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Evaluating a building-averaged urban surface scheme in an operational mesoscale model for flow and dispersion

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HIGHLIGHTS

- A building-averaged urban canyon scheme in a mesoscale model is evaluated.
- This scheme simulates the observed near-neutral to weakly unstable conditions at night.
- In contrast, the original slab scheme predicts weakly stable conditions at night.
- A better representation of the observed dispersion by the building-averaged scheme.
- Computational efficiency of the canyon scheme is on par with the slab scheme.

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ABSTRACT

A recently developed building-averaged urban surface scheme as coupled to an operational mesoscale model, TAPM, is evaluated for both flow and tracer dispersion using data from the 2002 Basel UrBan Boundary Layer Experiment (BUBBLE) conducted in the city of Basel, Switzerland. This scheme is based on the so-called town energy balance (TEB) approach and simulates turbulent fluxes using a generic canyon geometry to resolve energy balances for walls, roads and roofs. Air conditioning to close the building energy budget, in-canyon vegetation, and the effects of recirculation and venting of air within the canyon on turbulent fluxes are included. Comparison is also made with the original urban surface scheme of TAPM based on a simple slab approach with separate urban and vegetation–soil tiles and a specified anthropogenic heat flux. The results show that the new scheme leads to an overall improvement in the prediction of surface fluxes, and is able to reproduce the observed near-neutral to weakly unstable conditions at night, which is a feature of urban meteorology. In contrast, the slab scheme predicts stable conditions at night. The observed concentration fields from the tracer experiments are better simulated using the new scheme, but because there were no nighttime tracer releases, the capability of the new scheme under full diurnal conditions could not be demonstrated. For the applications considered here, the computational efficiency of the new scheme in TAPM is on par with the slab scheme.

1. Introduction

The role of a surface scheme in a mesoscale atmospheric computer model is to describe surface-atmosphere exchanges of momentum, heat and water, which influence the structure and evolution of the atmospheric boundary layer, and consequently dispersion of pollutants and tracers. Naturally, the type of surface considered is a critical parameter governing these exchanges. Urban surfaces have been shown to induce thermal and aerodynamic modifications, such as urban heat island and city-induced circulations (e.g., Oke, 1982; Grimmond and Oke, 1995; Bornstein and Lin, 2000; Martilli, 2003), which have important ramifications for air pollution transport.

The formulation of surface schemes for urban surfaces has traditionally been based on a simple slab approach that describes the urban surface as a concrete layer with modified roughness length and thermal properties (e.g., Oke, 1988). The operational mesoscale model TAPM (Hurley et al., 2005) for meteorological and air quality predictions uses this approach. More recently, schemes with canyon-based representations of the urban canopy have been developed that consider the effects of buildings, roads, other artificial materials used for construction and anthropogenic emissions on the surface energy budget (e.g., Masson, 2000; Martilli et al., 2002).

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Urban canyon schemes can be broadly categorised into single-layer and multi-layer formulations (Masson, 2006). An example of a single-layer scheme is the so-called town energy budget (TEB) approach of Masson (2000), which assumes a generic canyon geometry and separates the energy budget into roofs, roads and walls. All canyons in the domain under consideration are assumed to have the same height and width, are located along identical roads, and are distributed in all directions with the same probability. The two facing walls are treated identically for all processes, except for the direct solar radiation. At a given time step, the canyon orientation effects with respect to the sun or the wind direction are averaged over 360° for roads and walls, which allows the computation of averaged forcing for the road and wall surfaces (instead of resolving the energy exchange for each individual canyon). The approach includes shadowing effects and parameterises the in-canyon exchange of turbulent heat fluxes. The wind, air temperature and humidity profiles within the canyon are specified. Anthropogenic heat fluxes due to domestic heating and combustion are included, and building shapes and construction materials determine parameter values (e.g., emissivity, heat capacity and albedo). When this scheme is coupled to a mesoscale atmospheric model, the surface in the model is located almost at the roof level, the scheme is forced by only the lowest model level lying almost above the roof level, and the model only sees a constant flux layer as its lower boundary. The averaging over all canyon orientations in this scheme results in a computationally efficient formulation because relatively few individual surface energy-balance solutions are required together with simplified radiation interactions. Masson et al. (2002) and Lemonsu et al. (2004) evaluated the TEB scheme in offline mode by driving it with atmospheric data, and Lemonsu and Masson (2002) used it in a mesoscale model and applied it to the Paris area in France.

