

High-Resolution Air-Quality Modeling in Urban Areas—A Case Study for the City of Leipzig



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Abstract A multi-scale framework for urban air-pollution modeling is presented, which has been developed for the mid-sized City of Leipzig, Germany, and potential application in other cities. The model system consists of the urbanized chemistry-transport model COSMO-MUSCAT, which is enhanced by a newly developed CFD model to bridge the gap between neighborhood scale and street level. A first application of COSMO-MUSCAT as air-quality forecast model at continental to urban neighborhood scales for Central Germany and the City of Leipzig is presented for spring 2019. In addition, the CFD model is tested to be able to capture the typical urban flow patterns.

1 Introduction

The urban atmosphere is strongly influenced by a range of short-lived pollutants from multiple spatially and temporally varying sources. Many of them are known to cause adverse health effects (ultrafine particulate matter, soot, nitrogen oxides, ozone). Because of short lifetimes, these air pollutants show a high spatio-temporal

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variability, which currently cannot be adequately captured by stationary observations and air-quality models.

For a better exposure evaluation, and to scientifically study the small-scale variability and controls of air pollutants in cities, a flexible multi-scale system for air-quality modeling has been developed. It is based on a state-of-the-art chemistry-transport model (CTM), which is enhanced by a new Computational Fluid Dynamics (CFD) solver for application across entire urban areas. The model framework was first tested for the mid-sized City of Leipzig, Germany, within the knowledge-transfer project WTimpact. The model system was run operationally up to the 500-m scale for field campaigns in spring 2019 and as hindcast for the hot summer 2018. For model evaluation, long-term stationary and extensive mobile air quality measurements with sensor backpacks are available.

2 Methods

2.1 Multi-Scale Air-Quality Modeling Framework

A flexible framework for high-resolution air-quality modeling has been developed for the City of Leipzig and potential application in other cities. The core is an urbanized version of the multi-scale CTM COSMO-MUSCAT (Consortium for Small-scale Modeling model of the German Weather Service DWD—MULTiScale Chemistry Aerosol Transport model; Schättler et al., 2018; Wolke et al., 2012). The model system includes up-to-date production parameterizations for natural aerosol, including an advanced scheme for biogenic emissions and secondary aerosol formation, and considers complex multiphase chemistry. Anthropogenic air pollutant emissions are prescribed from latest inventories. In order to account for the impact of city morphology on air flow and radiation, the model is equipped with the Double Canyon Effect Parametrization (DCEP) by Schubert (2012). The required statistical input is calculated from a detailed 3-D city model in CityGML format using preprocessor tools in python language.

The simulations are realized with a nesting chain, where the horizontal resolution is gradually increased from 28 km over Europe to about 550 m over the city area. The outer domain, which provides the background concentrations over Germany, is driven by the global ICON forecast of DWD. Copernicus Atmosphere Monitoring Service (CAMS) forecasts provide the input for the aerosol and gas boundary conditions of the coarse domain. The meteorological initial and boundary data for the German domain come from the DWD COSMO-D2 forecast. The subsequent domains use the boundary conditions of the respective coarser model run. For the European domain, TNO-CAMS emissions are used, while for Germany, high-resolved point, area and road emissions are available from the German Environment Agency (Umweltbundesamt, UBA).

The system can be run in quasi-operational mode, which allows to accompany field campaigns. Another important feature is the visualization by interactive online mapping on the project website.

2.2 *Urban CFD Model*

In order to bridge the gap between the COSMO-MUSCAT results at neighborhood scale and street level, dynamical downscaling is applied. For the computation of wind fields considering the full physical presence of buildings, a CFD solver for incompressible flow equations has been developed following Gowardhan et al. (2011). The spatial discretization of the tendency terms involves a finite volume method on a uniformly structured cuboidal mesh. The velocity components are defined on the cell faces, while the pressure is a cell-centered quantity. Detailed building geometry data is used to compute effective volumes, as well as effective face areas of the grid cells. Advection is upwind biased and 3rd order spatial accurate. Time integration involves the fractional step pressure projection method, which is essentially an operator splitting. In a first step, the advection and diffusion tendencies are integrated explicitly using the classic 4th-order Runge–Kutta procedure. The pressure-gradient correction is computed afterwards implicitly from the divergence of the intermediate wind field using an efficient multigrid solver. After pressure projection, the final wind field satisfies the continuity equation. Turbulence closure is currently provided by a simple algebraic eddy-viscosity model, and skin-friction drag is parameterized from the effective cell-face areas. Finally, the air pollutant dispersion is computed by an advection–diffusion routine. In this approach, obstacles are represented by permeability fields, which allows spatial resolutions that can be significantly lower than needed to explicitly resolve buildings. This way computational costs are considerably reduced and, in future, the scheme may be used online in the CTM MUSCAT.

3 Results and Discussion

The multi-scale modeling framework was first tested in hindcast mode for the hot summer 2018, and as 48-h forecast for the field phases of the WTimpact project in spring 2019. Long-term stationary observations at four sites in the City of Leipzig and extensive mobile measurements from the WTimpact field campaigns are available for evaluation. The first comparison of the model results from the innermost domain to the monitoring station measurements shows a reasonably good agreement for the temporal evolution of PM_{10} , NO_2 , and O_3 at all sites. The levels of PM_{10} and NO_2 are matched well by the model at the urban background stations, as well as the concentration of PM_{10} in the city center. However, the observed values of NO_2 and O_3 are underestimated, in particular, at high traffic locations. This requires further analysis. A likely reason is a still too coarse horizontal resolution, but possibly

