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LARGE-EDDY SIMULATIONS FOR ATMOSPHERIC BOUNDARY LAYER FLOWS OVER COMPLEX TERRAINS WITH APPLICATIONS IN WIND ENERGY

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Abstract. Substantial increase of wind energy production has made modeling of atmospheric boundary layer (ABL) flows over wind farms an inportant research topic. In the present work, Large Eddy Simulations (LES) are carried out to investigate the turbulent boundary layer flows over the two-dimensional RUSHIL wind-tunnel hill and the LES model is successively applied for the Bolund hill, which represents a real complex terrain. In order to validate our LES methodology presented here, the LES results are compared against the wind-tunnel and field measurements. It is shown that present LES results are in good agreement with the measurements in both cases. Furthermore, the LES methodology is utilized to simulate wind structures over the real wind-farm topography located in South-East Finland, and the preliminary results are reported in the this paper.

1 INTRODUCTION

Nowadays, wind farms are often constructed in areas of complex terrains. Simulations of local atmospheric flows over complex terrains containing, e.g. hills, ridges, forests, and lakes are of great interest for many researchers in wind energy. The Reynolds-Averaged Navier-Stokes (RANS) approach using two-equation turbulence models has been widely used for simulating atmospheric flows over isolated hills [1, 2, 3]. This approach has been successfully extended to wind prediction over complex terrains such as the Askervein hill located in the Scotland and the Bolund hill located in the Denmark. Although RANS models have been performing reasonably well for the mean wind prediction over such topographies, they may not perform well in the flows containing complex phenomena such as streamline curvature, acceleration, deceleration and separation as they are calibrated in the simple flows. To overcome these issues, advanced methods such as Large Eddy Simulation (LES) is encouraged to be applied for such atmospheric flow simulations, although it is computationally far more expensive than the RANS approach.

Research reported in this paper is oriented towards LES for ABL flows over complex terrains. However, a systematic study of the boundary layer flow over an idealistic hilly terrain is a necessary step towards better understanding of the flow over realistic complex terrains. It is therefore desirable to compare LES results against the wind-tunnel or the field measurements to validate the LES methodology before employing it over practical wind farms.

In this paper, LES is performed to investigate the turbulent boundary layer flows over an isolated two-dimensional ($2D$) RUSHIL wind-tunnel hill profile [4] and the approach is successively applied for the Bolund hill. The LES results of an isolated $2D$ hill and the Bolund hill are compared with the RUSHIL wind-tunnel [4] and the field measurements [5], respectively. It is shown that the current LES produces reasonably realistic results and the agreement with the experimental results is reasonably good in both validation cases. Furthermore, the validated LES model is employed to simulate wind structures over a real wind farm located in South-East Finland, and the preliminary results are briefly reported in the paper.

2 NUMERICAL METHODS

Larger turbulent eddies which are the most energetic ones and responsible for the majority of turbulent transport, are resolved directly in a computational grid in LES, whereas eddies smaller than the grid size are more isotropic and are modeled using a Sub-Grid-Scale (SGS) model. In the current work, the filtered continuity and momentum equations for an incompressible fluid are solved by employing an unstructured finite-volume method based open-source code OpenFOAM [6]. The 4^{th} order time-accurate fractional step solver developed by Vuorinen et al. [7] is implemented into OpenFOAM and it is employed here. The solver uses the classical 4^{th} order Runge-Kutta (RK) scheme for the time integration and a projection method where the velocity field is corrected by using the pressure gradient in between the RK sub steps. The pressure is obtained by solving a Poisson equation. In addition, the one-equation eddy viscosity SGS model is employed to model the smaller eddies. The SGS equation is time-integrated numerically using the second-order backward implicit method and it is solved after the 4^{th} (last) RK sub-step. Moreover, all the governing equations are discretized in space using the central difference scheme.

2.1 Boundary conditions

The realistic upstream boundary condition at the inlet is one of the major difficulties in LES, especially in simulations of a flow over an inhomogeneous surface. The most accurate way of generating the genuine inflow turbulence is to run a so-called precursor simulation, either before the main simulation or simultaneously with it. In the present LES, the upstream boundary condition is developed using the so-called recycling (or mapping) method as described in [8]. In this method, a part of the precursor domain is combined into the main computational domain and the flow variables are sampled on a cross-wind plane which is sufficiently far downstream from the inflow plane. The sampled data are then recycled back to the inflow plane at each time step. By recycling the flow data from further downstream a recycling section is created before the hill section in which the flow is forced to become fully developed, and at the same time, the flow within this section is automatically fed into the main domain. In addition, the velocity flux is fixed at the inflow boundary in order to maintain the same amount of a volumetric flow throughout the simulation.

