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Experimental and computational investigation of the turbulent interaction between the atmospheric boundary layer and large wind farms

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Turbulent flow around large wind farms is characterized by a strong interaction between the atmospheric boundary layer (ABL) and wind turbines. Due to this interaction, turbulence properties in the ABL are locally affected, leading to changes in the local micrometeorology. Of equal importance is the fact that the flow within the wind farm is non-axisymmetric structure due to the presence of the atmospheric boundary layer structure, having a major effect on the overall power output. Understanding the role of vertical momentum transport and velocity fluctuations around and within a wind farm as well as quantifying the importance of topography effects are critical prerequisites for improving energy capture and facilitating the site-specific optimization of wind farms.

In the experimental part of this study, wind farm models with different configurations were placed in the boundary layer wind tunnel of the Saint Anthony Falls Laboratory at the University of Minnesota. The model wind farms consisted of 10 rows in the streamwise direction by 2-3 columns. A cross-wire anemometer was used to obtain high-resolution measurements of 2 velocity components (streamwise and vertical) inside and above the wind farms. Full characterization of the turbulent flow was obtained at a vertical plane parallel to the flow direction through the entire wind farms and at different spanwise vertical planes. Particle Image Velocimetry (PIV) was used to determine transport processes around the turbine top tip levels at different locations in the wind farm. Special emphasis is placed on the description of the enhancement of the turbulence levels in the wind farm as a function the number of rows of the wind farm as well as the growth of the internal boundary layer induced by the wind farm.

The experimental results are used to develop new parameterizations of wind turbines and validate a large-eddy simulation (LES) model of large wind farms. The LES model is based on the method of Kang et al. [Adv. in Water Resources, 34 (1), pp. 98-113, 2011]. The method can simulate flows over arbitrarily complex topography and is thus ideally suited for simulating wind farms over complex terrain. The spatially filtered Navier-Stokes equations are closed with the dynamic Smagorinsky model, discretized with central, second-order accurate fine difference formulas and solved with an efficiently parallelized solver based on a fractional-step approach. The wind turbines are parameterized using the actuator disk approach. Simulations are carried out for the wind farm configurations studied experimentally and the computed results are compared with the experimental data.