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Influence of morphologies on the microclimate in urban neighbourhoods

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A B S T R A C T

In the past decades the portion of the population living in urban areas has continuously increased. Due to the high building density, the microclimate in urban areas changes significantly compared to rural areas. The temperatures measured in urban areas are higher compared to the rural temperatures due to the urban heat island (UHI) effect. Furthermore, the longwave and solar radiation exchanges are influenced by shadowing, reflections between buildings and reduced sky view factors. The local urban microclimate has an influence on the energy demand of buildings and on human comfort and health in urban areas. In summer the human comfort in urban areas can decrease due to higher air and surface temperatures and lower wind speeds compared to rural areas. The local urban microclimate is difficult to predict because of the complex interaction of physical phenomena across a large range of time and length scales. Few guidelines exist for architects to mitigate UHI effects or its impacts. The aim of this paper is to model the urban microclimate with CFD and building energy simulations and to investigate in detail the influence of different urban building morphologies on the urban microclimate. This approach and the results of this study can be used to find measures to mitigate the UHI effect. The results show that building façade surface temperatures are mainly influenced by the distance between buildings. For urban morphologies with similar surface temperatures, the air temperatures can still strongly vary due to different wind flow patterns causing different rates of removing heat by wind.

1. Introduction

The microclimate in urban areas differs significantly from the climate in rural areas. The air temperatures are higher due to the urban heat island (UHI) effect and the wind speeds are, on the average, lower due to wind sheltering (Oke, 1987). The UHI effect is mainly caused by storage of solar heat in built construction materials with high heat capacity, reduced longwave radiation to the sky by reduced sky view factors, generation of anthropogenic heat, lack of evapotranspiration and reduced turbulent convection to remove heat (Santamouris, 2001a). Measurements in London showed up to 7 K higher air temperatures at night-time in the city compared to measurements outside the city (Watkins et al., 2002). In Athens the mean heat island intensity exceeds 10 K, which can double the energy demand for space cooling in buildings (Santamouris et al., 2001b). Future global warming and associated heat waves (Schär et al., 2004; Fischer and Schär, 2009) may further increase the temperatures in urban areas and can reduce the potential for passive night cooling significantly. The UHI effect not only influences the energy demand for air conditioning, but has also a large impact on the thermal comfort and health of the people living in urban areas.

Knowledge of the detailed urban microclimate is important for a wide number of applications. For example to get accurate results for building energy simulations, accurate microclimatic data at the building site are needed. Also city planners need finely resolved climatic data to improve the thermal comfort in existing urban areas or for planning new urban areas with high thermal comfort. For most cities the available climatic data are limited to very few measurement points. Besides local measurements, numerical simulations can be used to predict and study the local microclimate at the neighbourhood scale. Numerical simulations have the advantage that different building configurations can be evaluated to improve the local microclimate. Therefore results from numerical simulations can help city planners to decide on parameters like the building density or building geometries etc. for new urban areas. In the literature the local urban microclimate is numerically studied with different degrees of complexity. For different scales different numerical models have to be applied. In a large number of studies ENVI-met (Bruse and Fleer, 1998) is used to simulate the urban microclimate. ENVI-met is a model including the simulation of flows around buildings, exchange processes of heat and vapour,

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turbulence, impact of vegetation, bioclimatology and pollutant dispersion (Bruse and Fleer, 1998). Typical spatial resolutions are 0.5–10 m in space and 10 s in time. For the flow the 3D Navier–Stokes equations are solved with a k–ε turbulence model. The spatial resolution is relatively low; therefore no boundary layer is resolved at the surfaces, which makes it impossible to determine the wall heat fluxes at building façades from the flow simulations. Instead correlations of convective heat transfer coefficients are used. Alternatively also wall functions can be used to model the boundary layer, but are not implemented in ENVI-met. For the radiation a simplified model is used that describes how much the incoming radiation is reduced by buildings and plants. Using this method, Ali-Toudert and Mayer (2006) studied the local microclimate in street canyons for dry and hot climates. The focus was mainly on the aspect ratio and orientation of the street canyons and they found considerable influence of these two parameters on the thermal comfort inside the street canyons. Perini and Magliocco (2014) studied with ENVI-met the effect of vegetation on the thermal comfort in densely built urban areas. They show that with vegetation on ground and roofs, the air temperatures in summer can be reduced, the thermal comfort can be improved and energy for air conditioning can be saved. Taleghani et al. (2014) compared the local microclimate for different urban morphologies. This study shows that mainly shadowing is important for improving the thermal comfort. Orehounig et al. (2014) studied the effects of future climate change, building and vegetation configurations for a new urban development project in the city of Vienna using meso-scale weather models, ENVI-met and building energy simulation (BES). In conclusion these works show that ENVI-met can solve a wide number of physical phenomena numerically and can be applied to different urban configurations. However, to be able to solve all these phenomena, simplified numerical models have to be used and the spatial resolution has to be rather low. Therefore the accuracy is lower compared to other numerical models, which use more advanced numerical models and have higher spatial resolution, but need more computational power or can only solve for a smaller number of physical phenomena.

