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To cite this article: Felix Krimm *et al* 2026 *J. Phys.: Conf. Ser.* **3224** 022056

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Comparison of Measured and Simulated Turbine Response to Cold Pool Events

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Abstract. Certain weather conditions, such as cold pool events, lead to rapidly changing wind speeds and directions. In the WiValdi research wind farm, cold pool events were observed. Measured data of multiple physical quantities are available. To predict loads and power output during upcoming cold pool events, aeroelastic simulations will be used at the German Aerospace Center in the future. The input to these simulations should be generated from a meteorological forecast, which is still under development. Therefore, the measured wind conditions are used in place of the forecast in this study.

This study contributes to the preparation of such a forecast of loads and power. For high usability, the forecast must match reality in both the time domain and spectral characteristics. The results depend significantly on the wind input to the simulation, which is the focus of this article. Various wind fields representing cold pool events are generated from measured wind data and used in aeroelastic simulations. The simulated turbine response is compared to measurement data.

1. Introduction

The movement of heat and moisture in the vertical direction is called atmospheric convection. It can cause thunderstorms, typically including lightning, precipitation, and temperature changes. Precipitation induces a downdraft with descending air. When this air reaches the surface, it spreads outward. This event is called a cold pool gust front and is associated with rapid changes in wind speed and direction [1]. The wind ramp typically occurs on timescales of one to five minutes. The exact wind conditions and changes are highly dependent on the observer's location.

The impact of cold pool gust fronts on wind turbines is not adequately considered in the design load cases of IEC 61400 [2, 3]. The wind input for aeroelastic simulations is usually a wind field generated by a turbulence generator that incorporates spectral characteristics and coherence assumptions. While such wind fields resolve turbulence temporally and spatially, and statistically match realistic wind conditions and turbine loads, they lack event-specific detail.

Previous studies have examined loads during idealized thunderstorm downbursts [4, 5]. Experimental data are rare; wind tunnel experiments with a scaled-down turbine and a downburst wind were conducted by Zhang et al. [6]. To our knowledge, no full-scale measurements of turbine loads during cold pool events have been published.

In response to a cold pool, a wind turbine yaws and pitches to adapt to changing conditions. The wind direction can change faster than the yaw angle, leading to yaw misalignment,



potentially high loads, and turbine down-regulation. Even safety stops during such events have been observed at the WiValdi research wind farm [7].

Forecasts of wind conditions, turbine loads and power production are desirable. They could be used by wind turbine and power grid operators as well as turbine manufacturers to improve the operation and control of the wind turbines. By this, a reduction of damaging loads and disturbances and a stabilization of the power grid are conceivable.

Cold pool events are often not resolved spatially and temporally by numerical weather prediction (NWP) models. Therefore, more accurate, deterministic nowcasts with lead times of some minutes up to a few hours are under development at the German Aerospace Center (DLR). They will be based on extrapolations of radar observations and have a spatial resolution of about one kilometer and a temporal resolution of about five minutes, depending on the radar resolution. One approach being investigated at DLR is using nowcast results to predict power output and loads via aeroelastic simulations.

The WiValdi research wind farm [7] operated by DLR in Krummendeich, Germany is situated in coastal flatlands near the mouth of the River Elbe. This large-scale research facility contains two 4.2-MW wind turbines called OPUS 1 and OPUS 2, with a hub height of 92 meters and a rotor diameter of 116 meters. Thayer et al. [8] detected cold pool passages at the WiValdi research wind farm in recent years. Measurement data from turbine OPUS 1 are partially available for these events. These data will be used to develop and validate predictions of loads and power.

This study focuses on the generation of wind fields, representing specific events using different methods. Since meteorological nowcasts are not yet "fully functional", data from historical measurements is used instead. The event-specific input data does not inherently resolve turbulence spatially and temporally. These wind fields are used as input for aeroelastic simulations. The calculated turbine loads are compared to measurements and the agreement in time domain and the spectral characteristics is analyzed.

