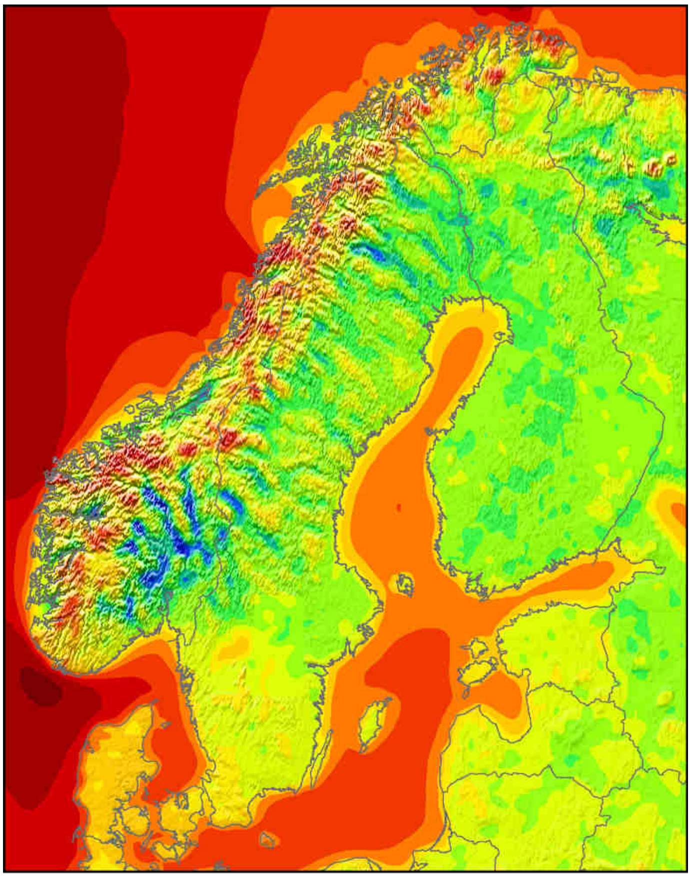
Documentation on the

anemos wind atlas for

Scandinavia / Baltic 10 km



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D-PL-17580-01-00

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1. Introduction

The **anemos wind atlas** for Scandinavia / Baltic 10 km (**SK-10km.E5**) represents a database containing long-term time series for the atmospheric parameters wind speed, wind direction, air temperature, air pressure, relative humidity, air density, precipitation, long- and shortwave radiation. The temporal resolution of the wind atlas is 10 minutes, the horizontal resolution is 10 x 10 km². It covers whole Northern Europe (Scandinavia, Baltic Sea and the Baltic countries). Fig. 1 shows the process chain of the development of the anemos wind atlas. The two main points are:

- Optimization of the model settings with subsequent WRF main simulation (Downscaling)
- Verification of the WRF main simulation with wind measurements

More detailed explanations of these points can be found in the following chapters.

