Interreg III B

Alpine Windharvest

ALPINE WINDHARVEST

Development of information base regarding potentials and the necessary technical, legal and socio-economic conditions for expanding wind energy in the Alpine Space*

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CFD Modeling Evaluation

(Summary of WindSim CFD modeling procedure and validation)

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ALPINE WINDHARVEST

…is an interdisciplinary research project funded by the EU Interreg IIIB "Alpine Space Programme" (Project No. A/I-2/3.1/5) and by national and regional co-financing bodies of the project partners. The project started in May 2002 and will end at the end of April 2005.

Background of the project:

Wind power became a leading renewable energy technology in flat terrain, especially near shore. While the alpine space also promises some excellent wind locations, much of the knowledge and experience accumulated about wind power so far cannot simply be transferred to the alpine setting.

The lack of experience concerns all levels of government confronted with problems of siting, spatial planning, nature protection/environmental impact analyses, road and electric grid requirements, appropriate tariff regulation etc. The project aims at remedying these deficiencies.

This lack of experience also regards entrepreneurs, investors and even producers of equipment given the special climatic and geological conditions. This increases economic risks, inhibits site exploration and planning activities even for attractive locations. The small number of existing projects in the alpine space impedes standard procedures.

Lack of experience also affects the acceptance of wind power by nature protection organisations and local residents. There is much need for additional knowledge and information; standard models for the resolution/mediation of conflicts will be useful.

For this reason, it is essential to pool the limited experience with wind power in the alpine space for synergy effects, cross-fertilisation and greater efficiency in developing data sets, methods, approaches and solutions for public and private actors, particularly since many of the underlying phenomena are trans-national while most research so far was primarily national (e.g. meteorology).

A common approach will facilitate a harmonised European approach to the problems under consideration, particularly with regard to government policy.

Main activities:

Develop knowledge basis for deploying wind energy:

a) Methods and instruments for identifying wind energy potential in complex terrain more efficiently (meteorologists, geographers, digital relief analyses and actual wind measurements; includes pilot measurements on specific locations).

b) Deal with problems peculiar to wind turbines in alpine conditions (blade icing; access - need for special mounting equipment); standardise technologies, estimates of access requirements (roads and grid). Common approaches for entire alpine space will create bigger market for improvements and induce responses from equipment manufacturers.

c) Analyse ecological impact of turbines in different alpine settings on fauna and flora according to altitude, soil/rock and meteorological conditions; establish check list of factors for whole alpine space. Develop strategies to minimise impact. Improve information for local/ regional authorities.

d) Analyse and compare legal, social, political and economic framework conditions for deployment of wind power in alpine space and their impact on its competitiveness. Formulate regulatory proposals.

e) Prepare methods of resolving conflicts between wind power and other interests (environmental organisations, local residents, hunting). Improve visualisations (more difficult in alpine terrain), standardise participation in administrative procedures and mediation. Facilitate work of local and regional authorities.

f) Measure potential contribution of this energy source to regional development, particularly when joined with hydro storage and electricity generation from biomass.

Alpine Windharvest Report Series:

The Alpine Windharvest Report Series is published by the Alpine Windharvest partnership network in order to disseminate the results of the project to the interested public and to experts in the field. Reports are edited by the responsible project partner(s) who commissioned and approved the report according to our internal division of labour. Reports can be downloaded from our homepage. Printed versions can be directly ordered from the project coordinator by e-mail: dieter.pesendorfer@sbg.ac.at.

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CFD Modeling Evaluation

Summary of WindSim CFD modeling procedure and validation

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Abstract

Within work package 7 of the Interreg IIIb (Alpine Space Program) project "Alpine Windharvest", CFD wind modeling was performed for 4 regions with 7 "hot spots" in Austria, Italy, Slovenia and Switzerland in order to gain know-how on CFD modeling in complex Alpine terrain, validate modeling results and promote wind power projects at the mentioned hot spots.

Validations of the modeling results were performed by comparisons of modeled to measured wind climatologies and by comparing modeled vertical wind profiles to profiles measured by SODAR. It was shown that WindSim provides a CFD modeling solution that fulfills the requirements for wind modeling in this type of terrain, in contrast to WAsP or similar diagnostic models.

Discrepancies between modeled and measured data could mainly be ascribed to terrain discretizations inherent to modeling as well as insufficient representation of obstacles, especially forests and hedges.

As is the case with any model of this type, WindSim is especially suitable for extrapolation of measurements within short horizontal distances and extrapolations from high enough measurement heights to hub height in nearby terrain with similar characteristics as the measurement site. High quality measurements at a height of at least 30 m above ground within the modeled park perimeter are essential.

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1. Introduction

METEOTEST was mandated within the Interreg IIIB Alpine Space Program Project 'Alpine Windharvest' with the implementation of work package 7 "digital relief analysis". In this work package one goal was to enhance wind assessments in alpine terrain.

Wind assessment in complex alpine terrain is a more demanding task than in flat terrain: Modeling wind conditions with standard linear models such as WAsP[1] does not sufficiently reproduce wind conditions in complex terrain. Yet in order to extrapolate on-site measurements to a wind turbine's position and hub height, appropriate modeling tools are essential. CFD modeling is a promising alternative to conventional approaches: With WindSim, a PC-based commercial CFD software for wind assessments is now available but has yet to prove its reliability for extremely complex alpine terrain.

It was therefore decided to perform Computational Fluid Dynamics (CFD) wind modeling with WindSim for several "hot spots" in order to achieve the following goals:

- gain know-how on CFD modeling procedures in alpine terrain
- validate CFD modeling results for alpine terrain
- promote regional development by supplying state-of-the-art wind assessments for wind energy projects

This report contains a short introduction to CFD theory and a description of the modeling concept. The results of CFD modeling in four regions covering seven "hot spots" are briefly presented. Validations carried out by climatology transfer and comparison of wind profiles to SODAR data in these regions are summarized. Recommendations on CFD modeling with WindSim in complex terrain are given.

Details on modeling setup and results for the individual regions and "hot spots" are documented in separate reports[2].

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1 www.wasp.dk

2 Schaffner et al., 2005: CFD Modeling Lungnau, Brenner, Franches Montagnes and Menina Planina. Alpine Windharvest Reports No. 7-8, 7-9, 7-10 and 7-11.

2. Modeling Concept

2.1. Introduction to Computational Fluid Dynamics

The physical aspects of any fluid flow (such as wind flow) are governed by three fundamental physical principles:

- Mass is conserved
- Newton's second law (force equals mass times acceleration)
- Energy is conserved

These fundamental principles can be expressed in terms of mathematical equations, which for fluid flow take the form of unsteady Navier-Stokes equations.

Computational Fluid Dynamics (CFD) is the science of determining a numerical solution to these equations whilst advancing the solution through space or time to obtain a numerical description of the complete flow field of interest.

In order to compute a numerical solution, the situation is discretized: Space is split into numerous small elements (boxes) for which flow is determined for small time steps. In wind energy applications this procedure is repeated until a steady-state flow is found for certain boundary conditions.

In contrast e.g. to WAsP, which calculates wind statistics by parametrizing the influence of topography, roughness and obstacles, CFD modeling computes the three-dimensional wind flow field. It can be compared to a virtual wind tunnel.

2.2. WindSim Basics

WindSim is based on the Phoenix 3D Reynolds Averaged Navier-Stokes solver. Solving the non-linear transport equations for mass, momentum and energy makes WindSim a suitable tool for simulations in both complex terrain, and in situations with complex local climatology. The Reynolds Averaged equations for conservation of mean mass and momentum are given in standard notation by Anderson et al, 1984[3]:

[3] Anderson et al., 1984.: Computational Fluid Mechanics and Heat Transfer. Hemisphere Publishing Corporation.

$$\frac{\partial U_i}{\partial x_i} = 0$$

$$U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \left(\overline{u_i u_j}\right)\right)$$

Where $\left(\overline{u_i u_j}\right)$, designed as the Reynolds stresses, is evaluated from the Boussinesq assumption:

$$\overline{u_i u_j} = -\nu_T\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) + \frac{2}{3}\delta_{ij}k$$

Where k is the turbulent kinetic energy, and ν_T is the turbulent viscosity. Different turbulence closures may be applied. In the presented material the standard k-ε model is used with standard setting of the model constants [2][4]:

$$\nu_T = c_\mu \frac{k^2}{\varepsilon}$$

$$\frac{\partial}{\partial x_i}\left(U_i \varepsilon\right) = \frac{\partial}{\partial x_i}\left(\frac{\nu_T}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right) + c_{\varepsilon 1}\frac{\varepsilon}{k}P_k - c_{\varepsilon 2}\frac{\varepsilon^2}{k}$$

$$\frac{\partial}{\partial x_i}\left(U_i k\right) = \frac{\partial}{\partial x_i}\left(\frac{\nu_T}{\sigma_k}\frac{\partial k}{\partial x_i}\right) + P_k - \varepsilon$$

By using transport equations for all variables including the turbulent quantities it is possible to capture downstream effects of terrain and roughness changes. In Figure 1 a simplified terrain with a sinusoidal variation illustrates how the development of a flow field evolves with a gradually growth of the boundary layer.

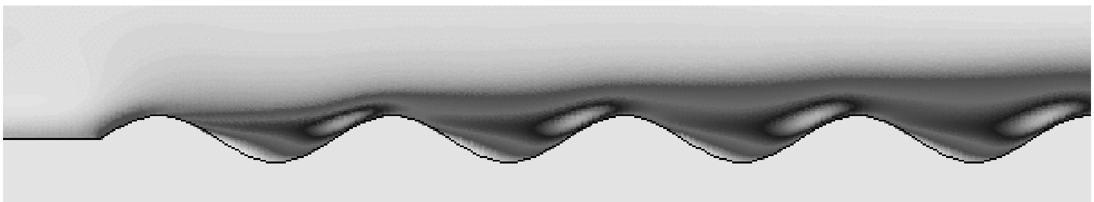

Fig. 1: Development of a flow field over a simplified, hilly terrain.

[4] Rodi, 1980: Turbulence models and their applications in hydraulic – A state of the art review. IAHR Monograph, Delft the Netherlands.

