DEVELOPMENT AND APPLICATION OF A MULTI-SCALE FLOW FIELD ANALYSIS SYSTEM FOR COMPLEX TERRAIN

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Abstract: An accurate representation of flow in complex terrain is of major importance particularly for air quality related issues as well as wind energy. For air pollution modelling, an adequate representation of low wind speed conditions and inversions is a key aspect. Local scale models can resolve topographic effects at fine resolution of order 100 m, however their initialisation and specification of boundary conditions is challenging. Regional models may represent the synoptic and regional flow pattern by using nesting techniques but still have limited resolution. Several studies reported wind speed biases over basins and valleys with different models at katabatic conditions, particularly during winter.
This study presents a multi-scale modelling approach to represent these different scales utilizing high spatial resolution models at the local scale. To realize this, hourly regional model results based on multi-nesting techniques were used to simulate regional flow at 1 km horizontal resolution and finally to initialise a local flow model at 250 m resolution Optionally, in case of strong differences between simulated wind speed and temperature, measurements were used to adjust the initialisation of the local scale model. The focus of this study is laid on challenging winter conditions with low wind speeds and inversions.

Key words: High Resolution Multi-Scale Flow Field Analysis, Complex Terrain

INTRODUCTION

Air quality related environmental assessment in complex terrain requires accurate wind fields with resolutions significantly below 1 km. Regional models are limited to minimum horizontal grid resolutions of about 1 km. Particularly challenging is an adequate representation of low wind speed (WS) conditions and inversions that are frequently encountered in valleys and basins causing poor dispersion conditions and may cause high air pollution levels. Particularly at stably stratified conditions, the representation of wind by regional and numerical weather prediction models is poor as reported by Jiminez and Dudhia, 2012, Sandhu et al., 2013, Uhrner et al., 2014. A wind speed (WS) overestimation in valleys was reported.
Local scale flow models can make use of high-resolution digital elevation model (DEM) and land-use data (e.g. CORINE land cover (Bosard et al, 2000) at minimum width of 100 m) to capture orographic and topographic features at fine resolutions, i.e. of order 100 m or even below. However, a major challenge is their initialisation and specification of boundary conditions at the local scale. Using wind and stability classes (e.g. Venkatram, 1996) from one representative measurement station to force the model is still a widely used concept at the local scale (e.g. Janicke and Janicke, 2004, Uhrner et al., 2014). However, this monitoring-based model forcing is rather restricted to small modelling domains (Uhrner et al., 2014).
Another option is to apply an ensemble of initial conditions (e.g. 18 different 20° flow directions, several different WS classes and 7 stability classes) to compute flow fields with high spatial resolution (Öttl, 2017). Thereafter, in a post processing procedure the best matching flow field is assigned to different monitored time series of WS, wind direction (WDir) and stability class. The advantage of this method is that several measurements located within the modelling domain may be used with the matching algorithm. However, this method relies on available measurements and is restricted to wind field reanalysis applications. Moreover, in order to be computationally efficient, it must be based on classified i.e. discretized simple initial conditions such as WS classes or WDir sectors.
In this work, a different initialisation and model forcing approach for complex terrain flow modelling is presented. Coupled multi-scale wind field computations are performed without using classified initial conditions.

AIMS

The aim of this study was firstly to use regional modelling results to initialise a local scale flow model to improve the representation of orographic and topographic features in mountainous terrain. For flow field reanalysis, a hybrid scheme which enables to use as well measurements to modify the regional-local scale model initialisation was developed and tested. Only in case of significant mismatches between simulated and monitored wind and temperature, regional model fields are adjusted by ground based measurements.

METHODOLOGY

In this study, the Weather Research and Forecasting model (WRF, Skamarock et al., 2008) was used at the regional scale with a multiple nesting strategy, starting at mainland Europe D01, Δx,y 25 km, D02 (see red rectangle Figure 1) Δx,y 5 km and finally D03 (see green rectangle Figure 1) at Δx,y 1 km, 130 km x 142 km. The ECMWF ERA-Interim (Dee et al., 2011) analysis was used to initialise WRF and the boundary conditions of domain D01. At the local scale the prognostic, non-hydrostatic model GRAMM (GRAz Meteorological Model, Almbauer et al., 2000, see Öttl et al., 2017 for details) model was used (see orange rectangle Figure 1).

