21st International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
27-30 September 2022, Aveiro, Portugal

RECENT DEVELOPMENTS IN HIGH-RESOLUTION WIND FIELD MODELLING IN COMPLEX TERRAIN FOR DISPERSION SIMULATIONS USING GRAMM-SCI

Dietmar Oettl

Regional Government of Styria, Austria

Abstract: The rather complex terrain in Austria requires that wind fields with sub-kilometer resolutions be generated prior to any kind of dispersion modelling. Proper modelling of highly-resolved flows in alpine regions is still a matter of research and no harmonized methodology is available at the moment. In order to harmonize the meteorological input for dispersion modelling at the regional level, authorities in Austria aim at providing so-called wind-field libraries for a certain reference year for all stakeholders involved in air-quality assessments. The region of Styria was the first one, who established a library using the prognostic, non-hydrostatic mesoscale model GRAMM with a horizontal resolution of 300 m in 2015. Over the years attempts have been made for improving the quality of the wind fields. One of the most challenging issues is the interaction between synoptic-scale flows and local thermally-driven winds. In this work the newly developed mesoscale model GRAMM-SCI is presented, which is driven by ERA5 reanalysis data. Especially, novel nudging techniques allow for nesting and downscaling wind fields with a horizontal resolution of 100 – 200 m. Moreover, a methodology called 'match-to-observation' will be presented, which greatly improves the final quality of wind fields. For the first time, a wind-field library for the reference year 2017 has been generated for Styria with this new approach.

Key words:** GRAMM-SCI, wind-field simulations, complex terrain, ERA5.**

INTRODUCTION

Dispersion modelling in complex terrain is challenging for several reasons but most notably due to the influence of the topography on the local flow field. In particular, the interaction between local thermally-driven winds and synoptic-scale flows influence the dispersion of air-borne substances. Prognostic non-hydrostatic wind-field models are nowadays widely used for providing flow fields for local-scale dispersion models. In Austria, the Graz Mesoscale Modell GRAMM (Oettl, 2020a) has become an important tool for local authorities for generating so-called wind-field libraries, which are subsequently used as input to the Lagrangian Particle Model GRAL (Oettl, 2020b). Up to now, these wind-field libraries were based on a methodology, which did not allow for a proper initialization of GRAMM using large-scale meteorological fields. Since 2019 the GRAMM model has been further developed by the Air Quality Control unit of Styria, Austria, in order to make use of ERA5 reanalysis data (Copernicus Climate Change Service, 2017) for initialization and for prescribing transient boundary conditions. Model description and evaluation studies in alpine regions have already been published by Oettl (2020c), Oettl and Veratti (2021), Oettl (2021), and Oettl and Bergamin (2022). A brief overview about the most important developments will be presented in the next chapter.

METHODOLOGY

Brief description of GRAMM-SCI

In the presence of forests a drag law has been introduced in the conservation equation for the wind components according to

$$-c_D \cdot n \cdot LAD \cdot |U| \cdot u_i, \tag{1}$$

where c_D is an empirical drag-coefficient (0.15n^2), n is the dimensionless vegetation coverage, LAD the leave-area density [m²/m³], u_i the wind-speed component [m/s], and U the total wind speed [m/s]. The heights of trees are assumed to be 10 m for agro-forests, and 20 m for all other types. Currently, fixed values for the leave area densities are applied: 0.1 m²/m³ for deciduous and agro-forests, and 0.15 m²/m³ for coniferous forests. It should be noted that Wagner et al. (2019) and Leukauf et al. (2019) utilized the same approach for the WRF model. Furthermore, as pointed out by Stuenzi et al. (2021) forests have a large impact on radiative and turbulent heat fluxes. One of the main sources for increased surface temperatures within the forest canopy during the night is the so-called below-canopy longwave enhancement. This effect has been accounted for in GRAMM-SCI in a simplified way by reducing the emissivities ε of forested areas.

