Numerical Simulation of Atmospheric Turbulence for Assessment of Wind Turbine*


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Abstract
To obtain basic understanding for the development of atmospheric turbulence assessment technique for wind-energy application, we examine the performance of turbulence simulation using the large-eddy simulation technique, focusing on grid dependency of predicted turbulence statistics. We test two different types of model codes, one derived from a numerical weather prediction (NWP) model and the other from a computational fluid dynamics (CFD) model. Both model types have advantages and disadvantages while applied to the atmospheric boundary layer with complex terrain, and it is the purpose of this study to examine their capability for use in simulating wind-farm turbulence. The first simulation uses an NWP model for an ideal atmospheric flow and the other uses a CFD model for flows over complex surface. The horizontal grid spacing ranges from 50 m to 300 m. The results show that a horizontal grid spacing of 50 m for both model types can reasonably capture the energy containing eddies and represent coherence structures and turbulence statistics, such as intensity, anisotropy and spectra of wind fluctuations. This study provides a guideline for using numerical simulations for turbulence assessment at wind turbine locations. It also suggests that the combination of NWP and CFD models may provide a better approach to assess atmospheric turbulence, for example by using an NWP model with fine grids to provide turbulent inflow boundary conditions for a CFD model.

Key words: Atmospheric Boundary Layer, Complex Terrain, Computational Fluid Dynamics, Inflow Generation, Large Eddy Simulation, Numerical Weather Prediction, Turbulence, Wind Power Generation, Wind Turbine

1. Introduction

A better understanding of turbulence phenomena of the wind field in the atmospheric boundary layer (ABL) is of practical interest in wind turbine engineering. Wind turbines are classified in three categories according to their sustainability to the fatigue- and ultimate-loads due to wind fluctuations, which are generated by atmospheric turbulence under the normal- and extreme-conditions (i.e., ordinary and strong wind conditions), by the international standard for their design requirement(1). The international standard defines the
categories of wind turbines using the reference turbulence intensity, which is the relative
(normalized by mean wind) turbulence intensity (90 % quantile of measurements that had
ten-minute-averaged wind speeds fall between 14.5 ms⁻¹ to 15.5 ms⁻¹, based on the one-year
observation); the three categories A, B and C are designed for the reference turbulence
intensities of 0.16, 0.14 and 0.12, respectively. The international standard stipulates
empirical and theoretical formulations of the relationship between the relative turbulence
intensity and ten-minute-averaged wind speed, and basics turbulence statistics, such as
anisotropy and spectra, to be used for calculating the fatigue- and ultimate-loads under the
normal- and extreme-conditions. These formulations are defined as functions of the
reference turbulence intensity. Thus, an accurate assessment of turbulence intensity for the
intended site of wind power station would allow for a proper selection of wind turbines and
mounting locations.

Unfortunately, such an assessment is not straightforward. One difficulty results from the
two different kinds of turbulence generation processes in the ABL, and both can strongly
affect the turbulence assessment under the normal- and extreme-conditions. The first kind is
mechanical generation due to surface wind shear with “micro-scale” disturbance (the order
of characteristic lengths are usually below several hundreds of meters), and the second is
meteorological effects due to “meso-scale” disturbance (the order of characteristics lengths
may exceed several hundreds of meters), convection or buoyancy forcing(6), or detached
eddies(3)(4)(5). The effect of complex terrains is particularly important for mechanical
generation because surface heterogeneities and undulations of the ground cause rapid local
changes in turbulence statistics near the ground(6). The existing standard for turbulence
assessment of turbine categories, A, B and C does not have the capability to include such
changes of turbulence statistics(7)(8), because they are applicable only to flat terrain sites.
Observations, which are generally used for estimating wind-field characteristics in the ABL
with measurement towers, are also difficult to capture the spatial variation of turbulence
statistics.