2. Example Cases

To compare simulations and measurement, two cold pool events that seem to challenge the turbine are selected as examples: January 6, 2025 at 04:50 p.m. and May 27, 2025 at 03:15 p.m. Figure 1 shows the radar reflectivity at these times over northern Germany. Since convection is linked to precipitation, the gust front is often associated with a high reflectivity gradient. The black arrows in Figure 1 indicate the overall wind. The location of the WiValdi wind farm is indicated by the red marker. For the surrounding 10-minute time windows, the wind speed and

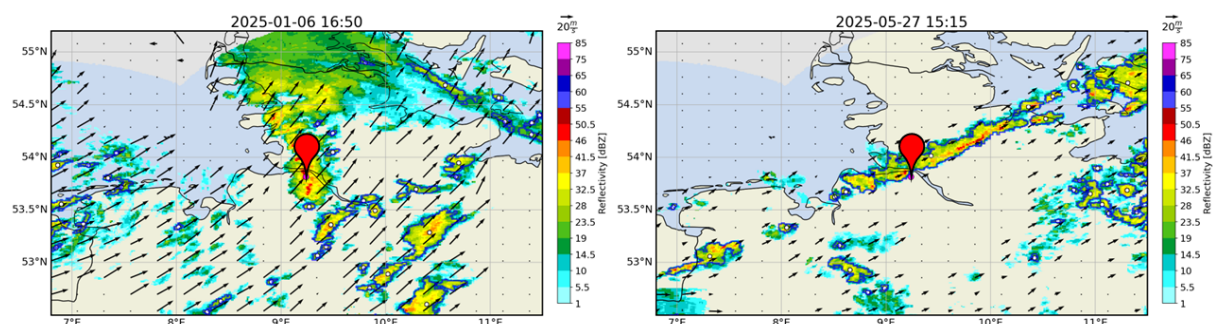


Figure 1. Snapshot of radar reflectivity over northern Germany, associated with the cold pool events on January 6, 2025 at 04:50 p.m. (left) and May 27, 2025 at 03:15 p.m. (right) in the DWD WN dataset [9]

direction measured on turbine OPUS 1 are shown in Figure 2 (blue dashed lines), as well as the temperature (red lines). The turbine's behavior—yaw and pitch angles and rotor speed—is also depicted.

