Project: **1069**

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

Principal investigator: **Gerard Kilroy**

Report period: **2025-11-01 to 2026-10-31**

1.1 Overview

In our previous application, we requested CPU hours to conduct simulations using the Weather Research and Forecasting (WRF) model (Skamarock *et al*., 2019). The goal was to generate realistic simulations for the DLR experimental wind park (WiValdi) located in Krummendeich, Northern Germany, supporting both internal project research and turbine operation planning. The core goals included producing month-long, high-resolution WRF simulations (July 2024 and July 2025) to build a robust dataset of convective cold-pool events for training machine learning (ML) algorithms as part of the internal DLR "In2Action" nowcasting project. A complementary goal was to perform high-resolution, turbine-resolving simulations using the Generalized Actuator Disk (GAD) parameterization to study how thunderstorm-induced cold pools affect wind turbine wakes, loads, and power output, validated against the extensive WiValdi observational network.

Operational forecasts for the wind park have been successfully produced for the majority of the first half of the year which provides guidance to turbine operators at our wind park. Unfortunately, long queue times on the Levante CPU system led to difficulties in producing timely operational forecasts for the second half of the year. As part of an internship project, a student began late this year to perform a systematic validation and verification of model forecasts (ECMWF and WRF) at the WiValdi site, compared to in-situ measurements. A publication on this topic is expected next year.

The month-long high resolution WRF simulations have previously been validated against observations and are now being implemented as input in an ML algorithm with the eventual aim to predict deep-convective wind gusts at turbine hub height. The project is in the early development phase as part of a Ph.D. position within our group, with early results presented this year at the European Academy of Wind Energy (EAWE) Ph.D. seminar (Essig *et. al.,* 2026). A series of publications on the tool architecture and results are expected in the coming years.

We requested CPU resources in order to investigate extreme cold pool events at very high resolution. 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). In Kilroy *et. al.,* (2026a) we presented this case study examining how a strong thunderstorm-induced cold-pool gust front affects wind turbine power output, wake structure, and mechanical loading at the WiValdi wind park site in northern Germany. We identified three distinct atmospheric regimes during the event: a marginally convective pre-gust boundary layer, a highly turbulent gust-front passage, and a strongly stabilized post-gust period. Wake analysis revealed that enhanced turbulence during gust passage reduces the wake velocity deficit and shortens the wake, whereas the stabilized post-gust environment produces a stronger, more persistent wake, highlighting contrasting turbulence and stability effects on wake recovery. The study underscores the importance of understanding cold-pool dynamics for wind energy forecasting. An additional case study with a more extreme wind direction change is currently in progress, with a publication expected early next year.

On top of this publication on the cold pool topic, where DKRZ resources were utilized, we also presented a poster at the EAWE TORQUE conference in Bruges this year (Kilroy *et. al*., 2026b) and a talk at the European Meteorological Society (EMS) Conference in Utrecht, 2026 (Kilroy *et. al*., 2026c).

We also requested GPU hours in order to test a new GPU-based LES fluid solver, which is being developed in parallel by the ECMWF and ETH Zurich. The Portable Model for Multi-Scale Atmospheric Prediction (PMAP; Krieger *et. al.,* 2025) 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.

As part of the current project phase in 2026, PMAP was validated against a set of test cases and standard benchmark simulations for basic atmospheric flow configurations that our group has previously carried out with EULAG. The validation focused in particular on the implementation of the backscatter subgrid-scale (SGS) model. A range of idealised atmospheric flows, including a stably stratified boundary-layer case and a neutrally stratified channel-flow benchmark, were re-run in PMAP and compared directly against the corresponding EULAG reference solutions. The comparison encompassed mean velocity profiles, turbulent kinetic energy and Reynolds stress tensor components. The results confirmed that the backscatter SGS closure in PMAP reproduces the turbulent statistics and the backscatter behaviour established in the earlier EULAG studies (Bührend and Englberger, 2026).

In a subsequent step, PMAP was coupled to the wiFI (Wind Farm Interface) model to extend its applicability to wind farm simulations for WiValdi. The coupling was first implemented and verified in offline mode, in which the wind turbine model is run independently and its forces are subsequently applied to the flow solver, and was then extended to a fully online (two-way) coupled configuration. Validation of the coupled system was carried out by reproducing the benchmark case presented in the study by Martínez *et al.* 2018, in which multiple flow solvers and wind turbine models are compared against each other. PMAP with the wiFi interface showed good agreement with the reference data as well as with the solutions obtained by the other solvers and turbine models evaluated in that benchmark (Yu, 2026). This confirms that the PMAP–wiFI system is now fully operational and ready to be deployed for simulations of the WiValdi wind farm.

Despite the positive advancements our group has made with PMAP this year, the allocated GPU hours for PMAP simulations were not fully utilized during the period so far due to several different factors. First, the start of the Exergy project was delayed. Second, the delivery of the most recent PMAP release to our group occurred later than anticipated, which in turn delayed our ability to couple the turbine parameterizations via wiFI as early as planned. Third, once operational, PMAP proved to be considerably less computationally expensive than originally estimated, meaning that the simulations we were able to complete required substantially fewer GPU hours. Now that the turbine coupling is complete, and the model has been sufficiently validated, we expect a series of publications from our group using this model in the coming years.

Literature cited in this report:

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