Renewable Energy 70 (2014) 142–152

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Mean and turbulent kinetic energy budgets inside and above very large wind farms under conventionally-neutral condition

Mahdi Abkar, Fernando Porté-Agel*

Wind Engineering and Renewable Energy Laboratory (WIRE), École Polytechnique Fédérale de Lausanne (EPFL), ENAC-IIE-WIRE, CH-1015 Lausanne, Switzerland

A R T I C L E I N F O

Article history:
Received 29 September 2013
Accepted 21 March 2014
Available online 21 April 2014

Keywords:
Atmospheric turbulence
Large-eddy simulation
Wind farm
Mean and turbulent kinetic energy budgets

A B S T R A C T

In this study, large-eddy simulations (LES) is combined with a turbine model to investigate all the terms in the budgets of mean and turbulent kinetic energy (TKE) inside and above very large wind farms. Emphasis is placed on quantifying the relative contribution of the thermal stratification in the free-atmosphere and wind-turbine spacing on the energy balance. The mean kinetic energy budget through the wind farms indicates that the magnitude of the kinetic energy entrainment form the free atmosphere into the boundary layer increases by increasing the density of the farms and decreasing the static stability in the free atmosphere, leading to larger power output from the wind farms. This entrainment is the only source of kinetic energy to balance that extracted by the turbines inside very large wind farms. In addition, it is shown that the distribution of the kinetic energy flux above the wind turbines, at top-tip level, is quite heterogeneous and its magnitude just behind the wind turbines is much larger due to the strong wind shear at that level. The simulation results also show that increasing the wind-farm density leads to an increase in the boundary-layer height, the ratio of the ageostrophic to the geostrophic velocity component inside the boundary layer, and the potential temperature near the surface. Detailed analysis of the TKE budget through the wind farms reveals also an important effect of the thermal stratification and wind turbine spacing on the magnitude and spatial distribution of the shear production, dissipation rate and transport terms. In particular, the shear production and dissipation rate have a peak at the turbine-top level, where the wind shear is largest, and their magnitude increases as the static stability in the free atmosphere and the wind-turbine spacing decrease.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

With the fast growing number of wind farms being installed worldwide, it becomes of scientific and practical interest to quantify how the large scale extraction of energy from the wind will affect the structure of the atmosphere, and vice versa. For instance, recent studies [1–4] show that large wind farms can influence near-surface wind, temperature and humidity, as well as surface momentum and scalar fluxes. But the influence of large wind farms on the atmospheric boundary layer (ABL) is not limited to the near surface quantities. For example, it has been shown that large wind farms can affect the structure of the whole boundary layer by changing the wind direction inside the ABL, as well as the boundary-layer depth [5,6].

Wind farms extract kinetic energy from the ABL winds. For a small number of wind turbines or at the leading edge of a large wind farm, this energy is mainly extracted from the incoming wind due the horizontal flux of kinetic energy. However, inside a large wind farm where the distance across the farm is much larger than the characteristic flow development length scale, nearly all of the energy must be entrained from the flow above through the vertical energy transport associated with turbulence [7–11]. Kinetic energy entrainment from the flow above has been quantified in previous numerical [7] and experimental studies [10,11] by performing the energy balance through very large wind farms. It was found that the vertical fluxes of kinetic energy are of the same order of magnitude as the energy extracted by the turbines. As a result, in very large wind farms, the entrainment of kinetic energy can be used as a basis to estimate the power output from the turbines. In a

* Corresponding author. EPFL-ENAC-IIE-WIRE, Building GR, Station 2, 1015 Lausanne, Switzerland. Tel.: +41 21 6932726.
E-mail address: fernando.porte-agel@epfl.ch (F. Porté-Agel).

http://dx.doi.org/10.1016/j.renene.2014.03.050
0960-1481/© 2014 Elsevier Ltd. All rights reserved.

real atmosphere, entrainment of kinetic energy is controlled by different factors such as Earth's rotation, surface momentum and buoyancy fluxes, and static stability of the free atmosphere immediately above the ABL [12]. Since the power extracted by the turbines in very large wind farms is directly linked to the entrainment of kinetic energy from the external environment, it is of great importance to investigate how the above mentioned parameters can affect the performance of wind farms.

Prior relevant numerical studies on the interaction between the ABL and very large wind farms using computational fluid dynamics (CFD) [5,7] have focused on the purely neutral ABL. In that case, the effect of surface buoyancy fluxes and free-atmosphere stratification can be ignored. Calaf et al. [7] used large-eddy simulations (LES) to study fully developed wind-turbine array boundary layer with varying turbine spacing and thrust coefficients under neutrally-stratified condition. They showed that, in very large wind farms, the vertical fluxes of kinetic energy mainly contributes to balance the power extracted by the turbines. Johnstone and Coleman [5] used direct numerical simulation (DNS) to examine the effect of an infinite array of actuator disk turbines on a neutral low-Reynolds-number Ekman layer. They showed that wind farms increase the boundary-layer depth, and the ratio of the ageostrophic to the geostrophic velocity component within the boundary layer. As will be shown in Section 4, increasing the ratio of the ageostrophic to the geostrophic velocity component as well as increasing the boundary layer depth leads to larger kinetic energy entrainment from the free atmosphere. Recently, Abkar and Porté-Agel [6] used LES to study the effect of free-atmosphere stability on the power extracted from very large wind farms under conventionally-neutral condition. Conventionally-neutral ABLs are defined as neutrally-stratified ABLs capped by the stably-stratified free atmosphere [13]. They showed that the presence of the turbines has significant effect on the growth of the boundary layer. In addition, it was shown that the thermal stratification of the free atmosphere reduces the growth of the boundary-layer height, leading to lower kinetic energy entrainment from the flow above and, consequently, lower power output from the turbines.

