Current Challenges for Numerical Weather Prediction in Complex Terrain: Topography Representation and Parameterizations

Brigitta Goger
Mathias W. Rotach
Alexander Gohm
Ivana Stiperski
Insitute of Atmospheric and Cryospheric Sciences (ACInn)
University of Innsbruck
Innsbruck, Austria
Email: brigitta.goger@uibk.ac.at

Oliver Fuhrer
Federal Office of Meteorology and Climatology (Meteo Swiss)
Zürich, Switzerland

***Abstract*—A very important component of modern weather forecasting is the use of numerical weather prediction (NWP) models. In the last years, the forecast quality of those models constantly improved, mostly due to major improvements in high-performance computing, which allows a finer horizontal grid resolution. Mountainous terrain, however, still poses a challenge for NWP models, mainly due to not sufficient resolution of the underlying topography, but also due to physical parameterizations based on assumptions for horizontally homogeneous and flat (hhf) terrain. In our study, we evaluate the performance of the high-resolution NWP model COSMO in complex terrain, namely in the Inn Valley, Austria. We compare the measurements of two representative weather stations (one located at the valley floor and one located at a north-facing slope) with the model and investigate the spatial variability of the simulated flow field. The model is generally able to simulate the thermally-induced circulation in the valley appropriately, however, there are differences between the two locations. The model has a worse skill at the slope site, which may be related to poorly resolved topography. Further, the model exhibits problems in simulating boundary-layer processes at both stations, which supports the hypothesis of insufficient parameterization of boundary-layer processes in complex terrain.**

***Keywords*—Atmospheric Science; Numerical Weather Prediction; Model Evaluation; Complex Terrain**

I. Introduction

Numerical Weather Prediction (NWP) has gone through significant improvements in the last 20 years [1]. Increasing computing power and efficient numerical methods as well as more sophisticated physical parameterizations led to a huge improvement of weather forecasts. Besides global weather prediction models and climate models, which operate on a relatively coarse horizontal grid spacing (Δx=10-50 km), and numerous limited-area models (LAM) are often operated by national weather services at specific areas of interest with much higher horizontal spacing of Δx=1 km or even less [2]. A higher horizontal resolution of NWP models leads to a better representation of the atmospheric boundary layer, which is the lowest part of the troposphere that results from the direct interaction between the earth surface and the atmosphere on time scales of around one hour [3].

In mountainous terrain, high-resolution NWP models bear a huge potential for better forecasts, because local weather is highly influenced by topography and the resulting mesocale and small-scale processes. The importance of the correct modeling of atmospheric processes in complex terrain has been pointed out frequently [4]–[6]. However, the modeling of atmospheric processes in complex terrain is often limited to idealized simulations [7]–[9] or to the simulation of "golden days" of extensive measurement campaigns [10]–[12]. Operational NWP models often have a horizontal resolution of several kilometers, while turbulence-resolving models (large-eddy simulations, LES hereafter) are very costly and are not yet suitable for operational usage. Between those two extremes in terms of horizontal grid spacing lies the so-called "grey zone" or "terra incognita" [13]. With a horizontal resolution somewhat between Δx=1.5 km and Δx=0.2 km turbulence or convection is not completely parameterized anymore, but also not yet fully resolved on the model grid. This partition of flow fields into a sub-grid and resolved part in the model leads to a so-called "double-counting" problem, followed by an overestimation of turbulent fluxes and exchange processes [14].

However, especially in mountainous terrain grey-zone simulations bear advantages in comparison to coarser models, since the topography, land-use, and soil moisture, which have a high impact on the resulting atmospheric structure, are much better resolved [15]. This suggestion is in agreement with [8], who concluded from their simulations of an idealized valley that the correct representation of topography has a larger influence on the correct simulation of the boundary-layer structure than the employed turbulence scheme. Besides the smaller impact, the physical parameterizations themselves pose a problem for simulations in complex terrain. Turbulence and radiation schemes were developed based on assumptions for horizon-

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tally homogeneous and flat (hhf) terrain and only treat the vertical exchange while not considering horizontal contributions. In mountainous terrain, however, turbulent boundary-layer processes are considered as fully three-dimensional [16], while incoming radiation has to be corrected for slope inclination angle [17].

In this work, we evaluate a pre-operational setup of a high-resolution state-of-the-art NWP model in truly complex terrain with high-quality measurements located in the Inn Valley, Austria. We try to disentangle the several contributions of multi-scale processes and their representation in the model.