Multi-layer canyon schemes (e.g., Martilli et al., 2002; Otte et al., 2004; Hamdi and Schayes, 2007) use a drag force approach to account for the vertical effects of buildings. In such a scheme, the lowest level corresponds to the real level of the ground (i.e. the road surface), and the street canyon is vertically partitioned into multiple levels above the ground with a separate energy balance equation solved at each prognostic air level inside the street canyon. Although multi-layer schemes are able to determine profiles of wind, temperature and turbulent statistics within the canyon, their main disadvantage is that the atmospheric model equations for momentum, heat, and turbulent kinetic energy (TKE) are modified and need to be solved for roads, roofs and walls separately, leading to a substantially complex coupling between atmospheric-model levels and the canyon-scheme levels and hence increased computational costs.

There have also been attempts to extend the single-layer TEB scheme to account for the vertical effects of buildings in a simplified manner (e.g., Hamdi and Masson, 2008; Masson and Seity, 2009). Such a scheme incorporates a drag force approach similar to that of Martilli et al. (2002), except that the prognostic air levels inside the street canyon are independent of the atmospheric model that is coupled above at a single forcing level and only one surface energy balance per wall is resolved (rather than at each level inside the canyon).

The single-layer TEB approach provides an efficient and physically realistic platform to incorporate urban surfaces into operational mesoscale models in a simple, averaged manner. It has been shown to accurately reproduce the surface energy budget, canyon air temperature and surface temperatures in urban areas (e.g., Masson et al., 2002; Lemonsu et al., 2004). In this paper, we evaluate a single-layer TEB scheme as modified by Thatcher and Hurley (2012) who coupled it to TAPM. The evaluation is carried out using both flow and tracer dispersion data from the Intensive Observation Period (IOP) of one month of the Basel UrBan Boundary Layer Experiment (BUBBLE) conducted in the city of Basel, Switzerland, in the summer of 2002 (Rotach et al., 2005). The model results are also compared with TAPM's original slab scheme.

Hamdi and Schayes (2007) applied their mesoscale model in a single-column mode to the BUBBLE IOP data, Hamdi and Masson (2008) applied their TEB to these data by running it offline forced by measurements, and Roulet et al. (2005) simulated these data using a multi-layer canyon scheme in a single-column mesoscale model driven by measurements. Rotach et al. (2005) and Batchvarova and Gryning (2006) simulated the BUBBLE tracer dataset using a Lagrangian particle model and the standard Gaussian plume approach, respectively, driven by measurements. To our knowledge, all previous mesoscale model applications to the BUBBLE dataset have not involved canyon schemes coupled to three-dimensional atmospheric models and have not simulated the tracer dispersion experiments.

2. BUBBLE field data

We use data from the IOP, 10 June–10 July 2002, of the BUBBLE experiment (see http://www.mcr.unibas.ch/Projects/BUBBLE). The BUBBLE measurements were made with the objective of studying boundary-layer and surface-exchange processes over different types of surfaces (i.e. urban, sub-urban and rural) and their role in the transport and diffusion of air pollution. Basel is a mid-size town with a built-up area of about 130 km^2 (Rotach et al., 2005). The main urban measurement tower, Basel-Sperrstrasse (Ue1), was 32-m high and located inside a street canyon in an area with dense, fairly homogeneous, residential building blocks, and a mean building height of 14.6 m above ground (or road) level (AGL). Location 3 in Fig. 1 corresponds to the meteorological tower Ue1. In the vicinity of the tower, the building height was 14 m AGL and the street canyon aspect ratio (i.e. height-to-width ratio) was about unity. The surface roughness length was 2.1 m, and the zero-plane displacement height was 9.5 m (Christen and Rotach, 2004). Sonic anemometers were installed at six levels, namely 3.6, 11.3, 14.7, 17.9, 22.4 and 31.7 m AGL.

To study dispersion, sulphur hexafluoride (SF_6) tracer was released at near roof-level at two locations, namely R1 (18.6 m AGL) and R2 (21 m AGL), over four separate days (Rotach et al., 2004; Gryning et al., 2005) (see Table 1 for release conditions and Fig. 1 for locations). The two sources were approximately 900 m apart. There were 19 SF_6 sampling locations, of which 13 were typically positioned 1.5 m above the roof level and 6 were street-level samplers, the latter in relatively open areas. The distance of the sampler closest to a source was 200 m and that farthest from a source was 2.5 km. Most samplers were located within 1.5 km from a given source.

Tethered balloon soundings were also carried out for 24 h starting from the afternoon of 4 July at Basel-Messe (Site Ue3 Fig. 1) in the city, measuring profiles of wind speed, wind direction, temperature and humidity.

Hourly-averaged data from the fixed monitoring stations and the tethered balloon data are used for model comparison. The BUBBLE data reveal the distinct influence of the urban surface on flow properties (Rotach et al., 2005). Luhar et al. (2006) previously used the BUBBLE flow data in conjunction with TAPM to evaluate relationships between urban and rural near-surface meteorology. All times given here are in Local Standard Time (LST).

3. Mesoscale model

The Air Pollution Model (TAPM, v4.0) developed by CSIRO (Australia) is an operational, inline, coupled prognostic