Recently, numerical simulations have become a powerful tool for studying complicated
These researchers have examined unsteady three-dimensional wind fields in the ABL over
complex terrains by using the large-eddy simulation (LES) technique. The LES codes used
by these researchers came from two modeling communities: one is computational fluid
dynamics (CFD) modeling(9)(10) and the other is numerical weather prediction (NWP)
modeling(11)(12)(13)(14). CFD models have been developed by the wind engineering
community and they can simulate micro-scale turbulence generated by complex terrains.
However, they are not applicable in representing turbulence generated by meteorological
processes such as convection and weather events. Contrary to this, NWP models are
suitable for simulating meteorological process including weather phenomena, but have
weakness in representing turbulence affected by complex terrains(15).

Using a combination of the NWP and CFD types of models might be one possible
approach to assess the atmospheric turbulence at wind farm stations, including complex
terrain sites for normal- and extreme-conditions. Meteorologically generated turbulence can
be predicted by an NWP model and mechanically generated turbulence predicted by a CFD
model. A major problem for such simulations is the proper grid resolution and the linkage
between an NWP and a CFD models. In this study, we examine the performance of
turbulence simulations from an NWP and a CFD models focusing mainly on the effects of
grid resolutions. We carried out two numerical simulations of atmospheric turbulence; one
is for an idealized atmospheric condition with an NWP model and the other is for a complex
atmospheric condition with a CFD model. We use various horizontal grid spacing ∆h
ranging from 50 m to 300 m to examine the grid dependency of predicted turbulence
statistics.
Nomenclature

\( f \): frequency
\( L \): length of computational domain
\( S \): power spectra
\( U \): time-averaged streamwise velocity
\( u_\tau \): time-averaged surface friction velocity
\( x \): streamwise coordinate
\( y \): spanwise coordinate
\( z \): vertical coordinate (height from the ground surface)
\( \sigma \): time-averaged turbulence intensity of velocity fluctuation
\( \Delta \): grid spacing

Subscript

\( h \): horizontal component
\( m \): maximum value
\( \text{ref} \): value at reference height
\( u \): value of streamwise velocity
\( x \): streamwise component
\( y \): spanwise component
\( z \): vertical component

2. Prediction of turbulence statistics using an NWP model

2.1 Experimental set up

We choose the Weather Research and Forecasting (WRF) model of Advanced Research version, which has been widely used all over the world for numerical weather forecasting. The model details are described in Skamarock et al. (16). Note that the present simulation is based on a large-eddy simulation (LES) version of the WRF, as described by Moeng et al. (17), in which the option of using a PBL scheme (i.e., a RANS model) is turned off. Hattori et al. (18)(19) have shown that the WRF-LES generates much better turbulence statistics in the ABL compared to using a PBL scheme. The Deardorff’s TKE (Turbulence Kinetic Energy) scheme is adopted to represent the three-dimensional subgrid-scale diffusion with the following model constants: the diffusion coefficient \( C_k = 0.19 \) and the dissipation coefficient \( C_\varepsilon = 0.93 \). We choose the fifth- and third-order differencing schemes for horizontal and vertical advection terms and the third-order Runge-Kutta scheme for time integration.

The test case we consider here is an idealized neutral ABL, which has been studied by Moeng and Sullivan (2). The terrain is flat, the surface roughness is homogeneous, and periodic boundary conditions are applied to both horizontal directions. The computational domain is \( 6 \times 6 \) km\(^2\) in horizontal directions and 2 km in the vertical direction. The geostrophic wind speed and the Coriolis parameter are set to \( 10 \) ms\(^{-1}\) and \( 10^{-4} \) s\(^{-1}\), respectively. The initial potential temperature is constant (300 K) below the boundary layer height (\( z \leq 1000 \) m, where \( z \) is a height from the ground surface), and a capping inversion is imposed above it. The momentum flux at the ground is predicted using Monin-Obukov similarity theory with a roughness height of \( 10^{-1} \) m. The horizontal grid spacing \( \Delta_h \) is varied from \( 50 \) m to \( 300 \) m and a vertical grid of \( 25 \) m is used for all simulations. The time step is \( 0.5 \) s for \( \Delta_h = 50 \) m and \( 1.0 \) s for \( \Delta_h = 100 \) m and \( 300 \) m. We previously checked effects of the time step on predictions and found that statistics do not show the tendency to increase or decrease against the time step, implying that these values of time step are sufficiently small for the grid spacing. Also, we had performed a sensitivity test on the vertical grid resolution and found that turbulence statistics remain similar (except near the surface, \( z \leq 30 \) m) when
the vertical grid spacing is changed from 10 m to 50 m. Also our simulations appropriately produce the logarithmic wind profile in the atmospheric surface layer, although slightly underestimate the wind speed near the ground (\(z \leq 30\) m), which is a common feature of NWP predictions\(^{(20)}\).

