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GRAMM/GRAL: COMPUTING AIR QUALITY MAPS AT THE URBAN SCALE

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Abstract: We simulate air pollution at very high resolution at the urban scale for two Swiss cities, Lausanne and Zurich. Combining very detailed emission inventories with high-resolution dispersion simulations, we compute air quality maps at the hourly scale for decade-long periods. Lagrangian dispersion simulations by the model GRAL are forced with high-resolution wind fields computed by the nested system GRAMM/GRAL: the meteorological mesoscale model GRAMM computes large scale wind fields forcing the microscale computations by the CFD model GRAL accounting for buildings and fine scale turbulence. Instead of performing transient simulations for the full period of interest, the temporal dynamics are approximated by an hourly sequence of steady-state solutions. This approach, applied to the modelling system GRAMM/GRAL, proved to accurately reproduce pollutant concentrations at affordable computational costs when compared to observations in different parts of the city and at different time scales.

Key words: *city scale, PM10, NO_x, CFD simulations*

INTRODUCTION

Air pollution is a major issue to be dealt with in urban areas. Air pollutant concentrations vary strongly within cities depending on the proximity to emission sources, meteorology, local dispersion, as well as on the background air pollution. To accurately assess air pollution exposure of citizens it is necessary to provide maps of air quality in different parts of the city at a very high horizontal resolution. Such maps can then be used by policy makers for designing effective mitigation measures, by sensitive persons to reduce their personal exposure, as well as in support to epidemiological long-term studies. However, due to the large spatial and temporal variations of pollutant levels in cities, producing such maps requires either dense observation networks or expensive high resolution dispersion models. To date, models capable of simulating the dispersion of air pollutants are usually one of two types: (1) coarse chemistry transport models where the concentrations are averaged over the city or over parts of it; (2) highly resolved CFD models that are too costly to be run on a regular basis for long time periods.

In the present work, we use an integrated modelling system based on the two models GRAMM and GRAL in order to bridge the gap between the two abovementioned types of models by combining the strengths of each of them. The distributed models have been modified to allow high-resolution long-term simulations with reasonable computational costs. The hourly time series of concentration maps are used in the framework of the Swiss Nano-Tera project OpenSense2, which aims at assessing the impact of air pollution on the health of citizens living and working in urban areas by combining dense sensor networks with high-resolution models to enhance results from epidemiological studies.

In the following, we present the assumptions behind the integrated modelling system and the set-up of the models for simulating NO_x and PM10 concentration maps at 5 m resolution for two Swiss cities, Lausanne and Zürich. The outputs of the modelling system are evaluated with regard to standard air quality observations existing in most cities. In the present paper, we show results for NO_x only.

METHOD AND MATERIALS

Description of the modelling system

The model system is based on two validated models: the meteorological model GRAMM (Almbauer et al., 2009), and the computational fluid dynamics (CFD) and Lagrangian transport model GRAL (Oettl, 2015). The regional model GRAMM computes high-resolution mesoscale wind fields in a domain covering the city and its surrounding area. It accounts for the effects of the topography and of surface fluxes of heat, momentum, humidity and radiation over different land use types. The boundary conditions in GRAMM are driven by typical profiles of temperature, pressure and wind depending on large scale forcing. Using the GRAMM wind fields as forcing initial and boundary conditions, the Reynolds-Averaged Navier-Stokes (RANS) CFD model GRAL resolves the modification of the air flow at the street and building scale in the area of interest. In GRAL, the computation of the turbulence is solved using a standard $k - \varepsilon$ approach. The modified flow field is then used to compute the dispersion of air pollutants from prescribed emissions for a variety of emission sectors (traffic, industry, heating systems, etc.) based on a Lagrangian approach.