MITRAS (Schlünzen et al., 2003) is a microclimate model that was developed to study the local microclimate in urban areas. MITRAS is based on a mesoscale model, but is able to resolve obstacles. In addition to wind, temperature, humidity and tracer concentrations also equations for cloud- and rainwater and for chemical reactions are solved. Bohnenstengel et al. (2004) conducted simulations with MITRAS to study the influence of thermal effects on street canyon circulations. They found that the large scale thermal stability has a strong influence on the circulation inside the street canyon. Schlünzen et al. (2011) showed how MITRAS can be coupled with mesoscale models to account for the large-scale phenomena in microclimate simulations and the influence of obstacles on the mesoscale simulations. Also MITRAS has a rather low typical spatial resolution of a few metres (e.g. 4 m in the study of Bohnenstengel et al. (2004) or 2.5 m in the study of Grawe et al. (2013)).

The advantage of conducting more detailed computational fluid dynamics (CFD) simulations (e.g. STAR-CCM, OpenFOAM, ANSYS Fluent) is that the domain can be resolved with a much higher spatial resolution and the more accurate models can be used; however the computational costs are increased. To determine accurately the convective heat transfer at the building façades, Saneinejad et al. (2012) conducted CFD (computational fluid dynamics) simulations coupled with a detailed radiation model and heat and moisture transport model for porous media for a two-dimensional urban street canyon. With this more complex approach, more detailed and accurate results can be obtained compared to the more simplified models (e.g. ENVI-met), but also more computational power is needed. Studies with a similar approach have been conducted to investigate the influence of the local microclimate on the space cooling demand of buildings in urban areas (e.g. Allegrini et al., 2012a; Bouyer et al., 2011). Toparlar et al. (2014) conducted a case study for an urban area in Rotterdam, where they used a commercial CFD code (ANSYS Fluent) to study the urban microclimate considering the wind flow and the radiative heat fluxes. A similar study was conducted by Santiago et al. (2014), who used CFD to simulate the wind flow and their own numerical model to determine the radiative heat transfer. Tominaga (2012) evaluated the 'breathability' of urban areas with CFD. The urban areas consisted of buildings with square footprints and different building heights. The results show high variability of the local air temperature and wind speeds depending on the heights of the individual buildings. CFD is not only used for studies at the neighbourhood scale; CFD with low spatial resolution is also used at city scale (e.g. Mochida et al., 1997; Ashie and Kono, 2011).

In this paper an approach (similar to the approach of Santiago et al. 2014) to simulate the local microclimate by coupling BES with CFD simulation is applied. CFD simulations are conducted to get accurate microclimatic results with high spatial resolution. Mainly two aspects are studied in this paper: (a) building surface temperatures and (b) outdoor air temperatures. The surface temperatures are important for the thermal performance of the buildings and for the thermal comfort of the pedestrians, the air temperatures are also important for the thermal comfort of the pedestrians as well as for the ventilation of the buildings. Compared to Tominaga (2012), who imposed the same temperature for all the building surfaces, here the building surface temperatures are different and simulated with a BES model. Simulations are conducted for different generic urban morphologies.

The structure of the paper is as follows. The different urban morphologies and the configuration of the buildings studied are given in Section 2. In Section 3 the numerical models of BES and CFD are presented. In Section 4 the simulation results are presented. Firstly the surface temperatures determined with BES for the different morphologies are compared. Then results of CFD simulations are presented for weather conditions for two different wind speeds leading to high surface temperatures. Finally the air temperatures determined with CFD are analysed. In Section 5 the obtained results are discussed and in Section 6 the conclusions are drawn.

2. Numerical model

The simulations presented in this paper are conducted for 6 different urban morphologies (Fig. 1) for the climate of Zürich (Switzerland). Five morphologies are typical for Swiss cities and one morphology is more generic (bottom left in Fig. 1). The number of buildings for each morphology is limited by the computational power that is needed for the CFD simulations. All buildings are modelled as office buildings with corresponding occupancies and internal gains (SIA, 2006). Ventilation and infiltration are considered

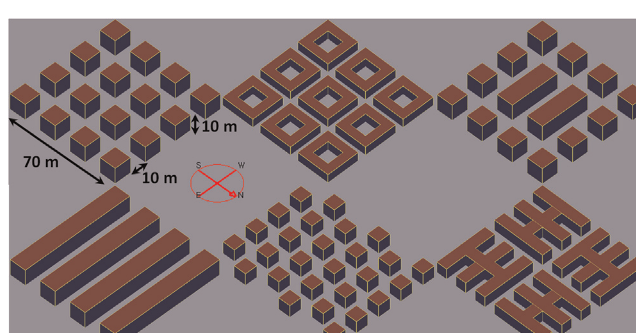

Fig. 1. : The layout and orientation of the urban morphologies under investigation.