CFD MODELING OF THE VERTICAL WIND PROFILE AND THE TURBULENCE STRUCTURE ABOVE COMPLEX TERRAIN AND VALIDATION WITH SODAR AND LIDAR MEASUREMENTS

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Summary

Vertical profiles of wind speed and turbulence intensity were modeled with the CFD model WindSim for a site in medium complex terrain in Croatia. The results were validated against SODAR and LIDAR measurements. A 50 m mast provided cup anemometer data.
The wind measurement campaign was carried out in Rudine/Croatia about 35 km north of Dubrovnik near the Adriatic coast. At this site the winds are known to be sometimes very strong. In particular the so called Bora, a gusty wind from north to north-east. One goal of the campaign was to examine the performance of SODAR and LIDAR instruments under harsh meteorological conditions. Both, SODAR and LIDAR showed very good performance with high data availability up to 100 m. Vertical profiles of wind speed showed only small increase with height for the prevailing wind directions north north-east and south south-east. Turbulence intensities calculated from SODAR and LIDAR measurements showed different values as a result of different sampling rates. However both data sets revealed almost constant turbulence intensities between 30 m and 100 m above ground. Turbulence intensities remained below class A of the IEC 61400.
For comparison the vertical profiles of WindSim, SODAR and LIDAR measurements were normalised to 50 m for all twelve 30° wind direction sectors. The normalised vertical wind speed profiles of SODAR, LIDAR and WindSim showed good agreement especially for the prevailing wind directions. Turbulence intensities calculated by WindSim show a weak decrease with height in contrary to the almost constant vertical turbulence intensity profiles of the SODAR and LIDAR measurements.

1. Introduction

The South East Europe Wind Energy Exploitation (SEEWIND) project [1], embedded in the 6th framework program of the European Commission, aims to gain experience in wind measurements, site development and operation of wind turbines in complex terrain. In order to get information about the vertical wind profile at two Bora-dominated sites in Bosnia and Croatia, SODAR and LIDAR measurements were carried out. Bora is a strong katabatic wind from north to north-east. Knowledge of the vertical wind profile and the turbulence intensities on Bora dominated sites will provide important information on the impact on a wind turbine operating under such conditions.
This study investigates vertical wind speed profiles and turbulence intensities at Rudine, a Bora dominated site in Croatia and evaluates the performance of the CFD modeling software WindSim [2] regarding the vertical profiles of wind speed and turbulence intensities.

2. Site Description and Instrumentation

The measurement site Rudine is located on a high plateau on the mainland of Croatia, about 35 km north-west of Dubrovnik, approximately 380 m above sea level (Fig. 1). The region is dominated by Karst and only low vegetation and the terrain can be described as medium complex.
A mast provided wind speed and wind direction data at 50 m height. Mast data were cleaned and corrected for long term conditions by the SEEWIND partner DEWI [3]. Fig. 2 shows the wind rose at Rudine at 50 m height from the mast measurement. The prevailing wind directions are north north-east and south south-east.
The installed SODAR was of type Aerovironment miniSODAR 4000F and the measurement heights ranged from 30 m to 150 m with 10 m intervals. The measuring rate was approximately 0.33 Hz and the averaging interval 10 minutes. The LIDAR was of type ZephIR [4] and the five measurement levels were set to 30, 50, 80, 100 and 150 m. The measuring rate was approximately 0.05 Hz and the averaging interval 10 minutes.
SODAR and LIDAR were installed within a distance of 10 m. The mast was located approximately 35 m away from SODAR and LIDAR to the south-east (Fig. 3). SODAR and LIDAR data were available only for a limited time period, this is 12 February to 5 May 2008 for the SODAR and 9 April to 5 May 2008 for the LIDAR. Only the period when both instruments were in use are considered for this data evaluation.

