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**MULTI-SCALE HIGH RESOLUTION FLOW MODELLING FOR LOCAL
SCALE AIR QUALITY ASSESSMENT IN COMPLEX TERRAIN**

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Abstract. An adequate representation of flow is essential for dispersion modelling and a challenge in complex terrain. Here, an efficient multi-scale modelling approach is presented which uses the advantages of regional/local scale model coupling, and model initialization with various wind measurements at the local scale. The ECMWF-ERA5 – WRF - GRAMM model set-up was run over one year for the 54 km x 48 km sized greater Graz area. Interrelated detailed high-resolution ($\Delta x, y = 0.1$ km) flow fields were obtained. Local scale features, such as katabatic/anabatic winds, are well represented in the greater Graz basin, in side valleys, slope and mountain top locations. Hourly flow fields over one year were reduced to 1031 characteristic flow fields. These reduced flow fields show good agreement across all 17 monitoring stations characterized by free flow conditions and are suitable for regulatory air quality applications.

Keywords: *Multi-Scale flow modelling, regional local scale model coupling, model initialisation, WRF, GRAMM*

INTRODUCTION AND BACKGROUND

The computation of flow fields covering flow features on various scales such as drainage flow, mountain wind systems, channelling as well as synoptic flow is a challenging task. The major challenges are the initialization and the specification of boundary conditions.

So far, local scale flow fields have been frequently computed by using one “representative” surface wind monitoring station for initialization and boundary conditions. However, this approach is limited to domains only a few kilometres in size or to areas with simple relief shape.

Another practical approach is to calculate an ensemble of precalculated flow fields using synthetic boundary conditions for classified wind direction (WD), wind speed (WS) and stability class. Standard wind profiles as a function of stability may be used for these synthetic initialized and boundary condition driven flow field simulations. In practice about 600 to 1500 “synthetic” flow fields result (i.e., 5 - 10 classified WS classes, 36/18 classified 10°/20° WD sectors using 7 stability classes). Thereafter, timeseries of monitored WS, WD and derived stability class at several monitoring stations may be compared with pre-calculated “synthetic” flow fields hourly over one entire year. The principle of these so-called Match-to-Observation (MtO) procedure is shown in equation 1; u_{iMon} , v_{iMon} are each half hour or hour i monitored wind components at the respective monitoring station j of up to k_{mon} stations within the modelling domain. Those are compared with nearest u_{sim} and v_{sim} wind components from monitoring station j over the time period $ntim$. The lowest value err_i indicates the best-fitting computed “synthetic” flow field for the date/time i .

$$err_i = \sum_{i(tMon)=1}^{ntim} \sum_{j=1}^{k_{mon}} \sqrt{[(u_{Sim,j} - u_{iMon,j})^2 + (v_{Sim,j} - v_{iMon,j})^2]} \quad (1)$$

For each hour or time step considering as well stability class the best matching flow field is listed. This list might be re-ordered to a frequency distribution which enables computationally efficient dispersion computations. The advantage of this MtO method is its simplicity and computational efficiency. Clear disadvantages are that vertical and horizontal wind variability from synoptic and regional flow is missing and therefore the MtO approach may fail for large areas using many monitoring stations representing different flow characteristics. However, for sub-domains acceptable flow fields are obtained.

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Here in this work, we use the ECMWF-ERA5 Re-analysis data set and nested WRF (Powers et al., 2017) model runs ($\Delta x, y = 3 \text{ km} \ \& \ 1 \text{ km}$) in order to approach finer resolutions and to initialize the local scale model GRAMM (Almbauer, 1995, Oetl, 2020). This “coupling” approach covers the synoptic flow features und also represents flow features on the regional scale. However due to the “top-down” approach and the sub-grid flow features in valleys, side valleys and slopes the initialized local scale model may start its integration far from reality. Even highly sophisticated local scale models may not be able to compensate inadequate initialization. Therefore, we make use of dense KIS (Climate Information System) project data for the Greater Graz area (see Figure 1). Monitoring data for surface winds and temperature are used together with WRF data to improve model initialization of wind and temperature profiles over the entire model domain. Finally, the MtO approach is used to reduce the huge data volume to create a computational efficient, still high-quality flow field library ideally suited to air quality modelling.

