Gesellschaft für Umweltmeteorologie mbH

Documentation

on the anemos wind atlas

for Poland 1 km ERA5

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1. Introduction

The **anemos wind atlas** for Poland 1km ERA5 (**P-1km.E5**) provides a long-standing time series database consisting of the atmospheric parameters windspeed and direction, turbulence intensity, air temperature and pressure, relative humidity, air density, precipitation as well as short- and long-term radiation. The **wind atlas** has a temporal resolution of 10 minutes, while the spatial resolution of 1.35 x 1.35 km² covers the whole of Poland as well as large parts of the Baltic Sea. The development process of the **anemos wind atlas**, as shown in Figure 1, consists of four major steps:

- Optimising the input data and model settings (Downscaling → dynamic nesting)
- MCP-Procedure
- Remodelling of the wind atlas to correct the raw data from the WRF model
- Extensive verification through wind measurements

More thorough explanations of the four steps found in Fig. 1 can be found in sections 3 - 9.

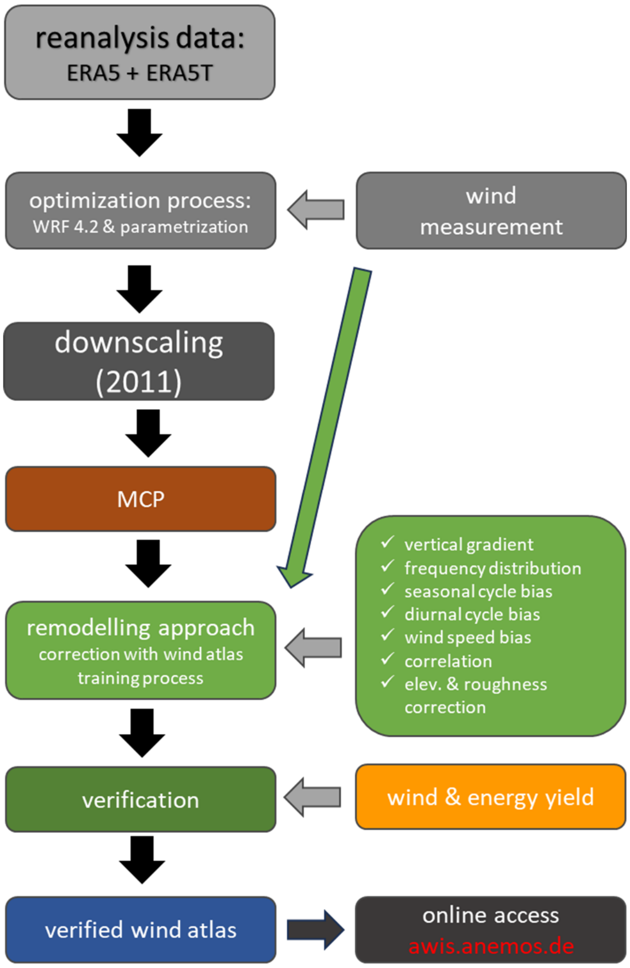

Fig. 1: Development process of the anemos wind atlas for Poland 1km.

2. The WRF-Model

The **P-1km.E5** was simulated using the mesoscale numerical weather prediction model **WRF** (**W**eather **R**esearch & **F**orecasting Model Version 4.2). The WRF-Model is a *State-of-the-Art*, next generation weather prediction system (coupled atmosphere-land surface model), which was developed in the 1990's at the **NCAR** (**N**ational **C**enter for **A**tmospheric **R**esearch).