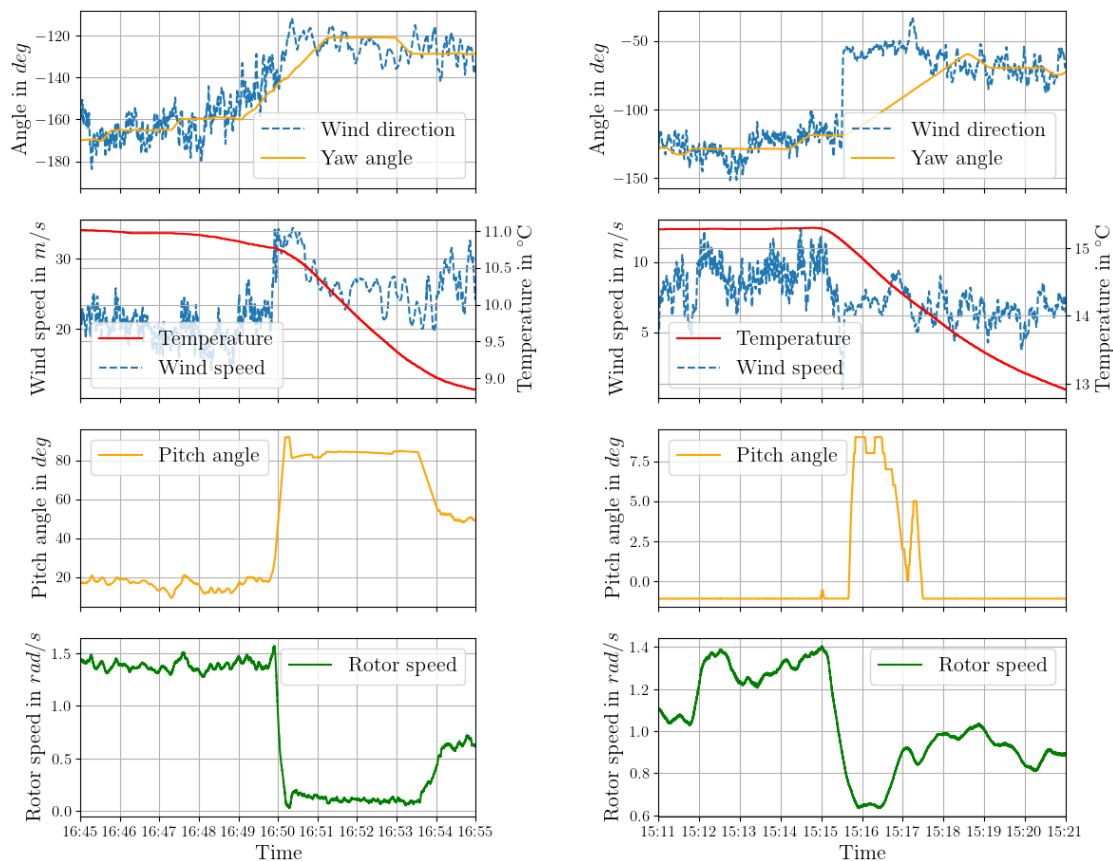


Figure 2. Changing environmental conditions at hub height and turbine response during the two example cases on January 6, 2025 (left) and May 27, 2025 (right)

On January 6, 2025, the wind speed increased from 20 m/s to 35 m/s during the gust front passage. The wind direction turned by approximately 50° in a clockwise direction. The turbine was initially operating at rated speed and then initiated a safety stop to reduce turbine loads. This occurred because the wind speed temporarily exceeded the turbine's cut-out wind speed. The yaw motion was able to follow the wind direction change.

On May 27, 2025, the convective cell grazed the wind farm rather than hitting it head-on, causing a large wind direction change of 70° in a clockwise direction. The wind speed was generally much lower than on January 6, 2025 and dropped from 10 m/s to 7 m/s during the event. The wind direction change was sudden, leading to temporary yaw misalignment and turbine down-regulation.

3. Simulation Setup

The first challenge is to generate realistic wind input data for the simulations. In this study, the simulated turbine loads should match the measurement in both the time domain and spectral characteristics. This holistic approach is necessary for reliable prediction. To focus on the wind

input, simulations are conducted using the multibody system simulation software Simpack [10] coupled with the aerodynamics module Aerodyn [11]. The turbine model is steered using measured pitch, yaw, and rotor angles instead of using a turbine controller to focus solely on the impact of different wind inputs. The prescribed angles are measured at OPUS 1 at a sampling rate of 100 Hz. For use in simulations, they are downsampled to 10 Hz and treated with a third-order Savitzky–Golay filter with a window length of 51 samples to smooth the signals and their derivatives.

In the WiValdi wind farm, measurements from anemometers on a met mast are available, as well as a measurement from an anemometer on the nacelle. The met mast provides multiple wind signals at different heights, enabling measurement of atmospheric boundary layer shear. However, the distance between the mast and the turbine is approximately 200 m, which already introduces differences in wind conditions, especially during transient events like cold pools. Therefore, the nacelle measurement is used, which provide wind speed and direction at a sampling frequency of 100 Hz.

