Large eddy simulation for atmospheric boundary layer flow over flat and complex terrains

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Abstract. In this work, we present Large Eddy Simulation (LES) results of atmospheric boundary layer (ABL) flow over complex terrain with neutral stratification using the OpenFOAM-based simulator for on/offshore wind farm applications (SOWFA). The complete workflow to investigate the LES for the ABL over real complex terrain is described including meteorological-tower data analysis, mesh generation and case set-up. New boundary conditions for the lateral and top boundaries are developed and validated to allow inflow and outflow as required in complex terrain simulations. The turbulent inflow data for the terrain simulation is generated using a precursor simulation of a flat and neutral ABL. Conditionally averaged met-tower data is used to specify the conditions for the flat precursor simulation and is also used for comparison with the simulation results of the terrain LES. A qualitative analysis of the simulation results reveals boundary layer separation and recirculation downstream of a prominent ridge that runs across the simulation domain. Comparisons of mean wind speed, standard deviation and direction between the computed results and the conditionally averaged tower data show a reasonable agreement.

1. Introduction

Wind energy has received increasing attention in recent years as a clean energy alternative to fossil fuels. Nowadays, the focus of wind project innovation is shifting from individual turbine performance to overall plant performance characteristics, which will significantly drive down wind electricity generation costs [1]. On-shore wind farms are often located in complex terrain with hills, ridges and mountain slopes. These topographic features can greatly affect the local flow features such as strong acceleration, separation and recirculation. A detailed wind analysis in the complex terrain is necessary since the flow characteristics have important impacts on the aerodynamic loads and power output of the wind turbines. On-site measurements are now increasingly complemented by numerical simulations of the atmospheric boundary layer (ABL) flows to provide more detailed insight into the local flow features [2].

Along with the increased use of numerical simulations comes the need to provide more evidence for the accuracy of the simulation results. However, recent efforts to validate simulation results of flows in complex terrain have struggled due to a lack of available measurement data for that purpose. In this work, we present a data analysis from meteorological towers and simulation
results for the ABL over an area in south-central Wyoming called the Sierra Madre (SM) site which is part of a wind energy project with approximately 1000 turbines planned for the SM and Chokecherry (CC) sites. Overall 38 meteorological towers have been installed to record data for a period ranging from 3 to 9 years with some of the towers still active. For this paper we consider an 8.5km × 7.5km area in the SM site that features a prominent ridge and contains 8 meteorological towers.

The simulations are performed with the OpenFOAM-based simulator for on/offshore wind farm applications (SOWFA) [3], which was originally developed by the U.S. Department of Energys National Renewable Energy Laboratory (NREL). SOWFA is an open source software containing an incompressible flow solver for Large Eddy Simulation (LES) of wind flow through wind farms. So far the solver has mostly been used for flat terrain simulations with and without wind turbines [4]. The basic terrain solver that is provided in the SOWFA package is extended with new boundary conditions which are more suitable for real terrain flow simulations. The main advantage of using SOWFA is that the underlying CFD library OpenFOAM is designed to handle arbitrary unstructured meshes which might be necessary for complex terrain simulations.

2. LES modeling and numerical solution

2.1. Governing equations

The filtered incompressible Navier-Stokes equations are used in SOWFA with the consideration of Coriolis forces and the Boussinesq approximation for buoyancy effect [3]. The filtered continuity equation is

\[ \frac{\partial \bar{u}_i}{\partial x_i} = 0, \]  

and the filtered momentum equation is

\[ \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial (\bar{u}_j \bar{u}_i)}{\partial x_j} = -\frac{1}{\rho_0} \frac{\partial \bar{p}}{\partial x_i} - 2\varepsilon_{ijk} \Omega_j \bar{u}_k - \frac{\partial \tau_{ij}}{\partial x_j} + \left[ 1 - \frac{(\bar{\theta} - \theta_0)}{\theta_0} \right] g_i. \]  

The equation for the filtered virtual potential temperature is

\[ \frac{\partial \bar{\theta}}{\partial t} + \frac{\partial (\bar{u}_j \bar{\theta})}{\partial x_j} = \frac{\partial q_j}{\partial x_j}. \]  

In these equations, the overbar denotes the LES filtering operation. \( \rho_0 \) is the constant density of incompressible air and \( \theta_0 \) is a reference temperature. \( \Omega_j \) is the planetary rotation rate vector at a point on the earth and \( g_i \) is the gravitation vector.

