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STREET-LEVEL MODELLING OF THE EFFECT OF CLIMATE ADAPTATION MEASURES ON AIR QUALITY

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Abstract: Cities play an important role regarding potential climate change impacts. Urban areas are often vulnerable and poorly prepared to respond to climate change impacts, such as heat waves. Within UrbanAdapt project we aim to perform high-resolution street-level modelling to evaluate different adaptation measures which are orientated to lower the temperature in the streets during hot summer days. The heterogeneity of urbanized land surface leads to a need for a very fine resolution when modelling air flows and temperature near to the surface. We have chosen the atmospheric model PALM as a tool for our simulations. PALM is a LES model which includes parametrizations of many atmospheric processes (e.g. land surface, plant canopy, solar radiation and convective processes) and also enables to involve pollutant dispersion. On the other hand, the parametrization of building surface energy balance is not included in the model. To account for the realistic implementation of urban canopy processes in complex urban geometry we enhanced PALM model including some of the most important urban canopy mechanisms. In order to evaluate the new module, we performed a field experiment, during which temperature of building facades and road surface on Prague crossroad were measured with infrared camera, during a summer heat wave episode. Newly developed module will be used to estimate the effects of different adaptation measures (planting tree alleys, changing wall paint colors), on air quality and thermal comfort of city inhabitants.

Key words: *Large Eddy Simulation, micro-scale modelling, climate change adaptation measures*

INTRODUCTION

Highly populated cities can be significantly affected by the climate change impacts. We expect that as a result of climate change, extreme events such as heat waves, droughts or floods will become more frequent. Nevertheless urban areas are often vulnerable and poorly prepared to respond to such episodes – particularly the extreme temperatures waves are even more pronounced in cities due to the effect of urban heat island (UHI). The project UrbanAdapt aims to start the process of preparation of cities adaptation strategies, develop adaptation scenarios and test their effects and benefits in the three pilot cities in the Czech Republic. The goal of our group in scope of the UrbanAdapt project is to perform modelling on street-level scale, assess suitable adaptation measures and evaluate their impact on thermal comfort of inhabitants and air pollution.

Urban surfaces pose a serious challenge for weather and climate modelling with the current generation of numerical models. Several approaches can be applied from purely statistical to highly complex dynamical models, each with its own advantages and disadvantages (eg. Mirzaei and Haghighat, 2010). Computational fluid dynamics (CFD) models are numerical models computing fluid flows and the interaction with surfaces. For larger scale applications their subclass, Large Eddy Simulations (LES) models, are usually applied. These use an explicit solution of the dynamic equations limited to a certain resolution combined with a parameterization of sub-scale processes. Based on preliminary testing, we have chosen LES model PALM (Raasch and Schröter, 2001; Maronga et al., 2015) for our application.

METHODOLOGY

PALM model

Developed primarily at Leibniz University in Hannover in cooperation with other institutes, the PALM model is a LES model focused on atmospheric modelling. Besides the general LES routines, it incorporates several meteorological modules dealing with processes such as radiation, atmosphere-land surface interaction, humidity and clouds or plant canopy. The model can be used in parallel mode thus allowing it to be run on clusters and supercomputers scaling up to tens of thousands of cores. One of the limitations of the current PALM model for the simulations of urban canopy processes is the fact that in the radiation model, land-surface scheme and plant canopy model, only flat topography is implemented. These modules are however crucial for our application and it was necessary to extend the model with urban surface model (USM) to account for complex urban geometry. The module is designed from scratch but it tries to conform to PALM design and utilizes some approaches of the original PALM land surface model. The calculation of the aerodynamic resistance for walls has been inspired by the approach used in the TUF-3D model (Krayenhoff and Voogt, 2007).

