Project: **1069**

Project title: **Boundary layer meteorology in complex terrain and for wind energy applications**

Principal investigator: **Gerard Kilroy**

Report period: **2024-11-01 to 2025-10-31**

1.1 Overview

In our previous application, we requested CPU hours to conduct numerical simulations using the Weather Research and Forecasting (WRF) model (Skamarock *et al*., 2019). The goal was to generate realistic, high-resolution simulations for the DLR experimental wind park (WiValdi) located in Krummendeich, Northern Germany, supporting both internal project research and turbine operation planning. The WRF model is a state-of-the-art mesoscale numerical weather prediction system widely used in atmospheric research. When configured with sufficiently nested domains, reducing horizontal grid spacing below roughly 200 m, WRF can operate in Large Eddy Simulation (LES) mode.

High resolution (5-m grid spacing) WRF simulations centred on the location of the DLR wind park in Krummendeich provided inflow wind profiles for our team to generate realistic atmospheric inflow for wind turbines using the EULAG (Prusa *et. al.,* 2008) model. In a recent publication, Wrba *et al*. (2025), we applied different data assimilation techniques to adapt the atmospheric inflow field towards previously defined wind profiles. We showed that the assimilation method based on the vibration equation is able to adapt the zonal and meridional velocity components of an atmospheric flow, while negative effects on the atmospheric turbulence are reduced. The benefit of such a technique which preserves atmospheric turbulence, is that one would require only a single computationally expensive precursor simulation (in order to spin up fine-scale turbulence). This precursor simulation can then assimilate, in theory, any observed or modelled wind field, without the need to perform a precursor for each individual case.

Computer hours were requested also to run WRF operationally. Forecasts for the wind park have been successfully produced for the majority of the year (pa.op.dlr.de/DFWind_PA/model.html), which provides guidance to turbine operators at our wind park. Additionally, the forecast data is saved and will be used in the coming years for identifying heavy load cases for wind turbines in the context of the internal project, In2Action. In particular, WRF is used to diagnose strong convective events involving cold pools.

Deep convective clouds, generate strong near-surface wind gusts (cold-pool gust fronts) that involve rapid changes in wind speed, direction, turbulence, and stability. These are factors that strongly influence wind energy production but remain poorly represented in current forecasting systems. In Thayer *et al.* (2025), we showed from observations at the WiValdi research wind park in northern Germany that convective cold pool passages substantially alter wind turbine rotor-layer conditions. Median cold-pool events show hub-height wind speed increases of up to 4 m s^{-1}, directional shifts of ~15°, and enhanced turbulence, leading to short-lived power gains of up to 50%. Radar image processing and cloud identification/tracking on the DKRZ machines supplemented wind park observations in this publication.

Further, we have quantified the effects of wind events using WRF in order to understand structures associated with more extreme events. In Kilroy and Thayer (2025a), we investigated a month-long WRF simulation with 1-km horizontal grid spacing in order to gain bulk-convective cold-pool characteristics over Germany. An analysis of the convection-permitting simulation, in comparison to DWD radar data, highlights the significance of cold-pool impacts for wind power systems. Both DWD observations and simulation output show that convective cell life cycles produce parabolic patterns in terms of size, rain rate, and reflectivity, with WRF broadly capturing these patterns while slightly overestimating cell intensity. An analysis of convective cell life cycles shows median estimated power production surges of between 33-60% over the cell lifetime, with peaks during the mid-to-late cell life cycle. Together, the observational and modelling perspectives emphasize that extremes associated with deep convection can rapidly and substantially affect wind park energy output. A better understanding of cold-pool processes is therefore essential for improving short-term forecasting and operational resilience of wind power systems under extreme weather situations.

On top of these two publications on the topic, we also presented talks at the Wind Energy Science Conference (WESC) in June 2025, and another at the European Meteorological Society (EMS) Conference in Ljubljana, 2025 (Kilroy and Thayer, 2025b). Finally, we recently reported our findings at the International Energy Agency (IEA) Wind Task 51 Workshop on Forecasting Extremes in the Power System, hosted by DWD in Offenbach in September 2025 (see references).

Further work on convective cold pools is ongoing. We are investigating extreme cold-pool events at very high resolution, with the results providing data for a range of internal DLR projects including DiRaWi, NearWake and In2Action. To this end, a particular cold pool event from the month-long simulation described earlier was re-simulated in a nested domain with higher resolution (20-m grid spacing). The aim of this simulation is to provide a case study of thunderstorm-induced cold-pool impacts on wind turbine power output and wake structure. Here, we plan to investigate the ability of WRF to produce realistic turbine wakes and validate with WiValdi observations. An extended abstract covering this work has been submitted to the TORQUE conference (torque2026.eu/).

We requested also a modest amount of GPU hours in order to test a new GPU-based LES fluid solver, which is being developed in parallel by the ECMWF. The Portable Model for Multi-Scale Atmospheric Prediction (PMAP) is an innovative atmospheric model designed to perform simulations across a wide range of spatial scales, from the global scale down to local resolutions of about 10 meters. Over the past year, we successfully configured PMAP on GPUs at DKRZ, testing several use cases including simulations of localized stable boundary layers and flow over complex terrain. One of our long-term objectives with PMAP is to simulate the stable boundary layer at our Wivaldi wind park in Krummendeich and to compare the model results with measurements. In the coming year, we plan to implement an appropriate subgrid-scale model to accurately represent stable boundary layer turbulence in large-eddy simulations, and integrate the generalized actuator disc method to parameterize the wind turbines within PMAP. Both developments will be validated through comparisons with measurements. A series of publications are expected from this work.

Literature:

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PMAP Model: PMAP