### 2.2 Results and discussions

Figures 1 and 2 show the vertical profiles of time-averaged relative [i.e., relative to \(U(z)\)] turbulence intensities \(\sigma / U(z)\) and its anisotropy \(\sigma_h / \sigma_z\) below \(z = 200\) m, where \(U(z)\) is time-averaged wind speed at \(z\) and \(\sigma_h\) and \(\sigma_z\) are turbulence intensities of the horizontal and vertical components. The intensities \(\sigma\) are calculated from the 3 components of the grid-scale (GS, or resolvable-scale) velocity field, plus the contribution from the subgrid-scale (SGS) taken to be \(2/3\) of the SGS TKE. Note that, the anisotropy computed from just the GS components became extremely large (\(\sigma_h / \sigma_z > 10\)) near the ground; this is probably due to the fact that the resolvable-scale eddy size in the vertical direction is significantly smaller compared with that in horizontal directions. The finer grids lead to stronger turbulence intensities, and also changes in its anisotropy. At \(z \equiv 50\) m – 100 m, roughly corresponding to the hub height of wind turbines, the increases in turbulence intensities are notable: the values of \(\sigma / U(z)\) for \(\Delta_h = 50\) m, 100m and 300 m at \(z = 50\) m are...
Tab. 1  Comparison of maximum value of intensity and anisotropy of velocity fluctuation, $(\sigma/u)_{\text{m}}$ and $(\sigma_h/\sigma_z)_{\text{m}}$, between present NWP prediction with grid spacing, $\Delta_h$, of 50 m and observation.

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<thead>
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<tbody>
<tr>
<td>$(\sigma/u)_{\text{m}}$</td>
<td>2.3</td>
<td>2.5</td>
<td>2.8</td>
<td>2.3</td>
<td>2.4</td>
<td>3.2</td>
</tr>
<tr>
<td>$(\sigma_h/\sigma_z)_{\text{m}}$</td>
<td>2.2</td>
<td>2.0</td>
<td>-</td>
<td>2.2</td>
<td>2.4</td>
<td>2.8</td>
</tr>
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Fig. 3  Color contour of instantaneous surface friction velocity with iso-surface of second invariant of deformation tensor for horizontal grid spacing of 50 m (a), 100 m (b), and 300 m (c).
Tab. 2  Computational parameters of turbulence simulation over complex terrain with CFD model.

<table>
<thead>
<tr>
<th>Site</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain size ($L_x, L_y, L_z$) [km]</td>
<td>(8.0, 5.0, 2.0)</td>
<td>(8.0, 5.0, 2.0)</td>
<td>(8.0, 5.0, 2.0)</td>
<td>(73.0, 30.0, 8.0)</td>
</tr>
<tr>
<td>Horizontal grid spacing $\Delta_h$ [m]</td>
<td>50</td>
<td>100</td>
<td>50</td>
<td>300</td>
</tr>
<tr>
<td>Minimum vertical grid spacing [m]</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>Time step [s]</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>2.0</td>
</tr>
<tr>
<td>Uppermost anemometer height [m]</td>
<td>69</td>
<td>69</td>
<td>40</td>
<td>58</td>
</tr>
</tbody>
</table>