These characteristics cannot be captured with simplified models commonly in use within the wind industry today. Notice that the flow condition depends on the number of hills upstream. A refined modeling around one of the hills would require information about the upstream conditions. This problem of setting proper boundary conditions is one of the challenges within numerical flow simulations in complex terrain.

Validations of WindSim have been performed in both smooth and gently complex terrain[5][6][7][8].

The input basis for WindSim consists of a digital terrain model on a proper length scale, according to the phenomenon under consideration. WindSim can be used in a variety of length scales ranging from detailed micrositing up to larger meso scale wind resource assessments. WindSim uses so called body fitted co-ordinates (BFC) with refinement towards the ground.

In addition to the digital terrain model, a similar model with terrain roughness must be supplied. The terrain roughness has a particular impact in a zone towards the ground.

Finally, WindSim needs climatological data from at least one point within the modeled area. With these primary inputs the wind resources for the whole area can be calculated, the energy production from any number of wind turbines can be obtained, and the area with infrastructure can be visualized in the 3D interactive visualization module.

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[5] Schaffner, Gravdahl, 2003: Wind Modeling in Mountains: Intercomparison and Validation of Models.

[6] Gravdahl, 1998: Meso Scale Modelling with Reynolds Averaged Navier-Stokes Solver – Assessment of wind resources along the Norwegian coast. International Energy Agency Annex XI, Risø Denmark.

[7] Leroy, 1999: Wind field simulations at Askervein hill. Internal VECTOR report.

[8] Gravdahl, Harstveit, 2000: WindSim – Flow simulations in complex terrain, Assessment of wind resources along the Norwegian coast. DEWEK.

2.3. WindSim Modeling Techniques

2.3.1. Gridding

The model domain is gridded into cells, for the nodes of which the calculations are performed: the higher the number of boxes, the better the resolution. The computing time needed is exponentially proportional to the number of cells. Figure 2 shows an example for the gridding of a model domain into cells.

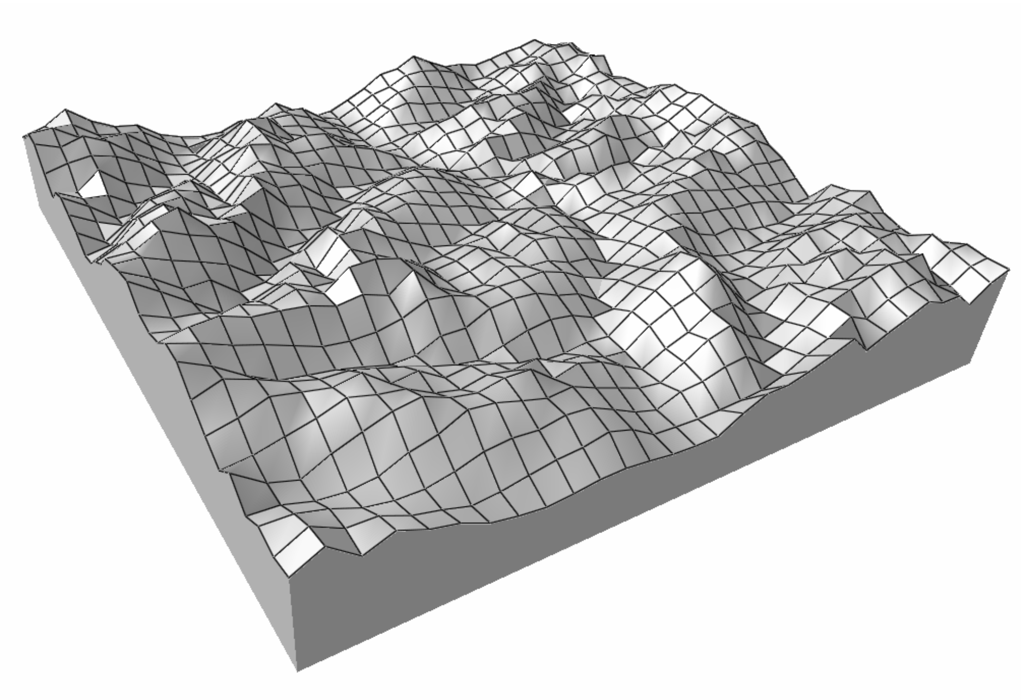

Fig. 2: Example for gridding of a model domain (Brenner viewed from the southwest, gridded into 30 x 30 cells of 1 x 1 km size each).

2.3.2. Nesting

Nesting allows calculating high resolution results with acceptable computing resources. The model can be refined in several nesting steps. The first step includes the whole model domain. Here, very general boundary and initial conditions are assumed: vertical wind speed as log profiles up to a defined height and constant wind speed above. The results of this step are used as boundary and initial conditions for the second nesting step, which is performed for a smaller area at a higher resolution. Further nesting steps can follow, until the desired resolution is reached. Figure 3 shows a nesting example.

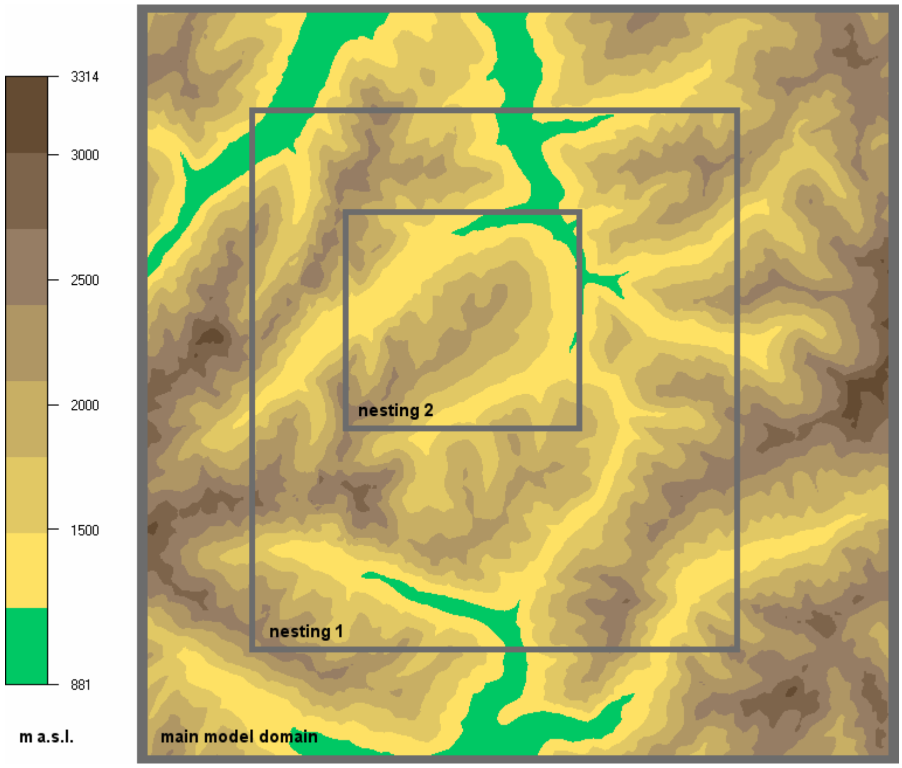

Fig. 3: Nesting example for Brenner, Austria and Italy.

2.3.3. Sectoring

Flow calculations are performed for a number of predefined wind directions at the model boundaries. Usually, 12 or 16 wind direction sectors are used. For each of these sectors, a flow calculation is performed until a steady-state solution is found. For laminar flow, it can be assumed that the flow fields for a certain sector will be proportional to the incoming wind speed and will not change their characteristics for different wind speeds. Figure 4 shows an example of computed wind flow.

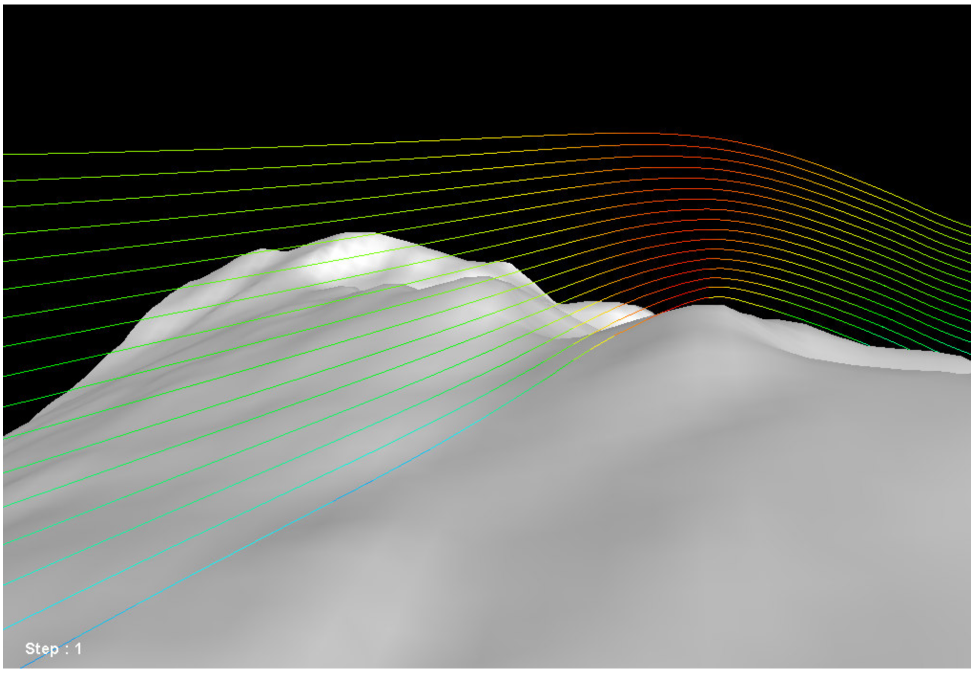

Fig. 4: Example for streamlines computed over a hill (Brenner, Austria and Italy; for wind direction 120°). The streamlines are colored according to wind speed.

2.3.4. Climatology and Weighting

In order to compute the wind resources, a local wind climatology (e.g. from a measurement station within the model domain) is needed. This climatology is split into the same wind direction sectors that were used for modeling. For all wind directions, the climatology's wind statistics are transferred to all other locations in the model domain by weighting it with the ratio of the computed wind speed between the climatology's location and the new location. Figure 5 shows an example of a wind resource map.

