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Turbulence upstream of wind turbines: A large-eddy simulation approach to investigate the use of wind lidars

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ABSTRACT

Despite the evolution of wind turbines, the way in which in-situ meteorological information is obtained has not evolved much. Wind vane and cup anemometers, installed at the turbines nacelle, right behind the blades, are still used. This near-blade monitoring does not provide any time to readjust the profile of the wind turbine, and subjects the blades and structure to wind gusts and extreme incoming wind conditions. A solution is to install wind lidar devices on the turbine's nacelle. This technique is currently under development as an alternative to traditional in-situ wind anemometry because it can measure the wind vector at substantial distances upwind. However, most used wind lidar systems are optimized for measuring within a fixed upwind range, but at what upwind distance should they interrogate the atmosphere? This work uses Large Eddy Simulations to create a realistic atmospheric flow to evaluate optimal scanning distances to learn about the incoming turbulence as a function of wind farm configuration and atmospheric stratification. A correlation model, based on a modified truncated normal distribution, has also been developed, which could be implemented within the feed-forward collective pitch control of the turbine, allowing for improved wind turbine readjustments.

1. Introduction

The continuous improvement of Light Detection and Ranging (lidar) technology over the past few years, with enhanced spatio-temporal resolution, improved signal-to-noise ratio, and considerable reduction of the physical package, has made this technology very appealing for wind energy applications. For example, several studies have illustrated the lidars' capacity to provide more accurate measures of the turbine's approaching wind vector in comparison to traditional wind vane and cup anemometers [1–3]. With this new capacity of staring ahead of the turbine's rotor blades, it is possible to improve the turbine's yaw alignment [4,5], and therefore enhance the turbine's harvested power [2,6]. In addition, wind lidars have also improved the measure of power curves [7,8] and the prediction of incoming flow turbulence [9], which results in a potential mitigation of the turbines' loads.

To study the detection of wind gusts, Harris et al. [9] installed a wind lidar on the nacelle of a 2.3 MW turbine. The wind measurements were performed at a constant upstream scanning distance of two-hundred meters for a period of 18 h. By comparing the lidar measurements with those provided by cup anemometers, they illustrated the potential of nacelle-mounted wind lidars to accurately measure incoming wind gusts. Other studies have focused on the use of wind lidars to enhance the harvested power by continuously readjusting the turbine's yaw alignment [2], and in designing collective pitch controls [10,11] to reduce the loads that wind turbines suffer from incoming turbulent gusts. By being able to measure the incoming flow ahead of time, it is, for example, possible to design control mechanisms that force certain wind turbines of a wind farm to be purposely yaw-misaligned, reducing the wake-to-wake interaction with downstream turbines [12]. This is for example the purpose of the control-oriented dynamic model proposed by Gebraad and Van Wingerden [13], or the approach explored by the National Renewable Energy Laboratory (NREL) at the Fishermens Atlantic City Windfarm. In this last case, an increase of 10% in power output for the overall wind farm and a reduction in successive wake-turbine interactions were reported [14]. Another approach, currently being explored, to enhance the wind farm power production, knowing the incoming wind vector ahead of time, is the use of collective pitch control algorithms. These have the advantage of not increasing the turbine's structural loads (as compared to the yaw-misalignment approaches [10]). Yet, this approach has only been explored under deterministic gust conditions, assuming perfect inflow measurements, and applying

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Taylor's frozen turbulence hypothesis. Similarly, numerical works from Dunne et al. [15] have also illustrated the potential of using a wind lidar control approach to reduce loads while maintaining rated power and rotor speed, and at the same time without significantly increasing the pitch rate.

Currently it is possible to readjust the pitch of the turbine's blades at a rate of 4–8°/s [10,16], meaning that with a sufficient warning-time, it should be possible to readjust the blades', reducing the structural loads produced by wind gusts. According to Mikkelsen et al. [3], the 'warning' time for the incoming winds gusts is of 5–10 s, depending on the mean incoming wind velocity. Therefore, the potential of using wind lidars to predict the incoming turbulent flow relies on the time-lapse with which turbulent events can be predicted before these reach the turbine blades. At this point, while the lidar-assisted collective pitch control and the pitching system have been proved to be fast enough to regulate the wind turbine [10,16], several questions remain to be answered with respect to the evolution of the turbulent flow within wind farms. For example, how far upstream should the wind lidars measure to observe rotor-disk correlated turbulence, and how does this upstream correlation distance change with atmospheric stratification?

In this work we explore the correlation between the rotor-disk and the upstream measured turbulence fields in a wind farm under different atmospheric stability conditions. The goal is to determine whether it is possible to timely readjust the turbine blades to protect them from potentially damaging turbulent gusts. For this purpose a set of atmospheric large-eddy simulations (LES), including wind turbines capable of yaw self-adjustment, has been considered. The atmospheric flow was forced with a constant geostrophic wind and a time varying surface temperature extracted from the Cooperative Atmospheric Surface Exchange Study (CASES-99) field experiment [17], hence reproducing a realistic diurnal cycle. The effectiveness of measuring the flow upstream of the wind turbine to predict incoming turbulence gusts is quantified, and correlation curves are developed to help wind turbine operators select the most appropriate upstream scanning distance for nacelle mounted wind lidars as a function of atmospheric stratification.