The effects of the unresolved scales on the evolution of \( \bar{u}_i \) and \( \bar{\theta} \) appear in the sub-grid-scale (SGS) stress \( \tau_{ij} \) and the SGS temperature flux \( q_j \). They are defined as

\[ \tau_{ij} = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j \]  

\[ q_j = \bar{u}_j \bar{\theta} - \bar{u}_j \bar{\theta} \]  

The unclosed SGS stress tensor and temperature flux must be parametrized using a SGS model as a function of the filtered (resolved) velocity and temperature fields. Also note that the transport equation for the potential temperature need only be solved for a non-neutral ABL. In both the momentum and potential temperature equations, the effects of molecular diffusion is neglected due to high Reynolds number of ABL flow. Hence the SGS effects are much more dominant unless the flow is very close to the ground. Near the ground surface, the ABL simulation will usually rely on the surface model in which SGS and viscous stresses and temperature fluxes are lumped together.
2.2. Sub-grid-scale modeling

A common parametrization strategy in LES consists of computing the SGS stress \( \tau_{ij} \) with an eddy viscosity theory \(^{[5, 6]}\) and the SGS heat flux \( q_j \) with an eddy diffusivity theory \(^{[7]}\). The deviatoric part of SGS stress tensor is parametrized as

\[
\tau_{ij} - \frac{1}{3} \delta_{ij} \tau_{kk} = -2 \nu_T \mathcal{S}_{ij}
\]

where \( \mathcal{S}_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \) is the resolved strain-rate tensor and \( \nu_T \) is the SGS viscosity given by

\[
\nu_T = (C_S \Delta)^2 \langle \mathcal{S}_{ij} \mathcal{S}_{ij} \rangle
\]

where \( \Delta = (\Delta x \Delta y \Delta z)^{1/3} \) is the filter width, and \( C_S \) is a non-dimensional parameter called the Smagorinsky coefficient.

The SGS heat flux is parametrized as

\[
q_j = -\frac{\nu_T}{Pr_t} \frac{\partial \theta}{\partial x_j}
\]

where \( Pr_t \) is the turbulent Prandtl number.

In this work, the Lagrangian-averaged scale-invariant (LASI) dynamic Smagorinsky model \(^{[8]}\) is chosen to model the SGS viscosity. The dynamic procedure optimizes the value of the Smagorinsky coefficient \( C_S^2 \) using information from the smallest resolved scales in LES without the need for a priori specification and consequent parameter tuning. The model is based on the Germano identity \(^{[9]}\):

\[
L_{ij} \equiv T_{ij} - \tau_{ij} = \overline{u_i u_j} - \tau_{ij}
\]

where \( L_{ij} \) is a resolvable turbulent stress tensor and \( T_{ij} \) is the SGS stress at a test-filter scale \( \Delta \) (typically \( \Delta = 2\Delta \)). The test filter SGS stress can be determined using the eddy viscosity model as

\[
T_{ij} - \frac{1}{3} \delta_{ij} T_{kk} = -2(C_S \Delta)^2 \mathcal{S}_{ij} \mathcal{S}_{ij}
\]

where \( C_S(\Delta) \) denotes the Smagorinsky coefficient at the test filter scale. Substituting the Eq. (10) and Eq. (6) into Eq. (9), in addition to the crucial assumption of scale invariance, \( C_S(\Delta) = C_S(\Delta) = C_S \), one can calculate the error incurred by using the Smagorinsky model in the Germano identity as

\[
e_{ij} = L_{ij} - \frac{1}{3} \delta_{ij} L_{kk} - (C_S)^2 M_{ij}
\]

and

\[
M_{ij} = 2 \Delta^2 (\mathcal{S}_{ij} \mathcal{S}_{ij} - 4 \beta \mathcal{S}_{ij} \mathcal{S}_{ij})
\]

where \( \beta = C_S^2(\Delta)/C_S^2(\Delta) = 1 \) indicates that the coefficient is scaled invariant.