A new 1.5-order turbulence closure solving the prognostic equation for the turbulent kinetic energy k has been introduced in the current model version using a diagnostic formula for the dissipation rate of the turbulent kinetic energy. The required length scale is hereby calculated according to the proposal of Bougeault and Lacarrère (1989). The original terrain-following grid of GRAMM has been replaced by a hybrid grid using terrain-following coordinates up to the highest elevation within the model domain. Above this height the model levels have exactly the same height above sea level. In this way, strong vertical temperature gradients, i.e. in the transition zone between the troposphere and stratosphere, are captured better improving the representation of large-scale thermal-pressure fields. In the nested model runs, meteorological fields of GRAMM-SCI are nudged towards the corresponding fields of the previous model run using the following equation:

$$\varphi_{Nest} = \varphi_{Nest} - \alpha(\varphi_{Nest} - \varphi_0)dt \quad (2)$$

$$\alpha = e^{-\gamma(z)} \quad (3)$$

φ_{Nest} is any quantity of the nested model run and φ_0 is the corresponding quantity of the model run used for nesting. The variable $\gamma(z)$ not only is height dependent, but takes different values depending on the considered quantity but also on the nesting methodology. In the first model run, where GRAMM-SCI is driven by ERA5 data, $\gamma(z)$ is different than in the second model run, where GRAMM-SCI is nested within GRAMM-SCI. In the last model run, a so-called final downscaling technique is applied, where GRAMM-SCI fields are interpolated on a grid with a very high spatial resolution on an hourly basis. The main idea of the whole nesting methodology derives from the fact that large-scale pressure gradients acting outside of small modelling domains cannot be captured anymore. Therefore, model forcing via lateral boundaries and tentatively nudging techniques are required. Numerous test runs for different areas indicated that the usage of a nudging technique improves results compared when forcing is invoked exclusively at the lateral boundaries. It should be stressed that within the boundary layer a maximum degree of freedom remains in the model equations (i.e. $\alpha \sim 0$) such that local winds can develop. For a detailed description of the entire GRAMM-SCI model the reader is referred to Oettl (2022).

Model setup

Three nested modelling domains have been used (Figure 1). In the largest domain, where GRAMM-SCI has been driven directly by ERA5 reanalysis data, a horizontal grid resolution of 1 km has been defined. ERA5 data based on 6-hour intervals were utilized and boundary conditions have been updated every 3 hours accordingly. 26 layers were defined in the vertical direction and the first grid point 5 m above the surface. The model top was set at 18 km, and the first domain covers an area of 350 x 250 km². In addition, three nested model domains have been defined with a horizontal grid resolution of 400 m, 25 vertical layers with the model top at 15 km. Eventually, 23 subdomains with a horizontal grid resolution of 200 m have been set up, where a downscaling technique has been applied.

In order to establish the wind-field library for the reference year 2017, the time-series for the months January, March, May, July, August, October and December 2017 have been computed, which took about 5 months computation time utilizing two workstations with 16 cores each. In a second step, these hourly stored meteorological fields have been used as input for the so-called match-to-observation algorithm (e.g. Berchet et al., 2017). Hereby, the best-fitting wind field and corresponding stability-class field (derived from the computed meteorological fields of GRAMM-SCI) for each hour of the year is selected based on all available meteorological observations within the modelling domain. The number of stations varyies greatly among the 23 subdomains between only 2 in an alpine area and up to 17 stations in the greater area of Graz. Naturally, with increasing number of available observations it becomes more difficult to select a simulated flow field that would fit perfectly to all observations. Horizontal meandering of atmospheric flows in low-wind speed conditions, which are extremly frequent in Styria, is one reason, why it is impossible to compute flow fields in perfect agreement with observed wind speeds and –directions at a multitude of monitoring stations at a particular hour of the year (e.g. Marth, 2019).

The final results, which cover the entire year 2017 - even though not the whole year has been simulated initially - will be presented in the next chapter.