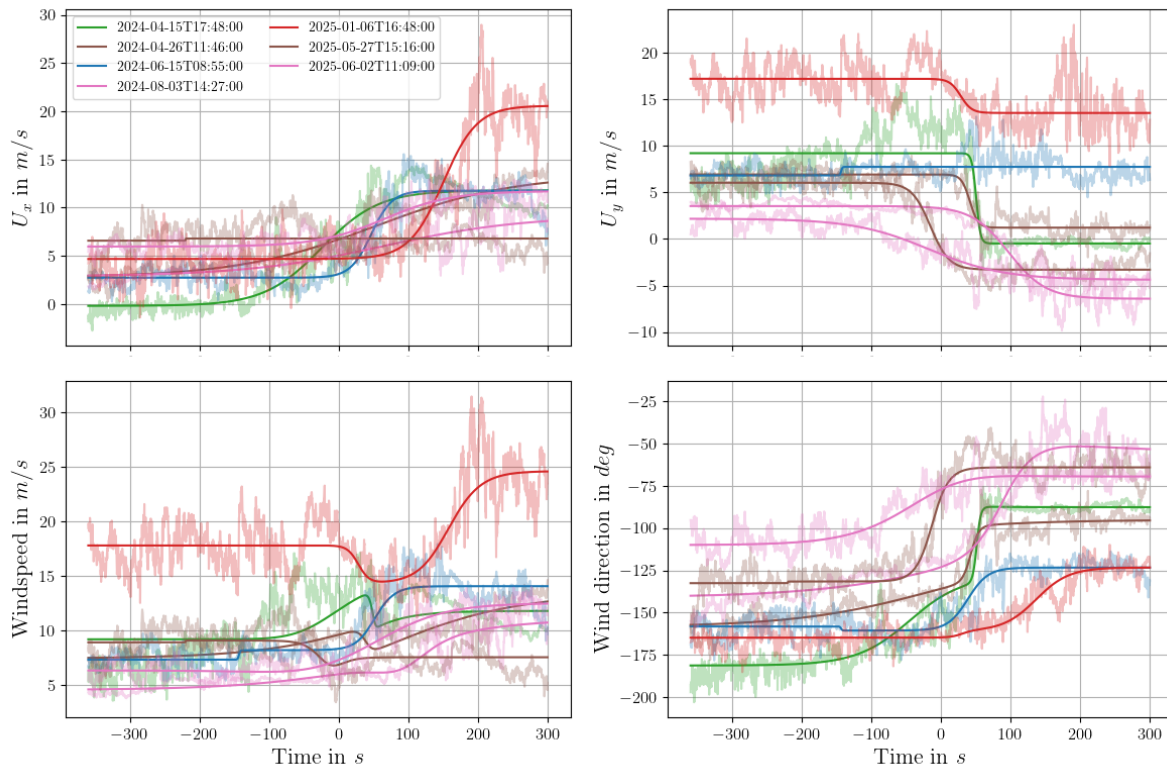


Figure 3. Representation of transient cold pool events by fitting logistic step functions to the horizontal wind speed components

One common approach is to use a single-point wind history as input without considering spatial effects within the rotor disc area [12]. Another approach is to generate a stochastic wind field using a turbulence generator such as TurbSim [13] or Pyconturb [14]. The latter allows constraining turbulence to measured wind data. However, this requires multiple measurement points to establish a realistic boundary layer profile. Moreover, every change in wind speed is modeled as turbulence, which does not accurately represent large coherent structures [15] such as cold pool gust fronts, especially if there is only one measurement point available.

Therefore, two modifications were implemented in Pyconturb to balance time-series fidelity and statistical accuracy. First, the "background flow" is subtracted from the input data before turbulence generation. This background flow can be either the measured data processed with a Butterworth low-pass filter or a logistic step function:

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}} + a \quad \text{where} \quad \begin{cases} L & \text{Magnitude of the wind speed change} \\ k & \text{'change rate' of the wind speed} \\ x_0 & \text{point in time of the change} \\ a & \text{initial wind speed} \end{cases} \quad (1)$$

fitted to the two measured horizontal wind components. The logistic step function was chosen because it effectively represents a range of observed cold pool events (Figure 3). It can be fitted to nowcast results, which typically have a low temporal resolution (one sample every few minutes). After turbulence generation, the background flow is added back to the turbulence box. This separation of deterministic and stochastic components is also used by Nguyen et al. [4].

The second modification to Pyconturb is the use of a prescribed shear exponent α when only one measurement point is available. The wind speed U at height z in the boundary layer is then:

$$U = U_{\text{ref}} \cdot \left(\frac{z}{z_{\text{ref}}} \right)^\alpha \quad (2)$$

with reference wind speed U_{ref} at reference height z_{ref} . For the example cases, the shear exponent is set to $\alpha = 0.25$, which aligns with the average measured at the met mast during the simulation period.

Simulations with Simpack and Aerodyn are conducted using five different wind input datasets:

- The measurement is used as a single-point history at hub height. Spatial differences within the rotor disc area are ignored, and only a shear exponent is prescribed. Therefore, it is inappropriate to consider higher-frequency wind fluctuations, so the time history has been low-pass filtered using a fourth-order Butterworth filter with a cut-off frequency of 0.05 Hz.
- A turbulent wind field is generated using Pyconturb without modifications. The spatial mean wind speed and direction over time are shown as the blue line in Figure 4. The time curve differs significantly from the measurement (black dotted line) for January 6, 2025 but matches better for May 27, 2025.
- For the 'separated wind' field (orange line in Figure 4), low-frequency components up to 0.05 Hz of the measured wind are assumed to be the background flow. This is assumed to be uniform across the rotor disc area. Before turbulence generation with Pyconturb, it is subtracted from the measured wind and added back to the turbulence box afterward.
- The 'separated class B' (green line) is identical to 'separated wind', but instead of interpolating turbulence characteristics from the measurement, a Kaimal spectrum with turbulence class B is used. For the spatial means plotted in Figure 4, the turbulence assumption has little effect.
- For the 'step function' (red line), the background flow is modeled as a logistic step in both horizontal directions. The time curves match the measurement better than the 'constrained turbulence' field but worse than the 'separated turbulence' field.

