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Comparison of results of an obstacle resolving microscale model with wind tunnel data

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HIGHLIGHTS

- The micro-scale model MITRAS is evaluated following an evaluation guide-line.
- The evaluation is successful for idealised test cases proposed by the guide-line.
- The procedure is extended for complex test cases based on wind tunnel measurements.
- This study highlights critical areas for the evaluation with complex test cases.

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ABSTRACT

The microscale transport and stream model MITRAS has been improved and a new technique has been implemented to improve numerical stability for complex obstacle configurations. Results of the updated version have been compared with wind tunnel data using an evaluation method that has been established for simple obstacle configurations. MITRAS is a part of the M-SYS model system for the assessment of ambient air quality. A comparison of model results for the flow field against quality ensured wind tunnel data has been carried out for both idealised and realistic test cases. Results of the comparison show a very good agreement of the wind field for most test cases and identify areas of possible improvement of the model. The evaluated MITRAS results can be used as input data for the M-SYS microscale chemistry model MICTM. This paper describes how such a comparison can be carried out for simple as well as realistic obstacle configurations and what difficulties arise.

1. Introduction

European air quality legislation requires EU member states to thoroughly assess the air quality in their respective territories (European Communities, 1996, 1999, 2000). These guidelines address 13 different pollutants and define metrics required for their assessment. Depending on the specific location of the assessment, different spatial representativeness of the metrics is required, ranging from at least 1000 km^2 for areas where the protection of the vegetation and ecosystems is subject of the assessment down to an area of no more than 200 m^2 in urban hot spot locations. To assess air quality for such a wide range of resolutions, a multi-scale numerical model system is required and thus M-SYS has been developed (Trukenmüller et al., 2004). M-SYS employs the mesoscale meteorology model METRAS (Schlünzen, 1990) and the mesoscale chemistry model MECTM (Lenz et al., 2000; Müller et al., 2000; Schlünzen and Meyer, 2007), and the respective microscale models MITRAS (Schlünzen et al., 2003; Lopez et al., 2005) for meteorology and MICTM (Grawe and Schlünzen, 2013) for chemistry, together with the required pre- and post-processors. These models use consistent equations, approximations, and numerical grids to simulate flow and transport and chemical reactions on the scales required by the EU guidelines. In order to investigate meteorological and chemical parameters on a spatial scale of $O(100\ m^2)$ in urban areas, the microscale model MITRAS is able to account for obstacles, such as buildings, explicitly.

Within M-SYS, results of the microscale meteorology model MITRAS need to be thoroughly evaluated before they can be used by the chemistry model MICTM to predict air quality at hot spot locations. Evaluation procedures have been proposed by VDI (2005)

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and European COST Action 732 (Britter and Schatzmann, 2007a; Franke et al., 2007; Britter and Schatzmann, 2007b). The procedure by VDI contains several steps for the comparison: As a first step it addresses the equations and approximations used in the model, and the documentation aspects. In the second step idealised test cases are to be calculated to test basic model properties, such as dependency on grid resolution and stationarity of the results. In a third step, model results are compared with high quality reference data from wind tunnel measurements. The procedure also contains requirements to be followed for every model application and outlines how to test the results of realistic model applications. This study presents the comparison of MITRAS model results with idealised as well as with realistic reference data for which the procedure described in VDI (2005) had to be adapted. This procedure has previously been applied for the evaluation of other models, e.g. MISKAM (Eichhorn and Kniffka, 2010) and OpenFOAM (Franke et al., 2012).

An overview of the model MITRAS is given in Section 2.1. Section 2.2 outlines the method used for the comparison and results are presented in Sections 3 and 4 for simple and realistic test cases, respectively. Section 5 provides summary and outlook.

2. Method

2.1. Model description

MITRAS is a 3-dimensional, prognostic, microscale numerical model for the prediction of flow and transport in the vicinity of obstacles, e.g. buildings. It has been developed based on the mesoscale model METRAS and they share many properties and program code. MITRAS calculates the flow field as well as potential temperature and humidity fields and can take into account effects of thermal stratification (Bohnenstengel et al., 2004). A major adjustment for the application within the obstacle layer is the explicit treatment of obstacles within the model domain. These not only affect the flow field, but can also incur shading effects and thermal effects of the building walls (Schlünzen et al., 2003). Typical domain sizes range between several hundred metres and a few kilometres horizontally, with a domain height of a few hundred metres.