II. Data and methods

A. Numerical Model

In this study, the COSMO (Consortium for Small-scale Modeling) model is used. The model was initially developed at the Deutscher Wetterdienst (DWD), but we use a pre-operational setup of Meteo Swiss (MCH). COSMO [18, see www.cosmo-model.org] is a non-hydrostatic limited-area numerical weather prediction model designed for operational use. It solves the governing meteorological equations on a non-uniform staggered grid. The code is parallelized and written in Fortan 90, and the present simulations are run with 512 cores on the Vienna Scientific Cluster [VSC-2, see http://vsc.ac.at/systems/vsc-2/hardware/ for technical details].

In our setup, the model consists of two domains. The outer domain is used for providing the boundary conditions, spans Europe, and is run on a horizontal grid of Δx=7 km (corresponding to the operational COSMO-7 set-up at MCH). The inner domain is operated on a horizontal grid mesh size of 1 km and with 80 vertical levels, while the lowest model half-level is located at 10 m above ground. The vertical grid is stretched and formulated in SLEVE coordinates [19], [20]. The inner domain (Fig. 1) consists of 800×600 grid points and spans the main Alpine range.

Our area of interest is the Inn Valley, Austria, which lies in the Eastern Alps surrounded by mountain peaks between 2000 m and 3000 m above mean sea level (amsl). The grid of the inner domain is able to resolve all major Alpine valleys and also some tributaries. A closer look at the terrain representation (Fig. 2) of the Inn Valley reveals the following: (i) the Inn

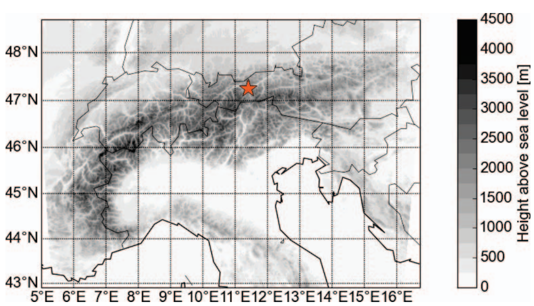

Figure 1. Location and size of the inner model domain. Grey-shading represents topography. The stars indicate the area of interest, the city of Innsbruck (Austria) and surroundings.

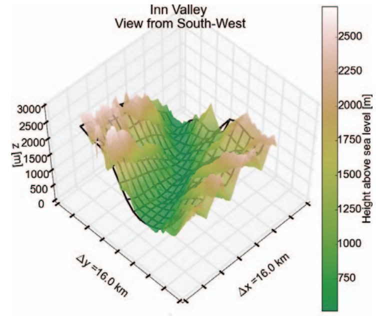

Figure 2. A 3D plot of the area of interest, the Inn Valley. The colors represent the real terrain, while the black grid shows the terrain as represented in the model on a grid spacing of Δx=1 km.

Valley itself is well-resolved both in width and height, (ii) slopes in the model are flattened (partly due to numerical stability considerations), (iii) mountain peaks are too low and side valleys are not fully resolved.

We select specific days for model case studies after specific criteria. In this study, we present a day with weak synoptic forcing and cloud-free skies which leads to a dominance of local thermally-driven flows. The model is initialized at either 00 UTC or 12 UTC and is run for 24 hours.

B. Measurements

We evaluate the model with the so-called "i-Box" measurements [21, submitted], which are located some 30 km east of the city of Innsbruck, Austria. The i-Box consits of several measurement sites, mainly flux towers measuring turbulent variables and remote sensing systems in Innsbruck. Fig. 3 shows the spatial distribution of the flux tower stations: The main station (Kolsass) is located on the valley floor, while the other stations are located on the north-facing and on the south-facing slopes and on a mountaintop. The different locations of the stations are representative for mountainous terrain and give an overview of the current atmospheric boundary layer structure. In this paper, we will mainly show results from the two stations indicated in orange in Fig. 3.