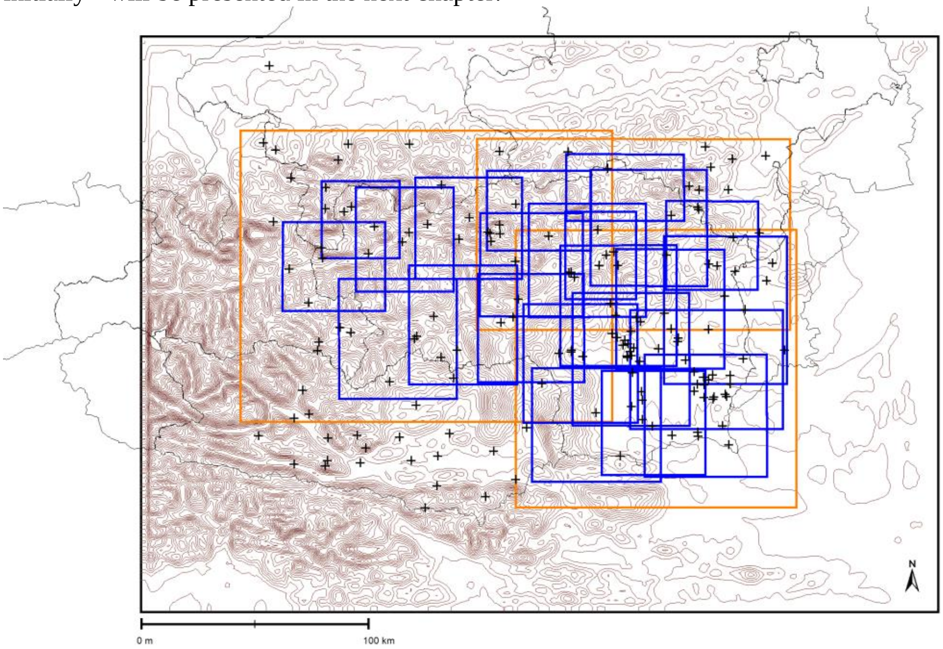

Figure 1. Model domain (black), nested model runs (orange), and downscaling domains (blue). Meteorological observation sites are indicated by crosses

RESULTS

Figure 2 depicts the mean hourly bias of wind speed and –direction averaged according to topographical characteristics of the monitoring sites. The largest bias of 3.4 ms^{-1} is found for monitoring stations at mountain sites due to the high absolute wind speeds usually observed at high altitudes, while the lowest wind speed biases (~0.5 m/s) are evident in basins and valleys characterised by low wind speeds. The differences in wind direction biases is smaller than for wind speed and varies only between 30 and 45 degrees, which is remarkable when considering the uncertainties in modelled wind directions associated with the unpredictable behaviour of horizontal flow meandering in low wind-speed conditions. The bias regarding the annual mean wind speed averaged over all available stations (in total 100) is less than 0.2 ms^{-1}. Even at the mountain sites the bias does not exceed 0.3 ms^{-1}, which would make the wind-field library probably suitable for the assessment of wind-energy potentials, too.

Figure 3 to Figure 6 illustrate a few examples of observed and modelled wind-direction frequencies. The colours indicate the frequency of certain wind speeds for each sector. Generally, very good results have been obtained with this respect for stations used for the match-to-observation algorithm. Nevertheless, a comparison with observations at monitoring sites not used for the match-to-observation algorithm (because these observations have been made in a different year than 2017) indicate also a satisfying performance of the modelling technique. A presentation of the evaluation at such sites is not possible here due to the page limitation. A comparison between the results presented in Figure 3 and Figure 5 is interesting, due to the fact that these monitoring sites are situated only 9 km apart. While the valley station is located at a height of 207 m above sea level, the hill station is at 415 m on top of a small hill. Though the vertical distance between the two sites is just about 200 m, a completely different wind regime is clearly visible. While westerly winds dominate at the valley station, caused by the valley of the river Mur, northerly and southerly winds are characteristic for the hill station indicating that large-scale pressure gradients already influence the station. Furthermore, the mean annual wind speeds are quite different. Notably, GRAMM-SCI is able to simulate such distinctive features.