METHODOLOGY

Variables for absolute pressure p , geopotential θ , potential temperature θ , humidity q and wind components (u, v, w) of a one year WRF-Modell run with $\Delta x, y = 1 \text{ km}$ were transformed to UTM33 and were interpolated on the fine GRAMM model grid, $\Delta x, y = 0.1 \text{ km}$. At the lateral borders the GRAMM model orography was smoothed in order to create a transition zone between the coarse and smooth WRF orography towards the fine and rough GRAMM orography.

The core of this modelling work is the hybrid model-nesting/monitoring data initialization. 12 wind monitoring stations were selected from 23 available KIS monitoring stations, see Figure 1. The selected monitoring stations are characterized by largely undisturbed air flow. After interpolation and assignment of the WRF wind and temperature data, they are compared with monitored wind and temperature data. If the relative difference criteria $crit$ between WRF interpolated wind components u_{mon} and v_{mon} are exceeded the WRF interpolated values are corrected.

$$|(u_{sim} - u_{mon})/u_{mon}| > crit \quad OR \quad |(v_{sim} - v_{mon})/v_{mon}| > crit \quad (2)$$

For $WS \leq 0.5 \text{ m/s}$ $crit$ is set to 0.35, for $WS > 0.5 \text{ m/s}$ $crit$ is set to 0.2. In case θ deviates $> 1^\circ\text{K}$, the WRF interpolated temperature and profile is adjusted. In order to account for prevailing large-scale winds above mountain tops a vertical weighting function was introduced to enable a transition between monitored surface wind and θ driven initialisation and the model coupling initialisation. Each grid point is weighted by the function described in equation (3), Δz is the distance of each grid point to the orographic model height $AH_{i,j}$, $Z_{wgt \max}$ is set to 1500 m.

$$zwgt_{i,j,k} = 1 - \Delta z_{i,j,k} / (Z_{wgt \max} - AH_{i,j}) \quad \text{with } zwgt_{i,j,k} \leq 1 \quad (3)$$

In order to use several measurements for the initialisation at the local scale, a weighting of the inverse distances of measurement sites to each grid point is carried out. A large 54 km x 48 km sized local-scale modelling domain was chosen (Figure 1) to represent comprehensive mountain and valley wind systems. For the KIS project, a comprehensive flow field library was generated, comprising 8760 hourly flow fields and additional temperature, humidity and other fields were obtained. Based on this detailed high-resolution data the ventilation of urban spaces during summer and winter has been evaluated, and many climate parameters like the number of tropical nights, heat waves, heating degree days etc have been considered. However, for regulatory purposes of air pollutants and odour the data volume is too large. Therefore, the above mentioned MtO algorithm is used to reduce the data volume and still retain the domain size and high quality.

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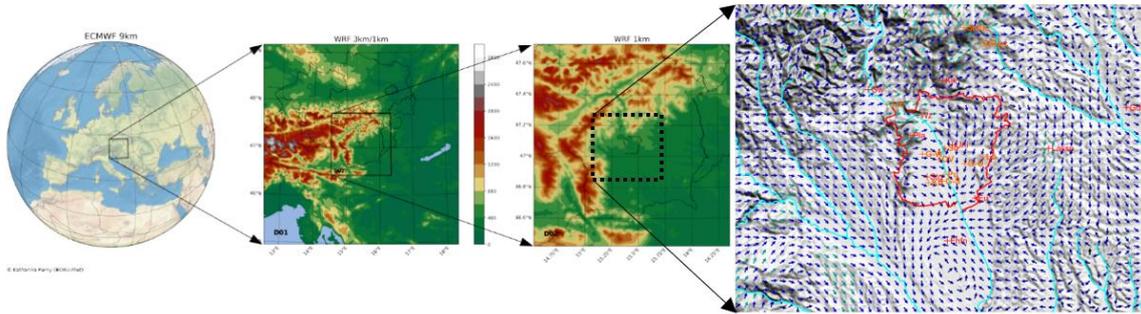


Figure 1: Multi-scale high resolution model set-up used for the Greater Graz area in the KIS project. Monitoring stations used for initialization (red) and for model validation (orange) and Graz municipality (red) are shown (right).