Urban surface model

The urban surface model extension of the PALM model consists of these submodules:

1. Physical properties of real urban surfaces (ground, walls and roofs) as well as virtual surfaces (top and lateral boundaries of the urban layer). The crucial challenge of this part is an effective and scalable design of the computation and data storage parallelization.
2. Calculation of *shape view factors* (SVF) and *plant canopy sink factors* (PSF). SVFs define the portion of reflected and radiated energy from one surface received by other surface. PSFs define the portion of energy absorbed by vegetation present in the gridbox.
3. Radiation model of urban surfaces. At the top boundary, USM receives radiation from the standard PALM radiation module and adds a description of radiation processes in the urban canopy layer where multiple reflections are considered.
4. Absorption of radiation by vegetation (trees and shrubs). The portion of radiative energy absorbed by vegetation in a gridbox is calculated. This produces a heat flux from the vegetation.
5. Energy balance of the *surface skin layer*. Energy balance equation is expressed in the standard form

$$C_0 \frac{dT_0}{dt} = R_n - H - G \ , \tag{1}$$

   where C_0 is the heat capacity of the surface skin layer, T_0 is the temperature at surface, R_n is the net radiation, H is the heat transfer between the surface layer and the air and G is the heat transfer between surface and the material of soil, wall or roof.

6. Heat transfer between surface and material. The transfer is calculated from temperature gradient and heat conductivity between land surface and air.
7. Heat transfer between surface layer and air. Heat transfer H is calculated based on aerodynamic resistence coefficient. This coefficient is parameterized according to Krayenhoff and Voogt (2007) for vertical surfaces (walls) while for horizontal surfaces it follows the approach used in the original LSM module of the PALM model.
8. Anthropogenic heat from transportation is modelled with real spatial distribution and daily profile of car density. The heat is incorporated into the surface heat flow.
9. Boundary conditions for the atmospheric component are cyclic at the lateral boundary. Large-scale wind, pressure and temperature are prescribed in configuration for idealized simulations while they are derived from simulations provided by the meso-scale model (WRF) for real case simulations.

TEST CASE

The implementation of urban surface module was tested both in idealized and real test cases. For real test case we chose an intersection of streets in Prague, Dělnická and Komunardů (Figure 1). For this purpose we prepared an extensive database of geospatial data and surface parameters. This database includes building heights to describe the domain topography, different surface and material parameters and also the position, height and leaf area density of existing trees.

Figure 1. Test case domain. Left: area of interest - intersection of streets Dělnická and Komunardů in Prague (source: IPR Prague). Right: 3D view of the modelled area (source: Google Earth).

The test case domain covered the horizontal area of c. 375 m x 225 m with vertical extent of 187 m; spatial resolution was 2 m x 2 m x 2 m. The time span of our simulation was 24 hours.

To collect data for the verification of our urban surface module we carried out an onsite measurement campaign where we measured the surface temperatures of walls and ground on the Dělnická and Komunardů intersection using the infrared (IR) camera. This measurements took place from July 2, 2015 15h CET to July 3, 2015 18h CET during the hot sunny day (maximum air temperatues were c. 33 °C). Example images taken during this campaign are in Figure 2.

Figure 2. Onsite measurement campaign. Left: east facing wall in visible spectrum with reference points. Right: east facing wall in infrared spectrum (8:11 CET).

We compared the results from the measurements to the model results. Figure 3 shows the comparison for the east facing wall (the same as in Figure 2). The agreement is good - the model is able to predict the maximum and minimum temperatures as well as time behaviour reasonably well.

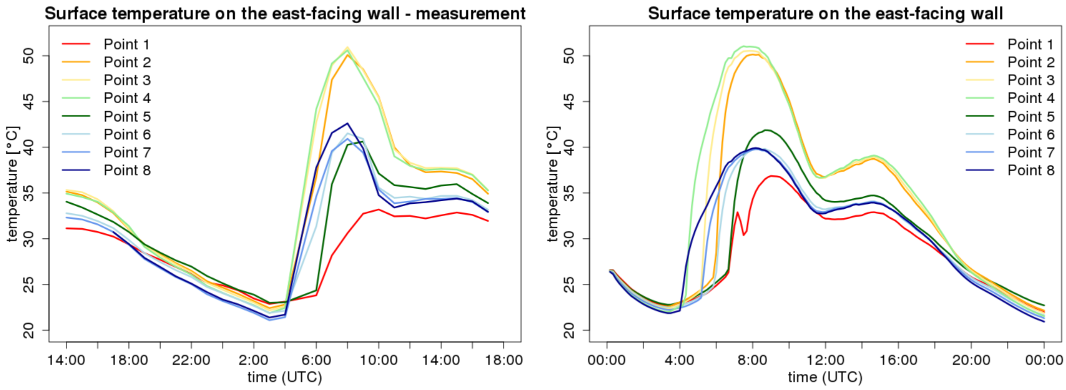

Figure 3. The comparison of the surface temperatures of east facing wall from measurement (left) and model (right). For coloring scheme of reference points see Figure 2.

