account for the radiation exchange between neighbouring buildings, the ground and environment. The heat flow through the walls is determined with a model based on the analogy with an electrical circuit (resistor-capacitor network). CitySim uses an hourly timestep, which cannot be changed. CitySim also includes HVAC and energy conversion system models. CitySim determines the heat balances for all building materials and for the ground (e.g. street) materials.

In this study, urban microclimates for six different urban morphologies are studied and their impacts on the space cooling demands of the middle building (Fig. 1). All buildings are 10 m high and the lengths of the buildings are between 10 m and 50 m.

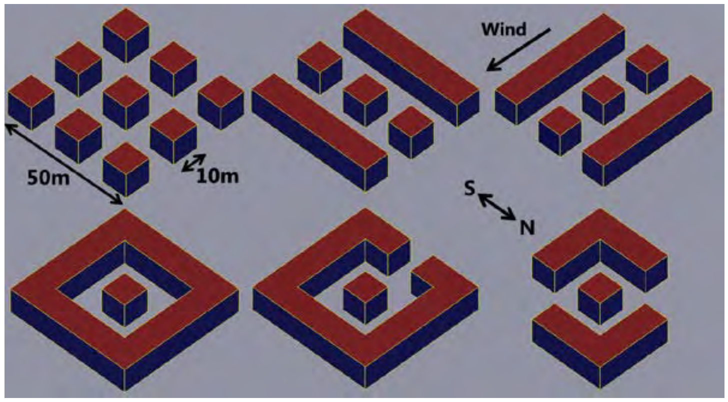

Figure 1. The layout and orientation of the urban morphologies under investigation.

All buildings are modelled as office buildings with corresponding occupancies and internal gains (SIA 2006). Ventilation and infiltration are considered. The glazing (G-value: 0.7, U-value: 1.1 W/m^{2}K) fraction of the buildings is 40 % and all façades have a solar reflectance of 0.4. The walls have a U-value of 0.5 W/m^{2}K (with inner insulation); the roofs have a U-value of 0.23 W/m^{2}K and the floors a U-value of 0.44 W/m^{2}K. The walls are made out of brick and the same material properties are used for the BES and urban climate simulations. External shading devices are used to protect the buildings from solar gains.
The simulations are conducted for the city of Zürich on June 21st. A generic heat-wave situation with ambient temperatures between 20 °C and 33 °C is assumed. Fig. 2 shows the variations of the ambient temperature during the day.

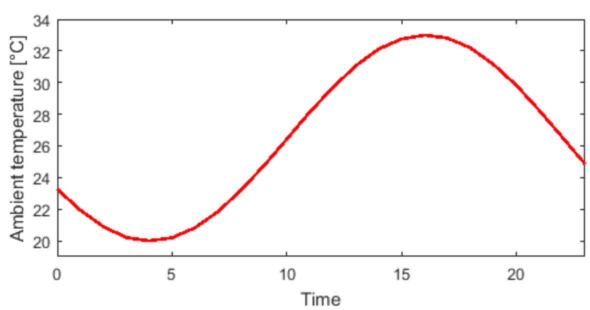

Figure 2. Daily variation of the ambient temperature.

The wind direction is assumed to be 270° for the whole 24 hours. At the inlet of the computational domain vertical profiles of the mean horizontal wind speed, the turbulent kinetic energy and the turbulence dissipation are imposed for a reference wind speed of 5 m/s at 10 m height. These profiles represent a neutral atmospheric boundary layer, where the turbulence originates only from friction and shear (Richards and Hoxey, 1993). The mesh, the computational domain size and the solution algorithm are in agreement with best practice guidelines (e.g. Franke et al. 2011).
Both the CFD as well as the BES are simulated for a number of 24 hour cycles until the results for the same hour of the day are the same for at least two consecutive cycles.
For each urban morphology four different BES are conducted. The first simulation is conducted with the default CHTCs used in CitySim and the ambient temperatures from the

weather file (shown in Fig. 2). A second simulation is conducted using the local air temperatures from CFD (with the default CHTCs). In the third simulation the local CHTC are used (with the ambient temperatures from the weather file) and finally the local CHTCs and local air temperatures are used for the simulations. Therefore it is possible to evaluate the impact of the different input parameters on the predicted space cooling demands.

RESULTS

Microclimate

First the predicted local microclimate is analysed, before the impact on the space cooling demands is studied. In Fig. 3, the local heat island intensities (temperature difference between the local temperature and the ambient temperature) for the warmest hour of the day are presented. The temperatures are locally 2 °C and more above the ambient temperature. This local temperature increase has an impact on the space cooling demands. Strong differences can be found for the different urban morphologies. Lower local heat island intensities (LHI) can be found for less dense morphologies and morphologies with open flow paths in wind direction. Fig. 4 shows the LHI shows during the coldest hour of the day. Here the LHI are lower, but the hot spots can be found in similar locations.