The objective of the present work is to perform full mean and turbulent kinetic energy budget analyses to provide a thorough understanding of the energy exchanges between conventionally-neutral ABLs and very large wind farms. Of particular interest is to quantify the relative contribution of different physical processes that affect the energy balance in the cases where the wind-turbine spacing and thermal stratification in the free-atmosphere vary. It is worth mentioning that such a comprehensive analysis has not been done before. In this study, a suit of large-eddy simulations of fully-developed wind-farm ABL flow is performed including the effect of earth's rotation and free-atmosphere stability. In the simulations, tuning-free Lagrangian scale-dependent dynamic models [14] are used to model the subgrid-scale fluxes, while the turbine-induced forces are parameterized with an actuator disk model [15]. The LES framework used in this work is described in Section 2. In Section 3, the results obtained from the LES of ABLs over very large wind farms are presented. The mean and turbulent kinetic energy budget analyses are presented in Section 4 and, finally a summary and conclusions are provided in Section 5.

2. Large-eddy simulation framework

2.1. LES governing equations

LES solves the filtered continuity equation, the filtered Navier–Stokes equations, and the filtered transport equation for potential temperature:

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0,$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{\partial \tilde{p}^*}{\partial x_i} + f_c \varepsilon_{ij3}\left(\tilde{u}_j - G_j\right) - \frac{\partial \tau_{ij}^{d}}{\partial x_j} + \delta_{i3} g \frac{\tilde{\theta} - \langle \tilde{\theta} \rangle}{\theta_0} - \frac{f_i}{\rho},$$

$$\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{\theta}}{\partial x_j} = -\frac{\partial q_j}{\partial x_j}, \qquad (1)$$

where the tilde represents a spatial filtering at scale $\widetilde{\Delta}$, t is time, $\tilde{u}_i$ is instantaneous resolved velocity in the i-direction (with $i = 1, 2, 3$ corresponding to the streamwise (x), spanwise (y) and vertical (z) direction, respectively), $\mathbf{G}$ is the geostrophic wind, $\tilde{\theta}$ denotes the resolved potential temperature (i.e., the temperature that an air parcel would have if brought adiabatically to a standard or reference pressure), θ_0 is the reference temperature, the angle brackets represent a horizontal average, g refers to the gravitational acceleration, f_c is the Coriolis parameter, δ_{ij} is the Kronecker delta, ε_{ijk} denotes the alternative unit tensor, $\tilde{p}^* = \tilde{p}/\rho + 1/3\tau_{kk}$ is the modified pressure, ρ is the fluid density, f_i is a body force (per unit volume) used to model the effect of turbines on the flow, $q_j = \widetilde{u_j\theta} - \tilde{u}_j\tilde{\theta}$ denotes the SGS heat flux, $\tau_{ij} = \widetilde{u_i u_j} - \tilde{u}_i\tilde{u}_j$ represents the kinematic SGS stress, and τ_{ij}^{d} is its deviatoric part. It should be noted that in the momentum conservation equation above, the buoyancy effects are accounted for via the Boussinesq approximation (see Stull [16] pp. 81–85).

In LES, all turbulent structures larger that the filter scale ($\widetilde{\Delta}$) are resolved and the contribution of the unresolved eddies or small-scale structures on the resolved field is parameterized using a subgrid-scale (SGS) model. A common parameterization strategy in LES consists of computing the deviatoric part of the SGS stress with an eddy-viscosity model [17], $\tau_{ij}^{d} = \tau_{ij} - 1/3\tau_{kk}\delta_{ij} = -2\widetilde{\Delta}^2 C_S^2 \left|\tilde{S}\right| \tilde{S}_{ij}$, and the SGS heat flux with an eddy-diffusivity model, $q_j = -\widetilde{\Delta}^2 C_S^2 \mathrm{Pr}_{sgs}^{-1} \left|\tilde{S}\right| \partial\tilde{\theta}/\partial x_j$, where $\tilde{S}_{ij} = (\partial\tilde{u}_i/\partial x_j + \partial\tilde{u}_j/\partial x_i)/2$ is the resolved strain rate tensor and $\tilde{S} = \sqrt{2\tilde{S}_{ij}\tilde{S}_{ij}}$ is the strain rate magnitude. C_s is the Smagorinsky coefficient and $C_S^2\mathrm{Pr}_{sgs}^{-1}$ is the lumped coefficient, where Pr_{sgs} is the SGS Prandtl number. Here, we employ the Lagrangian scale-dependent dynamic models [14] to compute the local optimized value of the model coefficients without any *ad hoc* tuning. In contrast with the traditional dynamic models [18,19], the scale-dependent dynamic models compute dynamically not only the value of the model coefficients in the eddy-viscosity and eddy-diffusivity models, but also the dependence of these coefficients with scale. More details on the formulation of scale-dependent dynamic models for the SGS stress and the SGS scalar fluxes can be found in Porté-Agel et al. [20], Porté-Agel [21] and Stoll and Porté-Agel [14].

2.2. Wind-turbine parameterization

To parameterize the turbine-induced forces, the actuator-disk model with rotation [15,22] is used. This model is based on blade-element theory and, therefore, it does not require resolving the boundary-layer flow around the turbine-blade surfaces, which greatly reduces the computational cost requirements compared with full-scale blade-resolving CFD model. This theory considers that each blade of a wind turbine can be divided into N blade elements which are assumed to behave aerodynamically as two-dimensional airfoils and to have no radial action on the flow. Through this model, the aerodynamic forces are determined using the lift and drag characteristics of the airfoil type as the well as the local flow conditions. Unlike the standard actuator-disk model,

Download English Version:

https://daneshyari.com/en/article/300060

Download Persian Version:

https://daneshyari.com/article/300060

Daneshyari.com