Project Title: Mesoscale to Microscale Coupling for Wind Energy Applications

Project team: PI Stefan Heinz, Department of Mathematics & Statistics; PI Michael Stoellinger, Department of Mechanical & Energy Systems Engineering

Total amount requested: $24,850

Description of the research problem: The coupling of mesoscale and microscale simulation methods (see the illustration in Fig. 1) is one of the biggest challenges for wind energy research [1]. Without having a proper solution for this problem, the accurate assessment of the potential and optimal use of wind energy resources are out of reach. There is a long-term collaboration of the Department of Energy (DOE), National Center for Atmospheric Research (NCAR), and Lawrence Livermore National Laboratory (LLNL) focused on a problem solution. But despite significant progress there is no indication that a convincing solution can be expected soon. Doubrawa & Munoz-Esparza [2] recently concluded "the need for a robust gray-zone modeling solution is urgent to ensure that research and technology decisions are based on reliable results".

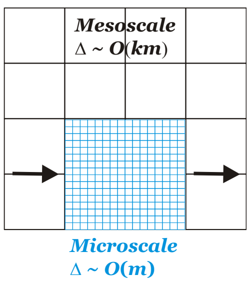

Fig. 1. Coupling of mesoscale and microscale simulations – a fundamental atmospheric science problem [1]. Δ refers to the characteristic grid size applied in simulations. Microscale simulations [large eddy simulation (LES) at the turbine & wind farm scale] can provide detailed information about terrain effects and interactions with structures such as wind turbines. The atmosphere drives changes at the wind farm scale, thus it is critical to model the variability at the mesoscale [using very different (RANS) methods].

The core problem is the incompatibility of fundamentally different simulation methods used at the mesoscale and microscale. Dr. Heinz published an exact mathematical solution (a minimal error simulation method) for this problem [3-5]: a new computational method called continuous eddy simulation (CES) has been introduced. Dr. Heinz is the PI of a related ongoing two-year NSF grant [6]. One goal of this project is the implementation of CES in NCAR's Weather Research and Forecasting (WRF) code, an open-source code used all over the world for many atmospheric simulations. Another goal is the analysis of new functionality features of CES. The project takes place via work of Dr. J. Singh at NCAR (she performs all simulations). The project includes a close collaboration with the NCAR colleagues Dr. B. Kosovic and Dr. T. Juliano.

This NSF project will end by 05/31/2024 because of lack of further postdoc funding for Dr. Singh. The project goals will be basically accomplished. However, the CES implementation in WRF turned out to be complicated and time-consuming, leaving little room for a comprehensive demonstration of model advantages. In particular, there was no chance to comprehensively address the coupling of mesoscale and microscale simulation methods. To overcome this issue, we propose an explicit demonstration of CES capabilities in regard to one of the most pressing atmospheric science problems: the coupling of mesoscale and microscale simulation methods.

Short-term objectives and workplan: There are two specific requirements, R1 and R2, to receive external funding for that:

- R1: Efficient, revealing demonstration of CES capabilities to solve the mesoscale to microscale coupling problem using a well appropriate code. Our WRF experience revealed considerable technical difficulties to realize such WRF simulations. Thus, we will use the open-source code OpenFOAM. CES is already implemented in OpenFOAM, which we use for many years.

- R2: To be indeed eligible for funding through NSF and DOE, it needs to be shown that such simulations can also be performed using codes such as WRF and the Energy Research and Forecasting (ERF) code [7], which have been supported by NSF and DOE for decades.

Requirement R1 will be addressed via this one year project by simulating test cases considered before in the NSF project (homogeneous convective boundary layer, sea breeze front simulation, mountain–valley circulation [8]) with OpenFOAM. Comparisons with available data will show the suitability of simulations for many resolution conditions. Modifications of such microscale simulations using mesoscale couplings are used to study the CES functionality of mesoscale to microscale couplings. Requirement R2 will be addressed via the continuing structure of the NSF project. Although there is no postdoc funding available anymore, there are ongoing efforts (involving the PIs, Drs. Kosovic, Juliano (NCAR), and LANL researchers) aiming at such accompanying WRF and ERF studies. This collaboration will also provide the collaborative basis of NSF/DOE projects. An external funding proposal meeting R1 and R2 will be developed.