2.1.1. Equations

The model equations are based on the Navier–Stokes-equations, the continuity equation and the conservation equations for further scalar properties, e.g. potential temperature and humidity which are all solved in prognostic equations. The ideal gas law and the equations for the potential temperature are solved diagnostically. MITRAS is a non-hydrostatic model and employs the anelastic approximation and the Boussinesq-approximation. Two options are implemented for the Coriolis force: the Coriolis parameter is either assumed to be constant throughout the model area, or the Coriolis force can be neglected altogether.

2.1.2. Turbulence parameterisation

To limit the computational cost, MITRAS employs the Reynolds-Averaged-Navier–Stokes (RANS) equations. Two separate turbulence parameterisations are implemented in MITRAS to close the set of equations. The Prandtl–Kolmogorow-approach employed throughout this study parameterises the exchange coefficient using the turbulent kinetic energy (TKE) and a mixing length. This mixing length is derived from the distance to the closest surface, which can be either the bottom of the domain or any obstacle surface. The alternative approach (not used in this study) parameterises the exchange coefficient using TKE and the dissipation. Details are given in Lopez et al. (2005).

2.1.3. Numerical grid

The equations are discretised using an Arakawa-C-grid, so that the vector grid points are staggered between the scalar grid points. To account for orographic effects in the model domain, the equations are solved on a non-Cartesian, terrain following co-ordinate system. Instead of the Cartesian vertical co-ordinate z, a vertical co-ordinate η is defined depending on the local orography height:

$$\eta = z_t \cdot \frac{z - z_s(x,y)}{z_t - z_s(x,y)} \tag{1}$$

where z_t denotes the height of the model top and $z_s(x,y)$ the orography height at location (x,y).

A non-uniform grid can be used in horizontal and vertical directions. An area of high spatial resolution can be defined and a constant (but changeable) factor is used to increase the grid width from one point to the next up to a specified maximum. Typical grid widths have a minimum of 1 m in horizontal direction. The resolution is mainly limited by computing cost and the requirement that the lowest grid level has to be large compared to the local surface roughness. The maximum grid size used in relevant areas of the domain is a few metres.

2.1.4. Numerical stability

MITRAS solves the momentum equations using the Adams–Bashforth scheme in time and centred differences in space. This method has a low numerical diffusivity compared to other numerical schemes, but may lead to short wave energy accumulation as a numerical artefact which might eventually result in numerical instabilities. As a remedy, 3- 5- and 7-point filters are implemented in MITRAS to contain short waves. In urban areas with very complex obstacle configurations, this can lead to problems, as grid points used in the filter may be located within obstacles, while only grid points outside of buildings can be used by the filter. For this study an alternative filtering has therefore been implemented which artificially increases the value of the diffusivity: A theoretical diffusivity can be calculated for the upstream scheme, which has an implicit diffusivity that depends on the local wind speed $|\vec{v}|$, the local grid width Δx and the Courant number Co. According to Schlünzen (1996) the additional diffusivity K_{num} is

$$K_{\text{num}} = 0.5 \cdot |\vec{v}| \cdot \Delta x \cdot (1 - Co) \tag{2}$$

The Courant number describes the ratio of local wind speed $|\vec{v}|$, local grid width Δx and the current length of the time step Δt: $Co \approx |\vec{v}| \cdot \Delta t \cdot \Delta x^{-1}$. The locally calculated exchange coefficient is increased by the respective value calculated using Equation (2). This artificially increased diffusivity was employed throughout the model domain for the complex test cases, while for the idealised test cases the traditional filter could be used.

2.1.5. Treatment of obstacles

To consider the influence of buildings on the flow in the model domain, these are explicitly included in MITRAS. A three-dimensional building mask is used, in which each grid cell is classified as *building* or *no building*. This information is used explicitly in all model equations using a weighing factor $Vol(x,y,z)$. Vol becomes 0 within buildings and 1 outside of buildings. Hence, the model equations only need to be multiplied by a weighting factor. For any variable Ψ this is

$$\tilde{\Psi}(x,y,z) = \Psi(x,y,z) \cdot Vol(x,y,z) \tag{3}$$

For the wind field this equation essentially creates zero wind speed within buildings and at all building surfaces.