Minimizing the error given by Eq. (11) by using the least-squares approach \(^{[10]}\) results in the optimal value of \( C_S^2 \) as

\[
C_S^2 = \left< L_{ij} M_{ij} \right> / \left< M_{ij} M_{ij} \right>
\]

where the angle-brackets denote some type of averaging. Often, the average operation is done over homogeneous planes, as with the planar-averaged scale-invariant (PASI) dynamic model, which works for flow over flat terrain.

In LASI dynamic Smagorinsky model, the angle-brackets is applied as the averaging for some time backward over local fluid along pathlines rather than over directions of statistical homogeneity. An exponential weighting function is chosen from the averaging with strongest
weighting at the point of interest. The $\langle L_{ij}M_{ij} \rangle$ and $\langle M_{ij}M_{ij} \rangle$ are denoted as $f_{LM}$ and $f_{MM}$, respectively. The relaxation transport equations thus obtained for $f_{LM}$ and $f_{MM}$ are

$$\frac{\partial f_{LM}}{\partial t} + \pi_j \frac{\partial f_{LM}}{\partial x_j} = \frac{1}{1.5\Delta(f_{LM}f_{MM})^{-1/8}} (L_{ij}M_{ij} - f_{LM})$$

(14)

$$\frac{\partial f_{MM}}{\partial t} + \pi_j \frac{\partial f_{MM}}{\partial x_j} = \frac{1}{1.5\Delta(f_{LM}f_{MM})^{-1/8}} (M_{ij}M_{ij} - f_{MM})$$

(15)

The Lagrangian-averaging scheme is well suited for the applications with heterogeneous spatial conditions since it preserves local variability, preserves Galilean invariance, and does not require homogeneous directions [11]. Therefore, LASI dynamic Smagorinsky model is suitable for simulations of flow over complex terrain.

2.3. Numerical Method

In this paper, the filtered governing equations are solved with an unstructured finite volume method using the open-source CFD software OpenFOAM with second order accurate schemes based on linear interpolation (corresponding to central differences) for spatial discretization. The time discretization is based on a second order accurate backward scheme and we limit the Courant number to $C_o < 0.7$ to keep the time discretization and splitting errors small. The pressure-velocity coupling is based on the PISO (Pressure-Implicit with Splitting of Operation) algorithm with updates of the temperature equation in the corrector steps [3]. The LASI dynamic Smagorinsky model is applied to model the effects of the subgrid scales and the relevant parameters of LASI quantities are initially set to $f_{LM} = 2.56 \times 10^{-6} m^4/s^4$ and $f_{MM} = 1.0 \times 10^{-4} m^4/s^4$ uniformly throughout the field such that the Smagorinsky constant is initially $C_S = 0.16$. The turbulent Prandtl number here is fixed to 1.0 [3].

3. Boundary conditions for complex terrain simulations

3.1. Inflow and outflow boundary conditions

The inlet boundary condition (BC) is of great importance in LES because the downstream flow development within the domain is largely determined by the prescribed inflow turbulence. The most accurate way of generating realistic inflow turbulence is to run a so-called ”precursor simulation” before the main simulation and to store the relevant flow variables in a plane every time step (or somewhat less frequent). The stored data is then used at the inflow boundary condition in the actual simulation with linear interpolation in space and time to allow for different grid sizes and time steps. For the complex terrain simulation, the inflow data is generated with a fully periodic precursor simulation of a flat terrain neutral ABL with the wind speed fixed to the conditionally averaged value of the tower SM 03 (see section 4.1 for details). The relevant flow variables that are sampled in a plane from the precursor simulation are mapped onto the complex terrain’s inlet boundary plane using linear interpolation in the cross-stream y-direction. For the vertical z-direction we use a coordinate transformation such that the z-location of the flat precursor data corresponds to a height-above-ground (HAG) in the terrain inlet plane. The HAG is simply determined according to the vertical distance between each face center of the inlet plane and the corresponding surface edge center. Thus, it is assumed that the boundary layer conforms to the terrain and that it is not modified. The terrain upstream of the inflow boundary is quite flat (see section 4.1 for details) which should make this approach a reasonable approximation. For the neutral ABL simulations presented in this work, only the velocity data is taken from the precursor (since the temperature distribution is uniform) and a zero normal gradient boundary condition is applied for pressure. For the outlet plane, the static pressure is fixed to a constant value and a zero normal gradient BC is adopted for all other flow variables.
3.2. Lateral and top boundary conditions
Due to the different edge shape on the boundaries of complex terrain, the lateral boundary planes cannot be modeled with a periodic boundary condition any more as is customary for flat ABL simulations. The irregular terrain shape may change the flow direction locally and the effect of the Coriolis force causes a veering of the mean wind direction. Thus, the lateral boundaries should allow for inflow and outflow. Similarly, the top boundary plane has to allow for flow entrainment such that a sharp down slope of the terrain does not lead to the same deceleration as it would in a channel geometry (with a slip or no-slip wall) or to allow for outflow in case of an obstruction to prevent flow acceleration due to mass conservation.