Boundary conditions on the ground surface have also been a challenge in LES. In order to avoid massive computational resources required for high Reynolds number flows such as the present flow, the use of the wall-function approach is essential. Furthermore, the roughness length z_0 of the rough surface is often implemented via the wall function. Here, the logarithmic wall function based on z_0 is implemented into our LES code in order to determine the ground surface fluxes on the surface boundary.

The static pressure is fixed to a constant value on the outlet plane and a homogeneous Neumann boundary condition is used for the rest of the flow variables. The slip boundary condition is used for all the flow variables at the top boundary, whereas periodic boundary conditions are set in the cross-wind direction.

3 WIND TUNNEL VALIDATION

Khurshudyan et al. [4] performed the RUSHIL wind tunnel experiments that simulated neutral ABL flows over the three different isolated $2D$ hills. Out of the three hills, the steepest hill is studied here. So far there have been numerous attempts to simulate the RUSHIL wind tunnel case mainly by using the RANS models [1, 2, 3]. The only LES studies reported for the RUSHIL case are by Allen and Brown [9] and recently by Chaudhari et al. [10]. In [10], LES are carried out over two different hills with aerodynamically smooth surfaces and at relatively low Reynolds number $Re_h = 3120$ based on the hill height and the free stream velocity.

3.1 Simulation setup

The hill height h is 0.117 m and the length is equal to $6h$ (=0.702 m) with a maximum slope of 26°. The simulation is performed in a 8.34 m $\times$ 2 m $\times$ 1 m domain which is equal to $71.28h \times 17.1h \times 8.55h$, as shown in Figure 1. The domain is discretized into

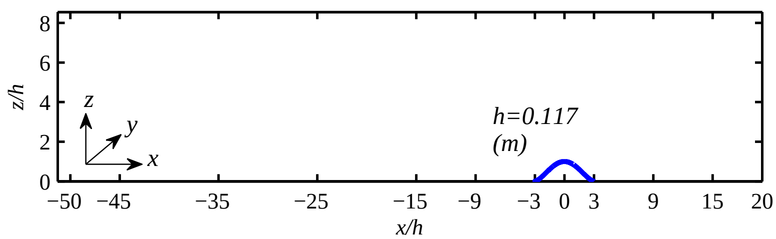

Figure 1: Side-view of the numerical model of an isolated $2D$ hill

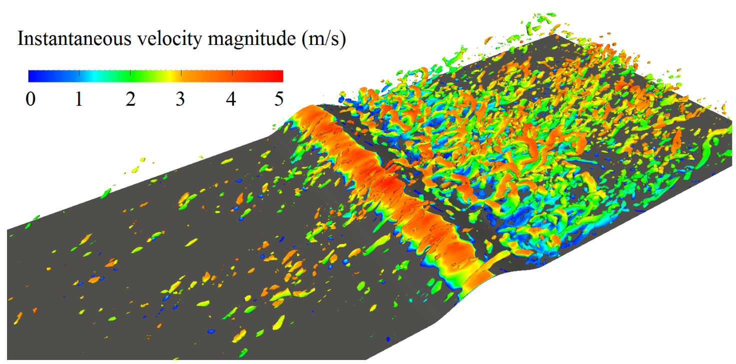

Figure 2: Iso-surfaces of the second invariant of the velocity gradient tensor Q colored with the velocity magnitude.

