Project: **1069**

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

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Report period: **2023-11-01 to 2024-10-31**

1.1 Overview

In the previous application, we requested CPU hours in order to produce numerical simulations using the Weather Research and Forecasting (WRF) model (Skamarock *et al.,* 2019), with the aim of providing realistic high-resolution simulations at the new German Aerospace Centre (DLR) experimental wind park (WiValdi) for internal project usage, and guidance for turbine operations. The WRF model is a state-of-the-art mesoscale numerical weather prediction system designed for atmospheric research. WRF can be run in Large Eddy Simulation (LES) mode when there are sufficient nested domains, so that the horizontal grid spacing drops below values of roughly 200 m. In the current project, we have produced simulations of the DLR wind park with grid spacing down to 5 m.

With high-resolution simulations in LES mode located over flat terrain, such as at the location of the DLR wind park in Krummendeich, Northern Germany in Krummendeich, Northern Germany, there are unfortunately issues in producing an accurate representation of turbulence. A paper has been published in the last year on this topic analysing these high-resolution simulations. Kilroy *et. al.*, (2024) evaluated WRF simulations of the WiValdi wind park in LES mode using a method to develop turbulence against on-site observations. To accurately resolve fine-scale turbulence, we employed a high-resolution nested innermost grid with 5m horizontal grid spacing. This work aimed to evaluate the ability of WRF-LES to accurately reproduce realistic turbulent characteristics in a quasi-neutral and quasi-stable atmospheric boundary layer (ABL), with the future goal of accurately representing also quasi-convective ABLs, and other atypical high-load weather events such as low-level jets, winter storms and convective cold pool events. The validation of the ability of WRF to produce realistic turbulence is important as models can provide information at much higher temporal and spatial resolution than observations alone, allowing for more accurate load calculations on turbines and energy output estimates.

To this extent, the so-called cell perturbation method (CPM) was developed over the last decade (Munoz-Esparza *et al*., 2014; 2018). This method helps develop realistic small-scale turbulence without the need for prohibitively long fetches by introducing stochastic temperature perturbations at the LES inflow boundaries. These perturbations trigger small-scale vertical motion that produce complex small-scale horizontal vortical motion. This method significantly accelerates the generation time of realistic turbulence.

The results from Kilroy *et. al.,* (2024) show that, while the version of WRF used (V4.4.1) is capable of reproducing the mean wind fields at the WiValdi wind park, it is unable to reproduce the turbulence characteristics observed. When the CPM method to accelerate turbulent motion generation is included, results are significantly improved. The WRF results with the CPM method included show excellent agreement with the $k = -5/3$ power law. In other words, the inertial subrange is successfully simulated with a similar energy equivalent of an idealized model designed to produce realistic turbulence.

In previous studies it was shown that WRF can develop realistic turbulence, albeit with a prohibitively long fetch distance. We show that, when the CPM is applied to all LES domains, realistic turbulence develops within the relatively short times calculated (7 hr run time) and within the relatively small domain. Without the CPM, turbulence does not develop in the domain shown. The results from this work were presented also at the TORQUE conference (https://www.torque2024.eu/) in May 2024.

In addition, wind profiles from these WRF simulations were used recently by our team to generate realistic atmospheric inflow for wind turbines using the EULAG (Prusa *et. al.,* 2008) model. These simulations were investigated in a study by Wrba *et. al*., (2024), which is currently in open review. In this study, data assimilation techniques are applied to adapt the atmospheric inflow field towards previously defined wind profiles. The aim is to provide date- and site-specific turbulent inflow fields for large-eddy simulations (LES) of the flow through wind turbines. To this end, a standard and a modified version of a Newtonian relaxation technique and an assimilation method based on the vibration equation are implemented in the geophysical flow solver EULAG. The extent to which they are able to adapt mean horizontal wind velocities towards target profiles (provided by the WRF simulations) and the impact on atmospheric turbulence of an idealized LES are investigated. This study shows the suitability of the vibration assimilation technique for adapting inflow fields for wind energy purposes.

Computer hours were requested also to run WRF operationally over the previous year. Operational forecasts for the wind park have been successfully produced for the majority of the year (https://www.pa.op.dlr.de/DFWind_PA/model.html) which provides guidance to turbine operators. Additionally, the forecast data is saved and will be used in the coming year for identifying heavy load cases for wind turbines. In particular, it is used to diagnose strong convective events involving cold pools and other high load/strong shear and veer events. These events are being studied in more detail with separate higher-resolution simulations.

In particular, cold pool events have been identified from these simulations and from observations at the wind park for the time period 2021-present. Selected time periods have been simulated in WRF with inner domains containing 100 m grid spacing. We find that the WRF simulations reasonably capture bulk cold pool behavior observed at the wind park (Fig. 3). The results from this work have been presented at the EGU conference in April 2024 (Thayer *et. al.,* 2024a) and at the EMS conference in September 2024 in September 2024 (Thayer *et. al.*, 2024a). The presented work provides a foundation for future analysis which will more robustly verify WRF output using additional WiValdi observations. At the moment, there are two papers in preparation on this topic.

Furthermore, resources were requested for the project ESTABLIS-UAS, which is funded as an European Research Council Starting Grant by the European Union. In this project, a fleet of unmanned aerial vehicles are developed to measure wind characteristics, temperature and humidity with high resolution and are deployed within the international field experiment TEAMx. WRF simulations were used as guidance for a preparation campaign which took place in Nafingsee (in the Austrian Alps) in September of this year. The results from the preparation campaign will be used to steer decision-making for the main 6-week long campaign which takes place next year.

GPU hours were requested to test a new model produced by the ECMWF. The model Finite Volume Model (FVM) is a nonhydrostatic finite-volume global atmospheric model formulation for numerical weather prediction with the Integrated Forecasting System (IFS) (Kühnlein *et. al.,* 2019). We did not use as many GPU hours as requested, as we ran into difficulties compiling the model in parallel for use with GPUs on Levante. We are currently working with the developers of the model in order to resolve these issues. We anticipate that this model has enormous potential for our team.

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