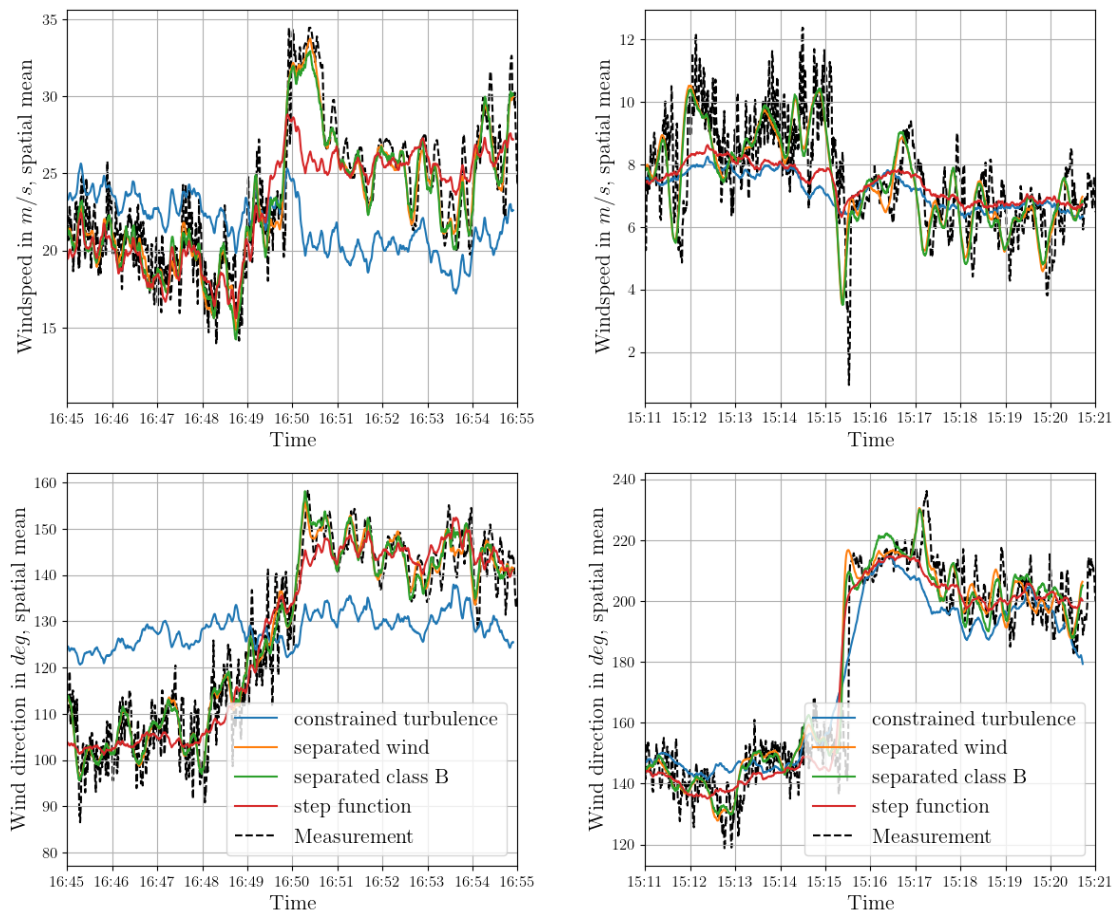


Figure 4. Wind speed and direction of the four generated wind fields compared to the measurement for the January 6, 2025(left) and May 27, 2025 (right) cold pool gust front passage

4. Results

The load comparison between measurement and simulations is based on IEC 61400-13 [16]. This standard proposes averaging quantities over 10 min, which is not applicable to a single 10 min event. However, the standard also proposes and applies comparison in the time domain, power spectral densities, and fatigue spectra. Since the detailed atmospheric conditions across the rotor disc area are unknown, introducing significant uncertainty, an exact match between simulation results and measured data is not expected. For reasons of confidentiality, the root bending moments in the Figures 5 and 7 are normalized linearly with the maximum measured flapwise bending moment in the May 27, 2025 case.

Figure 5 shows the maximum and minimum edgewise root bending moments during each rotor revolution in the upper plots, and the maximum flapwise root bending moment per revolution in the lower plots. Edgewise bending moments are primarily caused by gravitational forces, resulting in an oscillation with a sign change with each revolution. Flapwise bending moments, on the other hand, are primarily driven by aerodynamic forces. For both example cases, the bending moments calculated with the hub-height wind input are closest to the measurement, together with those obtained with the two separated wind fields. The step function wind field performs slightly better than the constrained turbulence field.