In section 2 the considered study cases are explained, and in section 3 the results are presented and discussed. In section 4 a simple model to predict turbulent gusts is presented and section 5 outlines the conclusions. Additional details of the numerical configuration can be found in the Appendix section.

2. Study cases

To numerically simulate the atmospheric boundary layer flow throughout a diurnal cycle, the filtered Navier-Stokes equations (NS) with conservation of mass, and an advection-diffusion equation for potential temperature are integrated in time. The atmospheric boundary layer (ABL) flow is considered incompressible and as a result of the high Reynolds number, the viscous terms are neglected. The wind turbines are represented with the actuator-disk model with rotation of Wu et al. [18], including the dynamic yaw-alignment of Sharma et al. [19], where the turbines have the capacity to realign their yaw alignment every 10 min. The numerical domain has a physical size of $L_x = 2\pi z_i$ m, $L_y = \pi z_i$ m, and $L_z = 3z_i$ m, where z_i is the height of the inversion layer. The grid resolution is equal to $d_x = d_y = 24.5$ m and $d_z = 7.8$ m, with a total of $256 \times 128 \times 384$ grid points, providing a large enough domain for developing realistic ABL flow conditions [20,21]. Also, this numerical resolution is fine enough to accurately resolve the wind turbines and the corresponding wakes [22]. For each diurnal cycle the associated computational cost is approximately 33,000 core hours. In this study, each simulation used 64 cores, hence leading to a total of about 21 days. The specific details of the numerical code are found in the Appendix as well as in prior studies from the same authors [1,19,21].

To evaluate the possibility of using nacelle-mounted wind lidars to foresee strong incoming turbulence ahead of time, two different wind farm scenarios with different wind turbine spacings have been considered. Each wind farm configuration has been evaluated through two consecutive diurnal cycles. First, a very large wind farm (VLWF) is considered, where the turbines are perfectly aligned and separated by a distance of $\sim 8D$ in the streamwise direction (s_x) and $\sim 5D$ in the spanwise direction (s_y). Second, a very sparse wind farm representative of the case of an isolated single wind turbine is also considered, where the turbines are in practice separated by a distance of $s_x \sim 63D$ and $s_y \sim 31D$, and referred as largely-spaced wind farm (LSWF).

The simulations were initialized with vertical profiles of velocity and temperature extracted from Kumar et al. [23], corresponding to a height-independent geostrophic wind, and a well mixed temperature profile matching the initial surface temperature of $278.6K$, with an inversion layer spanning from z_i to the top of the domain, with $z_i = 1000m$. To simulate a diurnal cycle, a time varying surface temperature is imposed (see Fig. 1a). Specifically

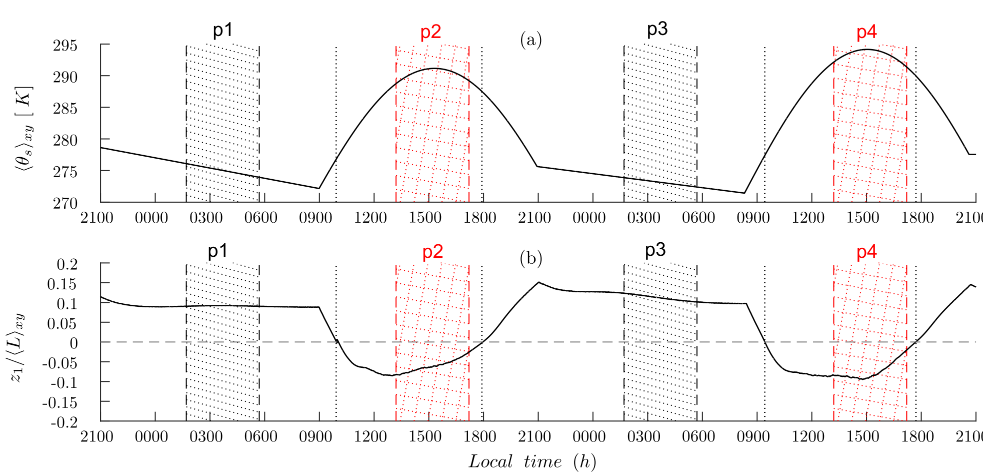

Fig. 1. (a) Spatially averaged and time-dependent imposed temperature at the surface of the domain $\langle\theta_s\rangle_{xy}$ [K]; (b) normalized stability parameter, $z_1/\langle L\rangle_{xy}$, where z_1 is the height of the first grid-point and L is the Monin-Obukhov length as a function of time. Four-hour periods marked with 45° dotted line (p1, p3), in black, and squared dotted line (p2, p4), in red, delineate time periods in which representative statistics are computed. Precisely, period p1 and p3 constitute the times between 0145 and 0545 h local time (LT) and p2 and p4 denote the time between 1315 and 1715 h of LT. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)