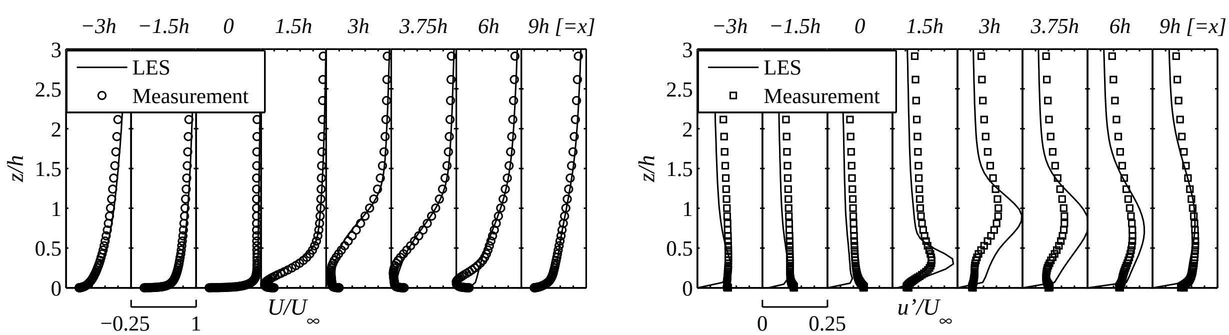

Figure 3: Vertical profiles of the mean wind-wise velocity U/U_∞ (left) and the wind-wise turbulence intensity u'/U_∞ (right) compared with measurements for flow over an isolated $2D$ hill.

$495 \times 136 \times 70$ hexahedron cells in wind-wise (x), cross-wind (y) and vertical (z) direction, respectively. The roughness-length z_0 is set to 0.000157 m. The Reynolds number Re_h based on h and the free-stream velocity U_∞ is about 31200, where the value of U_∞ is 4 m/s. These values are the same as those in the wind tunnel experiment [4].

3.2 Comparison

Figure 2 depicts the iso-surfaces of the second invariant of the velocity gradient tensor Q colored with the velocity magnitude in order to show the resolved small-scale turbulent motions. In Figure 3, the LES-predicted vertical profiles of the mean velocity and the turbulence intensity are compared with the wind-tunnel measurements. It can be seen that the overall LES prediction of the mean velocity is reasonably accurate. However, LES underestimates the flow separation in the lee-side. The predicted reattachment point is at $x = 5.41h$ which is somewhat more upstream than the measured reattachment point $x = 6.5h$. The LES prediction of the turbulence intensity is satisfactory compared to the measurements up to the hill summit $x = 0$ and also downstream of the separated-flow region $x > 6h$. Within the separated-region, LES overestimates the turbulence intensity in the shear layer between the slow recirculating flow and the faster flow above the separation regions. The overestimated shear stress is probably responsible for the slightly immature reattachment point as the vertical mixing of the momentum becomes overestimated. Although, the current results underestimate the flow separation and overestimate the turbulent intensity in the separated region, the present LES shows better agreement with measured data compared to other numerical studies. Also, our reattachment-length prediction is closer to the measurements than the value reported in [1, 9].

4 THE BOLUND HILL VALIDATION

The Bolund experiment performed during the period of three months from 2007-2008 is a field campaign that provides a new dataset for validating atmospheric flow models in a complex terrain [5, 11]. Bolund is a 12 m high, roughly 130 m long and 75 m wide coastal hill located north of Risø DTU (Technical University of Denmark) in Denmark. Figure 4 shows the Bolund orography data with the positions of measuring masts installed around the hill during the field campaign. Although the hill is relatively small, it contains much complex topography, including the steep vertical escarpment than that of the Askervein hill. Recently, the Bolund field campaign has got much attention as it is one of the latest field measured dataset in order to validate the micro-scale CFD models for wind energy applications. In the recent past, a few numerical studies have been reported for the Bolund case [11, 12]. In the present work, LES is carried out to investigate the atmospheric flow over the Bolund case. The field measured dataset contains the data from four different wind directions, but in our case, the simulation is performed only for one wind direction which is a westerly wind (270°).