0.2, 0.16 and 0.15, respectively. Table 1 shows that the maximum values of predicted turbulence intensity and anisotropy, ($\sigma/u_{t}$)$_m$ and ($\sigma_h/\sigma_z$)$_m$, for the case with $\Delta_h = 50$ m agree well with observations in the near-neutral surface layer over the homogeneous flat ground$^{(21)(22)(23)(24)(25)}$. (Note that, the intensities shown in Tab. 1 are normalized by the friction velocity $u_{t}$ in order to compare with the observations and these values are mainly generated by fluctuations with frequencies $f > 10^{-3}$ Hz$^{(19)}$. The turbulence intensity of streamwise ($x$ direction) component is large compared with that of spanwise ($y$ direction) component, which also shows good agreement with observations and the international standard for wind turbine design requirement$^{(1)}$. We also examine the change in grid-scale structural characteristics near the ground with varying the horizontal grid spacing. Figure 3 depicts a typical example of visualized instantaneous turbulence structure by plotting the contours of instantaneous surface friction velocity and the iso-surface of the second invariant of deformation tensor. The surface friction velocity closely relates to the wind field near the ground according to Monin-Obukov similarity theory. The second invariant of deformation tensor is widely used to represent the vortex structure; it captures the pressure minimum in a plane perpendicular to the vortex axis at high Reynolds number flows$^{(26)}$. Different horizontal grid spacing gives different turbulence structure. From all the simulations performed, we can recognize the streaky structure, which was also reported in previous studies$^{(2)}$. We also observe a close relationship between the streaks and the vortex field with more vortices in the region of small friction velocity, as also shown in previous studies$^{(2)(27)}$. Finer-grid simulation naturally predicts finer structure and a smaller characteristic length scale, which is estimated by the width of streaky structure. The LES with a horizontal grid spacing of 50 m yields a characteristics length scale similar to the observed in the ABL$^{(10)}$. We conclude that the NWP model chosen here can properly reproduce coherence structures and turbulence statistics in the neutral ABL if the grid spacing is fine enough.

3. Prediction of turbulence statistics using a CFD

3.1 Experimental set up

The CIMLES code$^{(28)(29)}$, which is a CFD model, is used for this study. This model uses a staggered grid system in the Cartesian coordinate for incompressible flows. All spatial derivatives are approximated with second-order center finite differences. The coupling scheme between the transport equations of mass and momentum is based on the S-MAC method, and the advection and diffusion terms are advanced with a third-order Runge-Kutta and a second-order Crank-Nicolson schemes, respectively$^{(30)}$. The ghost-cell immersed boundary method$^{(31)}$ is used to represent complex terrain in the Cartesian coordinate system. The velocity interpolation near the ground surface to calculate the velocity at ghost-cell points is carried out with an imaging-point velocity and with a ground-surface velocity; the ground-surface velocity is calculated by a logarithmic wall model for a rough wall$^{(32)}$. The roughness height is estimated by the land-use data presented by geospatial information authority of Japan, the spatial resolution of which is approximately 100 m. In addition, a mass source/sink is introduced at ghost-cell points to enhance the quality of the solution by
Fig. 4  Color counter of altitude in computational domain for Sites A (a), B (b), and C (c). White circle is for measuring location.
satisfying the continuity for the cell containing the immersed boundary. We use this CFD model to carry out a large-eddy simulation of the ABL. The sub-grid stresses are represented by a mixed-time-scale model. At the inlet location, we give an unsteady wind field generated by an artificial generation method proposed by Kataoka and Mizuno; we add a driver domain in front of the computational domain, and in this driver domain we carry out a turbulence simulation of an idealized neutral atmospheric surface-layer flow (over a flat terrain with homogeneous surface roughness without the Coriolis force) with a streamwise periodic condition and an imposed target vertical profile of the time-averaged wind speed with a logarithmic law. Here, we should stress that, as shown in previous section, an NWP-LES model with a fine grid spacing can also generate such an unsteady wind field. At the outlet location, an outflow boundary condition is imposed. Note that, this code (CIMLES) has been shown to be able to capture the turbulence structure with complex geometries through the comparison with wind-tunnel experiments.