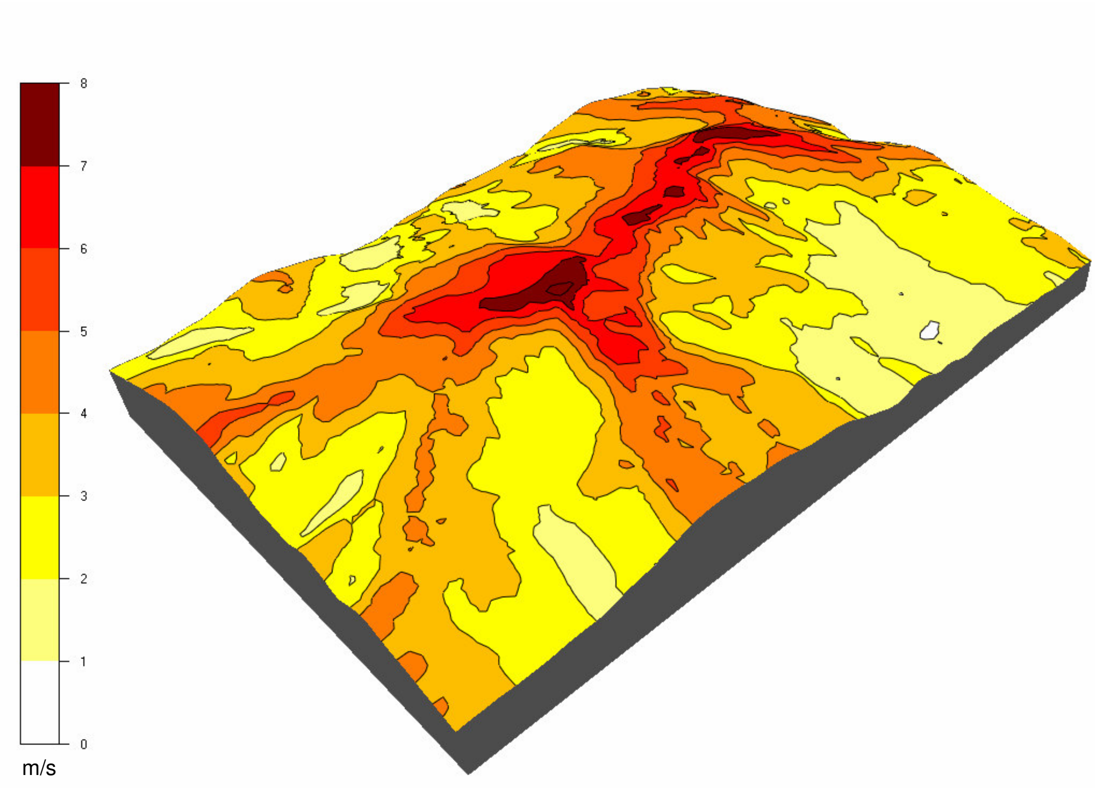

Fig. 5: Example of the resulting wind resource map at 50 m above ground (Aineck, Austria).

3. Modeling Results

CFD modeling with WindSim was performed for 4 regions with 7 "hot spots" with wind power projects that are under way (tab. 1). A separate report containing the details of the input data, the modeling procedures, the results as well as validation and uncertainty analysis was written for each region. Figure 6 contains a sample wind map of the Nösslachjoch "hot spot".

Tab. 1: CFD modeling performed within the Alpine Windharvest project.

Region	Hot Spot	Report
Lungnau (Salzburg, Austria)	Aineck	CFD Modeling 'Lungnau' Alpine Windharvest Report No. 7-8
	Windsfeld	
Brenner (Tirol, Austria and South Tirol, Italy)	Nösslachjoch	CFD Modeling 'Brenner' Alpine Windharvest Report No. 7-9
	Sattelberg	
Franches Montagnes (Jura, Switzerland)	St. Brais	CFD Modeling 'Franches Montagnes' Alpine Windharvest Report No. 7-10
	Les Breuleux	
Menina planina (Slovenia)	Menina planina	CFD Modeling 'Menina planina' Alpine Windharvest Report No. 7-11

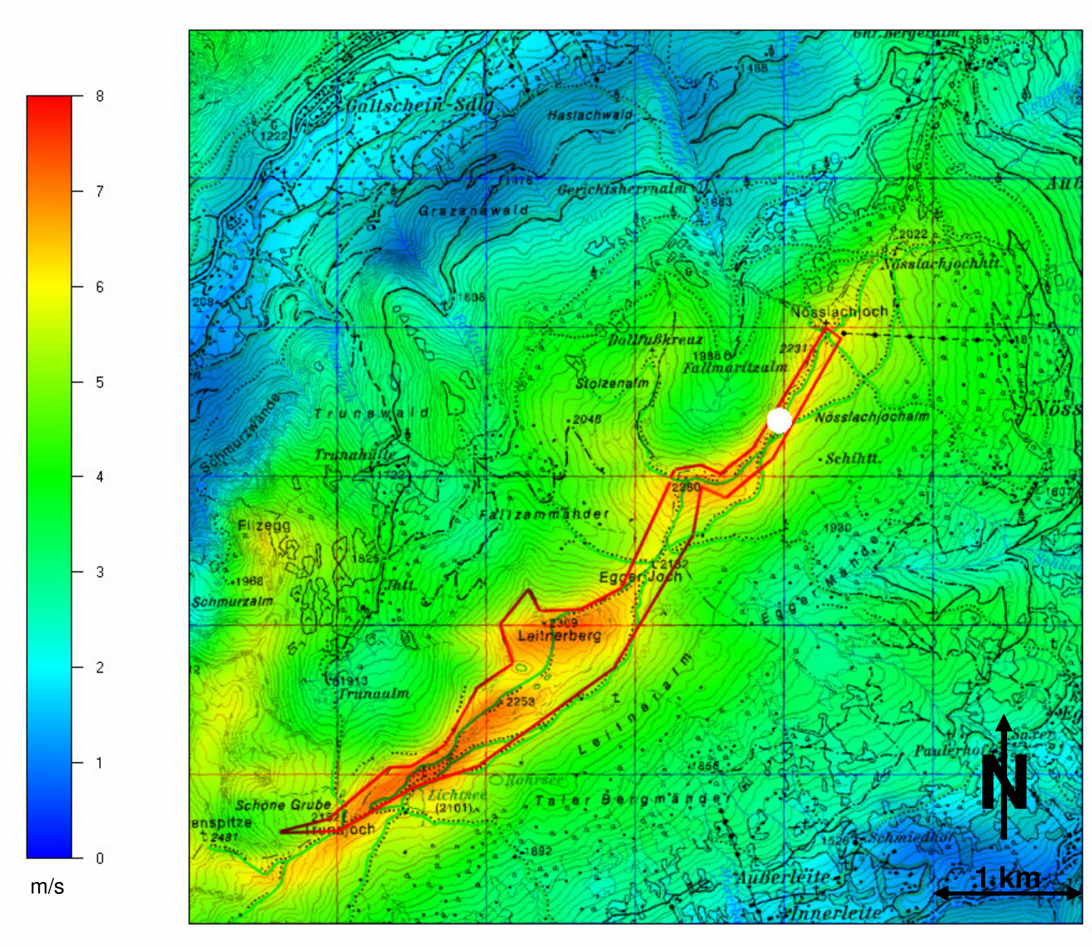

Fig. 6: Wind resources at 50 m above ground for Nösslachjoch, Brenner, Austria. The circle represents the location of the climatology. The red line represents the wind energy perimeter. Background map 1:50'000.

4. Validation

4.1. Climatology Transfer

Climatology transfer is achieved using the wind fields calculated by WindSim: A measured climatology location is transferred from the measurement location to an arbitrary location within the model domain by comparing the wind fields at both locations in all corresponding wind direction sectors.

For validation purposes, two measured climatologies from parallel measurement series at two locations are required. These climatologies are each transferred to the other location. The transferred climatologies are then compared to the original ones.

Homogenous parallel measurement series of wind speed and direction within one site were only available at Nösslachjoch. Climatologies of a two-month measurement period were transferred back and forth between the Nösslachjoch and the Leitnerjoch 12 m masts. The results are displayed in figures 7–10. As the climatologies are based on a short time series, the results of this validation should only be treated as an indication of the model's accuracy.

Wind direction shifts were very nicely reproduced, as is illustrated in figures 7 and 8. Changes in wind distribution were well reproduced while changes in mean wind speed between the two sites were roughly reproduced, with some 0.2 m/s difference between measured and modeled values (fig. 9, 10). The deviation in wind speed is not surprising: Both measurements were performed at 12 m above ground, which is in a very turbulent zone were small differences between real and model topography lead to significant changes in wind speeds. Additionally, horizontal model resolution was quite rough at 100 m. Therefore, the result can be considered as very promising.

Additionally, climatologies were transferred back and forth between Aineck and Windsfeld, which are approximately 25 km apart. Here, the climatology transfer had to be performed via a rougher model that covered both "hot spots". This was achieved by transferring the originating climatology to some hundred meters above ground in the final model domain of the originating "hot spot", then transferring it to a similar height at the new location in an intermediate nesting domain, and then transferring it down to measurement height in the final domain of the target "hot spot". When transferring from Aineck to Windsfeld, wind direction shifts were well reproduced (fig. 11). Vice versa, wind direction shifts were not reproduced so well (fig. 12), which was to be expected, as Windsfeld lies in a canalized wind flow. It is not possible to reverse this channeling effect. Both transfers do not reproduce wind speeds well. This is no surprise either, since the two sites are far apart in different wind regimes and up- and downstream effects are insufficiently reproduced in the model.