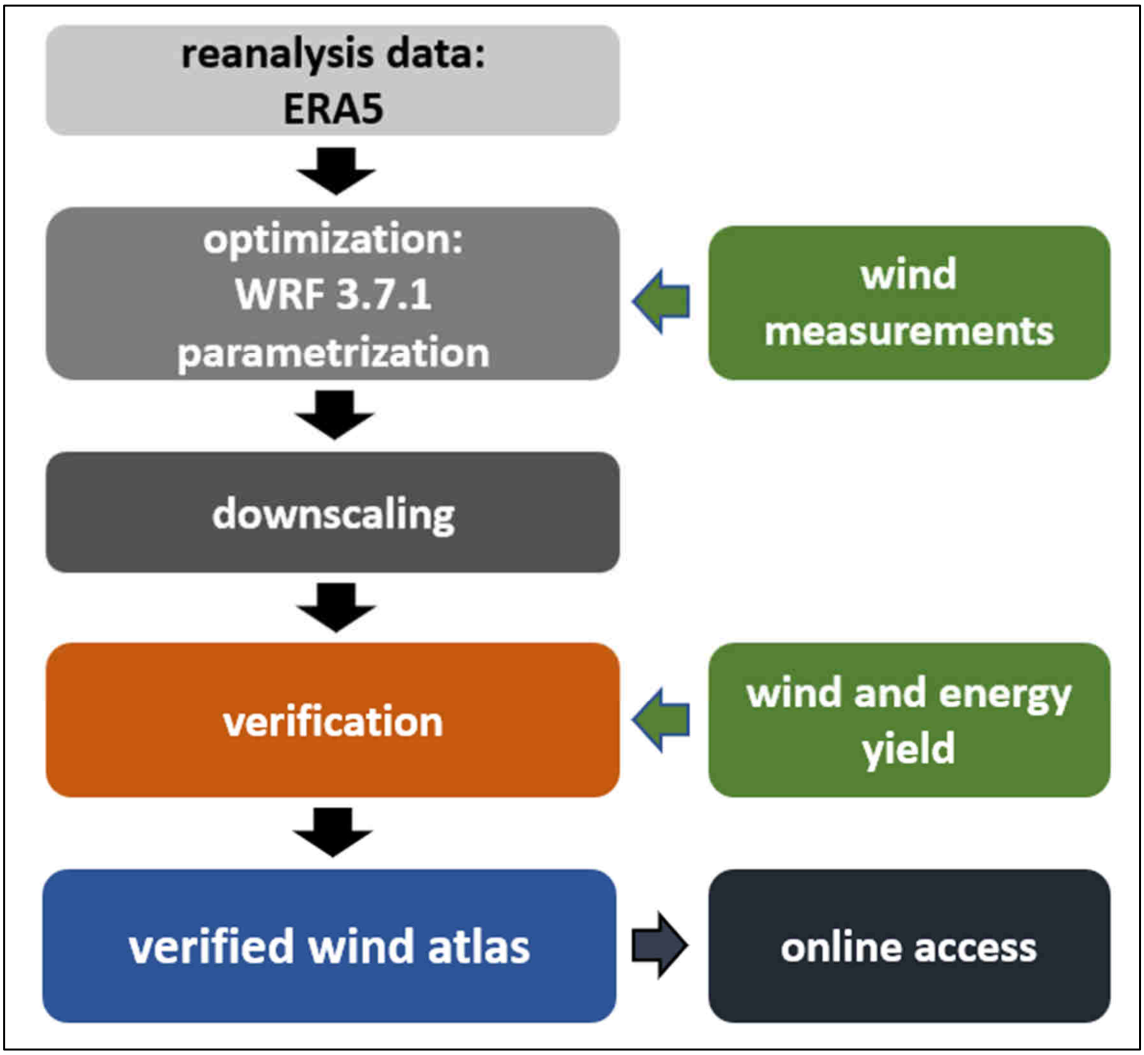

Fig. 1: Developmental steps of the new anemos wind atlas for Scandinavia/Baltic 10 km.

2. The WRF model

The wind atlas **SK-10km.E5** is created by means of the meteorological mesoscale model **WRF** (**W**eather **R**esearch & **F**orecasting model with the version 3.7.1). The WRF model is a state-of-the-art weather forecast system (coupled atmospheric-land surface model) of the next generation which was developed in the 1990s at **NCAR** (**N**ational **C**enter for **A**tmospheric **R**esearch).

WRF is a non-hydrostatic model (explicit calculation of the vertical velocity) and estimates for each time step the Navier-Stokes equations, which describe the atmospheric flow. Mesoscale processes such as the land-sea wind circulation can be sufficiently resolved by the model. However, microphysical processes as well as convection, radiation or planetary boundary processes have to be parameterized.

The WRF model with its so-called multi-nesting ability allows for a simultaneous calculation of several model domains with different grid resolutions (Fig. 2). This way, regional high-resolution simulations of the atmospheric circulation are possible, which employ detailed ground level information in order to take into account the impact of vegetation, roughness and orography.

