Does High-Resolution Hybrid Downscaling of ERA5 Improve Hub-Height Wind-Power Profiling in Complex Terrain?

Katarina Rac

Thomas Kienberger

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OVERVIEW

- **Topic overview and motivation**
- Data collection and preparation
- Modeling approach: theory and mathematics
- Preliminary results and insights

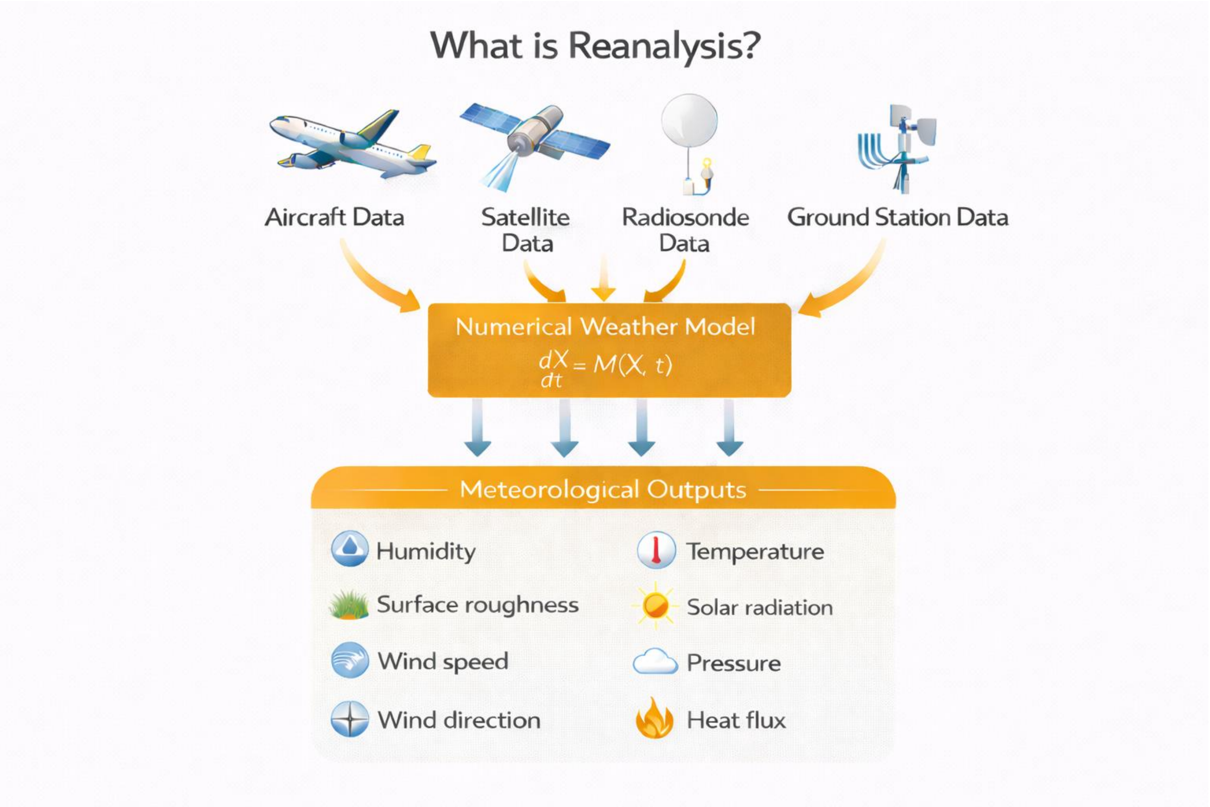
MOTIVATION

- Wind power:

$$\boldsymbol{P} = \frac{1}{2}\rho A \boldsymbol{v}^3$$

- Any uncorrected error in wind speed v is amplified by approximately a factor of **3** in the estimated wind power
- Accurate wind energy assessment therefore requires high-quality meteorological data with sufficient spatial and temporal resolution
- Problem over oceanic regions and regions of complex orography, global datasets often remain spatially coarse → Solution: **REANALYSIS DATA**

REANALYSIS ERA5 DATASET



- **ERA5 reanalysis data**:
  - 5th generation by the European Centre for Medium-Range Weather Forecasts (ECMWF)
  - Wind speed profiles at 10 m and 100 m
  - Atmospheric variables such as 2 m temperature, surface pressure, surface roughness, …
  - offers global hourly meteorological variables at ~30 km resolution
  - long temporal coverage
  - ability to represent wind conditions **in regions with complex terrain remains restricted** due to the coarse resolution