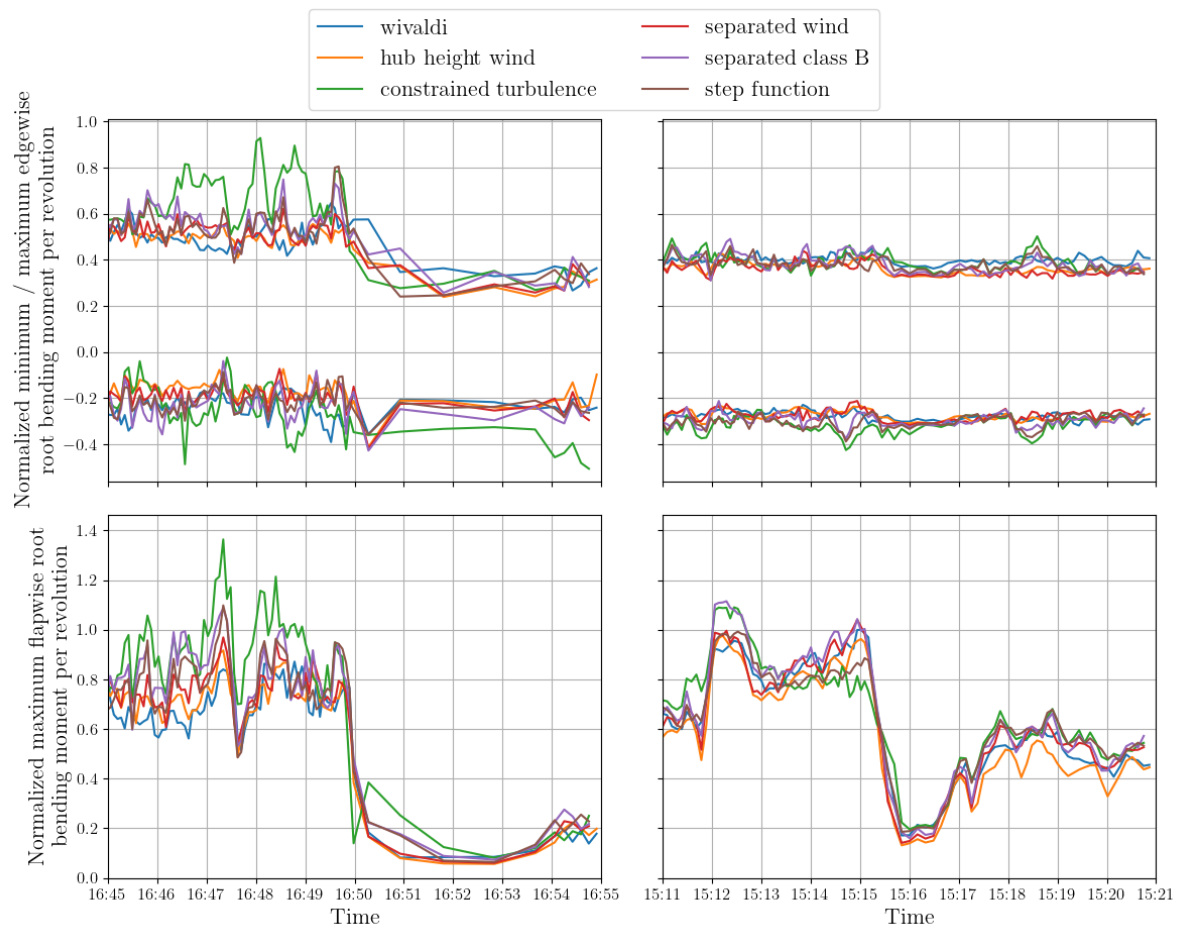


Figure 5. Minimum / maximum edgewise (top) and flapwise (bottom) root bending moments per rotor revolution of blade A over time from measurement and simulations with different wind fields on January 6, 2025 (left) and May 27, 2025 (right)