The PIs are well qualified for this project. Dr. Heinz developed CES methods and supervised related previous applications [3-6]. Dr. Stoellinger has an extensive experience with wind energy simulations. Both PIs collaborate with partners mentioned above for many years.

List of potential future partners: Dr. B. Kosovich (NCAR), Dr. T. Juliano (NCAR), Dr. S. Haupt (NCAR), Dr. J. Mirocha (LLNL), Dr. J. Peinke (University Oldenburg), Dr. B. Stoevesandt (IWES Oldenburg), Dr. P. Doubrawa (NREL), Dr. D. Muñoz-Esparza (NCAR).

A list of funding sources and programs: There are several funding sources, all of them are highly interested in a convincing, general, simple solution of the coupling problem of mesoscale and microscale simulation methods: (i) NSF (AGS, Div. Atmospheric & Geospace Sciences), (ii) DOE (Office of Energy Efficiency and Renewable Energy), (iii) DFG (German NSF, over the last years there are several opportunities to set up a collaboration between US and Europe).

References

1. Heinz, S. 2021 Theory-Based Mesoscale to Microscale Coupling for Wind Energy Applications. Appl. Math. Model. 98, 563-575.
2. Doubrawa, P. & Muñoz-Esparza, D. 2020 Simulating real atmospheric boundary layers at grayzone resolutions: How do currently available turbulence parameterizations perform?, Atmosphere 11 (4), 345.
3. Fagbade, A. & Heinz, S. 2024 Continuous Eddy Simulation (CES) of Transonic Shock-Induced Flow Separation. Appl. Sci. 14, 2705/1-2705/22.
4. Fagbade, A. & Heinz, S. 2024 Continuous Eddy Simulation vs. Resolution-Imposing Simulation Methods for Turbulent Flows. Fluids 9, 22/1-22/29.
5. Heinz, S., Mokhtarpoor, R. & Stoellinger, M. K. 2020 Theory-Based Reynolds-Averaged Navier-Stokes Equations with Large Eddy Simulation Capability for Separated Turbulent Flow Simulations. Phys. Fluids 32, 065102/1 - 065102/20.
6. https://www.nsf.gov/awardsearch/showAward?AWD_ID=2137351&HistoricalAwards=false
7. Almgren, A., Lattanzi, A., Haque, R., Jha, P., Kosovic, B., Mirocha, J., ... & Zhang, W. 2023. ERF: Energy Research and Forecasting. J. Open Source Software, 8(87), 5202.
8. Juliano, T. W., Kosović, B., Jiménez, P. A., Eghdami, M., Haupt, S. E., & Martilli, A. 2022 "Gray zone" simulations using a three-dimensional planetary boundary layer parameterization in the Weather Research and Forecasting Model. Mon. Weather Rev. 150(7), 1585-1619.

Budget and Budget Justification

Requested:	$24,850

Budget structure:

• PI S. Heinz (0.75 months summer salary plus 40.9% fringe benefits):	$12,699
• PI M. Stoellinger (.75 months summer salary plus 40.9% fringe benefits):	$12,151

Participation of the proposal team members:
The team members will provide unique, absolutely required project contributions. Dr. Heinz developed the theory for the novel simulation methods and he provided essential contributions regarding the computational analysis of the functioning of simulation methods. His involvement is the essential requirement to successfully deal with requirements R1 and R2. We note that the continuing structure of his NSF grant provides the basis for R2. Dr. Stoellinger is a leading expert on turbulent flow simulations and analysis, including a variety of wind energy research. His involvement is the essential requirement for the proposed computational analyses (R1). His expertise is also the essential requirement for R2, aiming at corresponding implementation in WRF/ERF codes (which have been supported by NSF and DOE for decades) and comparisons with results obtained under R1. It is worth noting that Dr. Heinz and Dr. Stoellinger successfully collaborate for 20 years.

Requirement of expenditures to accomplish the project goals:
The 75% summer salaries for the PI's are needed to ensure the PI's work as specified above. It is worth noting that the actual time commitment of the PIs will by far exceed the time covered by this support.