C. Model evaluation

Besides the challenges associated with the measurements in complex terrain themselves [22], the comparability with the

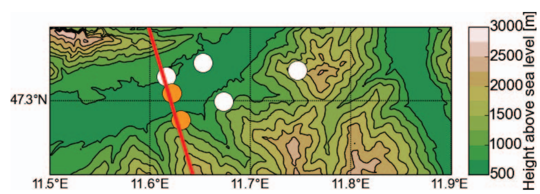

Figure 3. The i-Box stations (location indicated by points), with the real topography (isolines every 250 m in the vertical) of the Inn Valley. The stations of specific interest in this study are marked with orange dots: Kolsass (545 m amsl) on the valley floor and Hochhäuser (1008 m amsl).

model output has to be considered, too. The closest grid point in the model to the station is usually found by computing the Euclidean distance. However, in complex terrain, one should consider the fact that the "closest grid point" may be located at a different height, slope angle, or both. Therefore, we chose to include the eight "next closest" grid points in our model evaluation too, and created a small grid point "ensemble", which gives a first indication for inner-model variability. In the vertical, the first problem is the fact that the closest grid point is usually located at a different height than in reality. For certain meteorological variables, e.g. temperature, height corrections [23], [24] are well-established, however, for most other variables, vertical profiles have to be known to make assumptions. Furthermore, the lowest model level is usually not located at the same height as the sensor of the measurement station. In the present work, we did not apply any correction, however, these issues have to be considered when comparing direct model output with observation data.

III. Results

A. Daytime thermally-induced circulation

In this section, we present the results of a so-called "valley wind day" (16 Sep 2014) for two stations, namely Kolsass (545 m amsl, valley floor) and Hochhäuser (1008 m amsl, north-facing slope, slope angle 27°). On clear-sky days with weak synoptic forcing, a thermally-induced valley wind circulation establishes in valleys [25]. Soon after sunrise, upslope flows develop on sun-exposed slopes due to temperature difference between the slope layer and the valley atmosphere. In the Inn Valley, slope flows are not uniform on both slopes due to the west-east orientation of the valley [26]. Fig. 4 shows a vertical cross-section through the Inn Valley at 10 UTC from the direct model output. The model is able to simulate the slightly asymmetric up-slope flows on both slopes with sufficient quality.

Before or around noon, a strong up-valley wind establishes due to the stronger heating of the valley atmosphere over the adjacent plain, that can reach wind speeds up to 8 m s^{-1} [27], [28]. The typical structure of the up-valley wind at our area of interest is presented in Fig. 5. When the sun sets, the valley wind breaks down and down-valley drainage flows form usually later during the night (not shown).

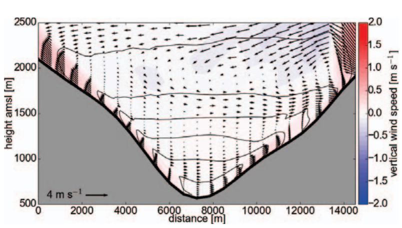

Figure 4. A south-north cross-section along the red line in Fig. 3 through the Inn Valley on 16 Sep 2014 (10 UTC) interpolated from direct model output. The colors indicate the vertical wind component, while the arrows indicate wind vectors.

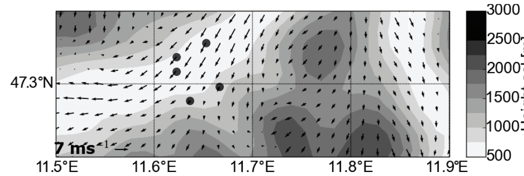

Figure 5. Simulated flow field in the Inn Valley at 16 Sep 2014 (14 UTC): Arrows indicate horizontal wind vectors at 10 m above ground level (lowest model level), with a reference vector in the lower left corner. Model terrain height is shown as gray shadings.

B. Spatial variability

When we compare timeseries of the model output with the observations (Fig. 6), we can immediately see the large spatial variability in both model and measurements. Although the stations are only a few kilometers apart, the wind regimes are distinctly different.

For the station on the valley floor, Kolsass (left panel in Fig. 6), the model is generally in good agreement with the observations. The daytime valley wind circulation is present, especially between 09 UTC and 18 UTC, where strong up-valley winds (wind direction $\approx 90°$) prevail. Differences in model and observations arise in the strength of the wind maximum and wind directions during the night.

For the station Hochhäuser (right panel in Fig. 6), a different picture emerges. First of all, the wind regime at this station is completely different from the valley floor station: The slope station is mainly dominated by (weaker) slope flows, which is obvious in both wind speeds (below 2 m s^{-1}) and in the wind direction (immediate changes after sunrise/sunset). The up-valley wind, however, influences the slope station especially between 09 UTC and 18 UTC; but is not as strong as on the valley floor.

