RANS TURBULENCE MODEL EVALUATION FOR NEUTRAL ATMOSPHERIC BOUNDARY LAYER SIMULATION OVER COMPLEX TERRAIN

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Abstract. *Computational Fluid Dynamics (CFD) has become an essential tool for wind engineers especially over the past years with the diffusion of highly comprehensive commercial codes. These commercial codes are sold as black box packages with little to none user access to internal routines and algorithms. Therefore it is imperative that these codes be evaluated and their modeling capacities assessed. Turbulence and near wall modeling are critical for any atmospheric boundary layers (ABL) simulation and are highly sensitive to the local mesh. When the Reynolds Averaged Navier-Stokes (RANS) equations are solved proper model choice is critical for reliable simulation results. This paper evaluates some of the RANS turbulence models available on the commercial CFD code, ANSYS CFX 11.0 (CFX), for the simulation of neutral ABL and attempts to define a proper numerical simulation procedure. Four RANS turbulence models including two-equations and Reynolds Stress models were evaluated together with two near wall models. A mesh and map digitalization sensitivity tests were also performed. Simulations were compared to experimental field data from the Askervein hill in Scotland. Results show that simulations performed with CFX on a proper mesh and topological map with a RANS Reynolds Stress turbulence models offers very good velocity predictions very useful in engineering projects.*

Keywords*: Turbulence model, complex topology, atmospheric boundary layer.*

1. INTRODUCTION

The Atmospheric Boundary Layer (ABL) has an important role in pollution dispersion, weather prediction, wind energy and electric energy distribution especially over highly complex terrain. Regions such as Minas Gerais state in Brazil have predominantly mountainous terrain which makes the evaluation of the ABL influence on structures and wind power availability very difficult. Meso-scale atmospheric simulation codes are generally limited for these types of terrains when the near surface characteristics are needed (Kristóf et al., 2009). Commercial Computational Fluid Dynamics (CFD) solvers generally employ the finite volume method with unstructured grids that are, in principle, capable of handling geometrical features of arbitrary complexity. These commercial codes are sold as closed packages with little to none user access to internal routines and algorithms. Therefore it is imperative that commercial CFD codes be evaluated and their modeling capacities assessed for ABL simulations.

One of the main difficulties to properly evaluate CFD codes is the lack of proper experimental data. Code evaluation has been performed in the past through wind tunnel measurements, such as those performed over a triangle ridge by Arya and Shipman (1981). These experiments are usually over simplified and present geometrical properties that are never found in the real world.

An alternative for numerical code evaluation are the field experiments conducted at Askervein hills by Taylor and Teunissen (1983, 1985 and 1987). Their measurements offer a rare data set that has been used to validate several numerical codes (Kim and Patel, 2000, Castro et al., 2003, Undheim et al., 2006, Benchmann el al., 2007, and Forthofer, 2007).

This paper presents an evaluation of the commercial CFD code CFX 11.0 (2007) for the simulation of a neutral ABL over complex terrain. The evaluation was performed simulating the wind flow over Askervein hill including a mesh and map discretization sensitivity study.

The objective of this study was to evaluate the performance of the Reynolds Averaged Navier-Stokes (RANS) turbulence models: RNGKE (Renormalization Group *k-ε*), SST (Shear Stress Transport *k-ω*), SSGRS (Speziale-Sarkar-Gatski Reynolds Stress) and BSLRS (Baseline Reynolds Stress) on the flow over complex topologies as part of the atmospheric simulation and measurement research program currently underway at the Department of Mechanical Engineering (DEMEC) of the Federal University of Minas Gerais (UFMG).

2. METHODOLOGY

The RANS equations for mass, momentum and turbulence model were used to model the wind flow over complex topologies. The Askervein hill (Taylor and Teunissen, 1983, 1985 and 1987) was chosen as the region modeled in this study due to the large dataset available for this region. The model and modeling details are presented in the next sections.

2.1. The model

The Askervein hill, shown in Fig. 1, has an approximately elliptic geometry with a 1 km minor axis and a 2 km major axis and is located at the southern end of the Outer Hebrides island chain near the west coast of South Uist. At the hill top (HT) Askervein reaches a height of 126 m above the sea level. The modeled domain comprehends 3.5 km of terrain surrounding the hill in both coordinate directions resulting in a 7 x 7 km domain. The total modeled simulated height was of 1.5 km.