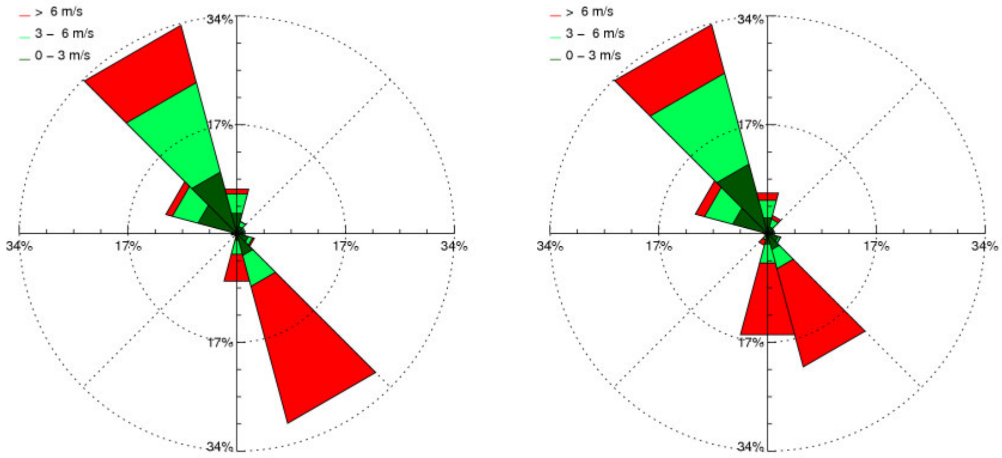

Fig. 7: Wind roses of measured (left) and transferred (right) climatologies at Nösslachjoch, Brenner, Austria.

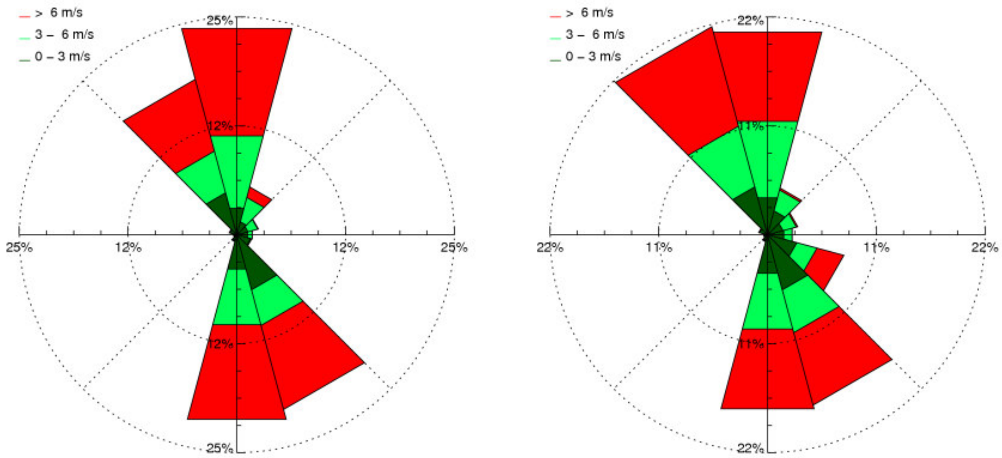

Fig. 8: Wind roses of measured (left) and transferred (right) climatologies at Leitnerjoch, Brenner, Austria.

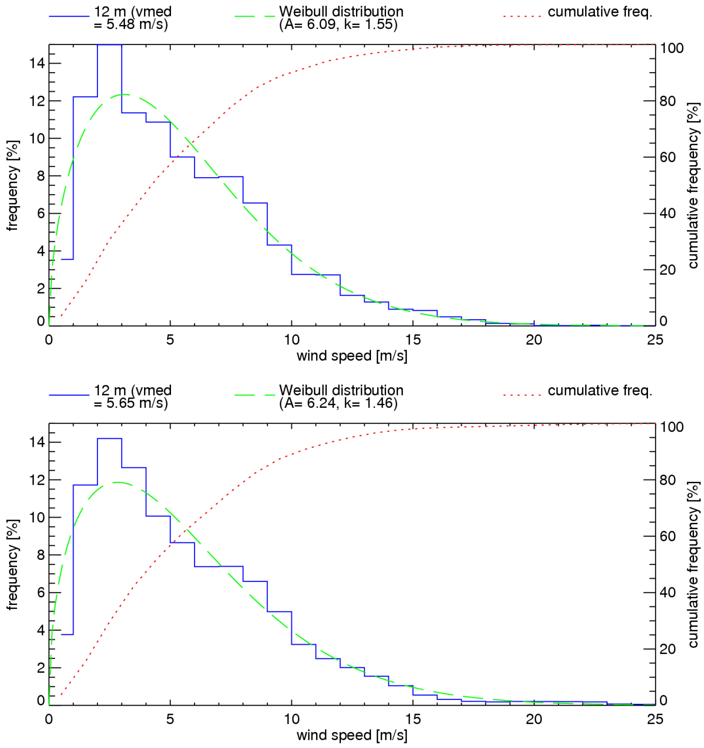

Fig. 9: Histograms of measured (top) and transferred (bottom) climatologies at Nösslachjoch , Brenner, Austria.

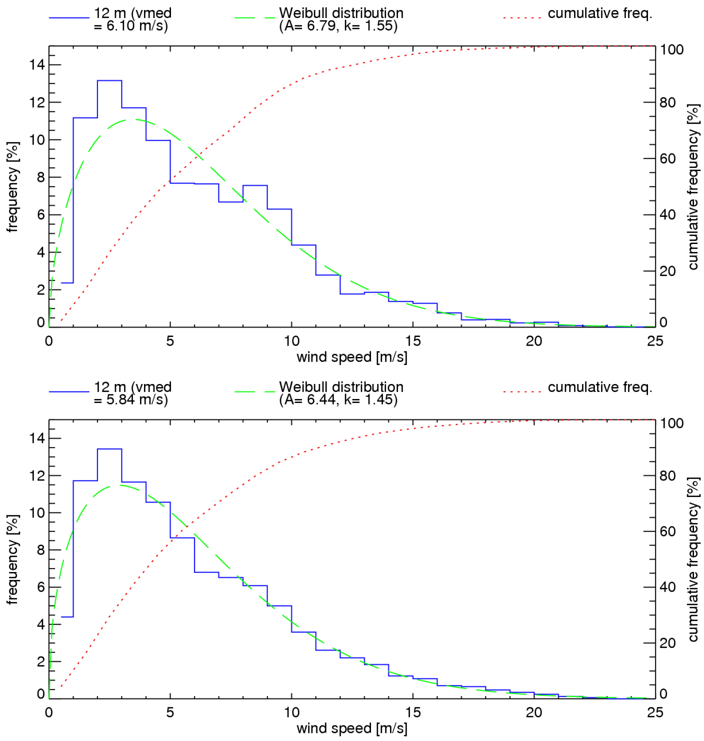

Fig. 10: Histograms of measured (top) and transferred (bottom) climatologies at Nösslachjoch, Brenner, Austria.

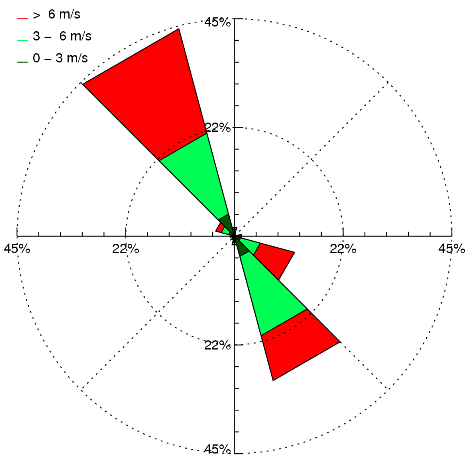

Fig. 11: Wind roses of measured (left) and transferred (right) climatologies at Windsfeld, Salzburg, Austria.

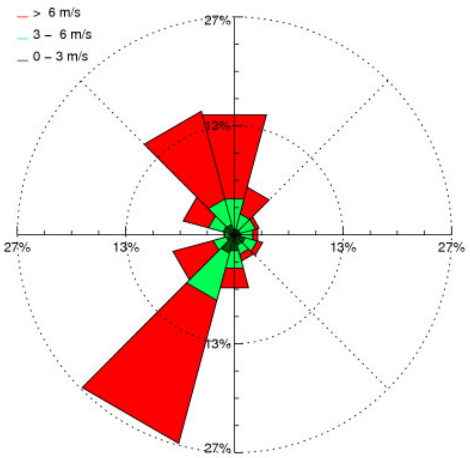

Fig. 12: Wind roses of measured (left) and transferred (right) climatologies at Aineck, Salzburg, Austria.

4.2. Comparison to SODAR Profiles

In work package 6 of the Alpine Windharvest project, SODAR measurements were performed at seven locations in the modeled "hot spots"[9]. Figures 13–15 show the SODAR measurement sites and figures 16–22 compare modeled and measured vertical profiles of wind speed, vertical wind component and turbulence for the main wind directions at these sites.

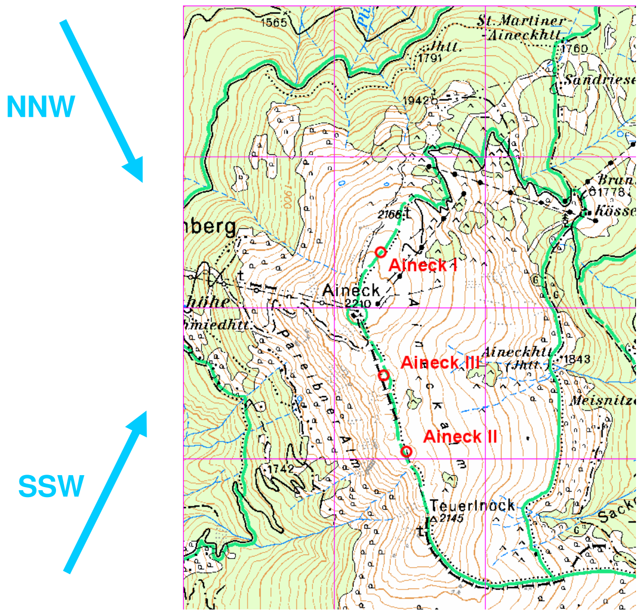

Fig. 13: SODAR locations (red circles) at Aineck, Salzburg, Austria (background map 1:50'000). Main wind directions NNW and SSW.