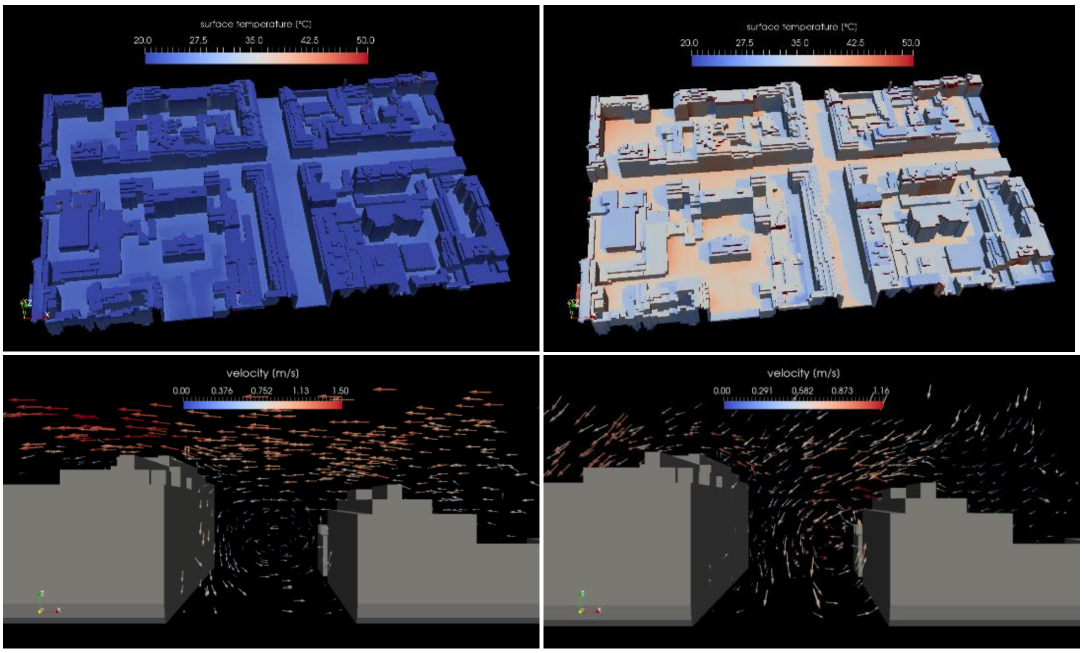

Figure 4. The comparison of surface temperatures (upper row) and flow field (bottom row) in two time instants - 23:00 CET (left column) and 7:30 CET (right column).

Figure 4 shows the dependency of the flow in the street on sun radiation. We chose two time instants - in the evening when the temperature gradients of walls are only mild contrary to the situation at the morning where the east wall is irradiated by sun. In the evening we can observe typical street flow pattern with one eddy (bottom left). On the other hand when the east wall heats up it influences the flow pattern in the street and two independent eddies are created. This is important observation as it shows the importance of correct implementation of urban surfaces as they can considerably influence the flow character and thus have impact on air pollution dispersion in the street.

CONCLUSIONS

We have developed a new urban surface model and incorporated it into LES model PALM. The model has been tested against IR camera measurements with reasonable agreement. Our current work covers the evaluation of different mitigation scenarios and estimation of their impact on thermal comfort of the inhabitants by means of mean radiant temperature. The scenarios include changes of urban surfaces (material of walls, replacement of ground asphalt with pavement), different scenarios of tree alleys (different tree species and locations) and other urbanistic changes (development plans). Further we will perform air quality simulations to assess the dispersion from local traffic sources under the conditions of assumed scenarios.

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