3. CFD Model WindSim

WindSim is a CFD-package for micrositing based on the more general CFD solver Phoenics. The CFD simulations are based on the integration of Reynolds Averaged Navier-Stokes (RANS) equations over a portion of the lower atmosphere. The RANS equations are discretised on a computational grid and integrated with a finite-volume procedure. Turbulence is calculated using the standard k-epsilon turbulence model which allows closing the set of equations. WindSim is able to assess wind resources with a high degree of accuracy. Even terrain with fairly complex features can be processed with WindSim. Three primary inputs are necessary to run WindSim, first a digital elevation model, second a roughness map and third a climatology. All these data sets were compiled and provided by the SEEWIND partner DEWI. WindSim offers the possibility to extract vertical profiles of various parameters, like for example wind speed and turbulence intensity, and that for each modeled height and sector. The values of the vertical WindSim profiles are only relative values which have to be scaled with a climatology. Tab. 1 lists the dimensions and grid sizes of the WindSim model calculations for the base and the nested model.

Tab. 1: Dimensions and grid sizes of WindSim.

Model	Base model	Nested model
Extension	14 x 11 km	6 x 3.5 km
Horizontal grid size	100 m	18.7(center) - 86.6 m 19.5(center) - 86.5 m
First 7 vertical levels above ground	12.8, 42.7, 80.9, 127.5, 182.5, 245.8, 317.6 m	5.5, 12.2, 34.0, 54.0, 77.0,103.3, 133.3 m

4. Methods

4.1 Vertical Wind Speed Profiles

Vertical wind speed profiles of SODAR and LIDAR measurements are only analysed qualitatively in this study, which means that only normalised data sets are compared. Wind speed profiles from both instruments are analysed for twelve 30° wind direction sectors. Furthermore the normalised vertical wind speed profiles of the WindSim model output are validated using LIDAR measurements.

4.2 Vertical Turbulence Intensity Profiles

Turbulence intensities (TI) from SODAR and LIDAR measurements are evaluated by calculating the ratio of the standard deviation wind speed ($sigma_U$) to the mean wind speed (U) according to the following formula: $TI = sigma_U/U$. Only wind speeds above 4 m/s are considered. As a consequence of the different sampling rate of SODAR and LIDAR standard deviations cannot be compared quantitatively. Finally vertical profiles of the turbulence intensities calculated by WindSim are verified using LIDAR measurements.

5. Results

5.1 Vertical Wind Speed Profiles

Comparison of SODAR and LIDAR Measurements

Fig. 4 and Fig. 5 show the vertical profiles of the wind speed from SODAR and LIDAR measurements for the main wind directions north north-east and south south-east and for different wind speed classes. The data sets are normalised to 50 m height. The increase of the mean wind speed from 50 to 100 m is in general small for the main wind directions, 6% and 5% considering the SODAR and 4% considering the LIDAR data. The profile shape is independent to the wind speed. The outlier in the SODAR profile at 40 m height is probably a result of an echo during data collection.

Comparison of LIDAR Measurements with WindSim

The levels of the WindSim model output do not agree with the measurement levels of the LIDAR. For comparison reason the wind speed data of the WindSim output level from 54 m was reduced linearly to 50 m and the model output data are normalised to this interpolated value. In Fig. 6 the vertical wind profiles normalised to 50 m from LIDAR measurements and WindSim model are compared for the two main wind directions. WindSim produces an increase from 50 to 103.3 m of 10% and 7% respectively; this means a slightly larger increase than seen in the measurements.

5.2 Vertical Turbulence Intensity Profiles

Comparison of Turbulence Intensities from SODAR and LIDAR

Fig. 7 and Fig. 8 show the calculated turbulence intensities from SODAR and LIDAR measurements up to 100 m height for the main wind direction sectors. Both data sets show an almost constant turbulence with height with a higher intensity of turbulence for the sector north north-east. The constant bias between SODAR and LIDAR data can be explained by different data sampling rate (see section 2).