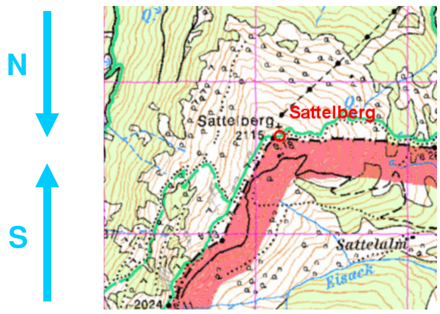

Fig. 14: SODAR location (red circle) at Sattelberg (background map 1:50'000). Main wind directions N and S.

[9] Cattin et al., 2005: SODAR Campaigns 'Aineck' I–III, 'Sattelberg', 'St. Brais', 'Peu Girard', 'Peuchapatte'. Alpine Windharvest Reports No. 6-2 to 6-8.

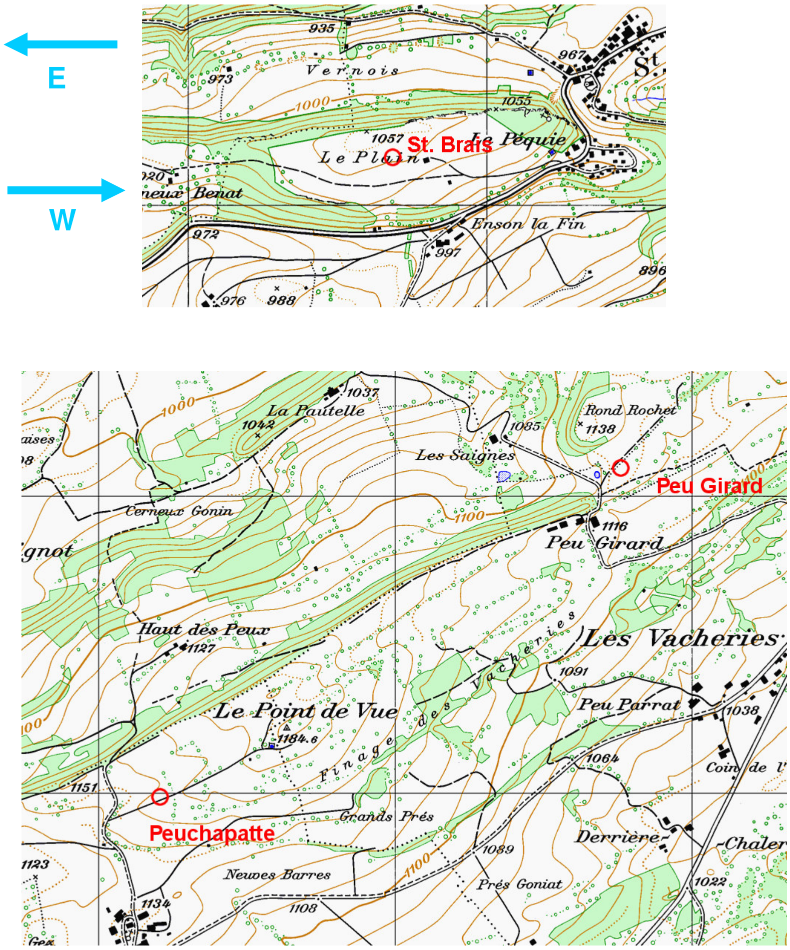

Fig. 15: SODAR locations (red circles) at St. Brais (top) and Les Breuleux (bottom), in Franches Montagnes, Switzerland. Background map 1:25'000 PK25 © 2003 swisstopo (DV606.1). Main wind directions E and W.

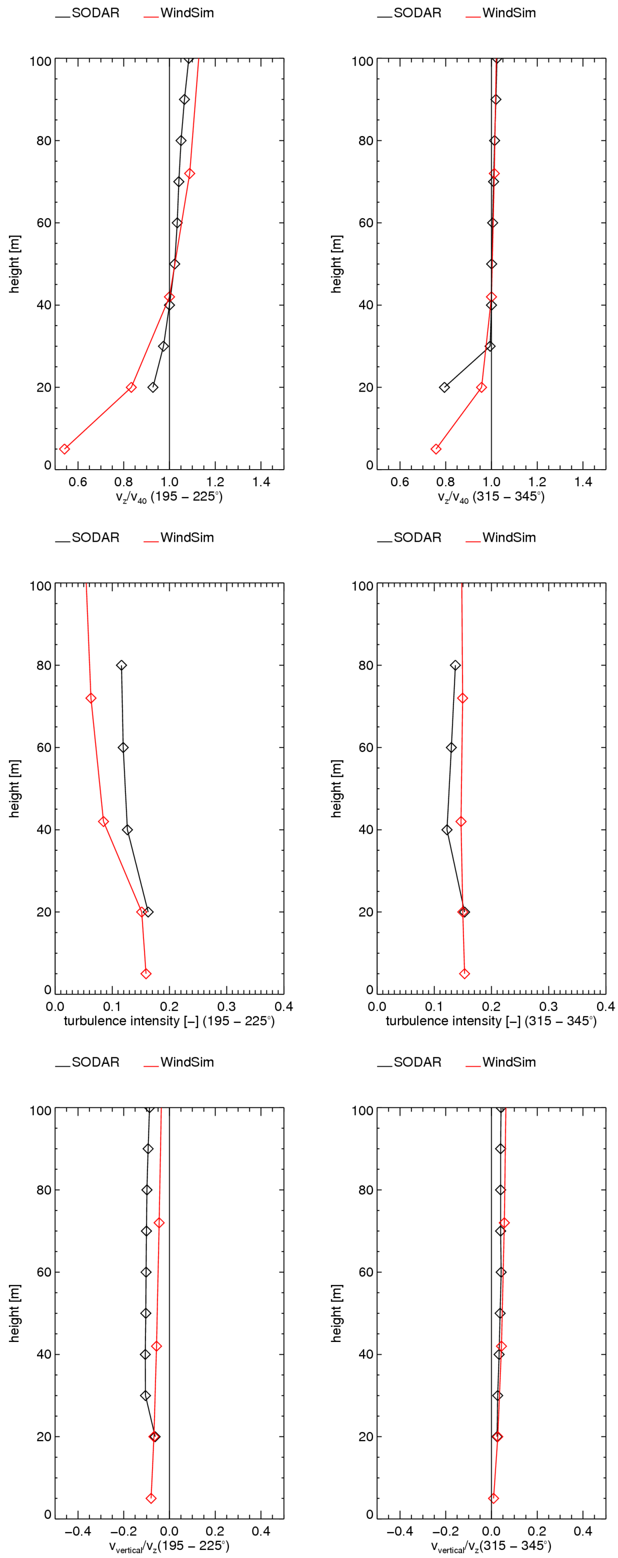

Fig. 16: Comparison of SODAR to WindSim profiles for location Aineck I and wind sectors SSW (left) and NNW (right): wind speed (top), turbulence intensity (middle) and vertical wind component (bottom).

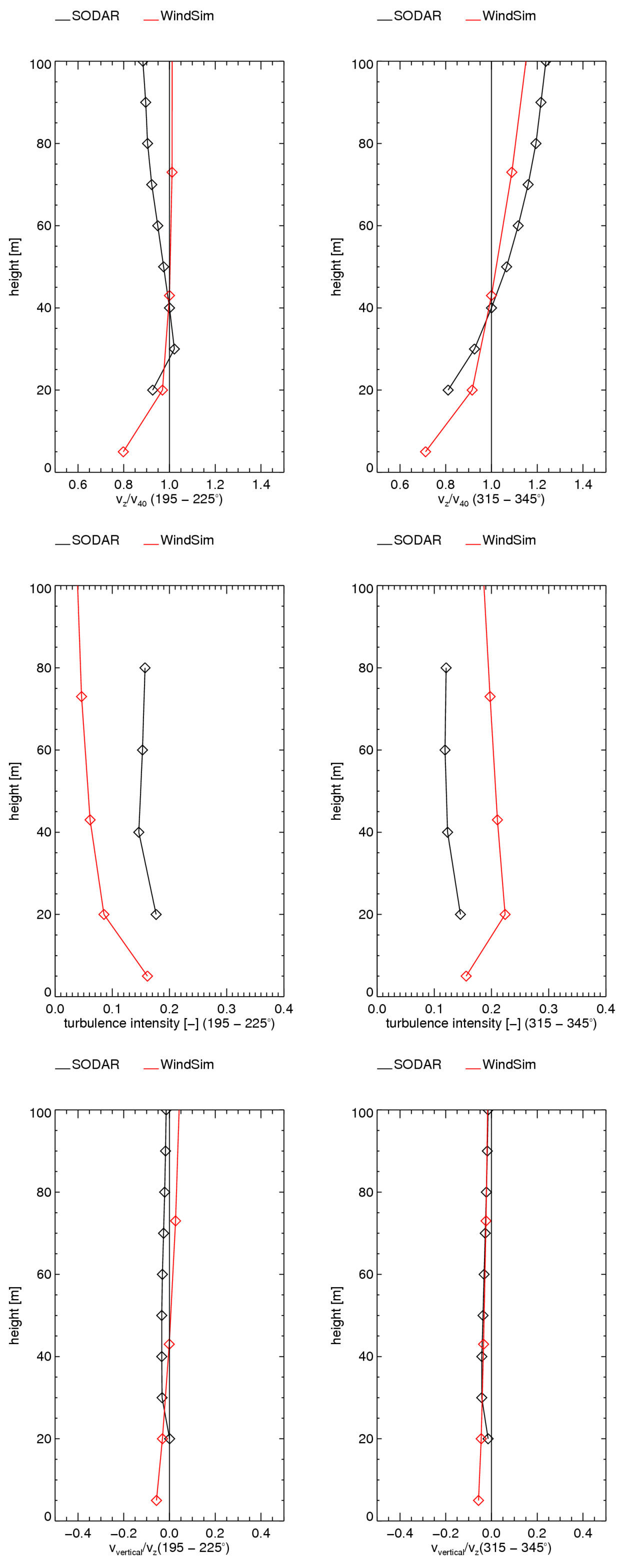

Fig. 17: Comparison of SODAR to WindSim profiles for location Aineck II and wind sectors SSW (left) and NNW (right): wind speed (top), turbulence intensity (middle) and vertical wind component (bottom).