WRF operates on a non-hydrostatic basis (explicit calculation of vertical wind speed) and solves the Navier-Stokes equations, which describe atmospheric flow, for each time step. Mesoscale processes, such as land-sea-wind systems or high-reaching convection (thunderstorm cells), can be adequately resolved by the model due to its high temporal and spatial resolution (10 min, 1.35 km). Parametrizations are used for microphysical processes as well as shallow convection, radiation, or boundary layer processes. The WRF model allows for the simultaneous calculation of multiple model domains with different grid resolutions through its capability for multiple nesting (Fig. 2). The multiple nesting method enables regionally high-resolution simulations of atmospheric circulation that account for the influence of vegetation, roughness, and orography by utilizing detailed surface information

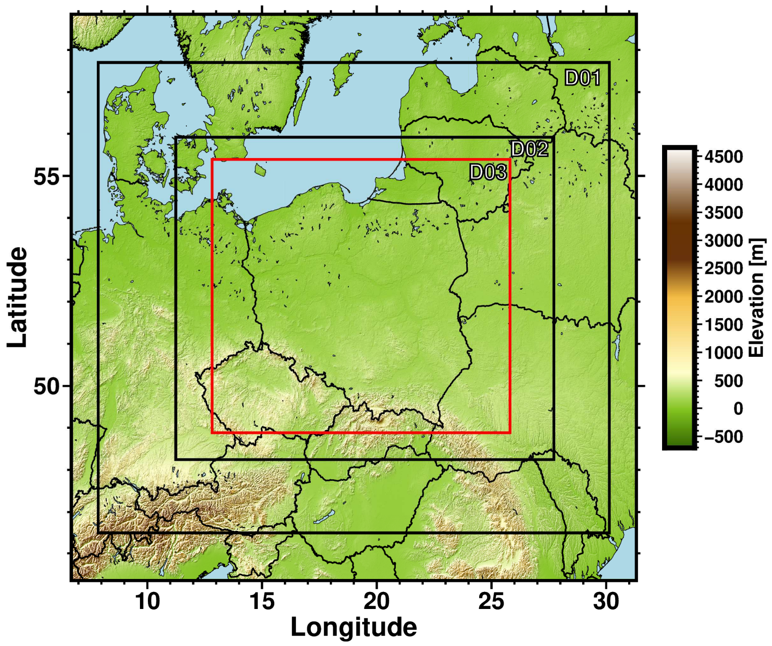

Fig. 2: Multiple nesting method using the three domains of the anemos wind atlas Poland 1 km. Domain D01 with 20.25 x 20.25 km²), Domain D02 (Nest) with 6.75 x 6.75 km² and Domain D03 (Nest, rot) with 1.35 x 1.35 km².

For the **P-1km.E5**, a nested structure consisting of three domains is used (see Fig. 2). The simulation domain consists of an outer domain within which two high-resolution domains are nested. The outer domain covers large parts of Central Europe and has a spatial resolution of 20.25 x 20.25 km². The middle domain, with a spatial resolution of 6.75 x 6.75 km², serves exclusively to ensure the stability of the model. Nested within this domain is the higher-resolution Poland domain (D03), which has a spatial resolution of 1.35 x 1.35 km². During the simulation, the three domains communicate with one another.

The outer domain provides boundary conditions for the respective inner domain, while the latter supplies the outer domains with higher-resolution calculations. During the simulation, new input data from the ERA5 reanalysis is assimilated into the WRF model on an hourly basis, which nudges the model in the correct direction (nudging method). The atmospheric state variables are output by the model in 10-minute intervals for each grid point. The vertical model structure of the atmosphere is very high-resolution, with 50 altitude layers. Fourteen of the 50 vertical levels are located in the lower 300 m alone, which is particularly relevant for wind turbines.

3. The Measure Correlate Predict (MCP) method

A method was developed that uses MCP to generate long-term time series for the Poland 1 km wind atlas. The WRF simulation at a resolution of 1.35 x 1.35 km^2 was calculated only for the year 2011. A Linear Least Squares MCP method (LLS) is used. The reference data used in the MCP method are derived from the EU-10km.E5 wind atlas[1], which is available for the period from 1999 to the present. Accordingly, the MCP-corrected Poland wind atlas on Demand is generated based on the EU-10km.E5 wind atlas. Only then are the newly generated wind atlas time series subjected to the remodeling process.