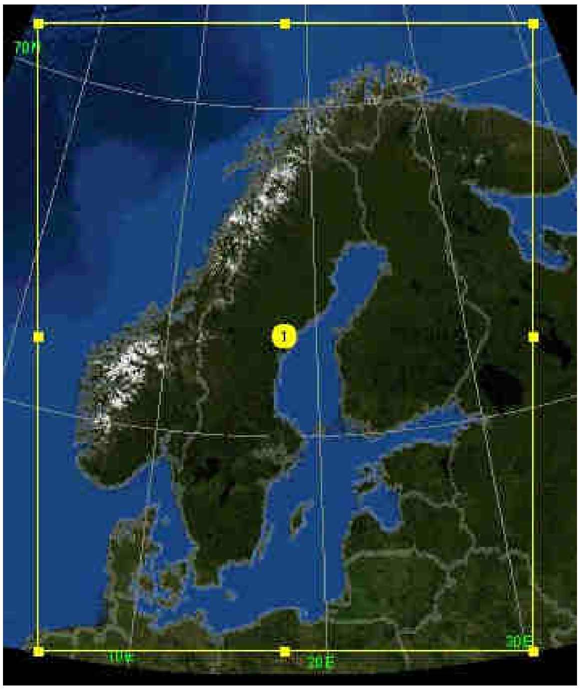

Fig. 2: Domain of the anemos wind atlas Scandinavia / Baltic 10 km. Domain with 10 x 10 km².

For the wind atlas **SK-10km.E5** one domain is applied (Fig. 2). The domain covers great parts of Northern Europe and has a spatial resolution of 10 x 10 km².

During the simulation, new input data are assimilated into the WRF model every hour, which forces the model into the right direction (nudging process). The atmospheric state variables are stored every 10 minutes for each grid point on a grid. The simulation covers the period 2000 up to date and is continuously extended. The vertical model structure of the atmosphere has a high resolution with 25 vertical layers. The lower heights, which are relevant for wind turbines (up to 300 m) contain already nine of the 25 vertical layers.

3. Input data

The WRF model requires surface data (soil temperature, soil moisture, snow, etc.) as well as all important atmospheric parameters (wind, temperature, pressure, relative humidity, etc.) as input data. For the wind atlas **SK-10km.E5** the new worldwide available ERA5 reanalysis data are used as input and driving data. The ERA5 reanalysis data are of higher quality than the former ERA-Interim reanalysis data regarding consistency and correlation. Therefore, the advantages of the ERA5 reanalysis data such as consistency, homogeneity, length of time series, continuous updates, onshore as well as offshore availability can be preserved or even amplified by the WRF model. In addition, the disadvantages of relatively low spatial (approx. 30 x 30 km^2) and temporal resolution (1 h) of ERA5 reanalysis data are surmounted by the anemos wind atlas **SK-10km.E5**.

The surface data are taken from the ERA5 data set as well. Thus, consistency of the radiation- and heat flow between surface and atmosphere is given. The surface data consists of four surface levels and contains i.a. soil moisture, soil temperature and snow.

The ground level elevations are taken from the SRTM data set (Shuttle Radar Topography Mission, USGS EROS Data Center) and interpolated onto the model grid. These data were collected in the year 2000 and are available with a spatial resolution of about 90 m. The vertical resolution is 1 m. Any information about vegetation or roughness conditions within the boundaries of the simulation area are derived from the USGS data set (United States Geological Survey). The grid data are available in a spatial resolution of 1 km.

4. Optimization of the model settings

The model settings and parameterizations (e.g. planetary boundary scheme, surface scheme, radiation scheme) were tested prior to the main simulation and optimized for the relevant atmospheric parameters (wind speed and wind direction). The model settings were compared with the Germany (**D-3km.M2**) and France wind atlas (**F-3km.M2**) and were verified with wind measurements (met masts and LiDAR, see Fig. 1). These tests show how the wind field near the ground reacts to different parameterizations and schemes (sensitivity tests). After that, the setting which yields the smallest deviations between model and observations was used for simulating the entire time period (> 20 years).

5. Statistical verification with wind measurements

The most important task after running the main simulation is its intensive verification with a variety of wind measurements. 19 measurements were used for verifying the **SK-10km.E5**.

Through the verification the quality of the main simulation is determined. The verification includes statistical key parameters such as mean values, coefficient of determination (R^2) or correlation (R), bias, root mean squared error (RMSE) and extreme values (QQ-plot). Additionally, vertical profiles, diurnal cycles, wind roses, and frequency distributions with Weibull parameters are checked.

The distribution of the measurement sites is roughly displayed with red dots in Fig. 3. The results of the verification are shown in Fig. 4 as an example for the measurement heights between 40 m and 120 m and in Fig. 5 for a measurement height of 100 m. For this purpose, the mean wind speed bias at the four offshore and 15 onshore stations as well as the coefficient of determination (R^2, hourly values) are calculated and graphically presented. Thus, a comparative evaluation between the measurements and the wind atlas (raw data) is possible. It should be taken into account that nine of the 19 stations are included when considering the measurements at 100 m height. The boxes represent the 25 % - 75 % quartile, i.e., the middle 50 % of the data, and the whiskers (antennas) the minimum or maximum. The mean value (median) is marked by a cross (line in the box).