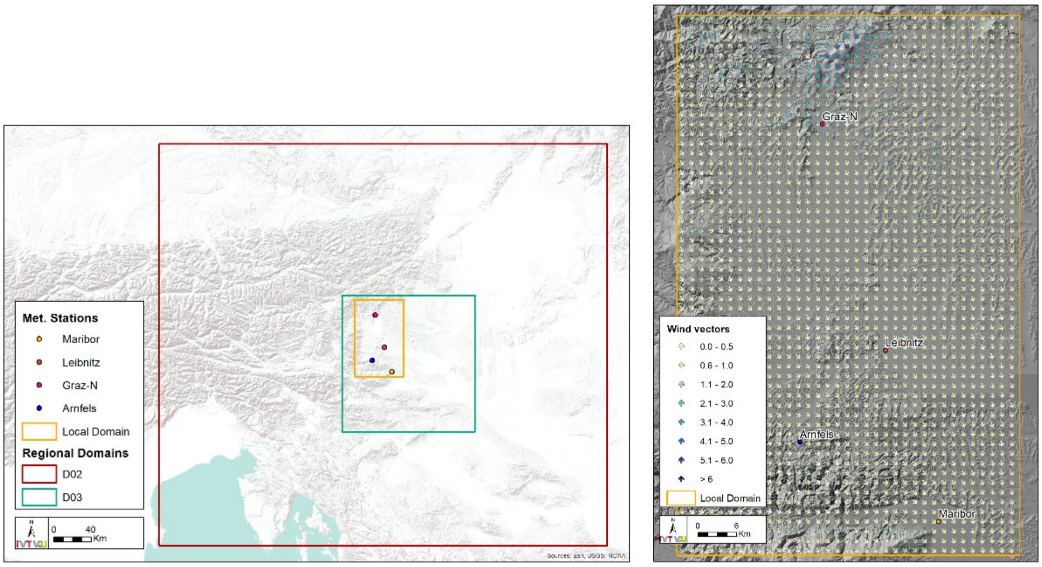

Figure 1. Approach and set-up. Regional domains D02 and D03 as well as local scale model domain are shown.

A regional-local scale interface was developed in order to extract and pre-process the relevant 3-d and 4-d fields (variables, grid specifications and regional orography), see Figure 2. WRF variables were transformed to UTM coordinates. WRF post-processed absolute pressure p, potential temperature θ, humidity q and horizontal wind components (u, v) are 3-d interpolated to the closest GRAMM grid points at Δx,y 250 m, each hour. A nearest neighbour method was used. At the fine local grid, these fields are used as a first guess for GRAMM initialisation, as these fields are distorted due to the fine orography (see height differences Figure 3). The GRAMM simulation solves for continuity within the 53 km x 84 km sized local scale domain using the SIMPLE algorithm (Patankar, 1980).

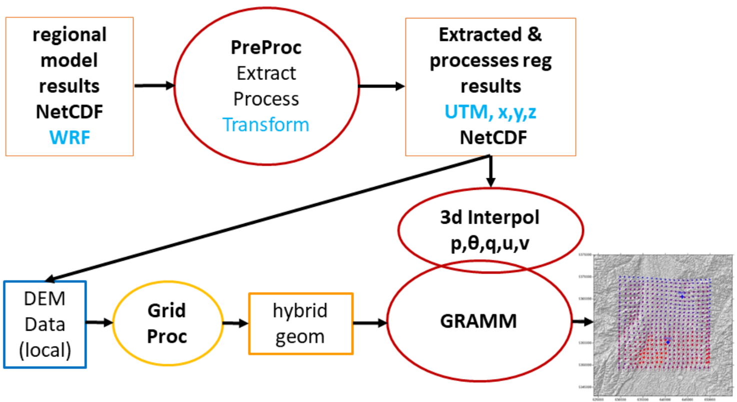

Figure 2. Schematic of the data flow regional-local and related processing and interfaces.