C. Turbulence structure

The turbulence kinetic energy (TKE) is an important quantity for describing the structure of the atmospheric boundary layer. Unfortunately, the TKE is usually not observed by operational weather stations; the i-Box stations, however, provide measurements of TKE as seen in Fig. 7. The station Kolsass (left panel in Fig. 7) exhibits in both observations and model

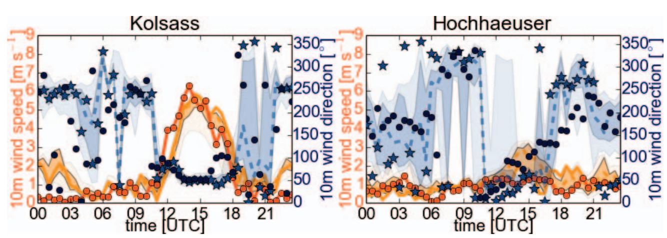

Figure 6. Time series of modeled and observed wind speed (orange) and wind direction (blue) at Kolsass (left) and Hochhäuser (right) for 16 Sep 2014. Points indicate measurements, while straight lines and stars indicate direct model output from the lowest model level. The grid point ensemble representing the 75% and 90% percentiles is also visible via the "clouds" around the model output.

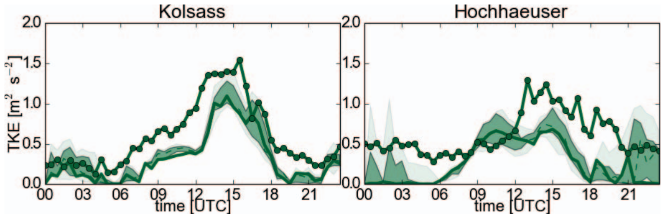

Figure 7. Time series of modeled and observed TKE of Kolsass (left) and Hochhäuser (right) for 16 Sep 2014. Points indicate measurements, while straight lines indicate direct model output from the lowest model level. The grid point ensemble is also visible via the "clouds" around the model output.

output low TKE values during the night, while during the daytime TKE is increasing until a maximum in the afternoon (15 UTC) is reached. This maximum in TKE correlates well with the valley wind maximum (Fig. 6), which indicates a shear-generated TKE production. Generally, the TKE structure is well represented, despite the general underestimation of absolute values.

At the slope station, Hochhäuser (right panel in Fig. 7), the model struggles to produce any TKE during nighttime. This is in disagreement with the measurements, which indicates sources of turbulence unresolved by the grid during nighttime. Another deficiency is the representation of the TKE structure during daytime, and the absolute values in the model TKE are in larger disagreement than for the valley floor station. An interesting feature to point out is the fact that the two stations have almost similar values in TKE maxima (1.5 m^2 s^{-2} in Kolsass and 1.3 m^2 s^{-2} in Hochhäuser), while the production terms are quite different [21, submitted]. This is another hint for some unresolved processes contributing to the TKE structure at Hochhäuser station, especially during the night.

IV. Discussion and Conclusions

In this paper, some of the challenges and shortcomings of a NWP model setup in truly complex terrain are discussed. We operate a high-resolution (Δx=1 km) version of COSMO in the Inn Valley, Austria, and evaluate the output with high-quality measurement data (i-Box stations). Two stations (valley floor and slope) are selected for comparison.

The model is generally able to simulate the daytime thermally-driven winds in the valley. The high spatial variability of the wind regimes is shown in time series of the wind speed and direction of model output and observations. Especially the up-valley wind is well-established at the valley floor station, while the slope flow-dominated station shows some shortcomings. One of the main reasons for this is probably the terrain representation: in reality, the slope angle of this station is 27°, while the slope in the model is much flatter (slope angle = 15°). Another aspect of this misrepresentation may be the the fact that shallow slope flows are not resolved correctly, since the lowest model level is located 10 m above ground.

A similar picture can be observed when the model is evaluated for the TKE: The valley floor station dominated by the up-valley wind generally shows a better performance than the slope station. Besides the terrain representation, in this case the model's turbulence parameterization [17, Appendix B] may be a further shortcoming. The parameterization is developed for hhf terrain, hence for flat, idealized surfaces, a condition, which is obviously violated at a sloped surface in complex terrain. The turbulence parameterization also only considers the vertical exchange while neglecting horizontal contributions. A switch to a 3D TKE scheme and corresponding inter-comparison studies are presently underway.

The nighttime TKE structure is misrepresented, which is related to the formation of a stable boundary layer, which is is known to be one of the major challenges for NWP models [29]. Many nighttime boundary-layer processes, such as intermittent turbulence events, nighttime downslope katabatic flows, weak gravity waves, and shallow inversions [30] are not resolved with the present horizontal grid spacing of Δx=1 km. For that, we are planning higher-resolution simulations with COSMO to estimate the impact of horizontal resolution on the correct simulation of the turbulence structure.

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