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Interaction between large wind farms and the atmospheric boundary layer

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Abstract

Accurate prediction of atmospheric boundary layer (ABL) flow and its interactions with wind turbines is of great importance for optimizing the design and efficiency of wind farms. This study first focuses on recent efforts to develop and validate a large-eddy simulation (LES) framework for wind-energy applications. The subgrid-scale turbulent fluxes of momentum and heat are parameterized using tuning-free dynamic models. The turbine-induced forces are parameterized using two types of models: an actuator disk model that allows for non-uniform force distribution and includes rotational effects, and an actuator line model. The LES framework is validated against wind-tunnel measurements collected inside and above a large model wind farm. Further, this framework is used to study wind-farm effects. Comparison of simulations of flow through both aligned and staggered wind farms shows important effects of farm layout on the flow structure and wind-turbine performance. We also investigate the impacts of wind farms on a stable ABL and a convective ABL.

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Keywords: atmospheric turbulence, large-eddy simulation, wind turbine

Nomenclature

ABL	atmospheric boundary layer
RANS	Reynolds-averaged Navier–Stokes
LES	large-eddy simulation
SGS	subgrid scale

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ADM-NR	actuator-disk model without rotation
BEM	blade-element momentum
ADM-R	actuator-disk model with rotation
ALM	actuator-line model
SBL	stable boundary layer
CBL	convective boundary layer
u_i	velocity
θ	potential temperature
τ_{ij}	SGS stresses
q_j	SGS fluxes
d	rotor diameter
S_x	streamwise spacing
S_y	spanwise spacing

1. Introduction

With the fast growing number of wind farms being installed worldwide, the interaction between atmospheric boundary layer (ABL) turbulence and wind turbines, and the interference effects among wind turbines, have become important issues in both the wind energy and the atmospheric science communities [1−3]. Accurate prediction of ABL flow and its interactions with wind turbines at a wide range of spatial and temporal scales is of great importance to optimize the design (turbine siting) of wind energy projects. In particular, flow prediction can be used to maximize wind-energy production and minimize fatigue loads in wind farms. Numerical simulation can also provide valuable quantitative insight into the potential impacts of wind farms on local meteorology. These are associated with the significant role of wind turbines in slowing down the wind, generating turbulence, and enhancing vertical mixing of momentum, heat, moisture and other scalars [4].

During the last decade, numerical simulation of wind-turbine wakes has become increasingly popular. Most of the previous studies of ABL flow through isolated wind turbines or wind farms have parameterized the turbulence using a Reynolds-averaged Navier−Stokes (RANS) approach [5−7]. However, as repeatedly reported in a variety of contexts [8], RANS is too dependent on the characteristics of particular flows to be used as a method of general applicability. Large-eddy simulation (LES) can potentially provide the kind of high-resolution spatial and temporal information needed to maximize wind energy production and minimize fatigue loads in wind farms. Only recently there have been some efforts to apply LES to simulate wind-turbine wakes [4, 9−12].

The accuracy of LES in simulations of ABL flow with wind turbines hinges on our ability to parameterize subgrid-scale (SGS) turbulent fluxes as well as turbine-induced forces. These forces are responsible for the development of the turbine wakes. In the next session, different wind-turbine models are discussed. This work is dedicated mainly to the study of the characteristics of wind-turbine wakes and their aggregated effect on wind-turbine performance as well as land-atmosphere exchanges (momentum and heat fluxes). We describe our LES framework in Sect. 2. The LES results are presented and discussed in Sects. 3 and 4, and a summary is provided in Sect. 5.