The lower boundary condition, i.e. the model orography changes substantially with increasing horizontal resolution and use of high resolution DEM. Figure 3 shows the related terrain height differences for the regional domain (D03) versus the local scale orography processed at Δx,y 250 m. In order to avoid severe distortions at the local domain boundaries, a hybrid orography grid processor was developed (Figure 2). At the 3 outermost grid points of the local scale domain, the regional terrain height is used and towards the core area there is transition zone from the regional towards the local orography at Δx,y 250 m. Here, 15 transition points were chosen. This approach can also be used in forecast applications.

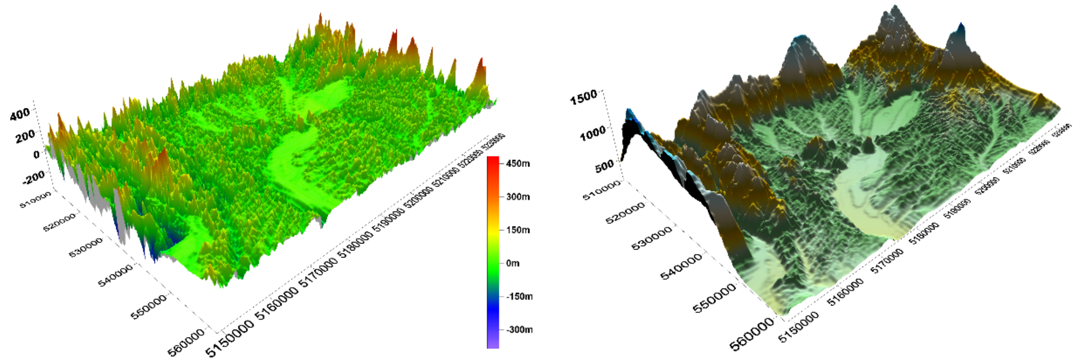

Figure 3. Difference regional – local orography (left) and processed hybrid orography with transition zone (right).

Uhrner et al., 2014, compared WRF simulated 10 m winds versus monitoring stations in Klagenfurt, Maribor and Leibnitz for a one month winter period. That period was characterised by calm wind conditions at all stations and a high air pollution burden. WRF simulated winds were overestimated by a factor of 2 to 3. WRF simulated solar radiation and temperatures were frequently overestimated compared to monitoring, resulting in poor representation of strong inversions. Apparently, there are periods where the valley and basin atmosphere is more or less decoupled from the synoptic or regional flow and a local monitoring driven model forcing at lower levels is important for flow field reanalysis applications. Therefore, a scheme was developed which enables a near surface monitoring based modified initialisation in case of significant WS and temperature mismatches. If the absolute values of the relative differences of the simulated (regional) and monitored wind component exceed the wind speed (*WS*) dependent criteria *crit* in equation (1), a monitoring based model forcing is employed:

$$|(u_{sim} - u_{mon})/u_{mon}| > crit \quad \&\& \quad |(v_{sim} - v_{mon})/v_{mon}| > crit \tag{1}$$

For $WS \leq 0.8\ m/s$ *crit* is set to 1, for $0.8\ m/s < WS \leq 1.5\ m/s$ *crit* is set to 0.5, and for $WS \geq 1.5\ m/s$ *crit* is set to 0.25. In case of potential temperature θ deviations above 1°K, the WRF interpolated temperature and temperature profile is adjusted. In order to account for prevailing large-scale winds a vertical profile weighting function was introduced to use the regional models output at the higher levels. Each grid point is weighted by the function described in equation (2), Δz is the distance of each grid point to the orographic model height, $H_{max\ peak}$ is the maximum peak height and H_{min} the minimum terrain height within the local model domain:

$$zwgt_{i,j,k} = 1 - \Delta z_{i,j,k}/(H_{\max peak} - H_{min}) , \qquad \text{with } zwgt_{i,j,k} \leq 1 \tag{2}$$

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. This modified initialisation approach is restricted to wind field reanalysis. A large local-scale modelling domain was chosen (Figure 1) to represent comprehensive mountain and valley wind systems.