To enable inflow and outflow type behaviors at lateral and top boundary planes, a new boundary condition is implemented in OpenFOAM which changes the BC type based on the local boundary face center flux from the previous time step. When the flux points into the domain, the BC behaves like an inflow boundary and thus the pressure BC is set to be zero normal gradient and the velocity component tangential to the face normal is also obtained from a zero gradient BC (i.e. it is set to the value of the tangential velocity component at the cell center). The velocity component normal to the face is simply computed based on the inward flux and face area. When the flux points out of the domain, the BC behaves like an outflow boundary hence the pressure BC is set to be a fixed value and a zero gradient BC is specified for the velocity vector. Furthermore, to enhance the numerical robustness of the new boundary condition, the boundary flux and tangential velocity are spatially filtered over the neighboring boundary faces.

3.3. Surface boundary condition
The surface shear stress on the ground is specified directly with the Schuhmann-Grötzbach \[3, 12\] shear stress model based on the logarithmic wall function with a roughness height of \(z_0 = 0.02m\) which corresponds to the fairly level grass plains on the real terrain site. The surface stress model predicts the total shear stress (including viscous and SGS stresses) based on the filtered velocity at the first cell center off the wall. To apply the log-law we first perform a local coordinate transformation into coordinates that are normal and tangential to the surface, then calculate the surface stress, and finally transform the surface stress tensor back into the global coordinate system of the CFD calculation. For all flat terrain simulations the Schuhmann-Grötzbach BC is based on horizontally averaged velocities. The terrain case does not have statistical uniformity in the horizontal plane but is still statistically stationary. Therefore, we use a running time average to obtain the local mean velocity for the Schuhmann-Grötzbach BC with an averaging time scale \(T_{av} = 1200\)s.

3.4. Boundary conditions validation
To test the new boundary conditions, a simple neutral ABL over a flat surface is considered. A periodic precursor ABL simulation is performed on a \(3km \times 3km \times 1km\) domain with resolutions of \(\Delta x = \Delta y = 20m\) and \(\Delta z = 10m\) using a driving pressure gradient such that the mean wind has a speed of \(U = 10m/s\) at a height of \(z = 60m\). The Coriolis force is included here such that the veering of the mean wind velocity with height causes the upper part of the south boundary to have mostly outflow and the north boundary to have mostly inflow. A slip-wall BC is specified at the top and at the bottom the Schuhmann-Grötzbach BC is applied. The simulation is run for 20,000s with a variable time step such that \(Co < 0.7\) to achieve a statistical steady state and then for 10,000s to obtain statistics and to store data at the inflow plane every other time step \(t_s \approx 1s\). The precursor data then drives a second simulation with the same domain and mesh resolution but with inflow/outflow and the newly developed lateral BC as discussed in section 3 above. Ideally, the statistical results obtained from the two simulations should be identical. The mean horizontal velocity (based on time and horizontal averaging) and the resolved stream-wise
velocity variance obtained from the precursor and the inlet/outlet simulation are compared in Figure 1. It is shown that the mean velocity is identical in both simulations but small deviations exist in the variance which is probably due to an insufficient long simulation run time for the inlet/outlet case. Overall, the good agreement shows that the new boundary conditions work well and do not cause any issues.