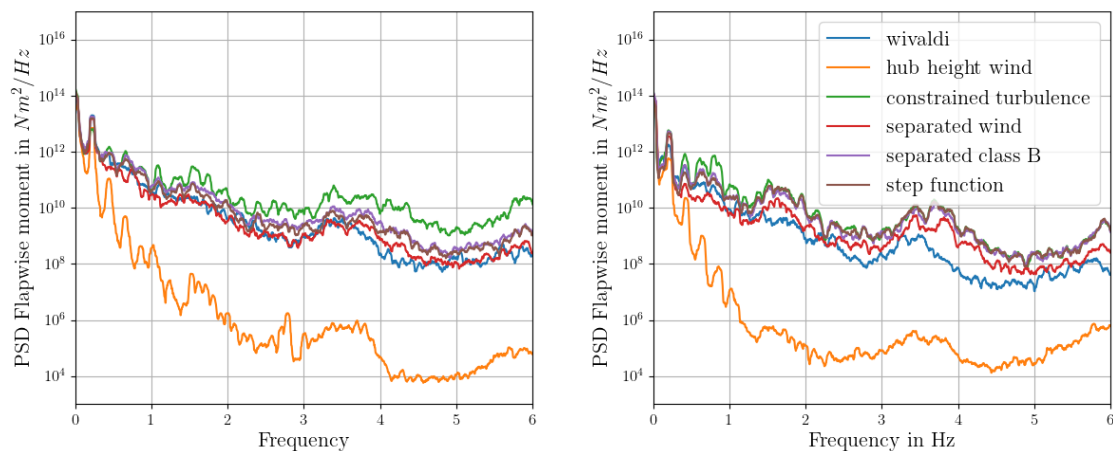


Figure 6. Power spectral densities of the flapwise root bending moment of blade A in measurement and simulations on January 6, 2025 (left) and May 27, 2025 (right)

Figure 6 shows the power spectral densities of flapwise root bending moments. The underlying time window is the same as the one shown in Figure 5. The results from the simulation with the hub-height wind input differ significantly from the measurement at frequencies above 0.3 Hz. This was expected because turbulence is not included. The loads from the simulation with the separated wind field best match the measurement, closely followed by the ones obtained with the other three fields. The simulations with all wind fields result in higher power spectral densities of the blade root bending moments than the measurement.

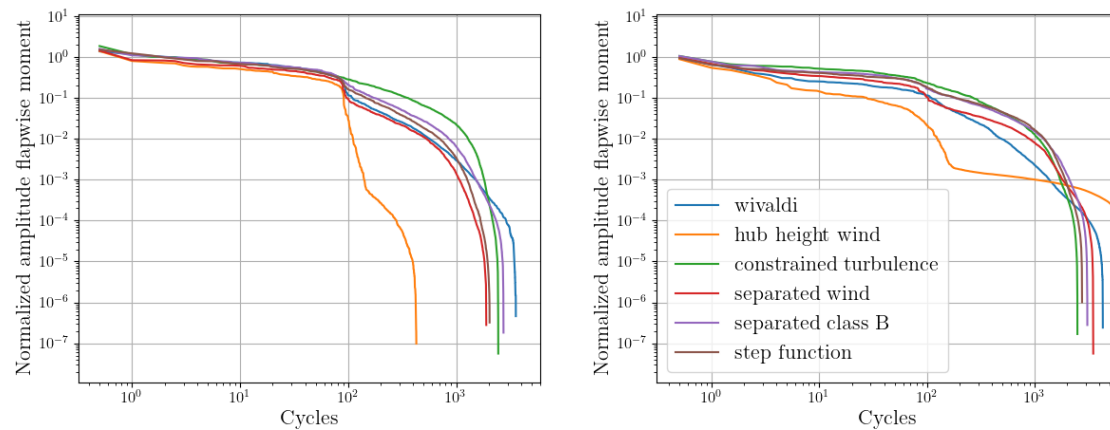


Figure 7. Fatigue spectra of the flapwise root bending moment of blade A for the cold pool events on January 6, 2025 (left) and May 27, 2025 (right)

To quantify damaging loads from a weather event, the fatigue spectra of measurement and simulation should match closely (Fig. 7). For the cold pool events considered, the simulation with the single-point history wind input yields lower fatigue loads than the measurement. The separated wind field performs best overall. Simulations with the other fields result in slightly higher fatigue loads than the measurement.