Instead of performing transient simulations of the nested system GRAMM/GRAL, the temporal dynamics are approximated by an hourly sequence of steady-state solutions. Thus, a catalogue of typical steady-state meteorological situations is first computed for a large number of physically possible meteorological situations. These situations are defined by discrete values of wind speed, wind direction and atmospheric stability, adding up to 1008 reference situations in the catalogue. Time series of air pollutant concentrations are then generated by selecting the GRAMM wind fields best matching to in situ wind measurements for each hour of the period of interest and by adding and scaling the corresponding contribution of various emissions sectors according to temporal profiles of emission. In the modelling system, the influence of pollution transported from remote sources to the city of interest is accounted for by adding observations of pollution in the rural environment around the city of interest to the simulated concentration maps.

Set-up for the city of Zürich and Lausanne, Switzerland

We set up the model system for the two urban areas of Zurich and Lausanne. GRAMM was computed at 100 m resolution on domains of 40 x 40 km² around the two cities. GRAMM was forced by topological information from the ASTER GDEM2 data set at 30 m resolution and by land use information from the Corine Land Cover data set at 100 m resolution. GRAL was run at 5 m resolution on domains of 5 x 5 km² centred on the densest parts of the two cities. The locations, geometry and heights of individual buildings were provided by the local authorities, as well as the magnitude and location of thousands of individual emission objects. In the emission inventories, streets are described as line sources, heating systems and individual stacks as point sources and sources that are difficult to precisely allocate are reported as area sources. The temporal profiles of emissions are based on either measured proxies of their variability (e.g., traffic count for traffic emissions, outdoor temperature for residential heating), or on aggregated temporal profiles deduced from the TNO-MACC inventory for Europe (Kuenen et al., 2011).

Meteorological observation sites used to select weather situations from the pre-computed catalogue are operated by the Swiss Federal Office of Meteorology and Climatology MeteoSwiss. They are located in open areas and winds are measured at 10 m above ground to guarantee a good representativeness and comparability with the mesoscale model. The GRAL concentration outputs are evaluated with in situ observations of NO_x and PM10 collected in the vicinity of streets or in the rural background by NABEL, the Swiss air pollution monitoring network. Observations from NABEL outside the city of interest are also used to constrain the background concentrations entering the domain of simulation. Regarding the availability of data, time series of hourly concentration maps were produced for the years 2013 to 2014 in Zürich and from 2005 to 2014 for Lausanne.

In the following, we present evaluation results only for the city of Lausanne.

EVALUATION OF THE MODEL

Representation of air flow

After matching weather situations to observations in order to generate the hourly sequence of steady-state solutions, it appears that about 200 out of the 1008 pre-computed reference situations in the catalogue represent more than 80% of the hours of simulation. Thus, air flow around the city is dominated by a limited subset of situations due to the prevalence of characteristic wind patterns related to local and regional processes (e.g., topography-driven winds, land-lake breeze, or downhill drainage of cold air in stable atmospheric conditions). When comparing the time series of simulated winds to observations at specific locations in the domain, these typical patterns seem to be well reproduced by the model, despite a general underestimation of wind speeds. Therefore, the approximated approach with a steady-state sequence appears appropriate for describing air flow around the city of interest in a cost-effective way.

At the building-resolving scale, despite the fact that the complex configuration of buildings is not perfectly represented at 5 m resolution, GRAL computes wind speed and direction in street canyons well, as it is shown in Figure 1 for the observation site LAU (top panel). However, the catalogue of wind fields computed by GRAL only accounts for a given status of construction of the city. New or demolished buildings are not represented in GRAL. In the bottom panel of Figure 1, red buildings were present in the model, but were not already built at the time of the measurements. As a consequence, simulated wind speeds are critically underestimated at this location and the direction of air flow is shifted in the model, which has a strong impact on the dispersion of very local emissions.

As for well-established city centres the configuration of buildings does not change drastically over the years (only a few dozen buildings were built or demolished during the window of simulation in our case), we assume that the overall wind flow in the city is represented in a very satisfactory manner.