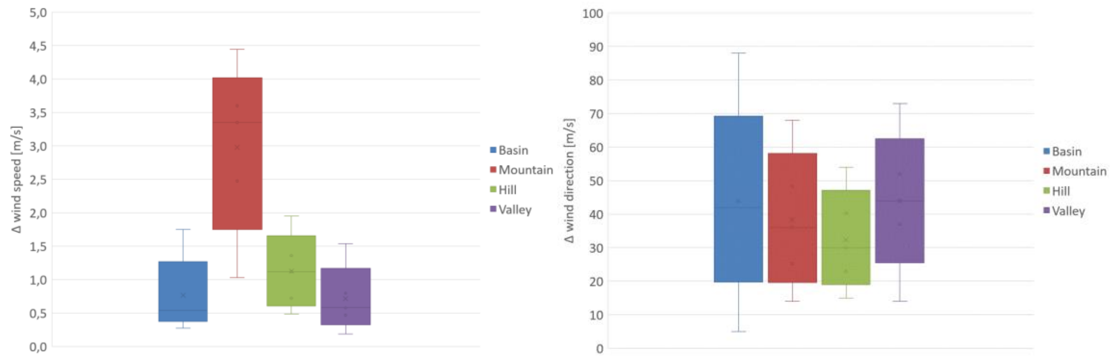

Figure 2. Hourly bias in wind speed and –direction averaged over the entire year and seperated according to the topographical characteristics of the monitoring stations used for the evaluation

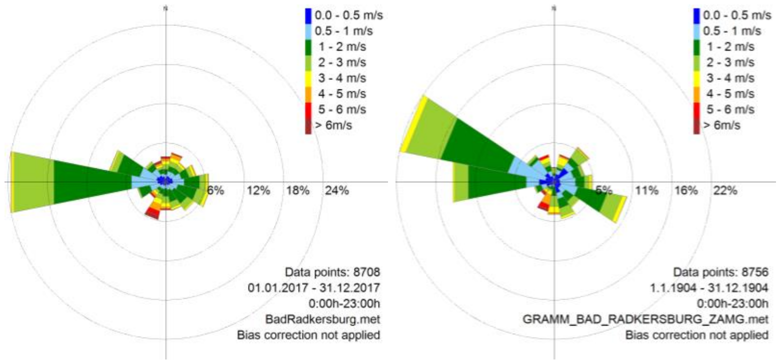

Figure 3. Comparison of observed (left) and modelled (right) wind-direction frequencies for a valley station

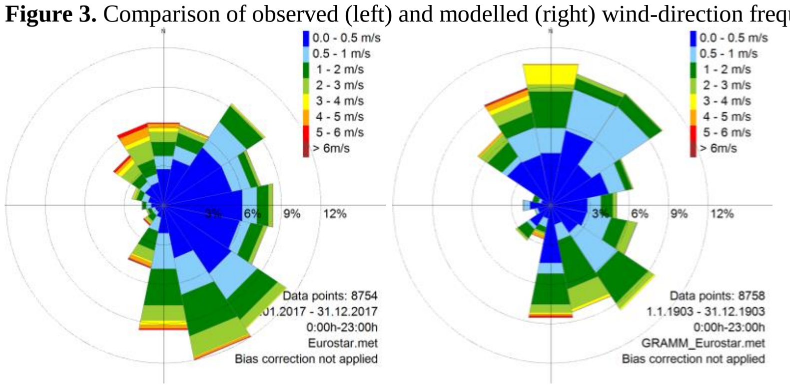

Figure 4. Comparison of observed (left) and modelled (right) wind-direction frequencies for a basin station

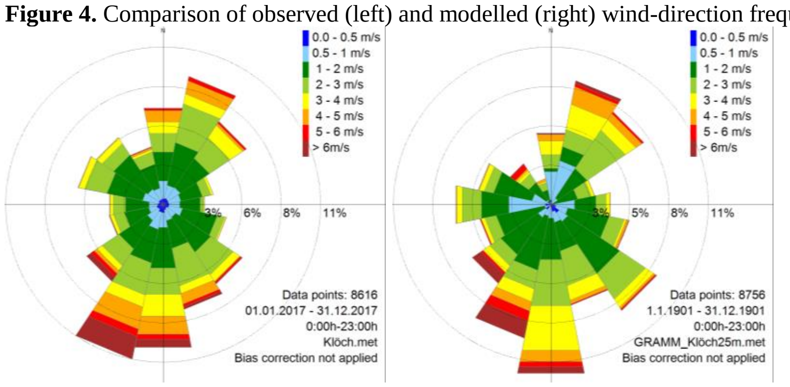

Figure 5. Comparison of observed (left) and modelled (right) wind-direction frequencies for a hill station

