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The influence of thermal stratification in the free atmosphere on the power extracted by a very large wind farm

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In the present study, the influence of thermally-stratified free atmosphere on the power extracted by a very large wind farm is investigated. A suit of large-eddy simulations of atmospheric boundary layer (ABL) flow inside and above an infinite wind farm is performed including the effect of earth's rotation and free-atmosphere stability. In the simulations, tuning-free Lagrangian scale-dependent dynamic models are used to model the subgrid-scale turbulent fluxes, while the turbine-induced forces are parameterized taking advantage of an actuator disk model. It is shown that for a given surface cover (with and without turbines) the thermal stratification in the free atmosphere limits the turbulent transport away from the surface compared with the unstratified case, leading to lower entrainment and boundary-layer depth. Due to the fact that in an infinite wind farm, vertical energy transport associated with turbulence is the only source of kinetic energy, lower entrainment leads to lower power production by the wind turbines. In particular, for the wind-turbine arrangement considered in this study, the power output from the wind farm is reduced by 40 percent when the potential temperature lapse rate in the free atmosphere increases from 1 to 10 K/km. Moreover, it is shown that the presence of the turbines has significant effect on the growth of the boundary-layer height. The output of LES is also employed to analyze the turbulent kinetic energy (TKE) budgets in a very large wind farm. It is shown that the shear production, which is the main source of TKE, has a peak at the top of the wind-turbine region where the strong wind shear occurs. This is consistent with the fact that the peak shear stress also occurs at the edge of the wind-turbine wake and has higher value compared with the surface shear stress in the absence of turbines. It is also shown that in a very large wind farm the energy transfer from the resolved-scale TKE to the SGS also has a peak at the top of the wind-turbine region. The LES data is further used to study the other terms in the TKE budget equation such as turbulent transport and diffusion by pressure effects and subgrid modes for different values of potential temperature lapse rate in the free atmosphere.