Comparison of LIDAR and WindSim Turbulence Intensities

Fig. 9 shows the turbulence intensities from LIDAR measurements and WindSim calculations for 30° wind direction sectors. LIDAR turbulence intensities are calculated only for wind speeds above 4 m/s. No turbulence was calculated for sectors/levels with less than ten valid 10 minute averages. General patterns of the WindSim turbulence intensities agree well with the LIDAR measurements. In the WindSim output the decrease of the turbulence intensity is more pronounced than in the LIDAR measurements. The agreement of the values for the main wind directions is a coincidence.

6. Conclusions

- Only small increase of wind speed with height at Rudine.
- Constant turbulence intensity up to 100 m height at Rudine.
- Good agreement of SODAR, LIDAR and WindSim vertical wind speed profiles.
- Determination of turbulence intensity difficult due to different sampling rate. More investigations on calculation of turbulence intensities are needed.

References

[1] SEEWIND, http://www.seewind.org/ (18.9.2008)
[2] WindSim, http://www.windsim.com/ (18.9.2008).
[3] DEWI, GmbH, Deutsches Windenergie-Institut
[4] LIDAR ZephIR, http://www.naturalpower.com/zephir-laser-anemometer (18.9.2008)

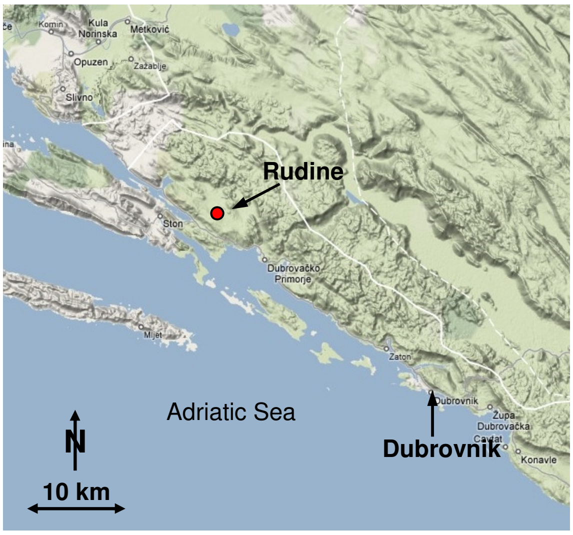

Fig. 1: Map of south Croatia with the wind measurement site Rudine.

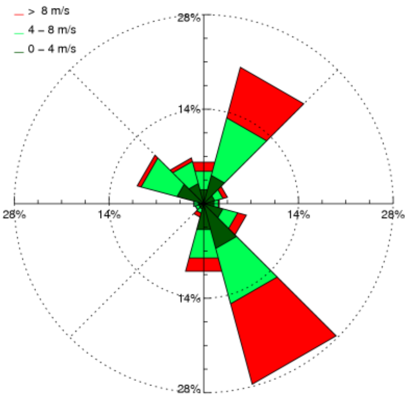

Fig. 2: Wind rose at Rudine at 50 m height.

Fig. 3: Picture of SODAR (left), 50 m mast and LIDAR (right) at Rudine facing south-east.

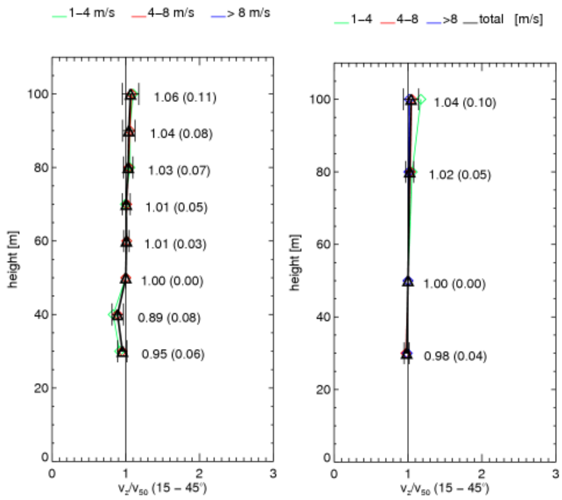

Fig. 4: Vertical wind speed profiles from SODAR (left) and LIDAR (right) normalised to 50 m for the wind direction north north-east, in brackets the standard deviations.