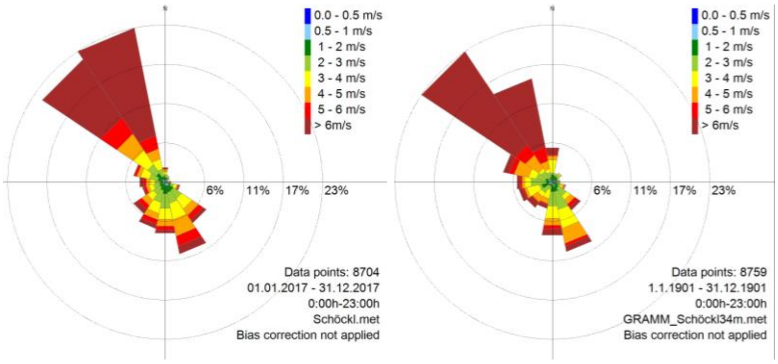

Figure 6. Comparison of observed (left) and modelled (right) wind-direction frequencies for a mountain station

REFERENCES

Berchet, A., K. Zink, C. Müller, D. Oettl, J. Brunner, L. Emmenegger, and D. Brunner, 2017: A cost-effective method for simulation city-wide air flow and pollutant dispersion at building resolving scale. *Atmos Environ*, **158**, 181-196

Bougeault, P., and P. Lacarrère, 1989: Parameterization of Orography-Induced Turbulence in a Mesobeta-Scale Model. *Mon. Wea. Rev.*, **117**, 1872-1890

Copernicus Climate Change Service (C3S), 2017: ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), date of access: *18 Mar 20*. https://cds.climate.copernicus.eu/cdsapp#!/home

Mahrt, L., 2019: Microfronts in the nocturnal boundary layer. *Q. J. Roy. Meteor. Soc*., **145** (719), 546-562

Oettl, D., 2020a: Documentation of the prognostic mesoscale Model GRAMM Vs. 20.1. Amt d. Stmk. Landesregierung, Graz, 125 pp (http://lampz.tugraz.at/~gral/)

Oettl, D., 2020b: Documentation of the Lagrangian Particle Model GRAL Vs. 20.1. Amt d. Stmk. Landesregierung, Graz, 208 pp (http://lampz.tugraz.at/~gral/)

Oettl, D., 2020c: Evaluierung des nichthydrostatischen mesoskaligen Modells GRAMM-SCI anhand der VDI Richtlinie 3783 Blatt 7. *Gefahrstoffe – Reinhaltung der Luft*, **80**, 318-324

Oettl, D., and G. Veratti, 2021: A comparative study of mesoscale flow-field modelling in an Eastern Alpine region using WRF and GRAMM-SCI. *Atmos Res*, **249**, 105288

Oettl, D., 2021b: Development of the mesoscale model GRAMM-SCI: Evaluation of simulated highly-resolved flow fields in an Alpine and Pre-Alpine region. *Atmos*, **12**, 298, doi: 10.3390/atmos12030298

Oettl, D., and L. Bergamin, 2022: Windfeldsimulationen mit GRAMM-SCI in herausfordernden topographischen Verhältnissen in der Schweiz. *Gefahrstoffe – Reinhaltung der Luft*, (in print)

Oettl, D., 2022: Documentation of the prognostic mesoscale Model GRAMM-SCI Vs. 22.6. Amt d. Stmk. Landesregierung, Graz, 125 pp (https://www.researchgate.net/publication/348620821_Documentation_of_the_prognostic_mesoscale_model_GRAMM-SCI_Graz_Mesoscale_Model_-Scientific)

Stuenzi, S.M., J. Boike, W. Cable, U. Herzschuh, St. Kruse, L.A. Pestryakova, Th. Schneider von Deimling, S. Westermann, E.S. Zakharov, and M. Langer, 2021: Variability of the surface energy balance in permafrost-underlain boreal forest. *Biogeosciences*, **18**, 343-365