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Multi-scale modeling of the urban meteorology: Integration of a new canopy model in the WRF model

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ABSTRACT

Urban parametrizations have been recently developed and integrated in mesoscale meteorological models for a better reproduction of urban heat islands and to compute building energy consumption. The objective of the present study is to evaluate the value of the use of a module able to produce highly resolved vertical profiles of these variables. For this purpose, the Canopy Interface Model (CIM) was integrated as an additional urban physics option in the Weather Research and Forecasting model. The coupling method is here detailed and its evaluation is done using a reference run based on a fine resolution WRF simulation. In order to keep both the CIM and the mesoscale model coherent, an additional term is added to the calculation of the CIM. Finally, the BUBBLE dataset is used to validate the simulation of the profiles from CIM. It is demonstrated that the proposed coupling improves the simulations of the variables in an urban grid and that the WRF + CIM + BEP-BEM system can provide highly resolved vertical profiles while at the same time improving significantly computational time. The data from these preliminary results are very promising as it provides the foundation for the CIM to act as an interface between mesoscale and microscale models.

1. Introduction

Meteorological mesoscale models were initially dedicated to weather forecasting without the need to detail interactions between urban areas and the atmosphere (Salamanca et al., 2011; Ching, 2013). In the last few years, urban parametrizations have been integrated in these mesoscale models to also simulate urban heat islands (UHI) (Masson, 2000; Kusaka et al., 2001; Martilli et al., 2002; Kanda et al., 2005; Liu et al., 2006; Kusaka and Kimura, 2004; Sarkar and De Ridder, 2011), building energy consumption (Krpo et al., 2010) and air pollution at the urban scale (Salamanca et al., 2011). Different schemes have been developed in recent years with the underlying purpose of developing systems that could help urban planners make decisions and propose sustainable urban planning scenarios to decrease UHI, building energy demand, or urban air pollution. Baklanov et al. (2009) gave a guideline for the level of complexity that is needed for urban canopy parametrizations based on the "fitness for purpose". For air quality, urban climatology, strategies to mitigate UHI and urban planning, it is necessary to have more detailed and precise meteorological vertical profiles and fluxes.

It is now well known that the urban climate depends on a series of processes taking place at different spatial (from global to local) and temporal scales (Oke, 1982), and that building energy demand and urban climate are closely related and interdependent (Ashie

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et al., 1999; Kikegawa et al., 2003; Salamanca et al., 2011). However using mesoscale meteorological models, with a high vertical resolution, to cover a whole urban area and resolving at the same time local building effects and UHI is still not feasible with actual computer performances (Martilli, 2007). Moreover the use of available microscale models (such as Envimet (Bruse and Fleer, 1998), CitySim (Robinson, 2012) or EnergyPlus (Crawley et al., 2008)) on more than a neighborhood (few streets) is also not feasible. Thus multi-scale modeling is often suggested and used as a solution.

Garuma (2017) has recently reviewed urban surface parameterizations. Models developed by Masson (2000) or Kusaka and Kimura (2004), have been integrated in mesoscale models. However since they are single-layered models they do not calculate high resolution vertical profiles in the urban canopy. Using the same method as Martilli et al. (2002); Kondo et al. (2005), who used a multi-layer model, Muller (2007) designed experiments to show that a canopy module can be used for an enhanced coupling with mesoscale models while at the same time reducing the computational cost. However in their work, the canopy model developed by Muller (2007) was not totally independent of the mesoscale model and hence cannot be easily introduced in another model. Furthermore, the canopy model resolves flow in the vertical direction and hence is neglecting the horizontal advection that is considered in a mesoscale model. Inconsistencies will thus arise between computations done with a multi-layer microscale model such as BEP-BEM and a mesoscale model. One way to ensure coherence in regional climate models, is to use nudging techniques to reduce errors between the driving field and the simulated field (Pohl, 2014; Omrani et al., 2015).

The Canopy Interface Model (CIM) that was recently developed and tested in an offline mode (Mauree, 2014; Mauree et al., 2015, 2017a) is here introduced in the Weather Research and Forecasting (WRF) community research model v3.5 (Skamarock et al., 2005, 2008). The objective is to build a multi-scale urban meteorological system that is able to produce highly resolved vertical profiles of meteorological variables in low-resolution mesoscale meteorological models. Additionally, the CIM can resolve the flow in two directions in the urban canopy. These profiles could thus be used to improve the computation of surface fluxes of momentum, heat, turbulent kinetic energy and humidity inside the mesoscale model and to allow at the same time for the coupling of a mesoscale model with a microscale model. Such a coupling between the CIM and CitySim, a micro-scale model to evaluate energy fluxes at the neighborhood scale, has recently been implemented (Mauree et al., 2017b, 2017c; Mauree et al., 2018; Perera et al., 2018).

The objective of the present article is to detail the steps followed to set up and evaluate the coupling. In Section 2 a brief description of the governing equations in WRF is given. In Section 3 it will be explained how the CIM has been integrated into WRF in order to keep in coherence both the mesoscale model and the CIM In Section 4 a description of the experiments conducted with WRF is presented. In Section 5 the results from a series of sensitivity tests are presented to evaluate the value of the use of the CIM and the coupling. Finally, the coupled system is ran over the City of Basel and the results from the simulations are compared with observations made during the BUBBLE experiment perfomed in Basel (Rotach et al., 2005). The last section is devoted to the discussions and the conclusions of this study.

2. Weather research and forecasting model

The Advanced Research Weather Research Forceast (WRF) (Skamarock et al., 2005, 2008), version 3.5, developed by the National Center for Atmospheric Research (NCAR) for research purpose, is used in the present study. A broad variety of physics and dynamics options have been defined by the scientific community. Only a brief description of the conservation equations and the physics options that are used to simulate the surface layer is given here. The objective of this section is mainly to help understand the coupling of the CIM with WRF, which will be fully described in Section 3.

2.1. Governing equations and turbulent closure

Following Ooyama (1990), variables with conservation properties (mass for example) are written with equations in their flux form and using a terrain-following mass vertical coordinate. We here present briefly these equations to prepare the presentation of the coupling with the CIM.

2.1.1. Momentum and heat

The following equation represents the conservation of momentum or heat.

$$\partial_t N + (\nabla . \overrightarrow{F_N})_\eta = F_N^s, \tag{1}$$

where N is the momentum for the x-, y- or z-directions or the heat and ${F_N}^s$ is the source or sink terms from the surface. The second term on the left hand side of the equation is a flux divergence term which represents the advection, the pressure-gradient and the diffusion terms. The latter is a function of the diffusion coefficients, $K_{h,\ v}$ which is described later. The $\nabla . \overrightarrow{F_N}$ term depends the eta (η) levels and the latter can be computed using:

$$\eta = \frac{(p_h - p_{ht})}{\alpha}, \tag{2}$$

where p_h is the hydrostatic pressure at this height and p_{ht} is the pressure at the top boundary. α is the mass per unit area within the column in the domain and is calculated as $\alpha = p_{hs} - p_{ht}$ where p_{hs} is the pressure at the surface.