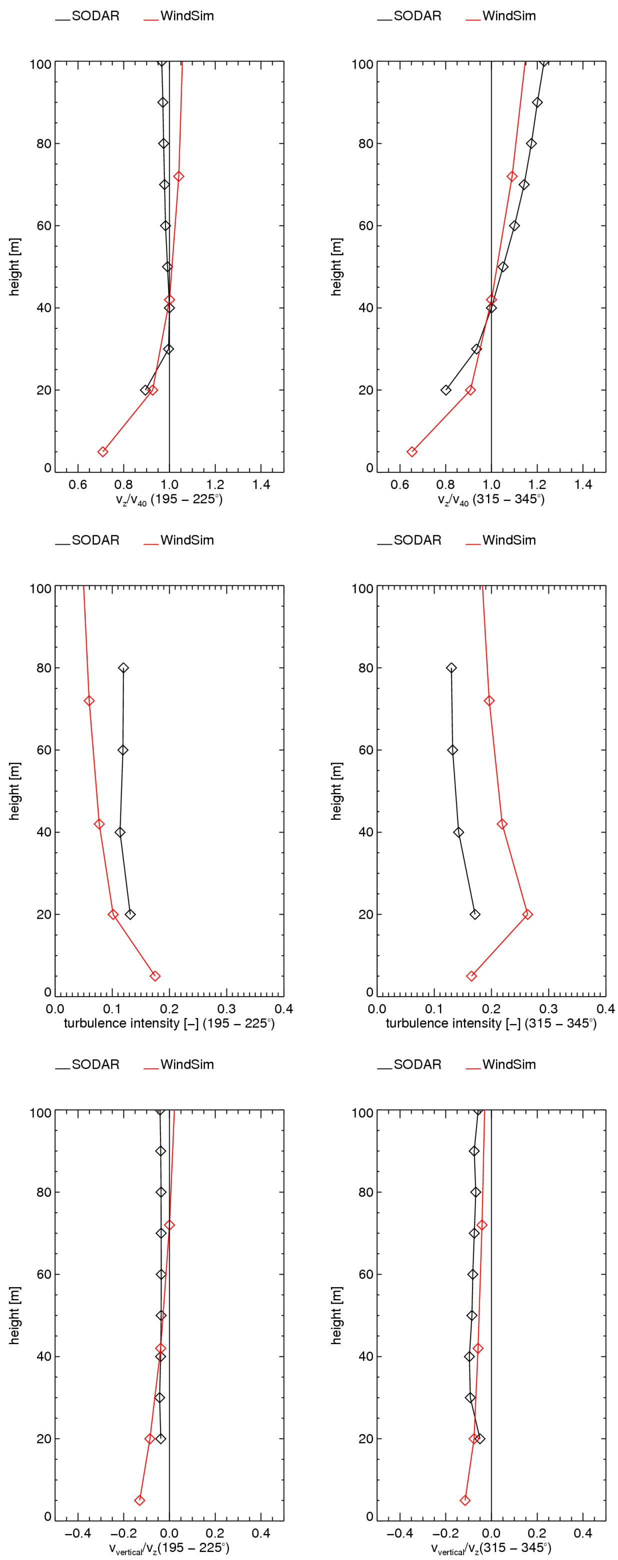

Fig. 18: Comparison of SODAR to WindSim profiles for location Aineck III and wind sectors SSW (left) and NNW (right): wind speed (top), turbulence intensity (middle) and vertical wind component (bottom).

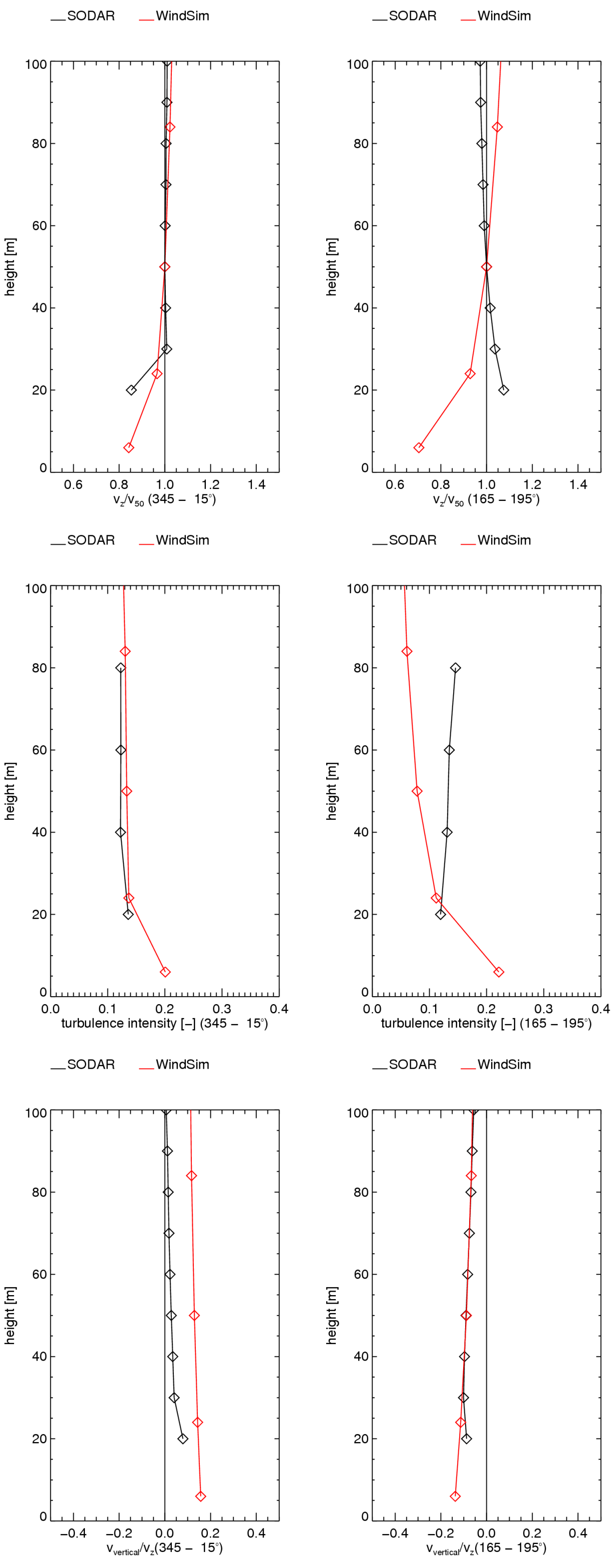

Fig. 19: Comparison of SODAR to WindSim profiles for location Sattelberg and wind sectors N (left) and S (right): wind speed (top), turbulence intensity (middle) and vertical wind component (bottom).

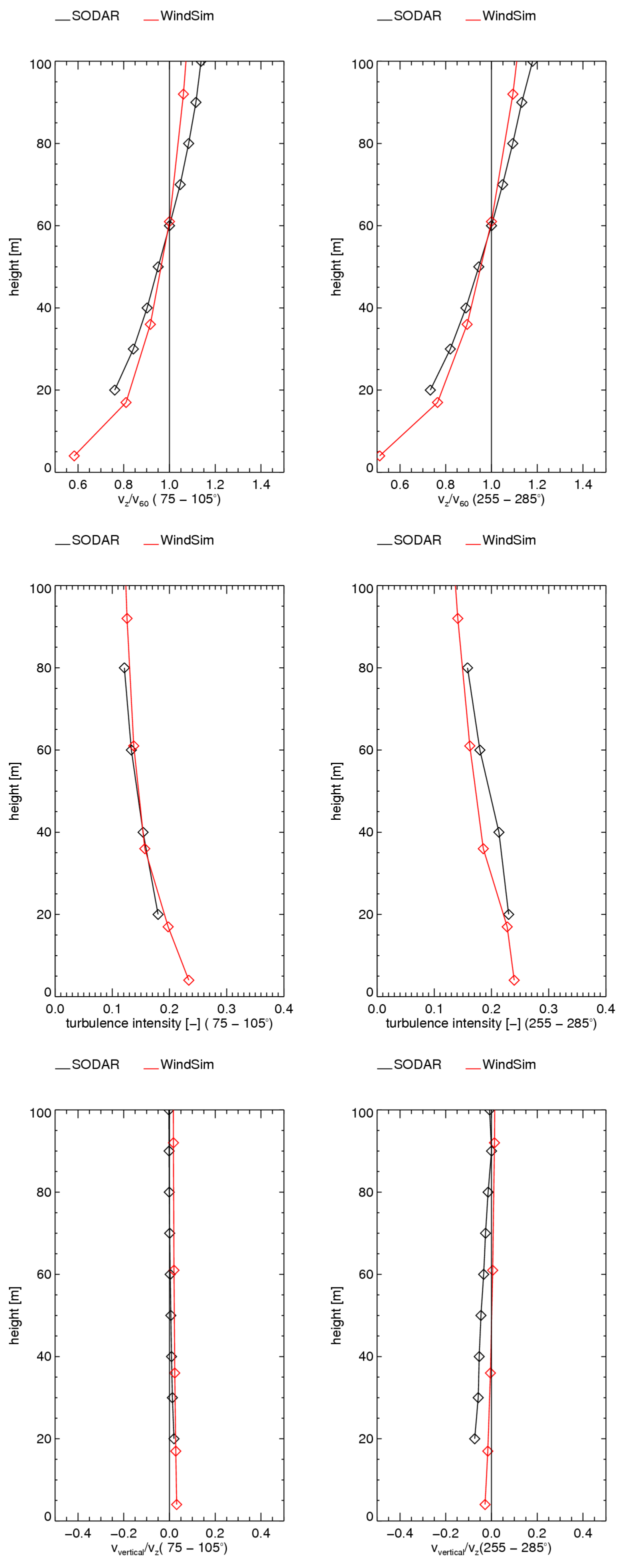

Fig. 20: Comparison of SODAR to WindSim profiles for location St. Brais and wind sectors E (left) and W (right): wind speed (top), turbulence intensity (middle) and vertical wind component (bottom).

