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Coupling of numerical weather prediction models and physical simulations for urban wind environment

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1. Introduction

Urbanization is an ongoing process which has a profound influence on weather and climate on earth. Cities impact weather and climate in variety of ways. For example, heat islands above cities have an impact not only on urban micro-climate in cities, but on climate of the whole region in which the cities are located (for an overview of the subject see, e.g. Oke, 1992; Arnfield, 2003; Mills, 2014). At the same time, cities are large sources of pollution and greenhouse gases (e.g. Janhäll, 2015). Urban environments are also rough surfaces that behave as irregularly shaped and spaced obstacles to the incoming wind, thus impacting micro- and meso-scale features of the wind filed. As a result of all these and many other meteorological factors (Mills, 2014), the planetary boundary layer (PBL) above cities – named Urban Boundary Layer (UBL) – is significantly different from the PBL above rural areas (Oke, 1992). The influence of urban environments on weather and climate is only set to increase (IPCC, 2013). The studies on urban weather and climate are carried out utilizing one, or combination, of the following techniques: in-situ measurements, numerical modeling, and wind tunnel experiments. In this paper, we are focused on discussion of a possibility to couple a numerical weather prediction (NWP) model with a state-of-the-art wind tunnel facility to investigate the structure of the wind filed in an urban environment.

There are three ways to perform the parametrization of the urban environments in the NWP models: (1) to vary the surface parameters in NWP model – slab models, (2) to couple an urban canopy layer model with NWP model, and (3) to couple microscale CFD model with NWP model. Slab models treat the urban environments as a flat terrain with a larger roughness length and smaller albedo compared to the rural areas. The urban canopy models can be divided into two groups: single-layer (Masson, 2000; Kusaka *et al.*, 2001) and multi-layer urban canopy models (Coceal and Belcher, 2004; Sabatino *et al.*, 2008). In the single-layer urban canopy models, the urban geometry and all the physical processes that take place in the urban canopy layer are constrained within the first layer of the NWP model. Unlike the slab models, the single-layer urban canopy models can account for the interaction between the solar radiation and the urban geometry, as well as for the existence of an exponential wind profile inside the urban canopy layer (Romanić *et al.*, 2015). The multi-layer urban canopy models, being the most sophisticated models for parameterization of the urban environments, take into consideration the vertical distribution of the sources and sinks of momentum, heat (and moisture) within the urban canopy layer. Thus, the multi-layer urban canopy models interact with several NWP model levels. Yet another approach to investigate and parameterize the urban environments is to couple the NWP model with a CFD model (Zajaczkowski *et al.*, 2011; Tewari *et al.*, 2010). In this approach, the NWP model outputs in the form of velocity, turbulence (and sometimes temperature) profiles are used as the inputs for the CFD models. The CFD models are then used to resolve the flow and heat distribution in the urban environments in great detail. Afterwards, the CFD results can be fed in the NWP model as surface boundary conditions.

In this study, we propose another approach for the investigation of the urban boundary layer. Namely, instead of coupling the NWP and CFD models, the NWP models could be coupled with physical simulators. A 3D physical model of an urban environment can be placed inside of the new generation of large multi-fan wind tunnels or 3D and time-dependent testing chambers such as the WindEEE Dome at the Western University. Then, the incidence wind and turbulence profiles (i.e. profiles at the edge of the urban environment) determined by NWP modelling can be physically modeled as inflow boundary conditions. The advantage of the physical micro-scale modeling resides in their demonstrated capacity to simulate a large spectra of flow scales from the top of the urban layer to the level of the detailed flow patterns around buildings and structure. For instance, for wind engineering problems the physical (wind tunnel) simulators are preferred as they can model peak values of both flow and surface pressures which are essential for determining design loads. Pollution dispersion, pedestrian comfort and any other urban wind environment studies also benefit from the same capacity of reproducing a large spectra of scales.

This paper is organized as follows. Set up of the NWP model used in this study is presented in Section 2. A detailed description of the WindEEE Dome is given in Section 3. Section 4 contains a discussion on the coupling of the NWP model with the WindEEE Dome.