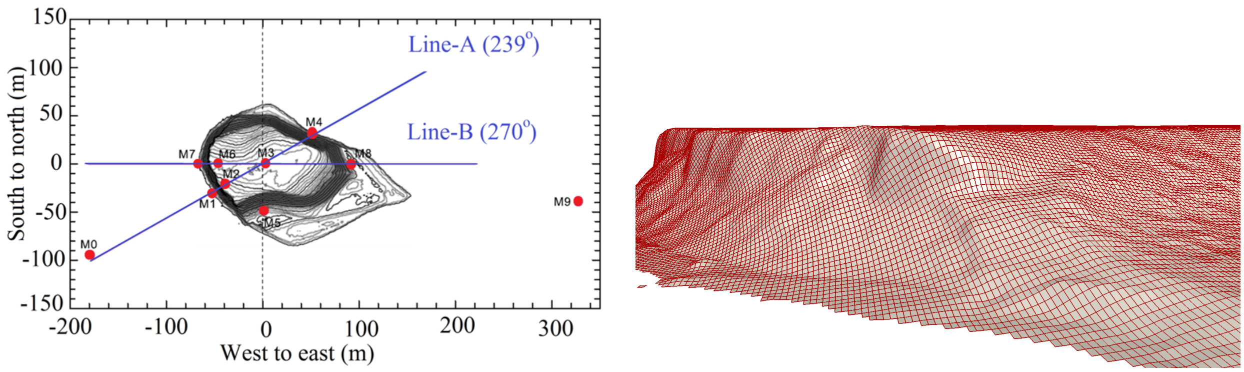

Figure 4: The Bolund orography with the mast positions along line A and B (left), and closer look on the Bolund hill model with the grid resolutions. The orography picture is taken from [5, 11].

4.1 Simulation setup

In order to insure the fully developed wind profile before the reference mast M0 installed at $x = -181$ m, the computational domain is extended from $x = -810$ m to 400 m in wind-wise direction. The center of the hill is located at $x = y = 0$ m. The height of the domain and the boundary-layer depth is set to 120 m which is roughly $10H$, with $H = 12$ m is the Bolund hill height. Also, the width of the domain is extended from $x = -205$ m to 185 m. Thus, a computational domain is of the size $1210 \times 390 \times 120$ m^3 in wind-wise, cross-wind and vertical directions, respectively. A domain is then discretized using a block-structured hexahedron mesh with finer grid resolution on the surface covering the hill part (see Figure 4). The grid size varies from the order of 10 cm to 10^2 cm scales. The whole computational grid consists of $940 \times 428 \times 100$ ($\approx 40,000,000$) hexahedron cells. The recycling plane is chosen to be at $x = -400$ m. The fixed values of $z_0 = 0.0003$ m and 0.015 m as suggested by [5] are used for the water and the hill surfaces, respectively. After the flow development, the results are time averaged over the last 600 s to calculate the flow statistics.

4.2 Comparison

Recently, Bachmann et al. [11] showed the blind comparison between the Bolund field measurements and the results from several different modeling approaches. In the comparison, results were reported from LES, RANS and linearized models as well as from the wind-tunnel and water-channel experiments. However, LES and the experimental results were unexpectedly poor compared to those RANS model results [11].

Figure 5 depicts the instantaneous iso-surfaces of the second invariant of the velocity gradient tensor Q colored with velocity magnitude. The iso-surfaces are highlighting the resolved small-scales turbulent motions over the hill. Next, the comparison between the present LES results and the field measurements recorded at different heights of 10 different masts installed over the Bolund is shown in Figures 6 and 7. In order to see

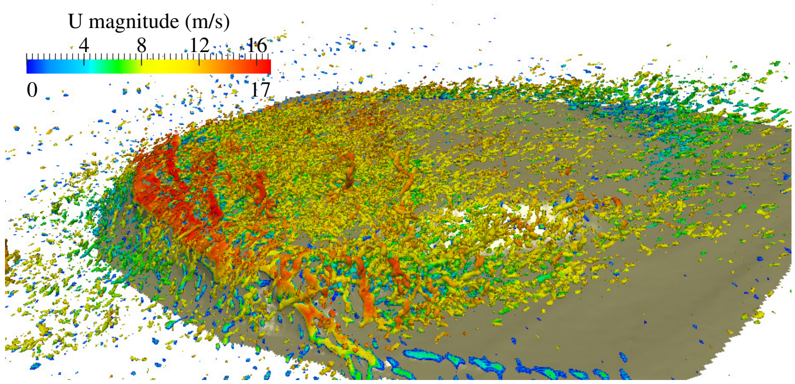

Figure 5: Iso-surfaces of the second invariant of the velocity gradient tensor Q colored with the velocity magnitude around the Bolund hill for the wind direction of 270°.