RESULTS

Figure 2 shows the surface wind field for the City of Graz and surrounding Alpine foothills illustrating the model systems capability representing cold drainage flows. Figure 3 shows a comparison of simulated and monitored results over one month for the Eurostar monitoring station located in the SE of Graz. The coupled model system is capable to accurately represent the alternating mountain valley wind system. Overall, high-quality flow fields were obtained not only within the Graz basin, but also at locations near side valleys, ridges, and mountain tops. Wind roses for the entire year are shown in Figure 4 for the monitoring station Straßgang (Stg, SW of Graz), in Figure 5 for Weinzöttl (Wz, N of Graz), Figure 6 Lassnitzhöhe (Lassn, outside to the E of Graz) and in Figure 7 the station Schöckl (Schkl) 1445 m a.s.l. At these locations the wind roses differ due to the impact of complex terrain and associated local wind systems.

In a further processing step, refined MTO algorithms (Oettl et al., 2023) were used as data reduction tool in order to describe an entire year by classified flow fields. The results are shown in the third column of Figure 4 to Figure 7. Compared with the results from the full flow field data set (Sim-All) the quality of the one-year run is captured in the reduced flow field library (Sim-Reduc).

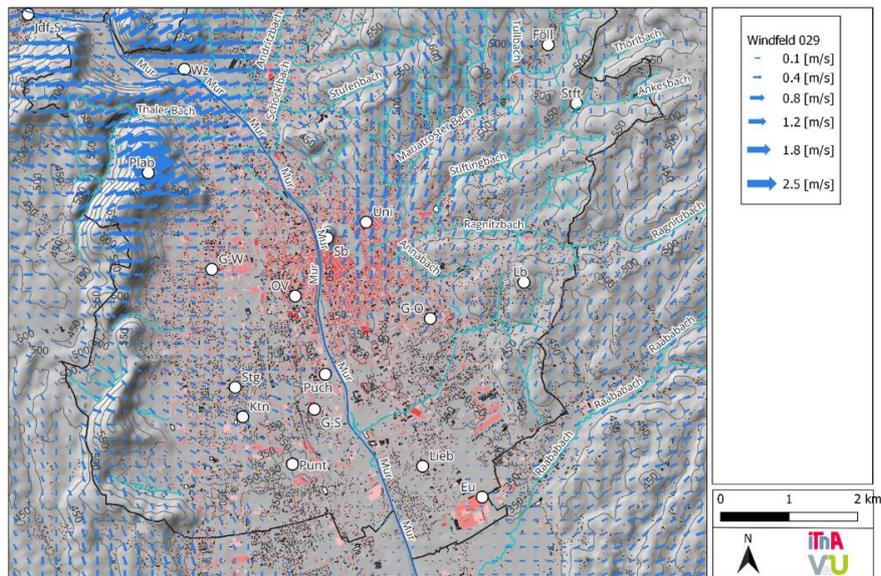


Figure 2: Surface wind field in the Graz Basin, 02.06.2021, 5:00.

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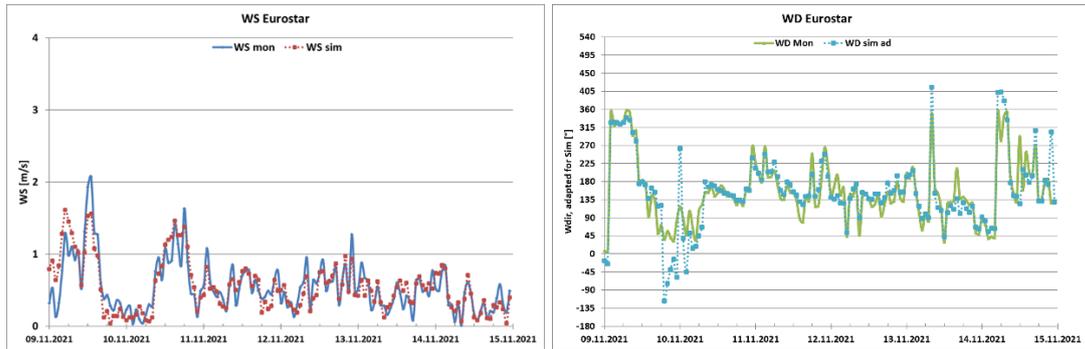


