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Coupled wind farm parameterization with a mesoscale model for simulations of an onshore wind farm

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HIGHLIGHTS

- Parameterized WRF model is applied to a real onshore wind farm.
- The simulation results agree well with the observed data.
- The parameterized method can predict the power output in real time.
- A real wind farm is simulated by WRF at a 200 m resolution for the first time.

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ABSTRACT

The mesoscale Weather Research and Forecasting (WRF) model coupled with wind farm parameterization is newly developed to simulate the wake flow and power production of a real onshore wind farm. First, wind farm flow field simulations are conducted with 1000 m, 500 m and 200 m horizontal resolutions, and the simulation results capture the wind farm observed data well. In addition, wind farm flow characteristics, power output, and influence on the atmosphere boundary layer (ABL) are resolved at a horizontal resolution of 200 m. The wake interactions, wind speed, and power output deficit in the wind farm are analyzed. The power comparison results prove that the proposed method can be applied to simulate the power output of a real onshore wind farm with high accuracy in real time. The influence of the wind farm on the ABL is also discussed. The results show that wind farm effects on the ABL occur mainly within the turbine rotor-spanned heights and the downstream regions behind the wind farm within 10 km, within which the speed deficit ratio can exceed 10%. For the region that is 18 km downstream of the wind farm, the average speed deficit ratio is only about 2%. This study is the first attempt to reproduce the wake flow and power output of a real onshore wind farm by the WRF model at such high resolution.

1. Introduction

As a promising form of clean energy, wind power is developing quickly around the world. Wind energy is one of the world's fastest growing energy sources and has a huge potential for large-scale commercial application [1]. China currently has the largest installed wind power capacity in the world, and the majority of this capacity is in onshore wind farms [2]. However, wind power curtailment is now the primary problem that limits the development of China's wind power industry [3]. The variation of wind power output is one of the main reasons for wind power curtailment. Therefore, accurate assessment of onshore wind farm flow field characteristics and power production is of great significance for the sustainable development of the wind power industry.

Traditional wind resource assessment mainly depends on wind speed observations at meteorological stations, but there are few sites available to provide these observations, and the observations are inconsistent in terms of time [4]. Compared with the traditional assessment method, the mesoscale simulation method can obtain flow parameters for the whole region rather than being limited to several discrete sites. The method based on the mesoscale meteorological model is gaining popularity in the assessment of wind power resources [5,6] and

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Nomenclature

Variables

A	area (m^2)
C_P	power coefficient
C_T	thrust coefficient
C_{TKE}	turbulence kinetic energy coefficient
D	diameter of the wind turbine (m)
F	forcing terms for U, V, W, Θ and Q_m (N/kg)
G	gravitational acceleration (m/s^2)
H	height (m)
N	total sample number
N_t	number of wind turbines
p	pressure (pa)
P	power (W)
p_0	reference sea-level pressure (pa)
$p_{ht,hs}$	hydrostatic pressure at the top an-d surface of the model (pa)
$p_{dht,dhs}$	dry hydrostatic pressure at the to-p and surface of the model (pa)
$q_{c,i,r,s}$	mixing ratios for cloud water, ice, rain water and snow
q_m	generic mixing ratios for moisture
q_v	mixing ratio for water vapor
Q_m	generic coupled moisture variable
R_d	the gas constant for dry air
t	time (s)
u	horizontal component of velocity in x-direction (m/s)
U	coupled horizontal component of velocity in x-direction (Pa m/s)
v	horizontal component of velocity in y-direction (m/s)
$\mathbf{v}$	three dimensional vector velocity (m/s)
V	coupled horizontal component of velocity in y-direction (pa·m/s)
$\mathbf{V}$	three dimensional coupled vector velocity (pa·m/s)
V_0	local wind speed magnitude (m/s)
V_{hub}	wind speed magnitude in the hubheight level (m/s)
ΔV	horizontal wind speed deficit (m/s)
w	vertical component of velocity (m/s)
W	coupled vertical component of ve-locity (pa·m/s)
Δx	horizontal grid size in the zonal directions (m)
Δy	horizontal grid size in the meridi-onal directions (m)
X_i	simulated value
Y_i	observed value
z	height (m)