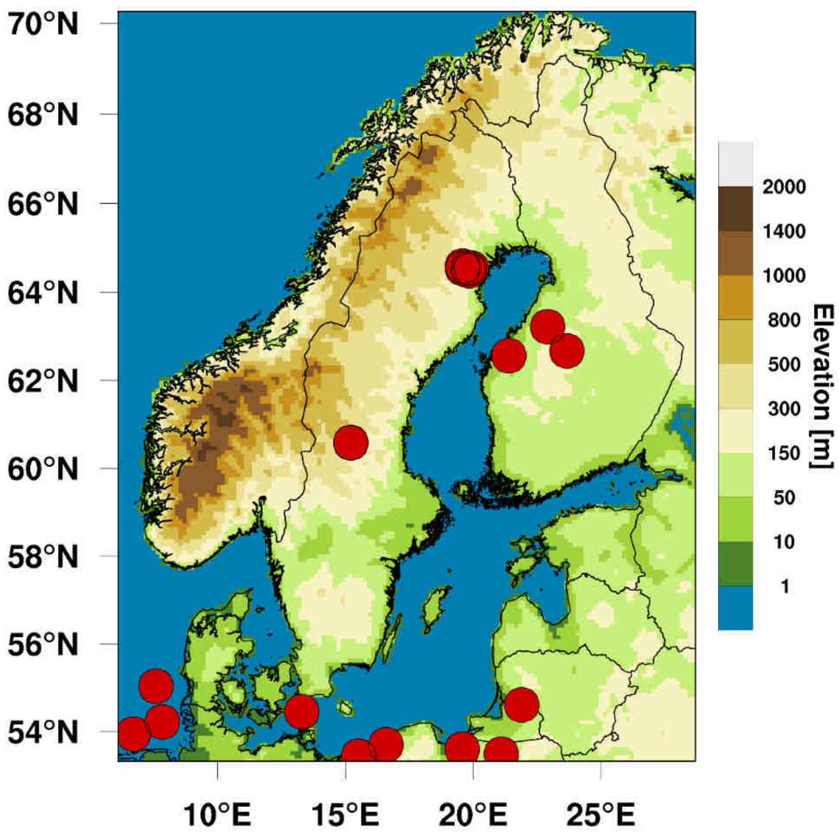

Fig. 3: Final model domain of anemos wind atlas Scandinavia / Baltic 10 km. The color bar shows the model elevation. Red circles mark roughly (± 50 km) the 19 measurement sites.

First, the mean bias and coefficient of determination (R^2) between measurement and simulation at all heights (top anemometer) are considered. Fig. 4a shows that the mean bias is positive for the onshore measurements and negative for the offshore measurements. In addition the R^2 is higher for the offshore sites than for the onshore sites (Fig. 4b). The mean bias is on average +2 % for all stations. Separated into the onshore measurements, the mean bias is +3 % and for the offshore measurements -2.4 %. The standard deviation for all locations is 4.7 %, which is below the 5 % mark. The R^2 value for the offshore measurements of 91.6 % is significantly higher than the onshore value of 75.5 %. Therefore, the results of the observations of all stations are improved by the offshore measurements.