State-of-Art

- Already in use:
  - RenewablesNinja (RN): normalized hourly wind power output (capacity factor) at a specific location, based on the reanalysis data and a pre-defined turbine hub-height
  - Global Wind Atlas (GWA): provides a climatology (multi-year mean) of wind speed and wind power density with ~250 m resolution at different altitudes
- Advantages and disadvantages:
  - Suitable for energy system modelling
  - RN: coarse spatial resolution, but high (hourly) temporal resolution → spatial corrections needed
  - GWA: high spatial resolution, but limited temporal resolution (climatological averages)
- Hu et al.: modell to downscale and correct reanalysis wind speed at 10 m altitude, but no interpolation to turbine hub height

GOAL

- Provide wind speed profiles with both high spatial and temporal resolution
- Develop a hybrid model combining physical and statistical corrections
- Correct wind-speed estimates derived from ERA5
- Translate wind fields into parameters relevant for energy system modelling
- Identify limitations and directions for further improvement

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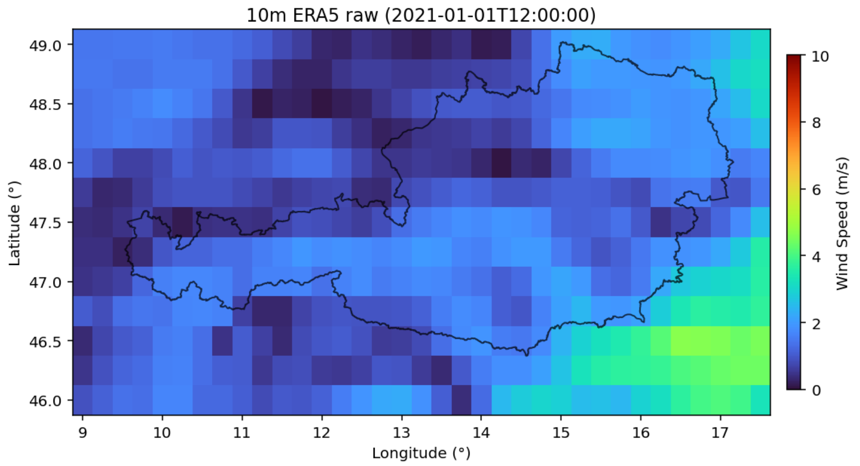
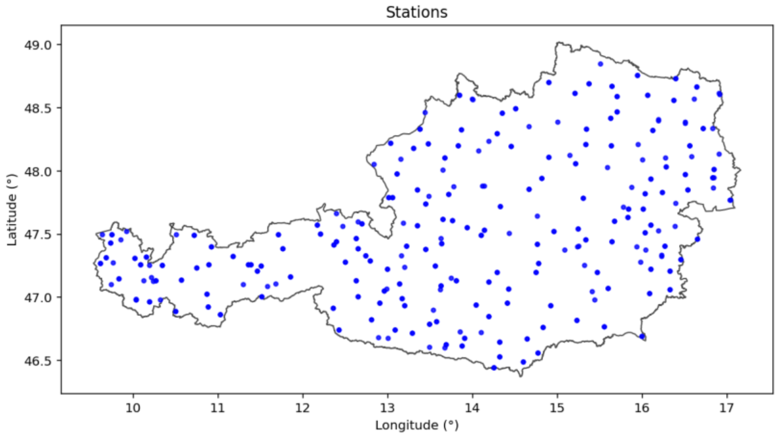
DATA COLLECTION AND PREPARATION

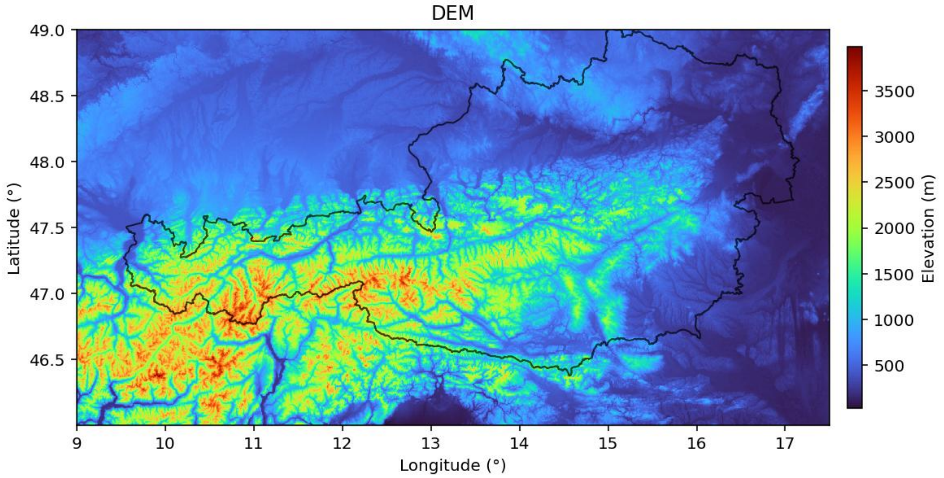
- ERA5 reanalysis dataset:



- Wind speed measurements:



- Digital elevation model (DEM):



- Turbine characteristics
  - Hub-height
  - Swept area

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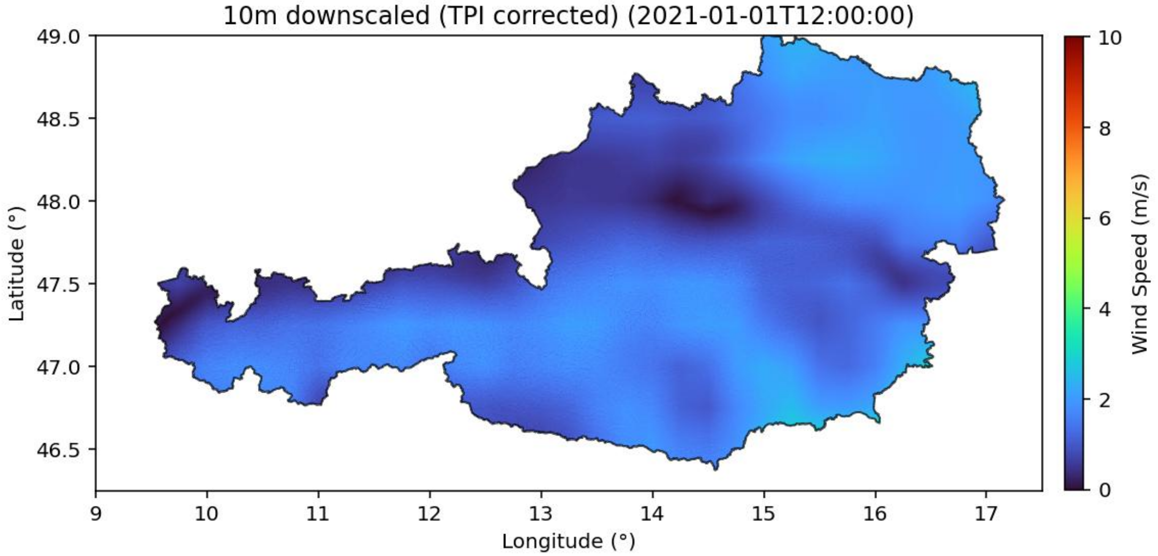
The Hybrid Modell

1. Downscaling and physical correction:
   – Topographic Position Index (TPI) to represent local exposure/sheltering



2. Statistical correction:
   – Bias correction: Quantile Mapping using empirical percentiles
   – Elevation stratification: learn QM functions per elevation bin (stations grouped by height)
   – Application: apply the bin-specific mapping to the full 500 m grid

THE HYBRID MODELL

3. Hub-height extrapolation using Monin-Obukhov Similarity Theory (MOST): links wind speed, turbulence and heat fluxes

$$U(z) = \frac{u^*}{\kappa}\left(\ln\left(\frac{z}{z_0}\right) - \Psi\left(\frac{z}{L}\right)\right)$$

$$\rightarrow \frac{U(z)}{U(10)} = \frac{\left(\ln\left(\frac{z}{z_0}\right) - \Psi\left(\frac{z}{L}\right)\right)}{\left(\ln\left(\frac{10}{z_0}\right) - \Psi\left(\frac{10}{L}\right)\right)}$$

with $\ln\left(\frac{z}{z_0}\right)$ being the logarithmic height term depending on **surface roughness** and $\Psi(\frac{z}{L})$ describing the **atmospheric stability** at specific altitude

4. Estimation of the wind power:

$$P(lon, lat, z, t, r) = \frac{1}{2} A(r)\rho \cdot v(lon, lat, z, t)^3$$

- with time and spatial dependent ρ:

$$\rho(lon, lat, z, t) = \frac{P\ (lon, lat, z, t)}{R\ \ \cdot T(lon, lat, tz\ t)}$$