Greek symbols

a	inverse density of air (m^3/kg)
α_d	inverse density of dry air (m^3/kg)
γ	ratio of heat capacities for dry a-ir at constant pressure and volu-me
ε	relative error
η	terrain-following hydrostatic-press-ure vertical coordinate
μ	hydrostatic pressure difference be-tween surface and top of the mo-del (pa)
μ_d	dry hydrostatic pressure difference between surface and top of the model (pa)
ρ	density of air (kg/m^3)
θ	potential temperature (K)
Ω	coupled coordinate velocity (pa·m/s)
Θ	coupled potential temperature (pa·K)
$\mathit{\Omega}$	contravariant vertical velocity (m/s)
Φ	geopotential (m^2/s^2)

Abbreviations

ABL	atmosphere boundary layer
ARW	Advanced Research WRF
CFD	computational fluid dynamics
FDDA	four-dimensional data assimilation
FNL	final analysis
KE	kinetic energy
MODIS	moderate-resolution imaging spec-troradiometer
NCEP	National Center for EnvironmentalPrediction
RMSE	root mean square error
S	south wind direction
SSW	south southwest wind direction
SSE	south southeast wind direction
USGS	United States Geological Survey
TKE	turbulence kinetic energy
WRF	Weather Research and Forecasting

wind speed forecasting [7,8]. At present, the mesoscale Weather Research and Forecasting (WRF) model has been applied in many studies in the field of wind engineering. Carvalho et al. [9–11] have conducted many wind resource simulation studies based on the WRF model in the past few years. Their simulation results were tested using different initial and boundary condition datasets and WRF models, which has provided a reference for subsequent WRF studies. The WRF model can also be used to study wind resources in complex terrains using high spatial resolution [12] or by coupling microscale models [13]. Combined with the large eddy simulation (LES) method, the WRF model is also capable of simulating microscale flow in the wind farm [14,15].

Most previous work based on the WRF model was conducted with large horizontal resolutions and could not capture the interactions between wind turbines and the atmosphere in wind farm. Wind farm power production assessment requires high-resolution simulation of atmospheric flow, and relies on accurate predictions of atmospheric conditions at various wind turbine heights [12]. By parameterizing the influence of wind turbines, the interaction between the wind farm and the atmosphere can be calculated in the mesoscale model. Some work has been done recently to parameterize that influence in the WRF model. Baidya Roy et al. [16] proposed that the turbine rotor can be considered as an elevated sink of resolved kinetic energy and a source of turbulent kinetic energy (TKE); they stated that a fraction of the kinetic energy, equal to the power coefficient (C_P), is absorbed by the turbine, whereas the TKE is defined as a constant value. In a more recent work, Fitch et al. [17] developed a wind farm parameterization method for the mesoscale WRF model in which the effects of wind turbines are represented by imposing a momentum sink on the mean flow, whereas the kinetic energy deficit is transferred into electricity and TKE. In their method, the proportion of kinetic energy absorbed by the turbines is equal to the thrust coefficient (C_T), and the fraction of energy quantified by the C_P is converted into electricity. The remaining fraction (C_T - C_P) of available kinetic energy is supposed to generate TKE inside the atmosphere boundary layer (ABL). Abkar and Porté-Agel [18] also developed a model to parameterize the effects of wind farms in large-scale atmospheric models, and in contrast to previous work, they calculated the turbine-induced force and the TKE using an analytical method. Their model takes into account the effect of wind farm density, wind farm layout, and wind direction in simulations. The wind farm parameterization method provides a way to study turbine wakes and the interactions between the wind farm and the ABL in the WRF model. Compared with the computational fluid dynamics (CFD) method, the parameterized WRF model is more efficient in obtaining the wake characteristics of wind farms while considering the impact of