We consider four simulation cases (Case 1–4); their computational parameters are summarized in Tab. 2. The simulations are carried out for the ABL at three observation sites (Sites A, B and C) above a complex terrain (shown in Fig. 4) where turbulence statistics were measured by using sonic anemometers with a sampling frequency of 10 Hz, which are suitable for turbulence measurements, in previous studies. The terrains are quite complex and the observations reveal high level of turbulence intensities at these locations. Site A is located at the top of a hill and Site B at a ridge, both near a coastline, whereas Site
C is located in a mountainous area far from a coastline. The horizontal computational domains are set to \(7.0 \times 5.0\) km\(^2\) for Sites A and B and \(73 \times 30\) km\(^2\) for Site C; the much larger domain needed for Site C is because we need to set the inlet condition at a flat terrain location as shown in Fig. 4. The vertical domain size is set to 2 km for Sites A and B, and 8 km for Site C; these sizes approximately correspond to four times of the maximum terrain height in the computational domain to prevent the numerical effects of the upper boundary condition on simulations. Case 1 uses a horizontal grid spacing of 50 m for Site A, Case 2 uses a 100 m grid spacing also for Site A, Case 3 uses a 50 m grid for Site B, and Case 4 uses a grid spacing of 300 m for Site C. The grid spacing varied vertically with fine resolution at the ground surface (shown in Tab. 2). Two sonic anemometers were mounted at Site C and three mounted at Sites A and B, at various heights in order to obtain vertical profiles of turbulence statistics. The heights of the uppermost mount of the sonic anemometers are 69 m, 40 m and 58 m for Sites A, B and C, respectively. The varying measurement heights enable us to check the performance of turbulence simulations at various heights. Note that, in comparing with prediction, the turbulence statistics, including power spectra, are calculated with measurements for 10 minutes only that have averaged wind speed larger than 20 m s\(^{-1}\) and a steady wind direction, which agrees with inflow direction of predictions (we had 6 periods in observations); this assures that the turbulence...
3.2 Results and discussions

Figure 5 shows the comparison of vertical profiles of time-averaged wind speed in streamwise components $U$ between predictions and observations. These profiles are normalized with the height of the uppermost mount of sonics, $z_{ref}$, and $U_{ref}$, which is the value of $U$ at $z_{ref}$. With the assumption of Reynolds number independence, we expect the normalized profiles to be universal (because $U_{ref}$ and $u_*$ are strongly related for mechanical turbulence) at each measuring location and therefore the comparison can be made between observations and simulations. The observed vertical profile at Site B (Case 3) shows more gradient below $z/z_{ref} = 1$ because the measurement height at this site (40 m) is much lower than that at Site A (69 m) and site C (58 m). The predictions with a horizontal grid spacing is mostly mechanically driven.
of 50 m (Cases 1 and 3) capture the vertical profiles of the observations. Contrary to this, the predicted profiles with horizontal grid spacing of 100 m (Case 2) and 300 m (Case 4) differ significantly from those of observations.

Figure 6 compares the vertical profiles of relative (normalized with $U(z)$) turbulence intensity, where $z$ is normalized with $z_{ref}$, between the simulations and observations. The observed profiles normalized by $U(z)$ remain at a value close to $0.1 - 0.2$, implying that the turbulence is generated mainly by the mechanical process. The numerical simulations with horizontal grid spacing of 50 m (Cases 1 and 3) provide a good prediction for turbulence intensity. Case 3 also captures the increase in the turbulence intensity towards the ground due to complex terrain. Case 1 also shows a reasonable agreement with observations for anisotropy of turbulence intensities, while Case 3 shows some quantitative discrepancies near the ground where the sub-grid scale (SGS) stress of vertical component becomes dominant. Comparing to Case 1 for the same site, the prediction from the simulation with a horizontal grid spacing of 100 m (Case 2) shows recognizable disagreement with observations, particularly the streamwise component (the solid curve). The prediction with grid spacing of 300 m (Case 4) at Site C differs significantly from observations. Here, we should stress that the predicted and observed turbulence intensities for Case 3 shown in Fig. 6 (c) are much larger than those estimated by the international standard for category A.