Figure 1. Validation of the inflow/outflow BC for the neutral ABL over flat terrain.

4. Simulation set-up and results

4.1. Domain selection and met-tower data analysis
A tentative simulation area containing typical complex topography in the form of a prominent ridge and including a large number of meteorological towers is identified within the SM wind site. The chosen 8.5km × 7.5km domain is shown in the top left of Figure 2 (locations of meteorological towers are marked with letters) and a photograph of the ridge is shown in the bottom left while a surface elevation contour is shown in the bottom right.

The meteorological tower SM 03 (indicated as tower “C” in Figure 2) is located very close to the inlet boundary of the domain and is selected as the reference tower for the conditional averaging procedure. By analyzing the 9 year wind data collected at tower SM 03, it is found that the prevalent wind is from south-west ($225^\circ$) with a mean speed of 10 m/s at 57 meters height. Thus, the orientation of the simulation domain is such that the inflow boundary is oriented to be perpendicular to the prevailing wind from the south-west. The SM 03 tower data is then used to calculate averages of all towers located in the domain based on samples (time instances) that are conditional on the SM 03 tower having

- a wind speed in the range of 10m/s ± 0.5m/s at a height of $h = 57m$
- a wind direction within $225^\circ ± 11^\circ$ at $h = 57m$
- only considering data from the month of June.

The conditionally sampled data at $h = 57m$ is shown in Figure 3 as wind roses for the eight towers in the domain. Due to the chosen conditions on tower SM 03 and the resolution of the wind roses there seems to be no variation in direction and wind speed at SM 03. The other two towers SM 05 and SM 18 located near the inlet show wind speeds and directions similar to those of SM 03 with little variation. This is important since the terrain simulations will be based on the mean SM 03 wind condition. Several of the towers downstream of SM 03 show a strong terrain induced variation of wind speed and direction.
It should be noted here that the adopted conditional averaging procedure includes samples from a wide range of atmospheric stability conditions. Unfortunately, the available tower measurements do not allow for a direct determination of the atmospheric stability. In the future we are planning to use time as a further condition such that we can roughly separate stable nighttime and unstable daytime conditions. For the remainder of this paper, we will assume that the “average” stability condition for June is neutral and thus all the LES will be performed without stratification.

Figure 2. Sierra Madra wind farm site topography information.

Figure 3. Conditionally sampled met-tower wind data at a height of \( h = 57 \) m shown as wind roses.

4.2. Flat terrain precursor simulation with neutral atmospheric boundary layer

The precursor simulation for the complex terrain case is a neutral ABL simulation over flat terrain with with fully periodic boundary conditions in the horizontal directions and a slip-wall boundary condition at the top plane. The simulation domain extends \( 5km \times 8km \times 1.3km \) in the streamwise (x), spanwise (y), and vertical (z) directions, respectively. Recall that the streamwise directions corresponds to the mean wind from the south-west (225\(^\circ\)). The grid resolution is given by \( \Delta x = \Delta y = 15m \) in horizontal and \( \Delta z = 10m \) in the vertical directions, respectively (corresponding to \( \approx 23 \) million cells). The Coriolis forcing at the averaged latitude of the wind site (\( \approx 42\)\(^{\circ}\)) is included. The precursor inlet planes are stored every \( t_s = 1s \) for the last 5,000s simulation time. To validate the precursor simulation results, the mean horizontal wind and standard deviation profiles are compared to the conditionally averaged data at the three heights of the reference tower SM 03 in Figure 4. The simulation results for the mean velocity are fairly close to the conditionally averaged met-tower data but a slight over prediction of the velocity standard deviation obtained from the simulation results can be observed. This is probably due to the fact that the simulations are based on a neutral ABL whereas the met-tower data contains samples from stable (smaller standard deviation) and unstable conditions (larger standard deviation). A small increase of the resolved streamwise velocity standard deviation is observed near the top boundary of the domain. This increase is due to the applied slip-wall BC. The slip-wall BC means a zero wall-normal velocity (impermeability) and zero gradients for the tangential velocity components (due to assumed zero viscous fluxes). Since no capping inversion is adopted in our simulations, velocity fluctuations are not completely damped near the top surface. The increase in resolved streamwise velocity standard deviation is now due to a redistribution of resolved vertical velocity fluctuations to the horizontal component due to wall blocking effects very similar to what is observed in real boundary layers. Since we use a very fine grid resolution this effect is more pronounced in figure 4 than in figure 1 where the simulation
results from a coarser flat ABL are shown. Applying a capping inversion layer would remove the increase and cause a monotonic decrease of the intensity of resolved fluctuations. We do not think that this artifact from the top BC has any influence on the lower parts of the ABL.