Figure 3: Simulated and monitored wind speed (left) and wind direction (right) at Eurostar station November 2021.

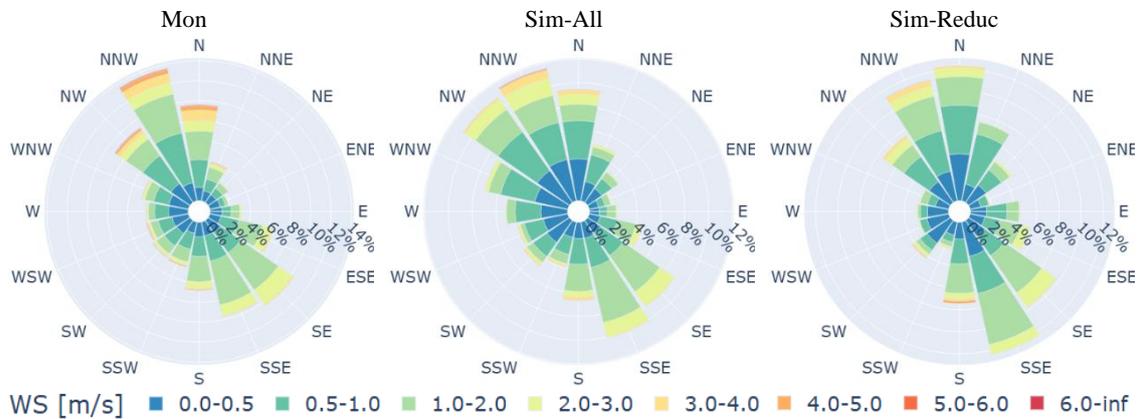


Figure 4: Monitored wind rose (left) simulated wind rose entire year (middle) and reduced one in Graz Straßgang.

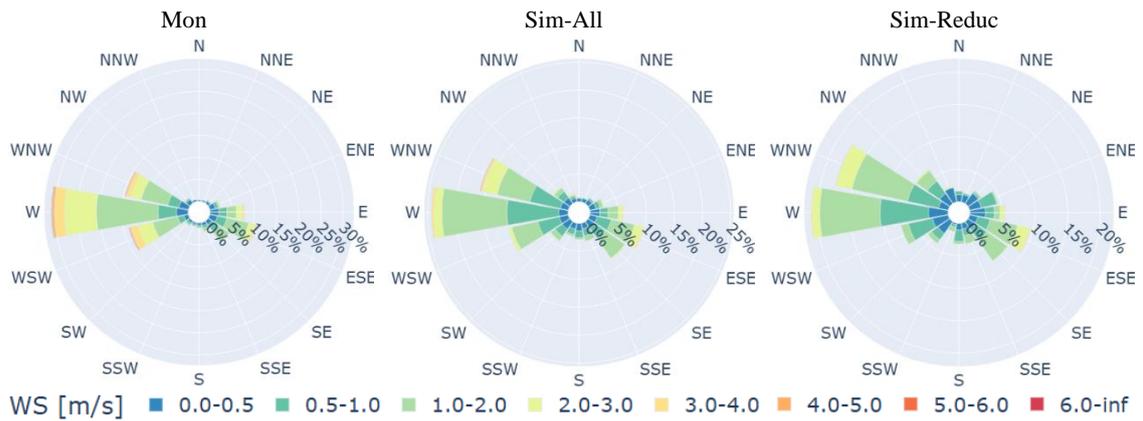


Figure 5: Monitored wind rose (left) simulated wind rose entire year (middle) and reduced one in Graz Weinzöttl.