4. Input data

The WRF model requires both surface data (including surface temperature, soil moisture, and snow) and all key atmospheric parameters (including wind, temperature, pressure, and relative humidity) as input data. For the **P-1km.E5**, the globally available ERA5 reanalysis data are used as atmospheric input data.

This means that the advantages of the ERA5 reanalysis data, such as consistency, homogeneity, the length of the time series, continuous updating, and availability over both land and sea, are preserved or enhanced through simulation with the WRF model. On the other hand, the P-1km.E5 significantly improves upon the disadvantages of the ERA5 reanalysis data, such as the relatively low spatial (approx. 30 x 30 km^2) and temporal resolution (1 h). The ERA5 reanalysis data is also used for the surface data. This ensures consistency in the radiation and heat fluxes between the surface and the atmosphere. The surface data are available in four vertical surface layers and include, among other things, soil moisture, soil temperature, and snow.

The terrain elevations are derived from the **SRTM** dataset (**S**huttle **R**adar **T**opography **M**ission, USGS EROS Data Center) and interpolated to match the model grid. The data was recorded in the year 2000 and is available at a horizontal resolution of approximately 90 m. The vertical resolution is 1 m. All information regarding vegetation and surface roughness within the simulation area is provided by the **CORINE** dataset from the European Environment Agency (**EEA**). This information is based on data from the Landsat-7 satellite at a scale of 1:100,000. The data is available on a model grid with a spatial resolution of 100 m.

[1] https://anemos.de/de/windatlas.php (See Documentation EU-10km.E5)

5. Optimising model settings

Prior to the main simulation, the model settings and parameterizations (including the boundary layer, surface, and radiation schemes) were tested and optimized for the relevant atmospheric parameters (wind speed and wind direction). The model settings were compared with the wind atlas for Germany (D-1km.E5) and verified using wind measurements (measuring masts and LiDAR). This test phase clearly demonstrates how the near-surface wind field responds to different parameterizations and schemes (sensitivity tests). The setting that most closely matches the observations is used for the simulation of P-1km.E5. This is based on the boundary layer parameterization MYNN at the order of 2.5, which is implemented in the WRF version 4.2 used and enables the derivation of turbulence intensity (TI) from the predicted turbulent kinetic energy (TKE).

6. Statistical verification using wind measurements to prepare remodeling

The most important task following the main simulation is comprehensive verification using numerous wind measurements. For the development of the P-1km.E5, measurements from 40 stations with a total of over 210 measurement heights were available, of which 20 stations were used for site-specific remodeling (training) and 20 for independent verification. On the one hand, the verification provides the forecast accuracy and quality of the main simulation; on the other hand, systematic errors are corrected in the final step, the *remodeling* (Section 7), and the quality of the atlas is improved. Statistical parameters such as the mean, coefficient of determination (R^2), correlation (R), bias, RMSE, and outliers (QQ distribution) are verified. Additionally, vertical profiles, daily and annual variations, wind roses, and frequency distributions with Weibull parameters are examined.

7. Wind speed optimisation (remodeling)

After the main simulation has been fully verified using all available wind measurements, the wind atlas is optimized through remodeling in the penultimate step of the process chain. First, correction factors for the diurnal and annual variations are developed using the available wind measurements. The model data are corrected by fitting a cumulative Gumbel distribution to the diurnal and annual variations. The Gumbel distribution is an extreme value distribution frequently used to model maxima or minima in meteorological and hydrological datasets. In the following, sector-specific training is performed using wind measurements from 20 locations, based on the deviations and their dependencies identified during the verification in Section 6. The remaining wind measurements are required for the subsequent independent verification of the remodeling procedure.