2. WRF – ARW model

2.1. Model setup

The NWP model used in this study is the Weather Research and Forecasting (WRF) – Advanced Research WRF (ARW) model (Skamarock *et al.*, 2008). The ARW core solves fully compressible, Euler nonhydrostatic equations on the Arakawa C-grid in the horizontal direction and on a terrain-following hydrostatic pressure coordinate in the vertical direction. The governing equations in their perturbation form solved by the ARW core are (Skamarock *et al.*, 2008): (1) the momentum equations, (2) the mass conversation equation, (3) the geopotential height equation, (4) the equation for the potential temperature, (5) the equation for conversation of scalars, and (6) the equation of state.

The day of simulation is 21 July 2014 and the simulation starts at midnight and lasts for 1 day. The model was centered for the city of Cacak (Čačak; LAT 43.8833°N, LON 20.3500°E), in Serbia. Cacak is a city located in the west-central part of Serbia and lies on the second largest river in Serbia (Zapadna Morava River). According to the 2011 census (Statistical Office of Republic of Serbia, 2014), the town had 73,331 people in 2011. The city is located some 144 km south of Belgrade (capital of Serbia). Cacak has humid cold continental climate with warm summers and cold winters (Peel *et al.*, 2007).

The nested run of the model had four computational domains with the parent-to-child grid ration of 3:1 and activated feedbacks between the child and parent domains. The horizontal resolution of the coarsest grid was 27 km, while the resolution of the finest grid was set to be 1 km. The integration time step was 180 s with 30 min between the calls for the radiation physics.

The physical package of the model includes: WSM3 scheme for microphysics (Hong *et al.*, 2004), RRTM longwave radiation scheme (Mlawer *et al.*, 1997), MM5 shortwave scheme (Dudhia, 1989), Monin-Obukhov parametrization of the surface layer with Carlson-Boland viscous sublayer (Paulson, 1970; Dyer and Hicks, 1970; Webb, 1970), Noah land surface model (jointly developed by NCAR and NCEP and based on Chen and Dudhia (2001)), Yonsei University planetary boundary layer physics scheme (Hong *et al.*, 2006), and Kain-Fritsch scheme for cumulus parametrization (Kain, 2004). The dynamics of the model uses the 3rd order Runge-Kutta time integration scheme with the second order diffusion terms evaluated on coordinate surfaces and the horizontal Smagorinski first order closure for vertical diffusion.

2.2 Results

The results of the model runs in the form of wind speed profiles are given for 6-hour intervals (00 h, 06 h, 12 h, 18 h), as portrayed in Figure 1.