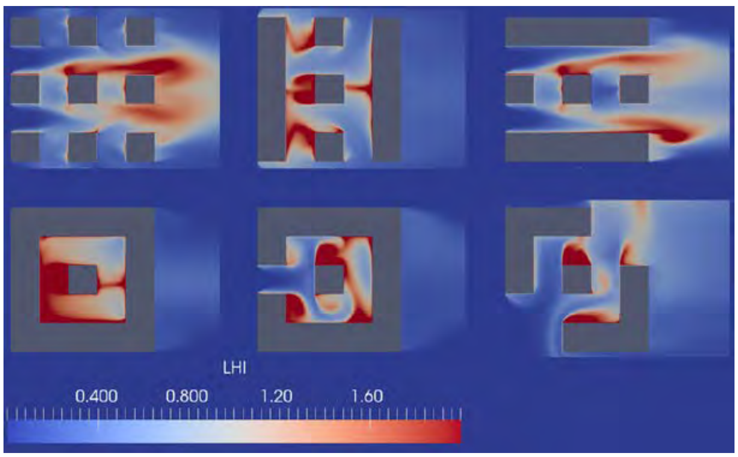

Figure 3. Local heat island intensities (LHI) at 2 m above the ground for an hour with an ambient temperature of 33 °C.

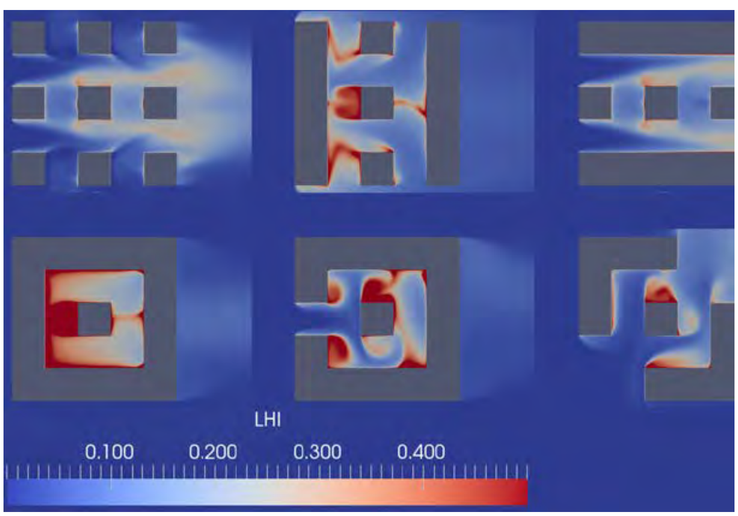

Figure 4. Local heat island intensities (LHI) at 2 m above the ground for an hour with an ambient temperature of 20 °C.

Space cooling demands

The differences in the local microclimate (discussed above) have an important impact on the energy performance of buildings in urban areas. The microclimate simulations show that the daily mean local heat island intensities in the air volume close to the studied building (used for the BES as input) are between 0.4 °C and 1.4 °C. The maximum local heat island intensities in this air volume are up to 2.7 °C. In Figure 5, the daily space cooling demands for the different urban morphologies are compared. For each morphology the space cooling demands are determine with the default settings of CitySim ("Base Case"), using the local air temperatures ("Local temperatures"), using the local CHTC ("Local CHTC") or using local values for temperatures and CHTC ("Local temperatures and CHTC"). The results show that predicted space cooling demands of the same building can vary up to 20 % depending on the local microclimate and on the degree of detail that the microclimate is modelled in the BES. The urban morphology has first of all an impact on the radiation exchange between the buildings, what causes the differences between the different base cases. Urban morphologies also lead to different wind patterns and local air temperatures, what increases the space cooling demands in urban areas. The contribution of these two effects have a similar magnitude for the here studied cases. The combined effect of the local heat islands and the decreased wind speeds is approximately the sum of the individual effects.