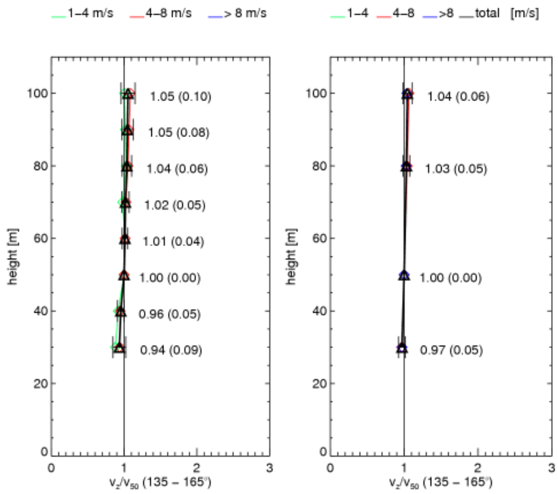

Fig. 5: Vertical wind speed profiles from SODAR (left) and LIDAR (right) normalised to 50 m for the wind direction south south-east, in brackets the standard deviations.

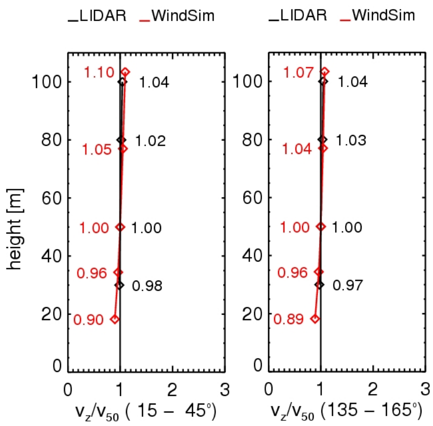

Fig. 6: Comparison of vertical wind speed profiles from WindSim and LIDAR data normalised to 50 m for the wind directions north-north-east (left) and south south-east (right).

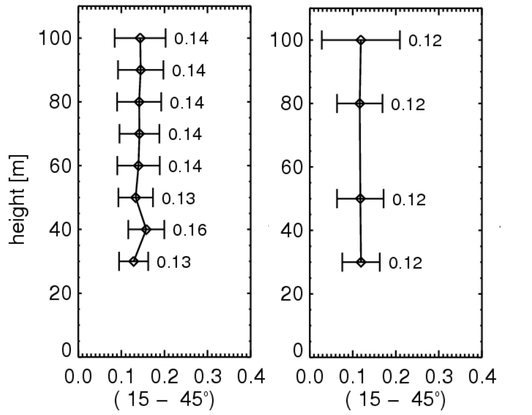

Fig. 7: Comparison of vertical turbulence intensity profiles from SODAR (left) and LIDAR (right) data for the wind direction north north-east. The bars indicate the standard deviation.

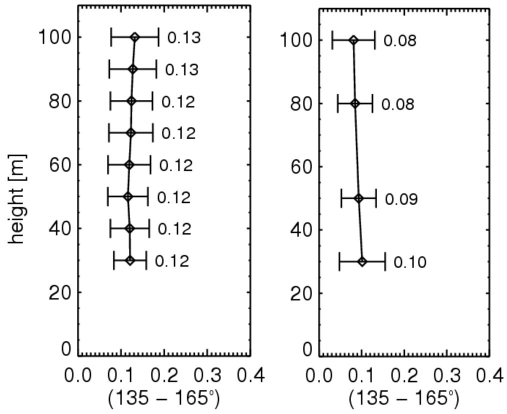

Fig. 8: Comparison of vertical turbulence intensity profiles for SODAR (left) and LIDAR (right) data for the wind direction south south-east. The bars indicate the standard deviation.