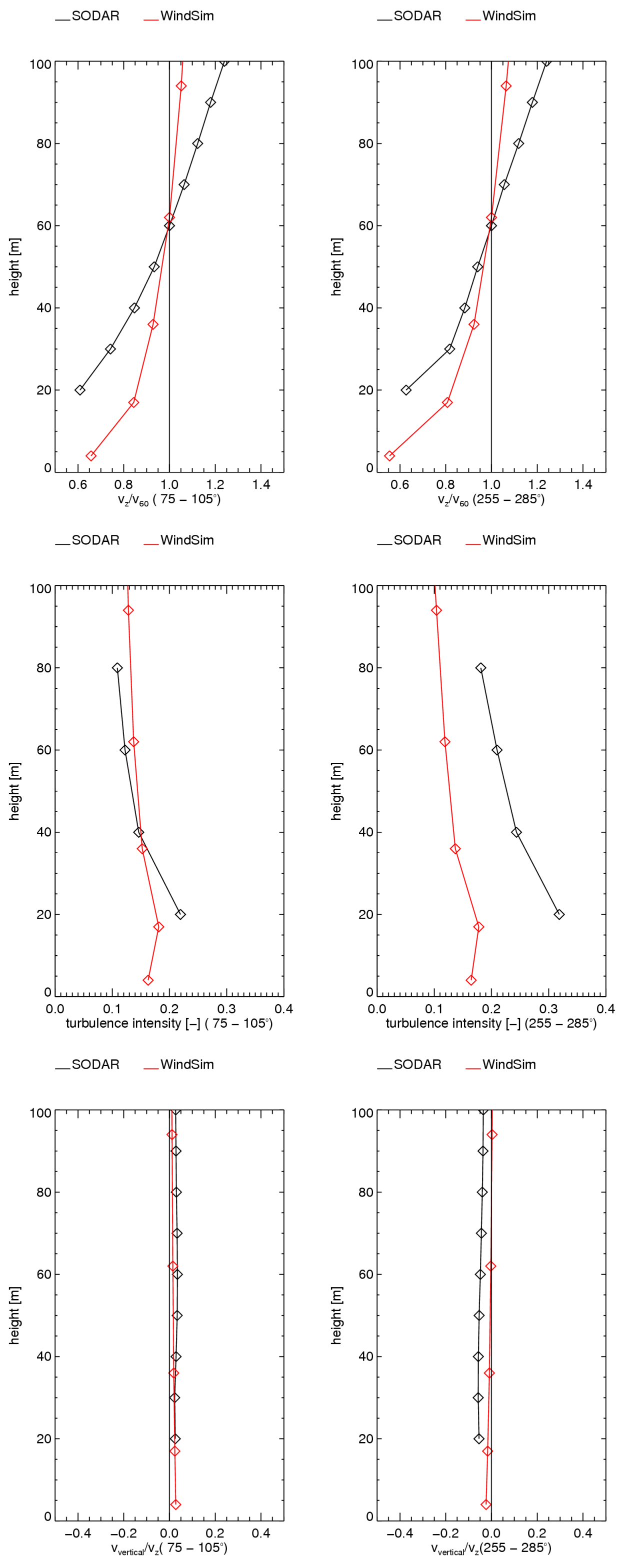

Fig. 21: Comparison of SODAR to WindSim profiles for location Peu Girard and wind sectors E (left) and W (right): wind speed (top), turbulence intensity (middle) and vertical wind component (bottom).

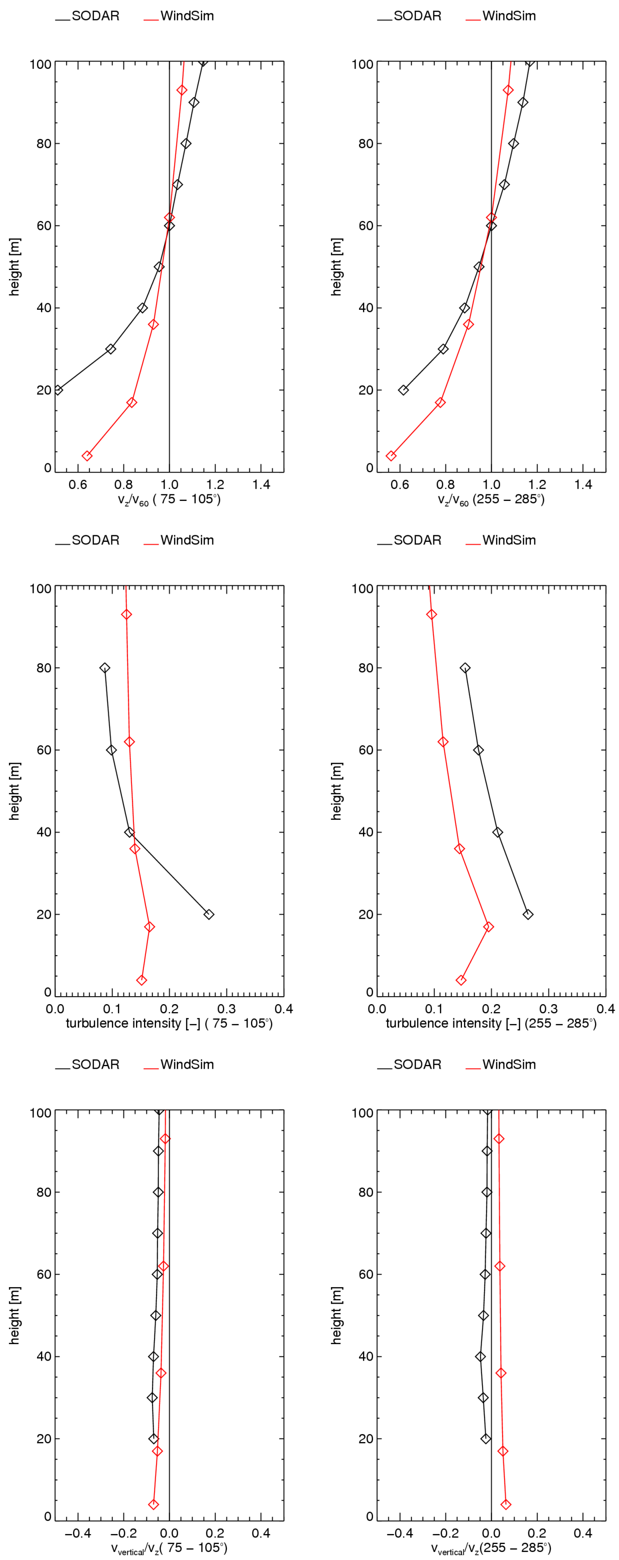

Fig. 22: Comparison of SODAR to WindSim profiles for location Peuchapatte and wind sectors E (left) and W (right): wind speed (top), turbulence intensity (middle) and vertical wind component (bottom).

Generally, the WindSim profiles fit the measured profiles quite well, especially if compared to results such as would be delivered by WAsP modeling, (e.g. see Schaffner et al., 2002[10]).

Comparison of wind speed profiles

WindSim seems to have difficulties to reproduce profiles where wind speed declines with height (top left hand profile in fig. 17; top left hand profile in figure 18 and top right hand profile in fig. 19). These profiles have in common that they were measured close to the edge of a steep slope in the wind direction. Is this discrepancy the result of "wrong" modeling behavior or of insufficient representation of the real topography in the model? Discretizing the terrain for modeling smoothes topography. With rougher resolution, more details are lost and the smoothing effect is stronger, which leads to less pronounced speed-up effects in the model. This is nicely illustrated in figure 23 for the Sattelberg SODAR location, where the terrain discretization leads to different characteristics of the location in the model than in reality, which may explain the difference between the modeled and measured profiles. At Aineck, this effect is less obvious, as a better digital terrain model is available there. In any case, as situations as described above are common in complex terrain, this question needs further investigation.

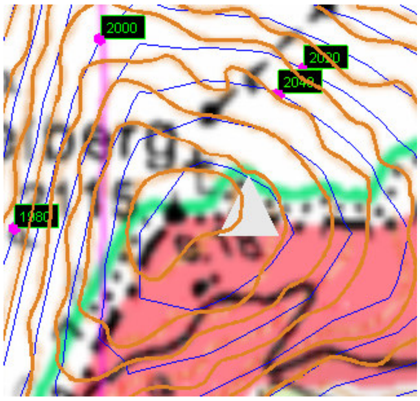

Fig. 23: Real topography (brown height contours) compared to model topography (blue height contours): In the model, the SODAR (triangle) is situated on a relatively smooth ridge while in the terrain, the SODAR was set up on a more pronounced edge where the terrain immediately declines towards south.

In the Franches Montagnes (fig. 20, 21, 22), wind speed generally increases very strongly with height, because of the influence of nearby forests and hedges. Figure 24 shows the effects of a forest on the vertical wind speed profile[11]. Obviously,

[10] Schaffner et al., 2001: Wind Modeling in Mountains: Intercomparison and Validation of Models.

[11] Stull, 1988: An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers.

these effects are insufficiently reproduced and wind speeds at hub height are underrated by the model, even though a relatively high roughness length of 1.5 m was defined for forest. However, has been established that the effects of trees can not be reproduced by roughness alone[12]. In WindSim there is a possibility to include semi-permeable obstacles, which might reproduce these effects more satisfactorily. Investigating this possibility was outside of the scope of the current project but will be addressed in the future.

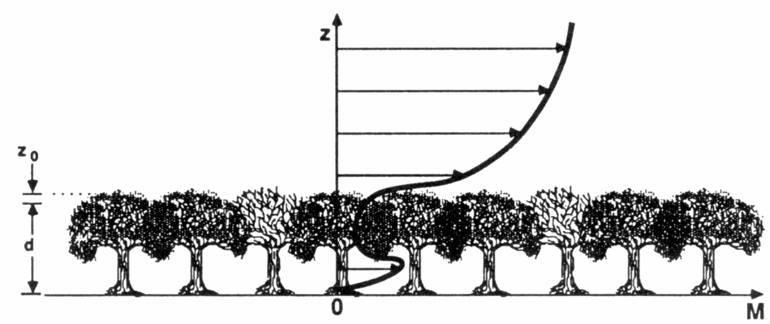

Fig. 24: Flow over a forest canopy showing wind speed, M, as a function of height, z. The thick canopy layer acts like a surface displaced a distance, d, above the true surface. z_0 = roughness length.