RESULTS

Results from two different WRF-GRAMM flow field computation approaches (App) are presented in Figure 4, for January 1st, 22:00, 2010. The synoptic flow pattern was predominantly north-easterly. In the first approach (App 1), GRAMM was initialised by WRF interpolated fields, see Figure 4 (top), in 2nd Approach (App 2), GRAMM initialisation used additionally ground based monitoring (Fig. 4 bottom).

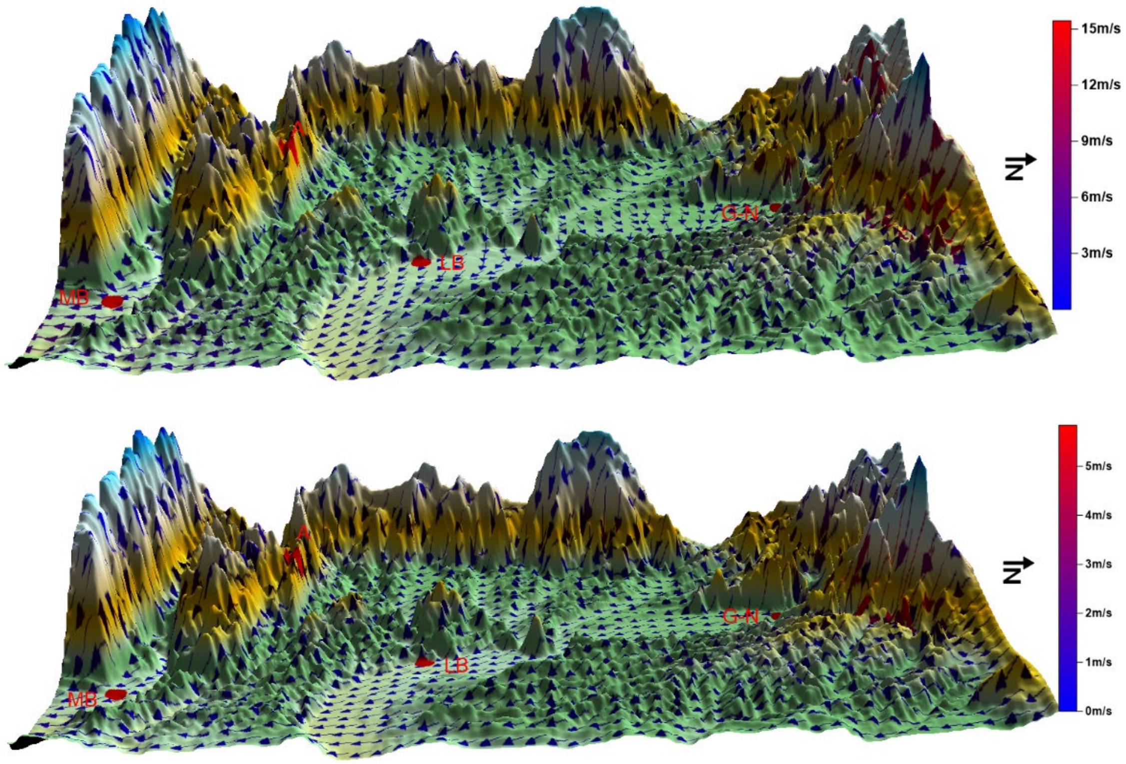

Figure 4. Local flow fields with WRF-GRAMM initialisation (top) and WRF/monitoring initialisation (bottom).

The wind fields are in principal quite similar, the flow is channelled and mountain winds prevail in the main valleys. The wind speeds are significantly increased at the high mountains north of the station Graz North (G-N, Fig.°4). In Figure 5 the simulated WS and WDIR are shown for the location Graz-North for the first 10 days of January 2010 (App 1). There is a fair match of simulated and monitored wind speed, on average simulated WS is overestimated by a factor of 1.4. At the stations Leibnitz (LB) and Maribor (MB) wind speed is overestimated by a factor of 1.09 and 1.35, whereas at the hill station Arnfels (A) the wind speed is underestimated (0.73). WDir is respresented well compared with measurements.