4.3. Complex terrain simulation with neutral atmospheric boundary layer

The terrain surface information of the chosen simulation area at the SM wind site is obtained from the 1-arc-second Shuttle Radar Topography Mission data set (SRTM) with approximately 30-meter horizontal resolution. A $8.5km \times 7.5km \times 1.2km$ simulation domain in the streamwise (x), spanwise (y), and vertical (z) directions, respectively, is selected which contains 8 met-towers. The domain is then oriented such that streamwise x-direction is along the mean wind direction from the south-west. Figure 2 shows a schematic of the simulation area at the SM wind site and figure 3 shows an elevation map with the location of the met-towers. The main ridge that runs through the domain has a maximum slope of around 15% near the SM 01 tower. Note that the inflow (y-z) plane is slightly smaller than that of the precursor simulation such that the linear interpolation of the inflow data can be realized. A structured grid with a horizontal

Figure 4. Comparison of the precursor simulation and conditionally averaged met-tower data at 3 height levels.

Figure 5. Surface topography with mesh details of the chosen simulation domain.
The inflow data is generated from the precursor simulation as described in section 4.2 with a driving pressure gradient such that the mean wind speed at \( z = 57 \text{ m} \) equals to 10 m/s, which corresponds to the conditional average of tower SM 03 at the same height. Note that the tower SM 03 is very close to the inlet boundary of the simulation domain to ensure a certain accuracy of precursor inflow mapping. The inflow, outflow, lateral, top, and bottom BC are as discussed in section 3.

**Figure 6.** Instantaneous stream-wise velocity color contours.

We will first analyze the simulation results qualitatively and then give a quantitative comparison with the met-tower data. Figure 6 shows a snapshot of the instantaneous streamwise velocity field in the whole domain and in selected cross-sectional planes. Regions with significant negative instantaneous streamwise velocity can be observed on the lee side of the steepest sections of the ridge near the north-west boundary at \( y \approx 7 \text{ km} \) and at the center at \( y \approx 4 \text{ km} \) indicating possible boundary layer separation and recirculation. Further evidenced for the existence of a recirculation region is given in figure 7 where instantaneous (top) and mean (bottom) vertical velocity contours are shown in the center plane at \( y \approx 4 \text{ km} \). The mean vertical velocity plot shows a recirculation region behind the ridge with a downward velocity region above of an upward velocity region very close to the surface (as opposed to the downward facing slope). Figure 8 shows instantaneous (top) and mean (bottom) contours of cross-stream velocity at the south side lateral boundary plane \( y = 0 \text{ km} \). The top region of the ABL displays a negative velocity (flow out of the boundary) and small positive values (inflow through the boundary) in the lower part. This turning of the flow is due to the Coriolis acceleration and the small scale variations are due to local slopes in the terrain. The figure clearly shows that the newly developed lateral BC allows for inflow and outflow through the boundary.

**Figure 7.** Contours of instantaneous and mean vertical velocity (m/s) in the center plane \((y \approx 4 \text{ km})\).

**Figure 8.** Contours of instantaneous and mean cross-stream velocity (m/s) in the south side lateral boundary plane \((y = 0 \text{ km})\).