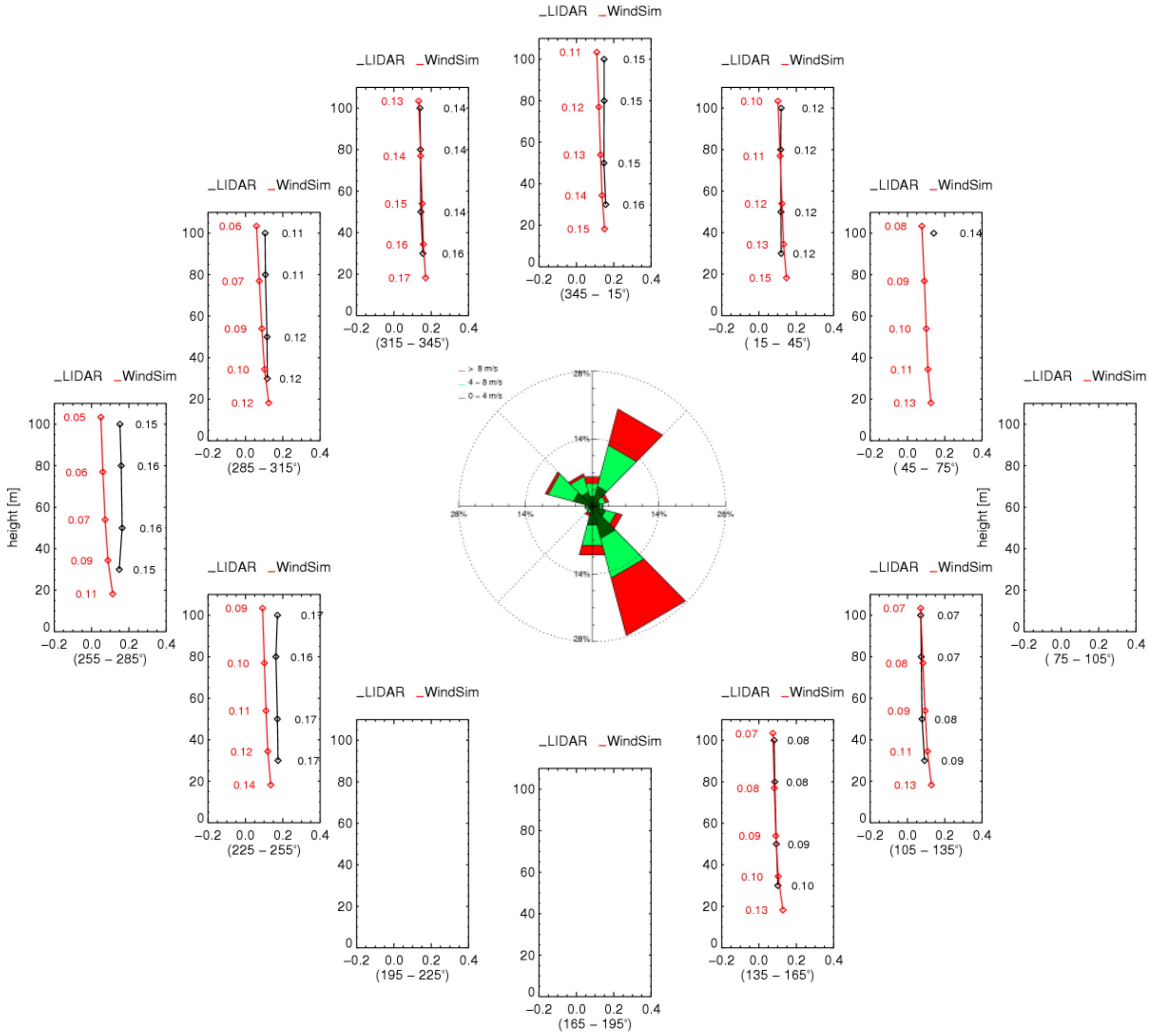

Fig. 9: Vertical profiles of turbulence intensities for 30° wind direction sectors from LIDAR measurements (black) and WindSim calculations (red) at Rudine. In the center the wind rose at 50 m from the mast measurement is displayed. Turbulence intensities are calculated only for wind speeds above 4 m/s. No turbulence was calculated for sectors/levels with less than ten valid 10 minute averages for the LIDAR measurements.