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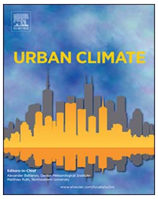

Evaluation of the QUIC-URB wind solver and QESRadiant radiation-transfer model using a dense array of urban meteorological observations

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ABSTRACT

This study assesses the performance of QUIC-URB, a fast-response urban flow model, and QESRadiant, a ray tracing radiation transfer model. Both models are components of the QUIC EnvSim 3D urban micro-scale model, which aims to simulate meteorological variables at high spatiotemporal resolution (~1 min, ~1 m) in urban settings. The evaluation was performed over a 5.85 ha sector of a university campus, in which complex 3D building geometry, vegetation, and various surface materials were modelled. First, wind speeds computed with QUIC-URB were compared to 30-min measurements over 10 days at 19 locations. Although results showed a significant underestimation for locations in the wake of buildings, considering model assumptions, its inexpensive computational cost, and measurement uncertainty, the agreement between computed and measured wind speeds is good ($r^2 = 0.53$, mean absolute error = 0.68 m s^{-1}). Second, incoming radiation computed with QESRadiant was compared to 2-min measurements over seven clear sky days at 17 locations. Overall, the agreement between computed and measured incoming solar radiation was excellent ($r^2 = 0.95$). For both models, simulations were run successfully on a standard laptop machine with highly reasonable computational cost, on the order of minutes.

1. Introduction

Urban climate models are valuable tools in practical applications such as air quality control, building energy efficiency analyses, and urban planning. Recently developed models tend to be more complex, at the expense of larger computational costs (Antonioni et al., 2012; Arnfield, 2003; Mirzaei, 2015; Wegener, 2011). Such models can broadly be categorized into three groups based on their spatial scale of interest (Mirzaei, 2015):

- *Building-scale models* focus on isolated buildings and can be utilized to control indoor air quality and thermal comfort (e.g., Crawley et al., 2001; Salamanca et al., 2010);
- *Micro-scale models* operate at the neighbourhood scale and are used among others in urban planning and pedestrian thermal

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comfort studies (e.g., Blocken et al., 2016; Taleghani et al., 2015);

- *City-scale models*, characterized by a coarse resolution, are used among others in the evaluation of urban-scale policies to mitigate urban heat islands (e.g., Leroyer et al., 2011; Yang et al., 2013).

Of the three, micro-scale models appear the most suitable given that they incorporate interactions between the urban surface and the flow while still being able to resolve buildings. Most existing micro-scale models use a computational fluid dynamics (CFD) approach, either by solving Reynolds-averaged Navier-Stokes (RANS) equations (e.g., ENVI-Met© (Ambrosini et al., 2014; Bruse, 2004; Elnabawi et al., 2013; Huttner and Bruse, 2009; Maggiotto et al., 2014; O'Malley et al., 2015; Ozkeresteci et al., 2003; Taleghani et al., 2015) and SOLENE-Microclimat (Bozonnet et al., 2013; Morille et al., 2015) or with Large-Eddy Simulations (LES; e.g., Antonioni et al., 2012; Neophytou et al., 2011). Although both RANS and LES can provide high resolution and accuracy given their physical bases, the required computation time is significant (particularly in the case of LES). An alternative to traditional CFD modelling is the use of a mass-consistent empirical diagnostic approach, in which flow fields around buildings are first prescribed based on geometry and then forced to satisfy mass conservation. These types of models, such as the Quick Urban and Industrial Complex 3D wind model (QUIC-URB) are known for low computational cost, simple boundary conditions, yet reasonably accurate results (Brown et al., 2010; Gowardhan et al., 2006; Gowardhan et al., 2010; Gowardhan et al., 2011; Hanna et al., 2006; Hanna et al., 2002; Hanna et al., 2011; Kaplan and Dinar, 1996; Pardyjak and Brown, 2001; Singh et al., 2008; Speckart and Pardyjak, 2014; Williams et al., 2004).