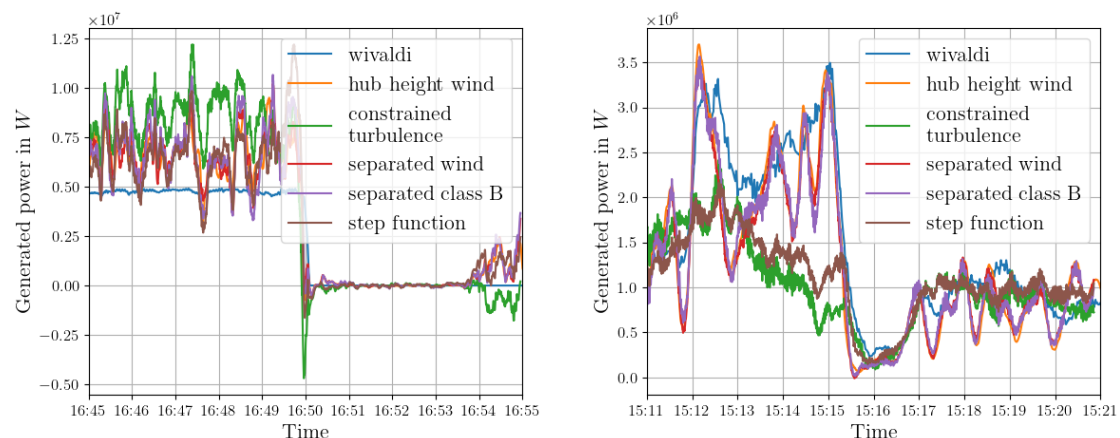


Figure 8. Power production of the turbine during the gust front passage on January 6, 2025 (left) and May 27, 2025 (right) in measurement and simulations

The generated power is a direct result of blade root bending moments, pitch angles, and rotor speed (Figure 8). The power reacts sensitively to fluctuations and phasing of these physical quantities. The calculations were performed using prescribed rotor, pitch, and yaw angles that do not perfectly match the local, statistical wind conditions. Even though the individually measured values could be reproduced satisfactorily by the simulation, the power calculation emphasizes the deviations. To improve the power results, a turbine controller is essential. Nevertheless, it is noticeable that the 'constrained turbulence' wind field represents the real wind conditions less accurately than the others. For the May 27, 2025 case, the 'step function' wind field is slightly better than the 'constrained turbulence' one, but worse than the others.

Overall, the results from the simulation with the single-point wind input match the measurement well in the time domain and the simulation is computationally the cheapest alternative. However, it is inappropriate for predicting load spectra and fatigue loads, as turbulence is ignored. The wind field with separately handled non-turbulent and turbulent components derived from the measurement performs best overall. A logistic step function provides a good approximation for the non-turbulent wind components in terms of wind speed and direction but results in larger deviations in load predictions. Nevertheless, it performs better than the 'constrained turbulence' wind field.

5. Conclusion and Outlook

This article aims to generate a wind field that adequately represents the wind conditions during a cold pool event, in order to calculate realistic loads during that event. To this end, the loads occurring in two example cases are compared between measurement and simulation, in preparation for forecasting loads and power during upcoming events.

The measurements of wind conditions, loads, and power output originate from the WiValdi research wind farm. There are no high-resolution wind measurements in the rotor disc area available, and a prospective forecast will have low spatial and temporal resolution. In this article, the nacelle wind measurement is used as simulation input. Different wind fields were generated using the open-source turbulence generator Pyconturb. Simulations were conducted for two exemplary cases: January 6, 2025, and May 27, 2025. For the simulations, Simpack and Aerodyn were used without a turbine controller, but with prescribed yaw, pitch, and rotor angles measured during the events.

To make a forecast of loads and power useful, the results should match measurements in both the time domain and frequency/fatigue spectra. This is best achieved by separately handling the turbulent and non-turbulent wind components. The non-turbulent part is defined as the low-frequency components of the measured wind speed. To generate a wind field from low-temporal-resolution data, the horizontal wind components were represented using a logistic step function, resulting in slightly poorer predictions of loads. A single-point wind input at hub height is suitable for time-domain predictions but inappropriate for load spectra, as turbulence is ignored.

In the future, more simulations will be carried out using wind data from meteorological forecasts instead of measurements. This data needs to be augmented with realistic turbulent components to generate a wind field that is sufficiently dense in time and space for aeroelastic simulations. This procedure can then be used to predict loads and power output for upcoming weather events. As yaw, pitch, and rotor angle are not known in a forecasting scenario, and especially to obtain realistic power values, a turbine controller has to be used.

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