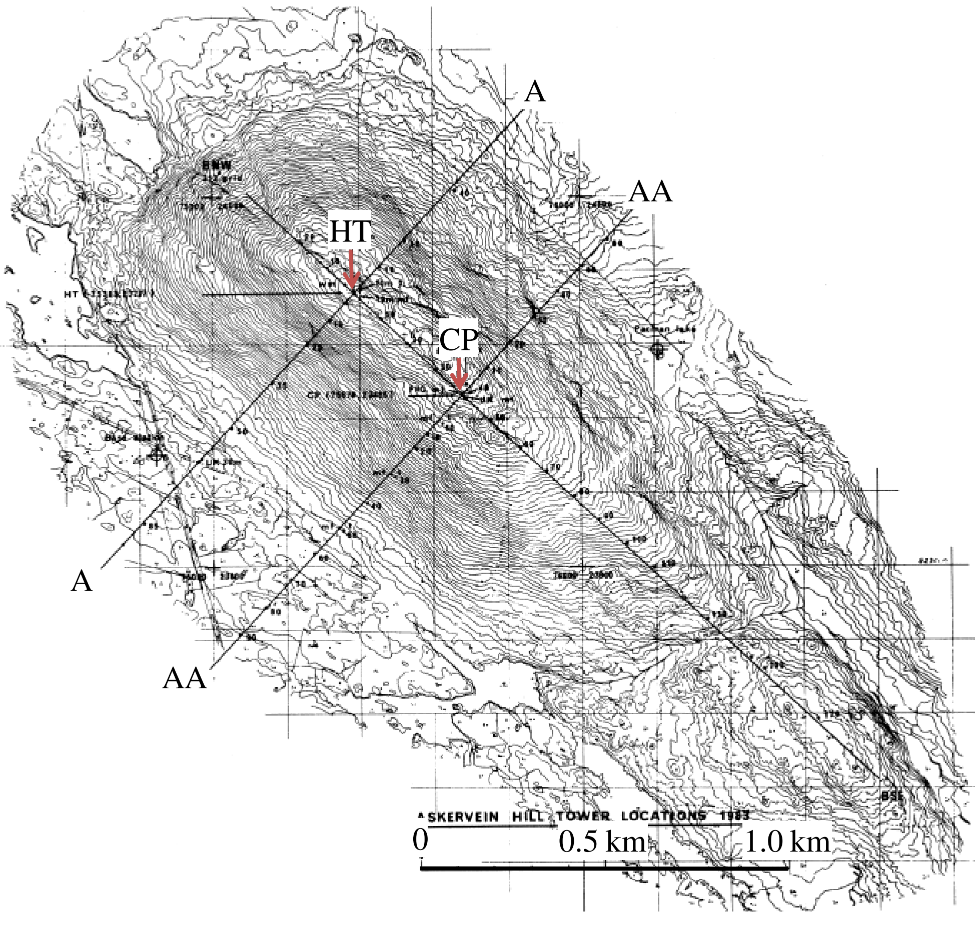

Figure 1. Domain topological details (Source: Taylor and Teunissen, 1983)

The topology was generated based on contour map data with a 10 m height interval resolution which is default for digitalized topological maps. The effect of the map digitalization resolution was evaluated through the generation of a topology based on a more refined version of contour map with a 2 m height interval resolution kindly provided by the Ordnance Survey and Dr. Ove Undheim.

2.2. The boundary conditions

The Askervein hill Project (Taylor and Teunissen, 1983, 1985 and 1987) provides an extensive dataset of measurements on neutral atmospheric conditions. The experiment of October 3 of 1983, designated as TU-03B, was chosen for this study. This day the measured wind direction was 210^{o} with a reference velocity (U_{ref}), registered 10 m above the ground, of 8.9 m/s

Inlet velocity profile was defined based on experimental data regression through a power law, presented in Eq. 1. The power law was used because of its best fit to experimental data and the poor fit of the logarithmic profile above

100 m that may be due to a layer of non-neutral stability (Forthofer, 2007). A comparison between the logarithmic profile, shown in Eq. 2, and the power law profile is shown in Fig. 2.