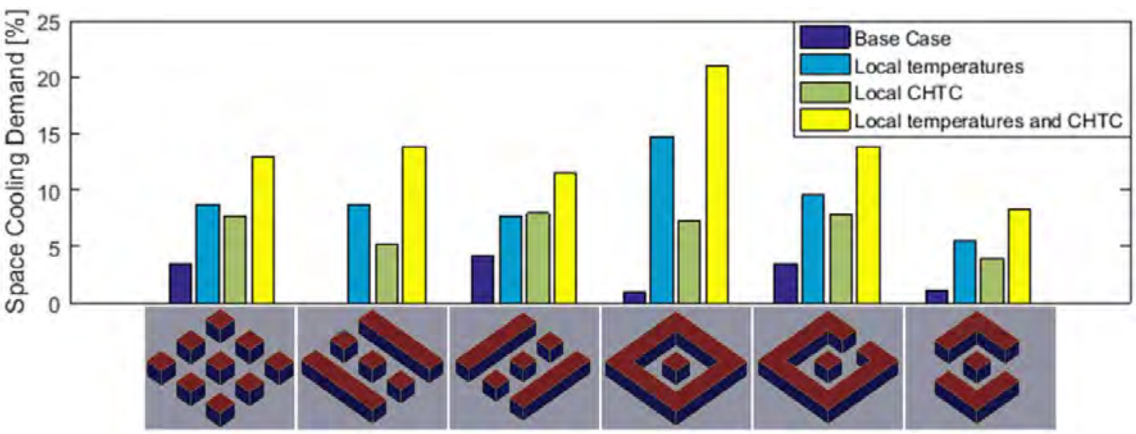

Figure 5. Normalized space cooling demands for different morphologies and microclimate boundary conditions (in percentage). Results are normalized by the case with the lowest daily space cooling demands (45.5 kJ/m^2).

DISCUSSIONS

The results of this study show a clear impact of the local microclimate on the space cooling demand of buildings in urban environments. Additional studies are needed to get more general conclusions, since the results here are limited to a (realistic) case study. Here the study is only conducted for one climate with the focus on a generic heat-wave. Also only one type of building was studied, but not all building types have the same sensitivity to the local climate. Additionally a number of simplifications were made here. The wind speed and wind direction are constant during the studied 24 hours and generic building configurations are used. Finally, the coupling between the CFD and BES can still be improved. With the models used in this study, the spatial resolution of energy fluxes and the temperatures of the building facades are significantly higher for the CFD compared to the BES.

CONCLUSIONS

In this study the impact of the local urban microclimate on the space cooling demand of a building during a heat-wave is investigated. A very detailed local urban climate model based

on CFD is used to predict the local microclimate for six different urban morphologies. The urban climate simulations show local hot spots between buildings with temperatures, which are more than 2 °C higher compared to the ambient air temperatures. The local heat island intensities are found to be larger during the day compared to the night. The BES show that the local hot spots lead to increased space cooling demands of an office building of 5-13 %. The lower wind speeds in the urban areas cause a further space cooling demand increase of 3-6 %. Finally, the radiation exchange with the neighboring buildings also has an impact on the space cooling demands of the studied building.
This study shows that it is important to not only account for the urban heat island effect in BES, but also considering the local heat islands that exist within the urban heat islands.

REFERENCES

Allegrini J., Carmeliet J. 2017. Simulations of local heat islands in Zürich with coupled CFD and building energy models. Urban Climate http://dx.doi.org/10.1016/j.uclim.2017.02.003

Bouyer J., Inard C., Musy M. 2011. Microclimatic coupling as a solution to improve building energy simulation in an urban context. Energy and Buildings, 43, 1549-1559.

Franke J., Hellsten A., Schlünzen H., Carissimo B. 2011. The COST 732 best practice guideline for CFD simulation on flows in the urban environment: a summary. International Journal of Environment and Pollution, 44 (1–4), 419–427.

Hensen J.L.M., Lamberts R. 2011. Building Performance Simulation for Design and Operation. Oxon: Spon Press.

Kämpf J. 2009. On the Modelling and Optimisation of Urban Energy Fluxes. PhD thesis nr 4548, EPF Lausanne (Switzerland).

Kubilay A., Derome D., Carmeliet J. 2017. Coupling of physical phenomena in urban microclimate: A model integrating air flow, wind-driven rain, radiation and transport in building materials. Urban Climate https://doi.org/10.1016/j.uclim.2017.04.012

McAdams W.H. 1954. Heat Transmission. Tokyo: McGraw-Hill Kogakusha.

Oke T. R. 1987. Boundary Layer Climates, 2nd ed., London: Methuen.

Richards P.J., Hoxey R.P. 1993. Appropriate boundary conditions for computational wind engineering models using the k-ε turbulence model. Journal of Wind Engineering and Industrial Aerodynics, 46–47, 145–153.

United Nations. World Urbanization Prospects: The 2014 Revision, (ST/ESA/SER.A/366), 2015.