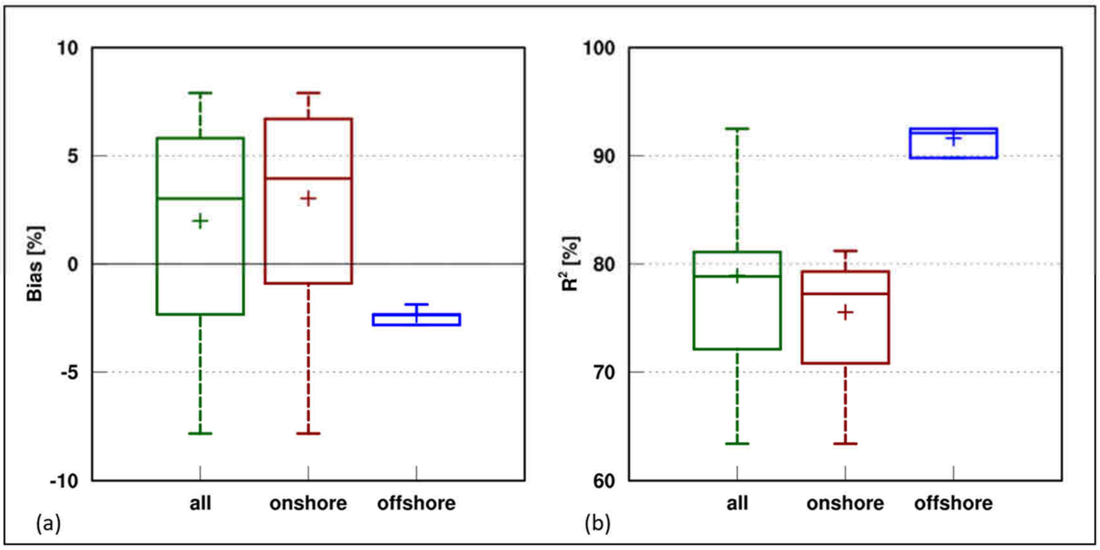

Fig. 4: Boxplot between 19 independent measurements and the anemos wind atlas at heights between 40 m and 120 m above ground. The bias (a) and the correlation (b) are shown.

In comparison to the previous analysis only the measurements at a height of 100 m above ground are considered in the following Fig. 5. The mean bias for all nine stations is +1.8 %. As could be seen before, there is a difference between the onshore and offshore measurements. With a mean bias of +3.8 % for the onshore measurements and -2.2 % for the offshore measurements, the mean bias of all stations is reduced (Fig. 5a). The standard deviation for all sites is 4.8 %, which is below the 5 % mark. Furthermore, Fig. 5b shows that the R^2 behave similarly to the previous analysis. On average, there is a R^2 of 83.1 % for the measurements at 100 m height. The average R^2 of 78.5 % for the onshore sites is significantly lower than 92.2 % for the offshore sites.

Overall, the results show a lower mean bias for the 100 m height compared to the highest measurement height of each station. Additionally, it can be seen that the R^2 is also higher when considering the 100 m compared to the measurements at the highest measurement height. Furthermore, it should be noted that the offshore locations improve the results due to a lower mean bias and higher R^2.

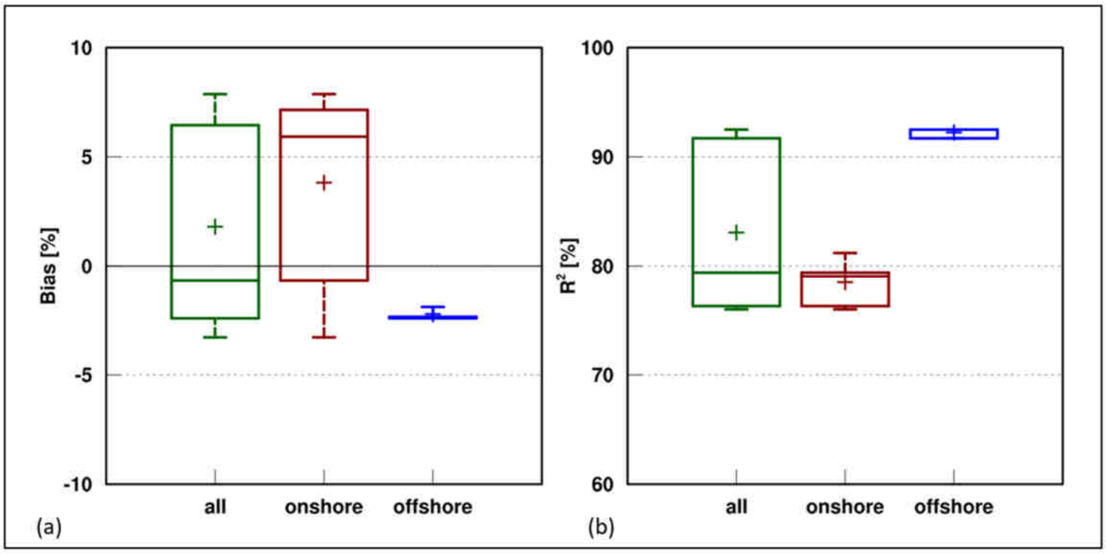

Fig. 5: Boxplot between nine independent measurements and the anemos wind atlas at 100 m above ground. The bias (a) and the correlation (b) are shown.

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