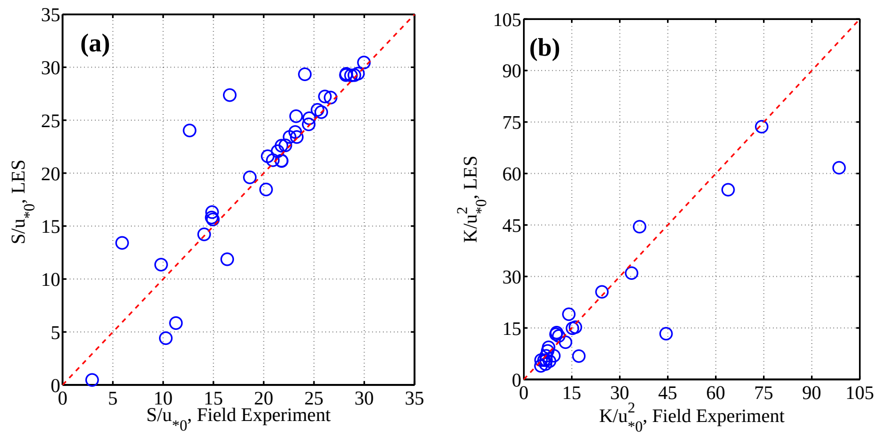

Figure 6: Scatter plots of (a) the normalized velocity magnitude and (b) the turbulent kinetic energy.

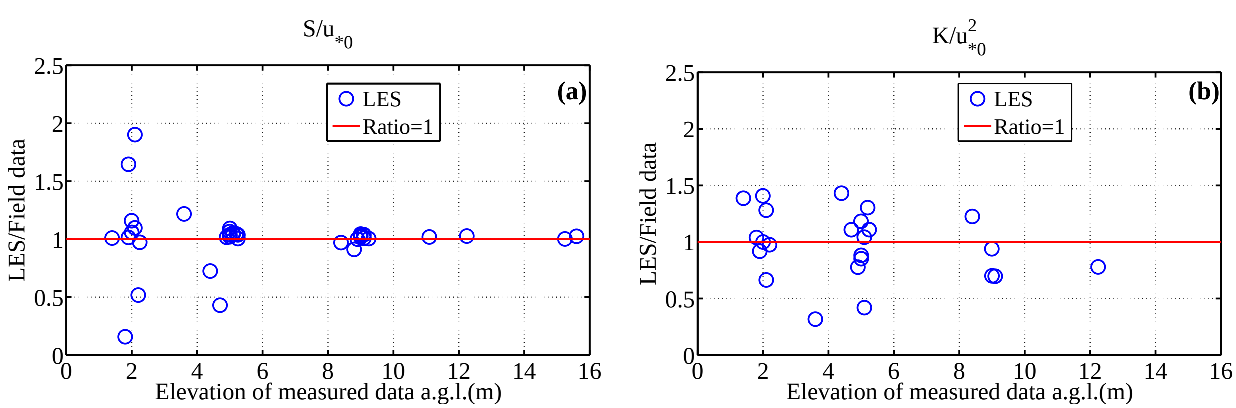

Figure 7: Ratio of LES results to field data for (a) the normalized velocity magnitude and (b) the turbulent kinetic energy.

the correlation of the results, the scatter plots of the field data against the LES results for the mean velocity magnitude and the turbulent kinetic energy (TKE) are shown in Figures 6(a) and 6(b), respectively. Here, all the results are normalized with the frictional velocity u_{*0} at the reference mast M0. It can be observed that the overall agreement is very good for both the velocity and the TKE, as most of the samples are lying on the diagonal line. Moreover, it is found that around 80% of the samples of the velocity and the TKE results are having the error less than 5% which is much more better prediction then the results reported in the blind comparison [11]. The rest of the samples of especially near the ground surface have much larger error which can be seen in Figure 7. The ratio of LES results to the field data for the velocity and the TKE is shown in Figures 7(a) and 7(b), respectively. According to the velocity ratio, LES shows slightly immature prediction near the surface (at 2 m height) locations of only few masts: M2, M6 and M8. Afterwards the results are in better agreement and give accurate matching with the field data above the height = 5 m. Unlike the velocity prediction, the TKE prediction at 2 m is slightly better than the prediction at 5 m. Also, level of overestimation is much reduced at the height = 2 m compared to that of velocity prediction. Above the height = 5 m, the TKE prediction is also improved. The flow separation occurs in the lee-side near the mast M8. Although, LES is able to captures the separation, the mean velocity is mostly underestimated at 2 m. On the other hand, the TKE profile is very well captured at M8 including the lower height.