Similar to atmospheric flows, radiative exchanges in urban areas are challenging to model given their complexity. Many radiative models follow one of two basic approaches: radiosity or ray-tracing. In radiosity methods (Matzarakis et al., 2010), radiative transfer is computed based on geometrical view factors and the radiation energy balance, while in ray-tracing methods (Halverson, 2012; Overby et al., 2016), rays of energy are tracked as they traverse through the medium of interest. In both cases, the model performance heavily relies on the accuracies of the digital elevation dataset used to build up the surface geometry and of the incoming solar radiation used as a top boundary condition. Due to computational expense, all radiation models must make simplifying assumptions, for instance the exclusion of anisotropic reflections and inter-reflections between surfaces and multi-reflections of a single ray (Freitas et al., 2015). In the same way, only a few models allow for tilted surfaces, distinct vegetation properties, or inhomogeneous building walls. While both types of radiative models are known to perform similarly (Beckers and Beckers, 2013; Gros et al., 2011), ray-tracing methods, like the one used in this study (QESRadiant, see Overby et al., 2016), afford expensive computation by exploiting highly parallel hardware called Graphics Processing Units (GPU).

One common characteristic of urban wind flow solvers and radiation models is that they both suffer from a lack of evaluation studies conducted over realistic urban terrain including trees, complex 3D geometry and various surface materials, mainly because distributed meteorological measurements over such environments are rarely available (Freitas et al., 2015). While most wind solver evaluation studies have been performed using wind-tunnel measurements over idealized geometries (Allegrini et al., 2015; Antonioni et al., 2012; Moonen et al., 2013; Nemati Hayati et al., 2017), fewer have used in situ urban meteorological data *(*Hanna et al., 2011; Neophytou et al., 2011*)*, with little to no consideration for the effect of vegetation on the flow. Similarly, incoming solar evaluation studies have mostly been restricted to a limited number of point measurements (El Mghouchi et al., 2016; Ineichen, 2016) or along a single vertical profile within a given city (Overby et al., 2016).

This study presents an assessment of the performance of the wind flow solver, QUIC-URB, and a radiation-transfer model, QESRadiant, both being components of a micro-scale model in development, QUIC EnvSim (QES), in reproducing observations from a dense array of measurements collected over a university campus. Although these two modules have been previously validated individually (Hanna et al., 2011; Neophytou et al., 2011; Overby et al., 2016; Singh et al., 2008), this study presents the first multi-site evaluation of a realistic urban setting that includes vegetation.

2. Model description

The goal of QES is to simulate energy, moisture and momentum exchanges between the airflow and adjacent urban surfaces (Bailey et al., 2014; Briggs, 2015; Overby et al., 2016). Hence, QES aims to simulate meteorological variables (air temperature, relative humidity, wind speed and direction) at high temporal (~1 min) and spatial resolution (~1 m). QES combines two distinct modelling systems: QUIC and EnvSim. At the moment of this study, those two systems are not fully coupled and have to be run independently. Since our study focuses on QUIC and the submodel QESRadiant of EnvSim, we will not describe the other submodels of EnvSim (the land-surface scheme and QESTransport).

2.1.1. *QUIC*

The Quick Urban and Industrial Complex (QUIC) dispersion modelling system is a fast-response, building-resolving dispersion model initially designed to simulate the dispersion of chemical, biological and radiological agents in urban areas in case of an accidental or deliberate release (Brown et al., 2014; Brown et al., 2010; Gowardhan et al., 2006; Gowardhan et al., 2011; Hanna et al., 2006; Nemati Hayati et al., 2017; Pardyjak and Brown, 2001; Singh et al., 2008). For a detailed description of the model, the reader can refer to Singh et al. (2008). QUIC combines three modules: (1) QUIC-URB, an urban wind model, (2) QUIC-PLUME, a dispersion model and (3) QUIC-Pressure, a pressure solver.

To build the domain geometry, QUIC can extrude buildings and trees from aerial maps to user-specified heights. Complex