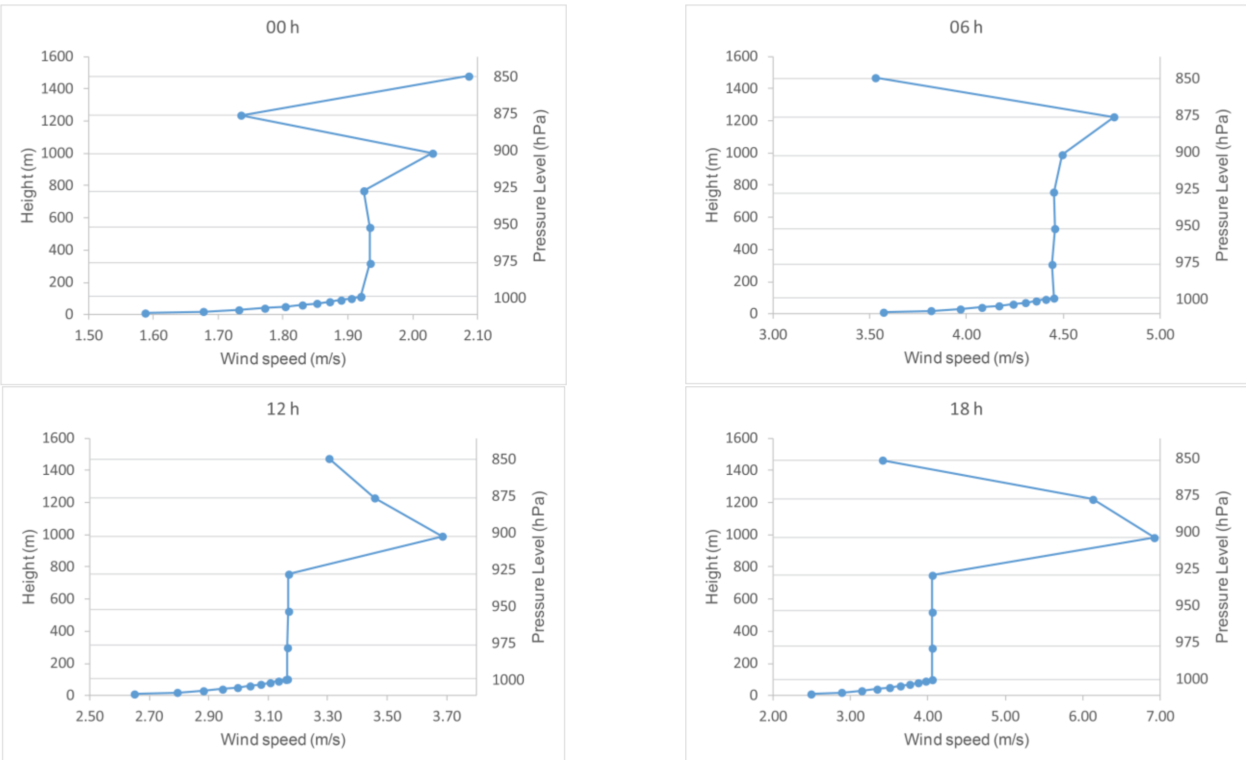

Fig. 1 Vertical profiles of wind speed for the city of Cacak (in Serbia) for 21 July 2014 based on the WRF-ARW simulation. The profiles are given at 6-hour intervals. See text for further details.

It is important to mention that the raw model outputs are in the form of zonal and meridional wind components and are given at the pressure levels indicated on the secondary *y*-axis in Figure 1. The wind components are then converted to wind speed and the geometric height of the pressure levels is calculated from their geopotential values. Wind speed at 10 m above ground (a.g.) is also calculated from the model outputs. In the last step, knowing the wind speed at 10 m a.g. and wind speed at the first pressure level (1000 hPa) that is usually around 100 m a.g., the interpolation of wind speeds for the heights between 10 m a.g. and the first pressure level is calculated at 10-m increments using the power law equation. The power law exponent in the power law equation is obtained from the wind speed at 10 m a.g. and the wind speed at the 1000 hPa pressure level. The wind profiles in Figure 1 depict several important features.

First, a typical diurnal variation of the mean wind speed inside the PBL is observed. Namely, the 10-m wind speed increases sharply after sunrise when convection in the atmosphere kicks in. After the sunset, the inversion in the surface sublayer is destroyed and the unstable PBL that develops in the morning is efficient at transferring the momentum from the higher levels to the surface layer, resulting in the observed wind speed increase. Second, a large geostrophic wind sheer is present at the top of the PBL (situated around 1000 m a.g.). However, despite this large shear, the fairly constant mean wind speed profile is observed in the mixed layer and strong wind shear in the surface sublayer. The constant wind speed in the mixed layer is due to the strong turbulent mixing generated by the convective motion and the Rayleigh–Taylor instability. The high-shear layer at the top of the PBL is usually called the transition layer. The wind profiles in Figure 1 resemble a simple three-layer model for an unstable PBL proposed by Garratt *et al.* (1982) in which the PBL is composed out of the Monin-Obukhov surface layer, mixed layer above it, and a capping transition layer on top of the mixed layer. Third, variability of the height of the PBL is also observed. The transition layer at 00 h was positioned at about 800 m a.g. while the same layer is found at about 1000 m a.g. at 06 h. Layer's height dropped back to 800 m a.g. in the two consecutive terms (12 h and 18 h).

3. Wind Engineering, Energy, Environment (WindEEE) Dome facility

WindEEE is the world's first 3D wind chamber, consisting of a hexagonal test area 25 m in diameter and an outer return dome 40 m in diameter. Mounted on the peripheral walls and on top of the test chamber are a total of 116 individually controlled fans and 202 louver systems. Additional systems, including an active boundary layer floor and "guillotine" allow for further manipulation of the flow. These systems are integrated via a sophisticated control system which allows manipulation of the flow with multiple degrees of freedom. WindEEE can generate straight flows but with a variety of time and space correlations as well as translating tornadoes or downbursts as large as 5 m in diameter. Furthermore, the generated flows can be straight, sheared or swirl winds of variable directionality. Therefore, a large variety of wind fields such as boundary layers, portions of hurricanes, tornados, downbursts, low level currents or gust fronts can be physically simulated. An active topographic capability enables a wide diversity of surface topographies at unprecedented scales allowing wind simulations over areas of the order of 10 km^2. The same system will be used to locally seed for the Particle Image Velocimetry (PIV) system that can measure the wind field over extended areas. A traverse mechanism will allow for a LASER head to traverse the flow in a multitude of vertical and horizontal sections in order to produce PIV wind field measurements with a full scale equivalent resolution of 10 m. In addition, measurement tools at WindEEE also include: Pitot tubes with the Pressure Scanner System, Cobra Probes that provide three-component velocity and local pressure as well as the hot-wire anemometers

These flow and measurement capabilities coupled with large scale detailed urban orography models and the capacity of NWP models to predict inflow conditions opens a new avenue in mixed simulation of urban wind environments.