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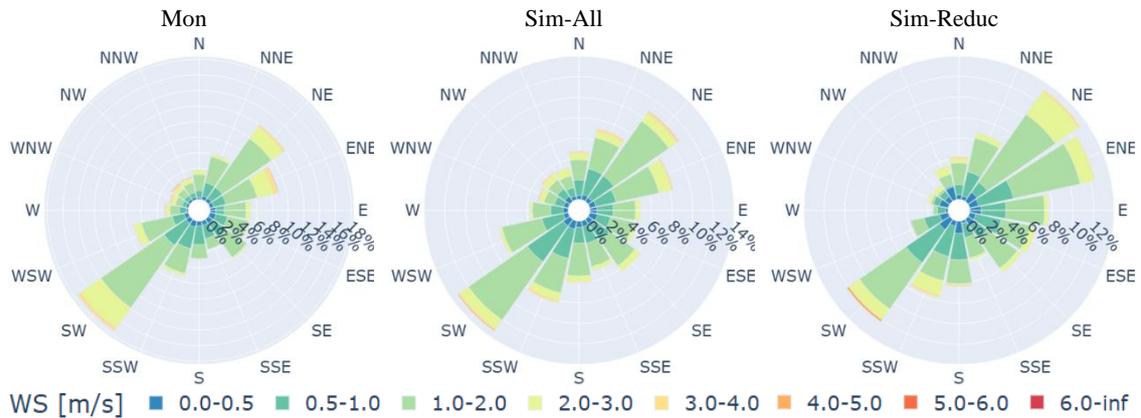


Figure 6: Monitored wind rose (left) simulated wind rose entire year (middle) and reduced one at Lassnitzhöhe.

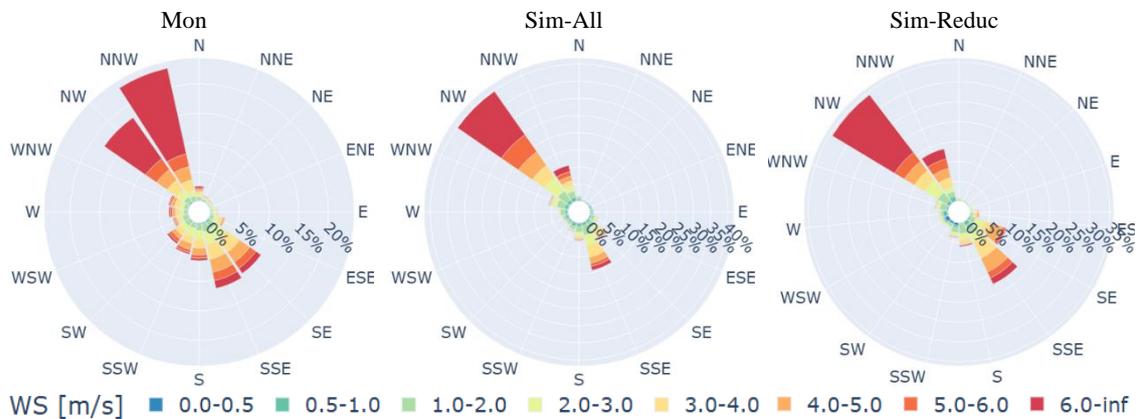


Figure 7: Monitored wind rose (left) simulated wind rose entire year (middle) and reduced one at Schöckl mountain.

SUMMARY

An efficient multi-scale high resolution ($\Delta x, y = 0.1$ km) flow modelling system was developed and validated. The modelling system successfully captured complex local alpine flow features like low wind situations, mountain valley, side valley and slope winds, as well as local vortexes. The coupled model system is used for climate related scientific issues and can be used for complex multi-scale air quality modelling. This all-year flow field library has a large data volume due to various WRF and GRAMM 3D fields for stored variables of interest.

The GRAMM Match to observations algorithms were used to reduce the data volume and to expand the applicability specifically for regulatory purposes. The reduced flow field library contains only 1013 classified flow fields.

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