For the 2nd approach (App 2) WS and WDir are shown correspondingly in Figure 6. Compared with the first approach simulated WS and WDir are improved at all 4 stations. There is a slight tendency towards underestimation of simulated winds.

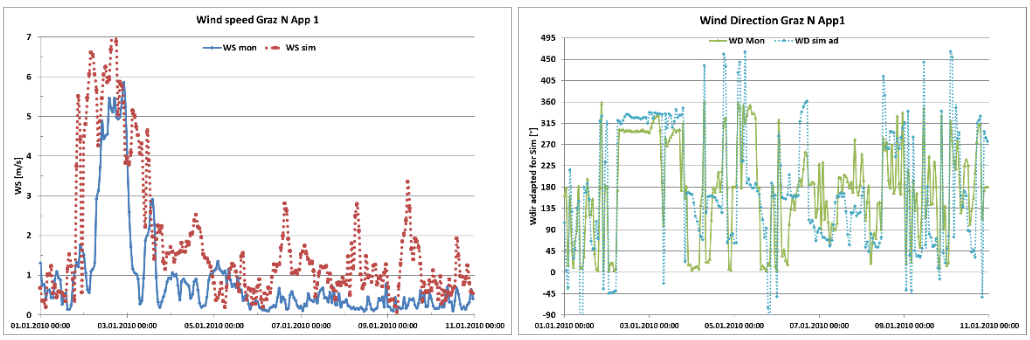

Figure 5. Monitored and simulated WS (left) and WDir (right) for Graz N, Jan. 2010, WRF-GRAMM initialisation.

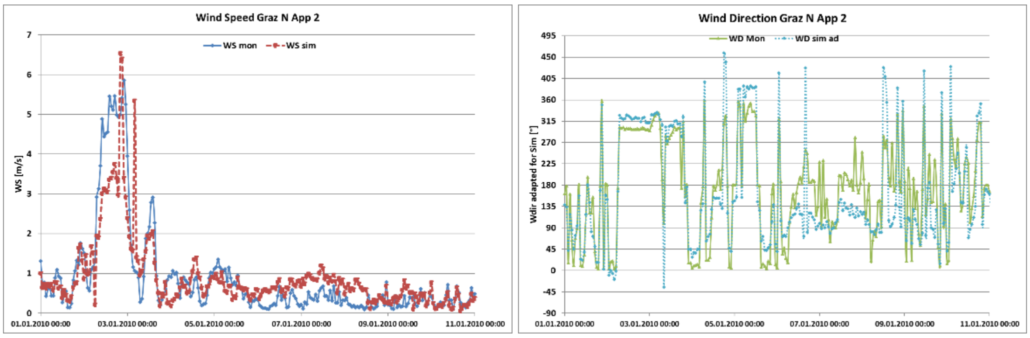

Figure 6. Monitored and simulated WS (left) and WDir (right) for Graz N, Jan. 2010, WRF-GRAMM/monitoring initialisation.

SUMMARY

Local scale flow field computations were carried out with GRAMM, which was operated at Δx,y 250 m. For model initialisation, regional WRF calculated fields (p, θ, q, u, v) were used. The regional model WRF was operated with nesting techniques using finest horizontal resolutions of 1 km. The combination of the regional scale model WRF and the local scale model GRAMM worked well and yields a good representation of mountain and valley wind systems. The representation of wind speed and wind direction was significantly improved compared to the regional scale simulations. The use of WRF-GRAMM significantly reduced excess momentum. However, at basin and valley locations simulated wind speeds are still overestimated (up to 40 %).

A modified initialization which enabled to use as well multiple wind and temperature measurements resulted in an excellent to good representation of wind speed and direction. However, there is a slight tendency of underestimating higher wind speeds (> 3 m/s) at basin and valley locations.

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