For a quantitative analysis, the mean wind speed, standard deviation and direction on each meteorological tower’s location are computed for a comparison with the corresponding measured
The wind roses from the simulation data are shown in Figure 9 on the left and the tower data are shown on the right both at a height of \( h = 57 \text{ m} \). The wind roses from the simulation results are in reasonable agreement with the wind roses from the conditionally averaged tower data with the wind direction most frequently between south-south-west (202.5\(^\circ\)) and west-south-west (247.5\(^\circ\)). The mean wind speed and wind speed standard deviation are shown in Table 1. Overall, the simulation results have the right trend but some deviations from the measurements can be observed. For example, the turbulent inflow for the terrain simulation is generated from the precursor which was driven such that the mean wind speed at \( h = 57 \text{ m} \) is equal to the SM 03 tower conditional average of 9.97 m/s. In the terrain simulations, tower SM 03 is located about 200 m downstream of the inflow plane and the calculated mean wind speed is with 10.9 m/s about 9% higher than the mean inflow value at the same height. This indicates that flow experiences a slight speed up within 200 m downstream of the inlet plane due to a slight up-slope of the terrain. Behind the main ridge there seems to be too much of a deceleration in the simulation (see results for SM 16 in table 1). If the top BC would not allow for flow going into the domain such a deceleration would be expected due to the mass conservation (larger cross-sectional area behind the ridge). The top BC adopted in the simulation does allow for entrainment but apparently does not provide enough inflow to prevent the deceleration. It is believed that both issues, the speed up on the up-will slope near the inlet and the too strong deceleration behind the ridge, can be removed by considering a larger overall height of the simulation domain which would reduce the influence of the top BC on the simulation results.

**Table 1.** Comparison of statistic results of simulated data and measured data

| Tower Number | Mean Velocity (m/s) | Standard Deviation (m/s) |
|--------------|---------------------|--------------------------|
|              | Simulated | Measured | Simulated | Measured |
| SM 01        | 12.00     | 12.58    | 1.10      | 1.02     |
| SM 03        | 10.90     | 9.97     | 1.00      | 1.11     |
| SM 05        | 10.81     | 9.70     | 0.90      | 0.98     |
| SM 09        | 8.98      | 9.93     | 1.33      | 1.23     |
| SM 15        | 9.55      | 9.58     | 1.05      | 1.16     |
| SM 16        | 7.33      | 9.41     | 1.30      | 1.33     |
| SM 17        | 11.00     | 9.44     | 0.97      | 0.81     |
| SM 18        | 7.43      | 8.77     | 1.55      | 1.44     |
5. Summary and conclusions

In this paper we have described the work flow to perform LES for a neutral ABL over real complex terrain by using NREL’s OpenFOAM-based SOWFA flow solver. A tentative terrain within the Sierra Madra wind site is selected and a structured Cartesian grid with vertical stretching is generated over the terrain’s surface. New boundary conditions have been implemented, which are more suitable for LES of ABL over real complex terrain. At the inflow boundary, the velocity is mapped from the corresponding data obtained from a precursor simulation of an ABL over flat terrain. A new BC type for the lateral and top boundaries that allows for inflow and outflow based on the local flux is developed and tested for a simple flat ABL case. Good agreement between the fully periodic and the inlet/outlet simulation with “open” lateral boundaries has been obtained.

The real terrain case is based on an area of $8.5 \text{km} \times 7.5 \text{km}$ in the Sierra-Madre wind farm site. The area contains eight meteorological towers and the tower SM 03 which is located very close to the inlet plane of the simulation domain is chosen as the reference tower. Conditional averages for all towers are calculated based on the reference tower SM 03 having wind speeds of $10 \text{m/s} \pm 0.5 \text{m/s}$ at $h = 57 \text{m}$ and a wind direction of $225^\circ \pm 11^\circ$ during the months of June over 9 years. A neutral precursor simulation over flat terrain is performed according to the reference tower conditions to obtain realistic inflow for the complex terrain simulation. The terrain simulation results show interesting flow features such as the separation behind the steeper parts of a ridge and the expected turning of the mean wind direction with height due to the Coriolis force. Comparing the mean wind speed, standard deviation and direction of the simulation data with the conditional averaged tower data reveals that the simulation results have the right trend but also some quantitative differences. Further improvements of the results could be achieved by increasing the height of the simulation domain in order reduce the influence of the top boundary on the simulation results. Furthermore, the horizontal resolution of the domain will be refined to 15 m in a future study to better capture the existing terrain features.

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