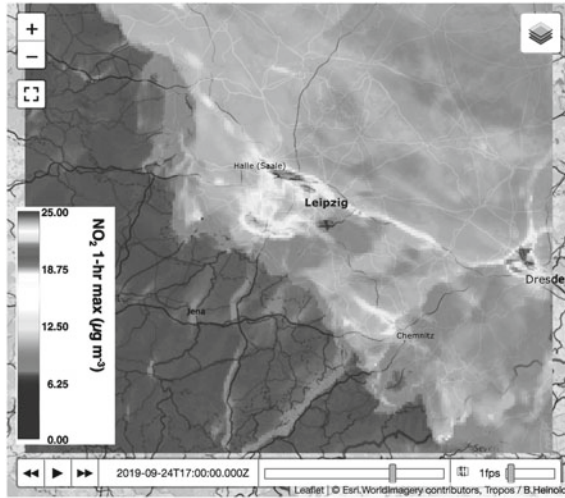


Fig. 1 Maximum hourly NO_2 concentration at surface as computed with COSMO-MUSCAT for Leipzig on 24 September 2019, 17 UTC. Screenshot of the interactive web map as provided within project WTimpact

also adjustments to the prescribed road traffic emissions may be needed. During WTimpact, the urban air-quality forecast was provided to the volunteers in the project via interactive web mapping for experimental planning and the interpretation of observations (Fig. 1).

In addition, the new urban CFD solver was tested for a subdomain over Leipzig with 150×100 grid cells and 20 m horizontal resolution. In Fig. 2, the CFD simulation is initialized and driven with a uniform wind field ($u = 5 \text{ m s}^{-1}$, $v = 0 \text{ m s}^{-1}$) at the domain boundaries. The building structure is described by permeability fields, calculated from detailed building-geometry data. For test purposes, a point source of arbitrary strength is placed at a building roof at 25 m height and another source emitting into the first model layer at the inner ring road of Leipzig. The dispersion of the tracers is as expected, e.g. with channeling in narrow inner-city roads and more diluted spread in wider areas, as well as downward mixing of the lofted plume in the lee of buildings (Fig. 2). The CFD solver is fully parallelized and efficient to be applied for the entire urban area of Leipzig. In a next step, the COSMO-MUSCAT model will be combined with the CFD solver for downscaling.

4 Conclusions

The multi-scale framework for urban air-pollution modeling presented here allows to visualize air-quality issues in cities, and provides a better exposure evaluation. The model system consists of the urbanized CTM COSMO-MUSCAT, which is applied at

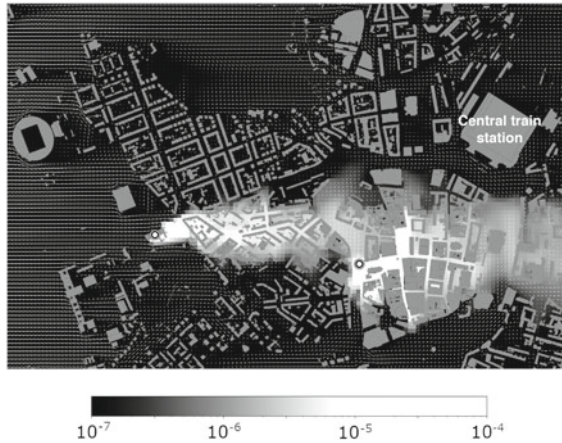


Fig. 2. 1st-layer tracer concentration over central Leipzig after one hour of simulation with the new CDF model. Point sources of arbitrary strength emit at a 25 m rooftop (left dot) and into the first layer (right dot)

continental to urban neighborhood scales (<500 m). A first application of COSMO-MUSCAT in urban air-quality forecast for the City of Leipzig is presented for May 2019. For downscaling to street-level, in a next step, the urban-scale modeling will be combined with a new CFD solver, which uses permeability fields to represent buildings that allow grid spacings larger than a typical street width. As shown in a first test, the CFD model is able to represent characteristic flow patterns. Near future work includes a thorough model evaluation of the coupled model framework with the unique set of mobile and stationary measurements available at Leipzig. Ultimately, it will be used to investigate the small-scale variability of short-lived air pollutants and their controlling factors in Leipzig, as well as potentially in other cities.

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References

- Gowardhan, A., Pardyjak, E., Senocak, I., & Brown, M. (2011). A CFD-based wind solver for an urban fast response transport and dispersion model. *Environmental Fluid Mechanics*, *11*, 439–464. <https://doi.org/10.1007/s10652-011-9211-6>
- Schättler, U., Doms, G., & Schraff, C. (2018). *A description of the nonhydrostatic regional COSMO-Model. Part VII: User's Guide*. Deutscher Wetterdienst (DWD).

- Schubert, S., Grossman-Clarke, S., Martilli, A. (2012). A double-canyon radiation scheme for multi-layer urban canopy models. *Boundary-Layer Meteorology*, 145(3), 439–468. <https://doi.org/10.1007/s10546-012-9728-3>
- Wolke, R., Schröder, W., Schröder, R., & Renner, E. (2012). Influence of grid resolution and meteorological forcing on simulated European air quality: A sensitivity study with the modeling system COSMO–MUSCAT. *Atmospheric Environment*, 53, 110–130. <https://doi.org/10.1016/j.atmosenv.2012.02.085>

Question and Answer

Questioner: Dr. Ronny Petrik.

Question: Is the jump from 28 to 2.2 km not much too high for the model dynamics?

Answer: This is not an issue, since the outermost 28-km domain covering Europe only provides the aerosol-chemical boundary conditions for the ‘German’ nest with 2.2 km grid spacing. The 2.2 km nest is driven by initial and boundary conditions from the DWD COSMO-D2 forecast, which also has a horizontal grid spacing of 2.2 km.