- Depending on turbine specific properties:

$$A(r) = r^2\pi$$

Overview

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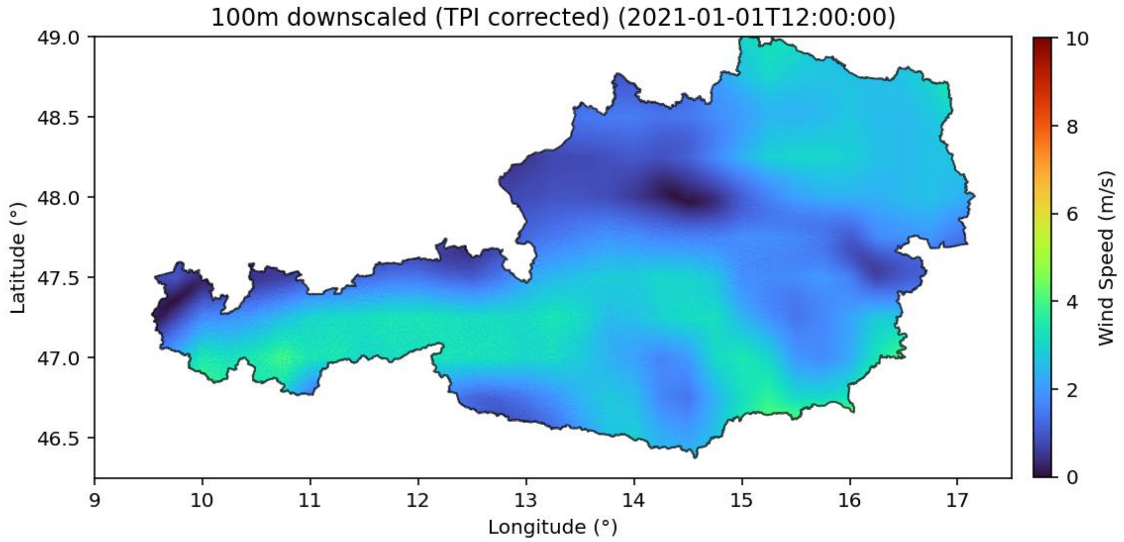
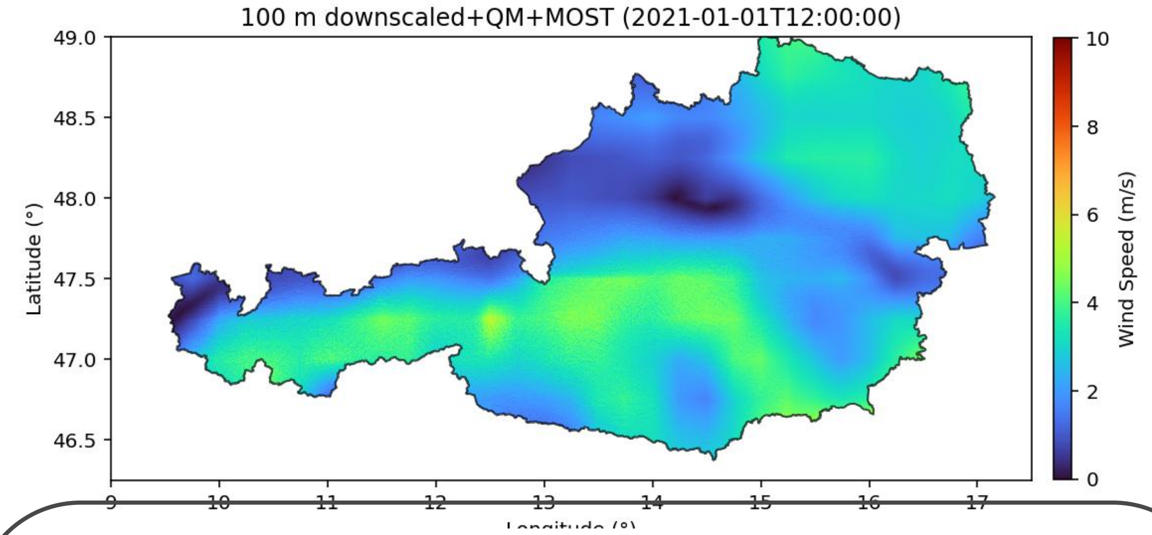
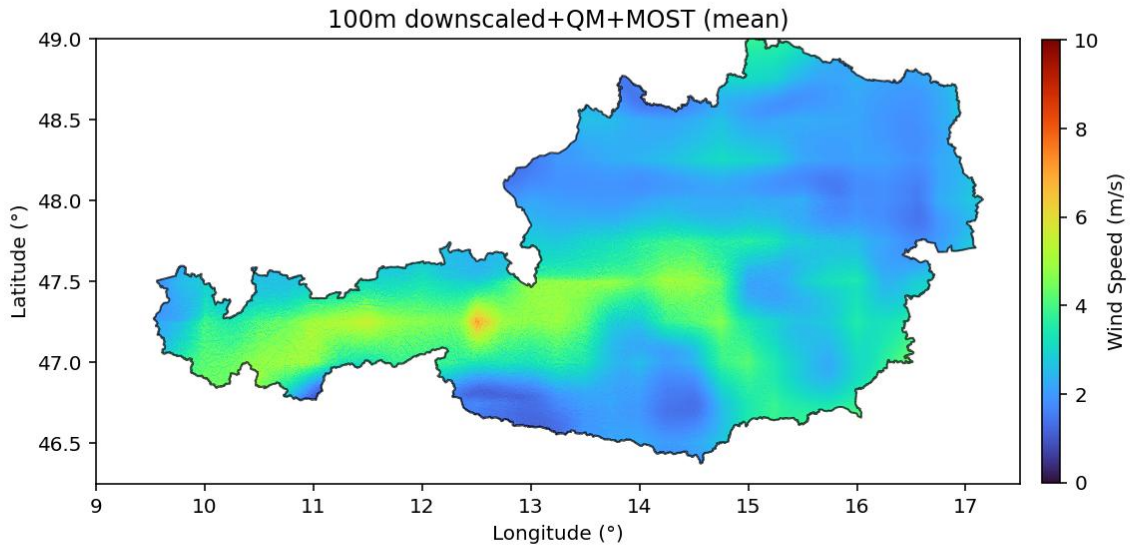
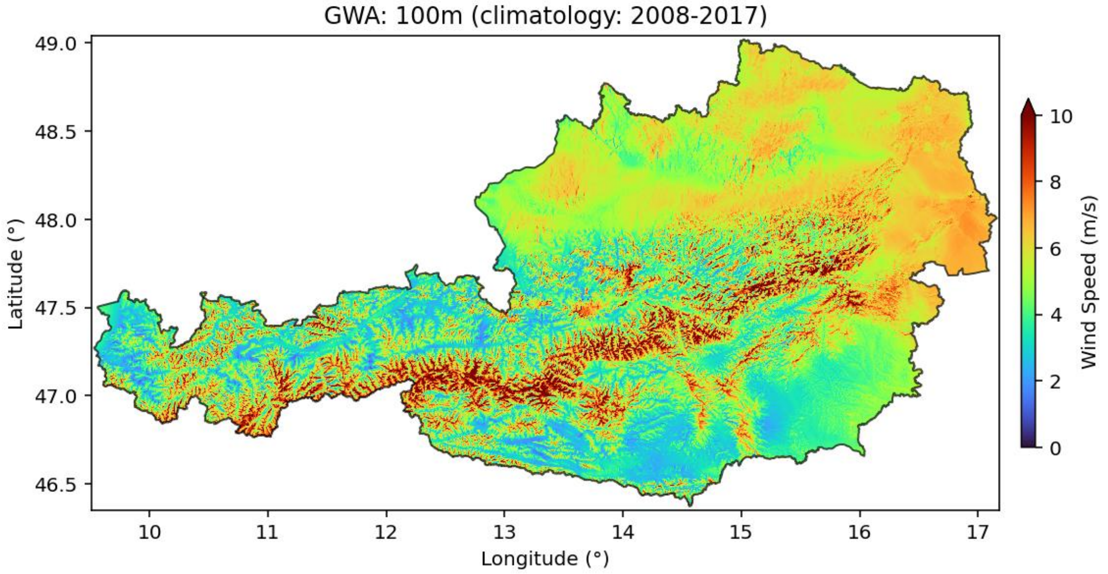
- **Preliminary results and insights**

PRELIMINARY RESULTS (ERA5 AT 100M)









PRELIMINARY RESULTS

- the terrain-based downscaling approach modifies the spatial pattern of the ERA5 wind fields and leads to a noticeable reduction in variance
- atmospheric-stability corrections yields wind-speed profiles with a more realistic vertical structure
- initial validation by comparing the mean, standard deviation and variance of the 100 m raw ERA5 winds and RenewablesNinja dataset with those of the downscaled and MOST-corrected fields: corrected data performs best in terms of statistical characteristics

Challenges & Future Insights

- Challenges:
  - Computation time
  - Data availability (e.g. for the QM and validation)
  - Data size (4D)
  - Intermediate storage Bottlenecks
  - Balancing model complexity vs. feasibility
  - Limited documentation of some datasets (measurement)
- Future insights:
  - Acquire further data
  - Extend the temporal resolution
  - Investigate the influence of the correction methods individually
  - Estimate the wind power including introducing turbine specific data

DIPL.-ING. KATARINA RAC

LEHRSTUHL FÜR ENERGIEVERBUNDTECHNIK
MONTANUNIVERSITÄT LEOBEN

www.evt-unileoben.at

katarina.rac@unileoben.ac.at

038424025426