4. Coupling methodology

The resolution of the NWP models is too coarse to represent small scale features on the surface such as individual buildings (even the whole city blocks), solar panels, wind turbines, small hills, etc. For that reason, the wind profiles from the NWP models can be simply interpolated from the models' grid points to find the incidence wind profiles at the point of interest. However, this purely mathematical procedure does not posses any physical information in the background and thus the interpolated incidence wind profiles do not, on general, resemble the reality. Another approach, as mentioned in Introduction, is to import the wind profiles, for instance from Figure 1, into a CFD model and perform a local-scale CFD simulation in order to obtain a 3D wind filed at the point of interest. The CFD models can be a powerful tool, however, as any numerical model, the results always contain some degree of error (Franke *et al.*, 2004). For instance, peak (gust) wind values obtained by CFD models are known to be unreliable and wind tunnel physical experiments are better option. Wind tunnels, on the hand, also have several limitations. For example, range of Reynolds numbers possible to reproduce in most wind tunnels is several order of magnitude below the value of the Reynolds number found in the real PBL (which is approximately 10^8 to 10^9). Furthermore, the straight flow wind tunnels are not capable to replicate the whole Ekman spiral that is typical for the PBL in the atmosphere. Namely, the straight flow wind tunnels cannot account for the vertical wind direction profile.

The WindEEE Dome, however, is not an ordinary wind tunnel. Its novel design enables it to overcome most of the restrictions related to the straight flow wind tunnels (Hangan, 2010). Therefore, we argue that a coupling between the NWP models, on one side, and the WindEEE Dome, on the other side, is a promising methodology for investigation of wind fields and wind flow characteristics on the local scales. The methodology can be described as follows. A NWP model with nesting can be used to obtain the wind speed profiles for the area of interest. The computational domain should have 3-5 nested domains and the finest domain should have the horizontal resolution of the order of few km (1-5 km). The WRF-ARW model, for instance, gives reliable results at these resolutions; the operational resolutions of the model at NCEP and NOAA/NSSL are 5.8 km and 4 km, respectively. The NWP’s wind speed profiles can than be reconstructed as the initial and boundary conditions inside the WindEEE Dome for the physical simulation of interactions between wind and building(s), urban environments (e.g. city blocks), solar farms, wind farms, hills, etc. This methodology offers several benefits compared to the NWP – CFD or NWP – straight flow wind tunnel couplings.

The turn table located in the center of the WindEEE Dome enables the rotation of the physical model and thus the simulation of the different incidence wind directions. The same analysis is very cumbersome in CFD models since simulations of different wind directions require generation of new meshes for each of the directions. A high-resolution CFD analysis are, furthermore, computationally costly (the computational time necessary to finish the simulation can easily take few weeks or more). Moreover, the peak wind or pressure coefficient values obtained by CFD models are often unreliable compared to the results obtained in the physical micro-scale modeling in WindEEE Dome. Straight flow wind tunnels, on the other hand, are not capable to reproduce complex wind profiles as depicted in Figure 1. The wind speed shears observed at the top of the surface sublayer and at the top of the PBL (see Figure 1) can hardly be simultaneously simulated in the straight flow wind tunnels. However, multiple fans at the WindEEE Dome’s 60-fan wall can simulate multiple shear zones within the flow. The wind direction profiles are also not possible to simulate in the straight flow wind tunnels. The hexagonal structure of WindEEE Dome complemented with individually controlled fans on the walls of the test chamber can be used to reconstruct the full Ekman spiral inside the PBL.

The coupling of NWP with WindEEE Dome is a promising methodology for wind engineering, energy, andenvironment studies, as well as for the micrometeorological studies of the PBL. The first experiments based on this methodology are set to be performed inside the WindEEE Dome and the results will be presented in the literature.

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