Figure 7 presents an example of predicted instantaneous wind field near Site B (Case 3)
in two vertical cross sections (one in $x$–$z$ plane and the other in $y$–$z$ plane) with a bird’s-eye view where colors show the contours of the instantaneous steamwise velocity. The complex terrain generates strong deformations of the wind field near the ground, which result in flow separations (shown by blue colors in the figures), and the extremely strong turbulence intensity, corresponding to Fig. 6 (c). This also causes rapid spatial changes in the wind field, indicating that the assessment of atmospheric turbulence, even for the spatial change in turbulence intensity near the measuring location, is vital for suitable siting of wind turbines at complex terrain locations.

From these results, we may conclude that turbulence simulations using a CFD model with a horizontal grid spacing of 50 m can reasonably predict turbulence statistics in the ABL even over complex terrain. To clearly understand the meaning of the horizontal grid spacing of “50 m”, we investigate the behavior of power spectra of streamwise wind fluctuations, $S_u$, at $z_{ref}$. Figure 8 compares the predicted power spectra with observations, and also with the results derived from the empirical formulations described by the international standard(1). The profiles are normalized with frequency $f$, the variance of wind speed fluctuation $\sigma_u$, the sonic height $z_{ref}$ and the wind speed at that height $U_{ref}$. These profiles indicate that the simulations with the horizontal grid spacing of 50 m (Cases 1 and 3) clearly capture energy containing eddies, even when their characteristics length scales shift due to complex terrain (between Sites A and B). The rapid decay at the high frequency region from the simulations is due to numerical truncation and is expected. The predicted power spectra with the horizontal grid spacing of 100 m (Case 2) and 300 m (Case 4) significantly differ from observations even in the energy-containing-eddies region, and thus these grid sizes are not suitable for predicting turbulence statistics in the ABL. (The implausible peak of $S_u$ for Case 2 may result from numerical instability, which causes large wind fluctuations at a low frequency; but so far we could not clearly grasp the source of the instability).

4. Summary and conclusions

NWP models are suitable for simulating meteorological processes with meso-scale phenomena but have weakness in representing the effect of complex terrains on micro-scale, whereas CFD models have the capability to simulate fine turbulence structures generated by complex terrains but are not applicable in representing turbulence generated by meteorological processes. Thus, using both NWP and CFD types of modeling might be a possible approach to assess the atmospheric turbulence at wind power stations, including complex terrain sites.

Here we examined the performance of turbulence simulations by both model types, focusing on finding a proper grid size. We carried out two types of LES’s; one uses an NWP model to simulate an idealized ABL and the other uses a CFD model to simulate the ABL over complex terrain. We tested various horizontal grid spacing $\Delta h$ ranging from 50 m to 300 m to examine the grid dependency of predicted turbulence statistics. The present simulations clearly show that a horizontal grid spacing of 50 m, which has been used by other simulation(9)(10)(11)(12)(13)(14), can firmly capture the energy containing eddies and also properly represent coherence structures and turbulence statistics, such as intensity, anisotropy and spectra of wind fluctuations, which are used for calculating designe loads of wind turbines. This is true for both NWP and CFD models despite the essential difference of their numerical schemes.

This study suggests that using both NWP and CFD types of models may provide a better approach to assess the atmospheric turbulence at wind power stations. As described in previous studies(9)(10), the technique in generating unsteady inflow boundary conditions is a major issue for LES using a CFD model. This issue was also raised by a wind tunnel study(6) where they showed that imposing the same vertical profiles of time-averaged wind speed at
the inflow does not yield the same vertical profiles of turbulence statistics downstream, due
to the effects of detached eddies. Using an NWP model as LES to provide the inflow
boundary condition might solve this problem. Nevertheless, there are other issues associated
with using an NWP type of LES for atmospheric turbulence, such as the terra-incognita
subgrid-scale (SGS) issue\(^{(38)}\) and the nesting problem between domains with various grid
sizes\(^{(17)}\), they need to be investigated before we can use the numerical assessment technique
for wind-energy application.

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