The training process determines scaling parameters using multiple linear regression analysis, which are then applied to the wind atlas time series. The model searches for dependencies between the scaling parameters and subgrid information (orography, roughness, etc.) and uses them if they are sufficiently significant. Consequently, the scaling parameters developed during the training can be used to correct all grid cells using the subgrid information. Ultimately, the remodeling improves the statistical parameters as well as the frequency distribution with Weibull parameters and the vertical profile.

In summary, daily and annual trend corrections were applied to correct the systematic bias in the daily and annual trends that is already present in the reanalysis data. Additionally, roughness and vertical corrections were applied.

8. Site-specific time series of wind speed

As part of the remodeling process, a site-specific elevation and roughness correction was developed using CFD simulations at various complex measurement sites. The 1.35 x 1.35 km² wind atlas time series for the test sites are modeled at high resolution using the Meteodyn CFD model. Using the empirical elevation correction and the best available, freely accessible DGM datasets for Poland, the wind atlas is scaled to a 20 x 20 m² grid.

Elevation and roughness correction is part of the remodeling process and accounts for differences between the grid cell and the measurement. In addition, site-specific topographic correction—particularly in complex regions—significantly improves the estimated average wind speed. In flat terrain, the elevation correction has no effect, while the roughness correction makes a significant contribution in cases of complex vegetation changes at lower elevation levels. The correction function is applied for each time step when reading out time series of wind speed.

9. Verification after remodeling

Site-specific remodeling generates a dataset that provides a reliable basis for further analysis. Figure 4 shows a comparison of independent measurements with the anemos-P-1km.E5.

Fig. 4a shows the coefficient of determination R^2 based on 10-minute averages for two altitude ranges. Independent measurements (N=20 and N=9, respectively) are compared with the wind atlases EU-10km.E5 and P-1km.E5. In the altitude range from 60 m to 100 m, the P-1km.E5 achieves an average R^2 of 0.70 ± 0.04, while the EU-10km.E5 is at 0.68 ± 0.04. Between 100 m and 140 m, the P-1km.E5 also shows better agreement with an R^2 of 0.71 ± 0.05. Overall, the P-1km.E5 thus exhibits a higher correlation than the EU-10km.E5.

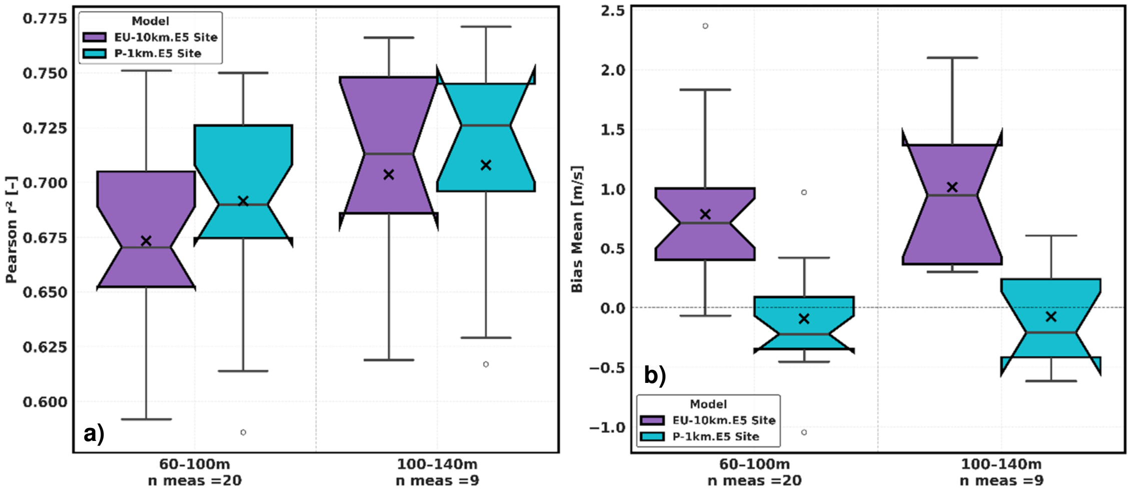

Fig. 3: Coefficient of determination R^2 (a) and mean bias (b) of wind speed, validated against independent measurements at two height levels (N=20 and N=9, respectively; for each station, the measurement height closest to the bin center is used). The box plots show the median (line), mean (cross), interquartile range (box), outlier limits (whiskers), and 95% confidence interval of the median (notches).