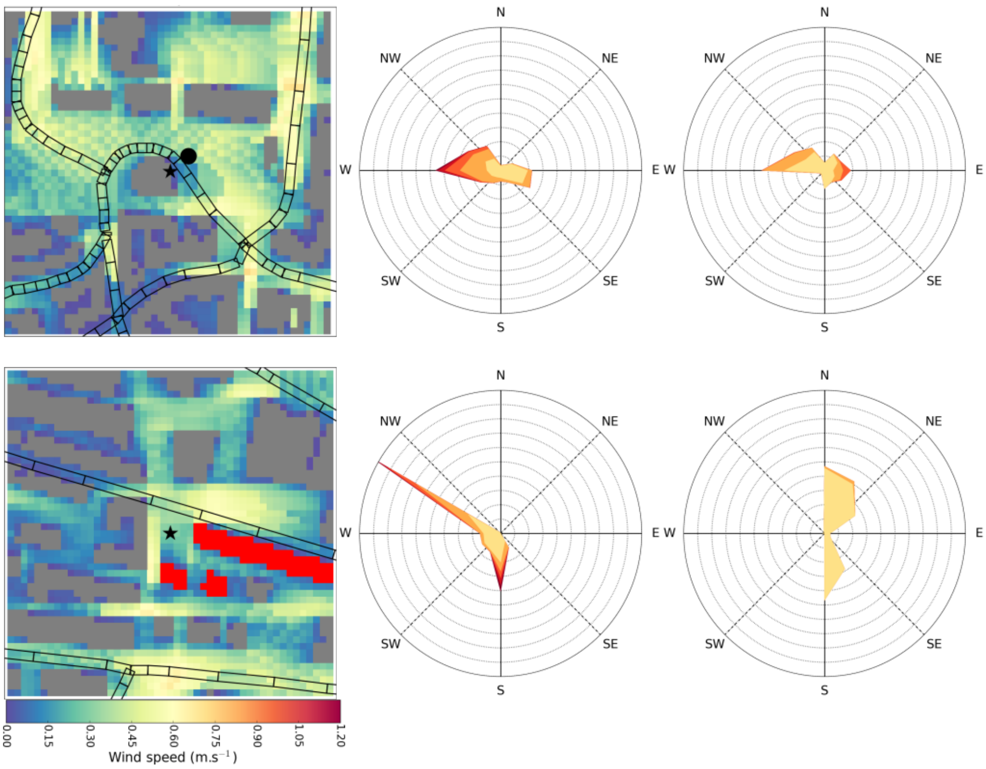

Figure 1. Local situation of two observation sites (top: LAU; bottom: DGE07) and observed (left) and simulated (right) wind roses. Observations are located at the black stars. For LAU, the wind measurements (black dot) are slightly shifted compared to the concentration observations (black star).

Spatial and temporal variability of pollutant concentrations

The time series of concentrations are compared to in situ observations at several different locations in the city (urban background, traffic, city centre). The four sites used for the evaluation of the model in Lausanne are shown in Figure 2, aside quantile-quantile plots. For three of the four sites, NO_x concentrations are very well reproduced below 150 $\mu g.m^{-3}$. For these sites, the normalized mean bias is also very low (1%, 2% and 25% for the three sites respectively), proving the capability of the model to reproduce the steep concentration gradients in the vicinity of local emissions and in complex building configurations. As more than 95% of the domain is simulated with concentrations below 150 $\mu g.m^{-3}$, it is expected that the integrated system provides a very reliable spatial distribution of pollutants in the city. The forth site (blue cross and line in Figure 2) is the same site as in the bottom panel of Figure 1. It confirms that the static catalogue, with no change in the building configuration, can locally diverge from the real situation, and in our case critically underestimate the dispersion of local emissions, leading to overestimated simulated concentrations.