Comparison of turbulence profiles

SODAR measurements are suitable for quantifying turbulence[13]. Generally WindSim tended to reproduce the shape of the turbulence intensity profile. In some cases, big discrepancies between modeled and measured turbulence were found: Most of them could be explained by terrain simplifications effects in modeling mentioned above.

- In figure 16 in the middle left hand profile, turbulence was underrated in the model. Here, the wind flows from SSW over the Aineck peak towards the site (see fig. 13). On the peak, a lot of infrastructure (huts, ski lift masts and cables as well as fences) disturb the wind flow. These obstacles were not included in the model, which might explain the discrepancy.

- In figures 17 (middle left), 18 (middle left) and 19 (middle right), measured turbulence increases with height while modeled turbulence decreases. These sites have in common that the measured vertical wind speed profiles decrease with height, which is not reproduced by the model. Again, general-

[12] Presentations at Tree Workshop by BWEA on 17.03.2004.

[13] Albers et al., 2004: Measurement of Atmospheric Turbulence with SODAR-System. DEWEK 2004 Proceedings.

ized topography and disregarding small-scale obstacles could be the cause for the differences in turbulence.

- In the Franches Montagnes turbulence was reproduced very well for the site St. Brais (fig. 20). This corresponds with a very good wind speed fit on this site. For the other two sites (fig. 21 and 22) turbulence was underrated by WindSim in the lower levels, which was to be expected, as the effects forests and hedges are insufficiently reproduced (see comparison of wind speed profiles). The forest's effects are revealed by the high measured turbulence intensities of up to 3.2 at 20 m above ground.

Turbulence was best reproduced in situations where the terrain is more or less uniform in the main wind direction and is therefore better represented in the model (fig. 16 middle right, 19 middle left, 20, middle left and right).

Comparison of vertical wind component profiles

The profiles of vertical wind component are a good check for the quality of representation of the real terrain by the model terrain. A large discrepancy of this parameter is only seen at Sattelberg (fig. 19), where the real terrain was insufficiently represented (fig. 23).

5. Conclusions and Recommendations

5.1. Conclusions

In the framework of Alpine Windharvest work package 7, it was possible to gain important experience concerning CFD modeling with WindSim in complex, Alpine terrain. It was shown that WindSim provides a CFD modeling solution that fulfills the requirements for wind modeling in this type of terrain, in contrast to WAsP or similar diagnostic models. In order to get reliable results it is essential to obtain accurate input data and to carefully plan and evaluate each modeling step. Some recommendations are given in section 5.1.

As is the case with any model of this type, WindSim is especially suitable for extrapolation of measurements within short horizontal distances and extrapolations from high enough measurement heights to hub height in nearby terrain with similar characteristics as the measurement site. High quality measurements at a height of at least 30 m above ground within the modeled park perimeter are essential.

A few situations were encountered in which the observations were insufficiently reproduced. Strategies to solve these problems are discussed in this chapter. Some limitations and aspects needing further study are listed in section 5.2.

5.2. Recommendations for CFD Modeling in Complex Terrain with WindSim

5.2.1. Input data

Any modeling result is only as good as its input data. What applies to wind assessments in simple terrain is even more important in complex terrain as errors can be multiplied in highly variable wind fields.

<u>Wind climatology</u>

A highly accurate long-term wind climatology at an adequate position and height is the basic and most important requirement for accurate modeling results. Errors in the input wind climatology will be spread to the whole model perimeter by WindSim's weighting procedure. The following aspects should be considered:

- Perform professional on-site measurements according to the established standards.
- In cold climate, include some form of protection from icing (heated or ice-resistant sensors).
- Accurate wind direction measurements are essential (due to the highly variability of wind conditions in function of direction).

- Adapt redundancy in electronics and sensors to harsh conditions.
- Obtain at least one year of data (without gaps).
- Measure as high above ground as possible (at least 30 m; preferably 50 m), as lower measurements will be too strongly influenced by the small scale surface that can often not be reproduced in sufficient detail in modeling due to discretization.
- Wisely choose the measurement site: It should be within the planned wind park perimeter at a well exposed and characteristic location. Avoid obstacles, extreme locations (on top of ledges or cliffs) and locations where the wind is canalized.
- If topography characteristics within the wind park perimeter change significantly, measurement at several sites might be needed.
- Obtain accurate and homogenous reference data that correlate well with the on-site measurement data in order to calculate a reliable long term climatology.
- Precisely determine the measurement location (e.g. with GPS) and note coordinate system, map projection and datum. A 360° panorama from the measurement site can be very helpful when interpreting modeling results.
- Obtaining a climatology by climatology transfer from a nearby site when no on-site measurements are available is usually not a solution in complex terrain. Transferred climatologies reproduce wind direction shifts well, but there will be differences in absolute wind speed.

<u>Air density and power curve</u>

- Wind power is proportional to air density. Calculate the site's air density at hub height precisely from temperature and pressure measured on-site or at a nearby measurement station.
- WindSim (and other models) adapt power curves to air density proportionally. This correction does not exactly match the real behavior of the power curve at lower air densities. The power production can be under-estimated by up to 3.6% for low air density.[14] For best results, obtain a power curve that is adjusted to the site's air density and turbulence from the turbine manufacturer.

[14] http://www.windpower.org/en/tour/wres/guidep.htm

Topography

- As was shown in the validation with SODAR measurements, generalized terrain can cause substantial modeling errors. It is therefore essential to obtain a precise digital elevation model with a good resolution of 50 m or better. Roughness information should be available at a resolution of 100 m or better.

- Account for horizontal shifts due to different map projections or datums. Small horizontal deviations will result in large height differences in complex, variable terrain. Check the topographical data well around the site for shifts, inconsistencies and errors.

- Carefully define and map roughness lengths around the wind park perimeter. For more distant regions, roughness can be estimated from land use data.

Obstacles

- Obstacles can not be easily included in the model. Therefore chose measurement locations away from the influence obstacles.

- A known difficulty is including forests or hedges in the model. The effects of forests and hedges can not be sufficiently reproduced by roughness. Forests should be included as semipermeable obstacles, but experience has yet to be gained in this field.

5.2.2. Model domain, nesting

Carefully choosing a modeling domain is essential in order to include all relevant effects, avoid undesirable effects and attain a sufficient result resolution.

Nesting enables including relevant up- and downstream effects at a lower resolution and still obtaining high resolution results for the wind park site with acceptable computational time.

As was shown in the validation with SODAR measurements, it is essential to do modeling at the best possible resolution in the final nesting step in order to obtain accurate results.

We recommend observing the following aspects:

- Preliminary test runs for main wind direction sectors help recognizing problematic input conditions early.

- Choose the initial model domain to include relevant up and downstream effects in the main wind directions.

- Wisely select nesting domains in order to ensure correct up- and downstream wind conditions (valley systems, blocking mountains etc.) and to avoid undesirable boundary effects.

5.2.3. Checking, Validation

Checking results in a variety of ways is an integral part of the modeling procedure:

- Check resulting wind field for absolute values as well as plausibility with respect to topography (wind speed maximums at implausible locations e.g. valleys, depressions).
- Check model edges and roof for blocking effects.
- Climatology transfers are a good validation method for short distances. Enough consistent, overlapping measurements free from small-scale surface influences are required at both locations.
- SODAR comparison is very good validation method. Care should be taken when comparing values close to the ground (< 30 m) as these are problematic in SODAR measurements as well as in modeling.

5.3. Limitations and shortcomings of WindSim

Being a model, WindSim strongly simplifies the environment it represents. It is important to be aware of these simplifications when modeling and interpreting model results. It is often possible to adapt the model setup and input data in a way to minimize adverse effects on the results.

The following list contains some of the more important limitations of WindSim:

- WindSim assumes a neutrally stratified atmosphere. Of course, this does often not represent the real situation, especially in Alpine regions, where inversions and thermal effects have a big influence on wind. However, for a restricted area, wind flow will mainly be determined by the small-scale topography and can therefore be well reproduced by WindSim's "wind channel approach", if a wind climatology is available within this area.
- WindSim does not provide an easy method of including obstacles. Usually, problems can be avoided by positioning wind measurements outside of obstacles' influence. However, problems arise with forests and hedges, the effects of which can only insufficiently be by roughness. Investigations on how to include these effects – possibly by defining semipermeable obstacles – should be performed.
- The nesting procedure imposes artificial walls on the top border, as well as on the east and west borders for simulations for sectors 0° and 180° and on

the north and south border for simulations for the sectors 90° and 270°, which could impose unphysical directional shifts and blocking effects. These problems can be avoided by raising the top boundary to a height where wind flow is horizontal and by choosing model boundaries for which there is little wind speed deviation on the side borders. Fulfilling the latter condition is often problematic in complex, Alpine terrain. According to Vector, a better procedure for determining in- and outlets will be developed for WindSim.

- As mentioned above, WindSim (and other models) proportionally adapt power curves to air density. This correction does not exactly match the real behavior of the power curve at lower air densities. The power production can be under-estimated by up to 3.6% for low air density.[15] For best results, obtain a power curve that is adjusted to the site's air density and turbulence from the turbine manufacturer.

- In extremely complex terrain it was found to be difficult to run the model in the desired high resolution, as no convergent solution could be established. This could be caused by single cells which are too steep, improper boundary conditions from coarse model due too small scale topography changes or flow separation out of model box.

A list of known bugs and shortcomings of WindSim is available at the WindSim homepage (www.windsim.com).

In the scope of this study, it was not possible to consider all aspects of CFD modeling with WindSim. We especially plan to examine the possibilities of including forests and hedges more closely in the near future. Additionally, we plan to perform more validation studies with more suitable measurements at higher model resolution.

[15] http://www.windpower.org/en/tour/wres/guidep.htm