From the current results of the Bolund case, it can be seen that the overall agreement between the LES results and the Bolund field measurements is very good at most of the locations. Also, the agreement is better than the previous results reported in the blind comparison especially those of LES and experimental model results [11].

5 TEST CASE: LES FOR THE WIND-FARM SITE

The LES methodology presented and validated with the wind-tunnel and the real field measurements is further utilized to simulate wind structures over a real wind farm located in South-East Finland, and the preliminary results are briefly shown here. Figure 8 illustrates the wind-farm topography colored with the height above the local water level and the locations of 6 wind turbines. The LES calculation is performed over relatively small topography containing a region of 1000×800 m^2. The simulated test section is marked with a box (see Figure 8) in which two wind turbines are also located. However, the modeling of the wind turbine is not the subject of the current paper, and it is therefor ignored here.

In order to used the recycling method for generating the LES-upstream boundary condition, a computational domain is additionally extended up to 1000 m with uniform height on the upstream side, that it, opposite to the wind-wise direction. The domain-height is set to 200 m from the water level. Thus, the actual computational domain is of the size $2000 \times 800 \times 200$ m^3 in wind-wise (x), cross-wind (y) and vertical (z) directions, respectively, as shown in Figure 9. The domain is discretized into $492 \times 202 \times 70$

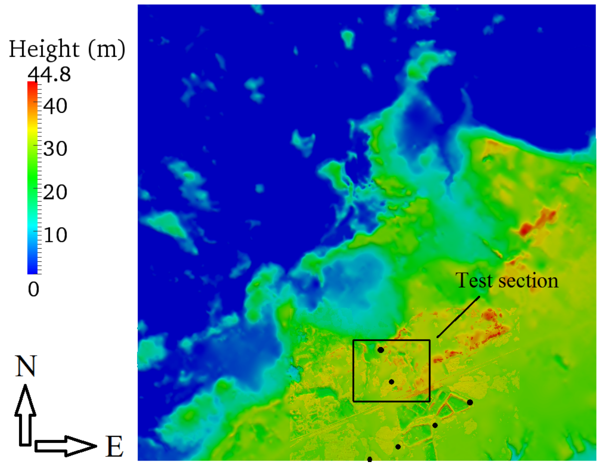

Figure 8: The wind-farm topography colored with the height above the lake-water level. The black dots are the actual positions of the wind turbines.

computational cells, which resulted in a grid resolution of $\Delta x = 4 \sim 5$ m, $\Delta y = 4$ m and $\Delta z = 1 \sim 7$ m. The uniform roughness-length $z_0 = 0.015$ m is used throughout the ground surface to maintain a fully-rough turbulent boundary layer. In simulation, the recycling plane is chosen to be 700 m far downstream from the inflow plane, and the inflow wind direction is from north to south. The free-slip boundary condition is used at top and two side walls boundaries. The initial condition is directly imposed from another LES results of the fully developed flow over the flat terrain so that faster flow development in the simulation of complex terrain can be achieved. To visualize typical wind flow patterns over a terrain, only the instantaneous results at flow physical time $t = 1500$ s are reported here.

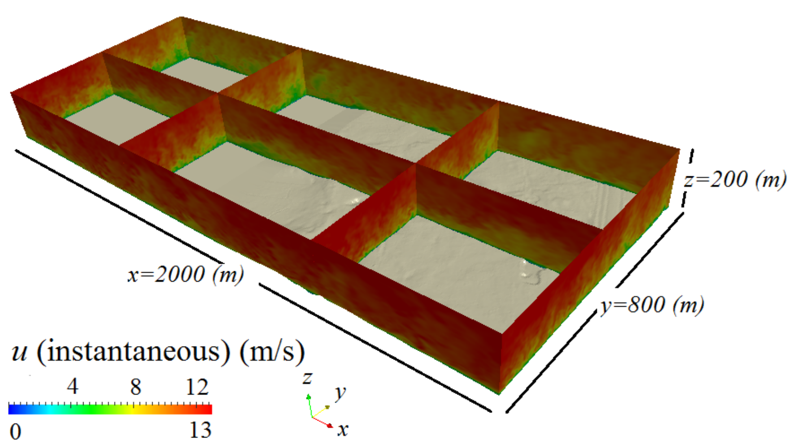

Figure 9: Instantaneous wind-wise velocity contours.