The temporal variability of pollutants is also very well reproduced (no time series shown here). Long-term trends (25% of decrease in observed NO_x concentrations in our case) are very well represented when updating the emission inventory according to nationally declared emission trends. The model also manages to represent the year-to-year variability related to changes in meteorological situations between one year and the other. The seasonal cycle of concentrations (winter high related to higher emissions and more stable weather conditions) is also well reproduced, though the timing of the increase (respectively the decrease) of concentrations in autumn (in spring) is generally delayed by a few days to weeks in the model. This is likely related to a hysteresis in the behaviour of citizens when using heating systems, which is not properly reproduced in our system. Synoptic alternation between stagnant and windy situations is very well simulated as well, with a correlation coefficient of 0.8 between simulated and observed daily averages. Thus, the integrated system proves to be very performant for the representation of short-term pollution event. In the case of NO_x concentrations, the background deduced from observations in the rural environment around the city plays a marginal role and only at the temporal scales longer than a day. Only a few winter peaks are partially explained by increased background concentrations (associated to large scale stable situations and recirculation of polluted air masses). At the seasonal and yearly scale, the background remains mostly below 10 – 15% of the city signal. Therefore, we can deduce that the steady-state approach is really performant for simulating the short- and long-term variability of pollutant in cities. At the hourly scale, the diurnal cycle of concentrations (mostly related to human activity and emissions) is reasonably well simulated with correlation coefficients of 0.5 – 0.6 depending on the observation site. Nonetheless, at this particular scale, observed concentrations exhibit an already strong correlation to the variability of traffic load (up to 0.5), which mitigates the potential benefits of using a full physics model.

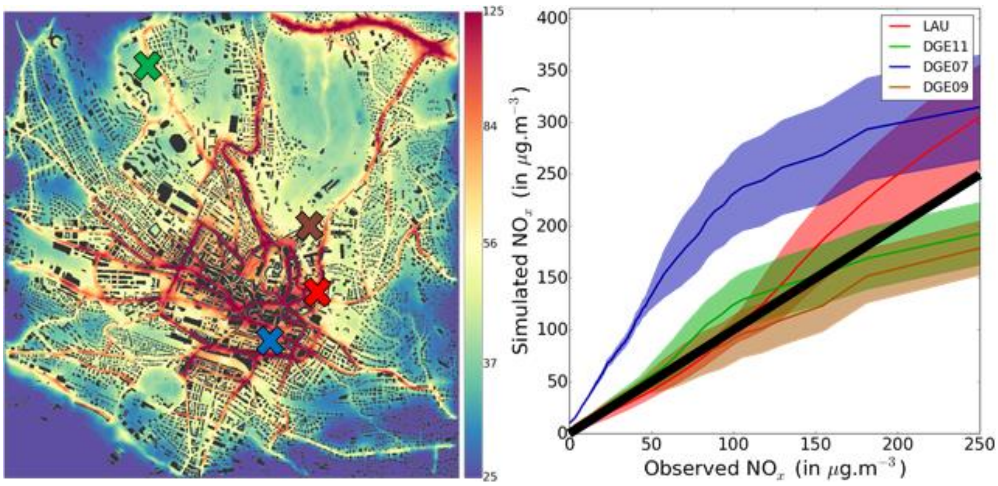

Figure 2. Left: yearly average NOx concentrations over the city of Lausanne; location of four evaluation sites. Right: quantile-quantile plot for the four observation sites in Lausanne. The black line is the 1:1 line.

CONCLUSIONS

We applied a simplified approach for representing the transient evolution of concentration levels at a very fine scale in cities with affordable computational costs. This approach is based on sequencing pre-computed steady-state representative situations. The sequencing is based on in situ observations of winds compared to mesoscale high resolution meteorological simulations. This cost-effective approach proved to be sufficiently accurate when compared to in situ observations of winds and concentrations. The main air flow patterns are represented by the integrated system from the mesoscale to the street level. Thus, the Lagrangian simulations of pollutant dispersion reproduced the spatial distribution of pollutants at a very fine scale and their temporal variability from the hourly scale to the multi-annual trends.

This flexible integrated system can be used for urban planning and pollution abatement measures by policy makers and in support to epidemiological studies for assessing the health impact of pollution on individuals. In this framework, additional active species would be necessary, requiring the development of new modules in our integrated system to simulate the photochemistry and the transformation of particulate matter in a cost-effective way.

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