A significant improvement is evident in the bias (Fig. 4b). Between 60 m and 100 m, the mean bias of the P-1km.E5 is -0.09 ± 0.43 m/s, which is significantly lower than that of the EU-10km.E5 at 0.79 ± 0.59 m/s. At the same time, the interquartile ranges for the P-1km.E5 are clearly reduced. A similar picture emerges between 100 m and 140 m: While the EU-10km.E5 exhibits a systematic overestimation of 1.01 ± 0.65 m/s, this is significantly reduced by the P-1km.E5 to -0.07 ± 0.43 m/s.

10. Optimising wind direction

To quantify systematic deviations, the wind direction time series from the P-1km.E5 sensor were first validated using mast measurements. Circular statistical parameters were used for the analysis.

The analysis revealed an average positive bias of approximately +6.3° (clockwise rotation) for the P-1km.E5. This bias shows a clear altitude dependence and decreases gradually from approximately +8.4° at 60 m to approximately +3.3° at 240 m. Based on the high-resolution bias values, a linear altitude-dependent correction was derived and applied to the time series of wind direction.

11. Areas of application

Thanks to its site-specific remodeling method and comprehensive verification using measurement data, the wind atlas represents the most powerful dataset currently available for Poland. The correction and validation steps described allow for a significant approximation of the absolute measured values, thereby substantially expanding the wind atlas' practical scope of application. The wind atlas, including optimization, is suitable for the following application areas, among others:

- ✓ **Wind potential (wind speed, Weibull A & k, power density)**
- ✓ **Long-term data (including intra-year) with wind measurements and yield data**
- ✓ **Yield calculations with / without losses on a 10-minute basis**
- ✓ **Yield index**
- ✓ **Extreme wind calculations**
- ✓ **Turbulence intensity calculations**
- ✓ **Market value analyses**
- ✓ **Revenue forecasts**
- ✓ **Risk / Portfolio analysis**
- ✓ **SCADA data analysis**

12. Literature

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13. Appendix

Tab. 1: Licenses DGM

Name Digital Elevation Model (DEM)		Version	Link	License
Euro DEM	Pan-European Height Dataset at Medium Scale	EuroDEM 2023	https://www.mapsforeurope.org/datasets/euro-dem	https://ome-download-data.s3.eu-west-1.amazonaws.com/euro-dem/documents/EuroDEM_2023_Attribution_Statement.pdf
MV-1m	Mecklenburg-Vorpommern DGM 1	aktuellste Version	https://www.laiv-mv.de/Geoinformation/Geobasisdaten/Gelaendemodelle/	https://www.govdata.de/dl-de/zero-2-0
BB-1m	DGM Brandenburg + Berlin	02.06.2016 00:00:00	https://geobasis-bb.de/lgb/de/geodaten/3d-produkte/gelaendemodell/	https://www.govdata.de/dl-de/by-2-0
SN-1m	DGM Freistaat Sachsen	aktuellste Version	https://geoportal.sachsen.de/cps/metadaten_portal.html?id=a3dba5b2-0118-4d76-ab78-ba656a1b489e	https://www.govdata.de/dl-de/by-2-0
PL-20m	Poland DGM 20	aktuellste Version	https://www.gov.pl/web/gugik-en/data	https://creativecommons.org/licenses/by/3.0/pl/
CZE-5m	DGM 5m	aktuellste Version	https://geoportal.cuzk.cz	Creative Commons CC BY 4.0 License