Figures 9 and 10 show the instantaneous wind-wise velocity contours on different cross-

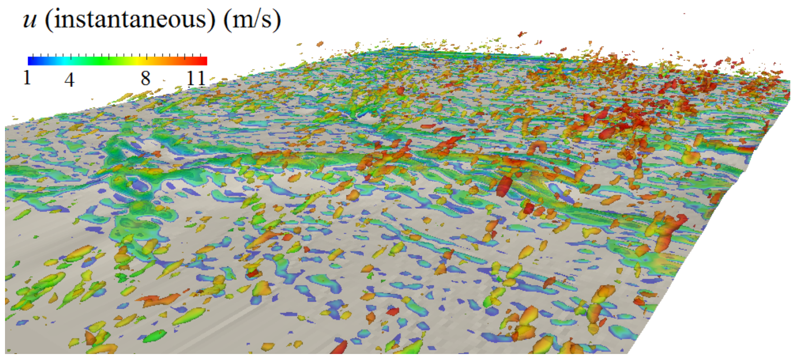

Figure 10: Iso-surfaces of the second invariant of the velocity gradient tensor Q colored with the wind-wise velocity.

sectional planes and the iso-surfaces of the second invariant of the velocity gradient tensor Q colored with the wind-wise velocity, respectively. The iso-surfaces are highlighting the resolved complex turbulent flow structures on the surface. It is seen that LES does not predict the flow separation except in few small places, although the orography is complex. This is perhaps because of the coarser grid resolutions used in all the directions. Also, the terrain geometrical complexities should not be smoothen much in order to investigate local flow behaviours. In the near future, LES will be carried over more larger region covering whole wind farm site and if possibly with slightly finer grid resolution. Also, the next task involves implementations of actuator disk and forest canopy models to design the present LES code for typical wind park simulation.

6 CONCLUSIONS

In this paper, we have carried out LES to investigate the turbulent boundary layer flows over complex terrains. The simulations are performed over two different topographies: an idealized $2D$ RUSHIL wind-tunnel hill profile and the real complex Bolund hill located near Risø-DTU, Denmark. The realistic upstream boundary condition at the inlet is one of the major difficulties in LES, especially in simulations of a flow over an inhomogeneous surface. In order to develop the upstream boundary-layer flow, the so-called turbulence recycling method is employed. The 4^{th} order time-accurate Runge-Kutta method based fractional step solver developed by [7] is implemented into OpenFOAM and has been utilized in the current work. Moreover, the logarithmic wall function based on the roughness-length is also implemented into our LES code to determine the ground surface fluxes on the surface boundary.

In the paper, the LES results are compared with the RUSHIL wind-tunnel measurements [4] and also with the real field measurements of the Bolund hill [5]. In $2D$ hill case, the mean velocity prediction is fairly good at most of the locations. Although results underestimate the flow separation, the predicted reattachment-length is indeed closer to measurements compared most of the studies reported in the past for this particular hill case [1, 2, 9]. The turbulence intensity is over-predicted only in the flow-separated region, but outside that region, LES profiles follow the measurements. In the Bolund case, the overall agreement between the LES results and the field measurements is also good at most of the locations. Only at few lower positions, LES results seem to be slightly immature, but above the height= 5 m, the prediction accuracy is much improved. Moreover, the obtained results are better than the previous LES and experiential results reported in the blind comparison [11]. From the overall prediction obtained in the present work, it can be concluded that the present LES model is able to reproduce the complex turbulent flow structures of the local atmospheric flows over a complicated terrain such as the Bolund hill.

Furthermore, the LES methodology validated over the wind-tunnel hill and the real Bolund hill is utilized to simulate wind structures over a real-life wind farm topography located in South-East Finland, and the preliminary results are reported here. In the near future, actuator disk and forest canopy models will be implemented into the present LES code in order to simulate wind flow over a typical wind park.

7 ACKNOWLEDGMENTS

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