$$U_{pow} = 6.0712(y + y_o)^{0.1578} \quad (1)$$

$$U_{log} = \frac{u^*}{\kappa} \ln\left(\frac{y+y_o}{y_o}\right) \quad (2)$$

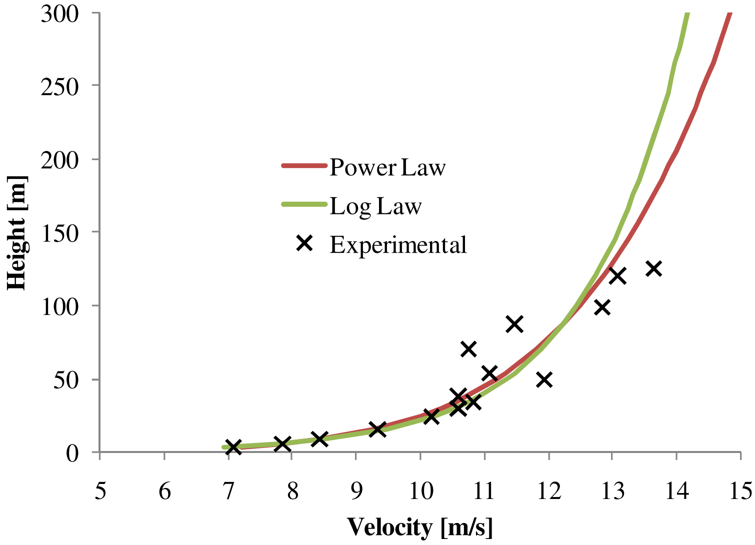

Figure 2. Velocity profile comparison

Registered winds are nearly perpendicular to the long axis of the hill, originating from the southwest where there is a fairly flat terrain (Taylor and Teunissen, 1983). This condition allows that a fully developed profile for the turbulence kinetic energy and eddy dissipation be defined upstream of the hill according to Eq. 3 to 5.

$$\varepsilon_{(y)} = u^{*3}/\kappa(y + y_o) \quad (3)$$

$$k_{(y)} = u^{*2}/\sqrt{C_\mu} \quad (4)$$

$$u^* = \kappa U/ln\left(\frac{y+y_o}{y_o}\right) \quad (5)$$

Where κ is von karman constant 0.41, y_o is the roughness height, U is the local velocity and y is the height above ground. At the hill and surrounding area the vegetation is low and uniform, permitting that a constant roughness height of 0.03 m be considered at the surface of all simulated region.

2.3. The numerical simulation

The numerical evaluations were performed using the commercial CFD code CFX 11.0 (2007) that is based on the finite volume method. The RANS equations for mass, momentum and turbulence model were solved. The central differencing and the hybrid second order schemes were used, respectively, to discretize the diffusion and advection terms of the equations. A residual RMS target value of 10^{-4} was defined for all the simulations. Up to five parallelized Intel Core D 2.8 GHz personal computers with 4 GB of RAM were used on the simulations.

The two equation RNGKE and SST turbulence models and the seven equation SSGRS and BSLRS turbulence models were evaluated in the simulations.

The *k-ε* turbulence model (Launder and Spalding, 1974) assumes that the turbulence viscosity is related to the turbulence kinetic energy (*k*) and eddy dissipation (*ε*). The RNGKE model (Yakhot and Orszag, 1986) is an improvement of the model to take in account the small scale turbulence in the average flow. In CFX 11.0 (2007) the RNGKE model uses a scalable log-law wall-function to model the flow near no-slip walls. The scalable approach limits the lower value for the dimensionless distance from the wall (y^+) used in the log-law to 11.06.

The Shear Stress Transport-*ω* (SST) model (Menter, 1994) is a blend between near surface *k-ω* model, which relates eddy viscosity to the turbulent eddy specific dissipation rate (*ω*), and core flow *k-ε* model. The model includes a function to modify the turbulent eddy viscosity to account for the transport of the turbulent shear stress. In CFX 11.0

(2007) the SST model uses an automatic wall treatment to model the flow near walls. This approach gradually switches from a log-law to a viscous sub–layer wall function as the mesh is refined.

The Speziale-Sarkar-Gatski Reynolds Stress (SSGRS) model (Speziale et al., 1991) solves six transport equations, one for each of the turbulent stresses, also called Reynolds stresses, and a closing equation for the turbulence eddy dissipation. This model uses the same near wall treatment as the RNGKE model in CFX 11.0 (2007).

The Baseline Reynolds Stress (BSLRS) model solves six transport equations, one for each of the Reynolds stresses, and one additional equation that is a blend between ω and ε transport equations similar to the SST model (Menter, 1994). This model uses the same near wall treatment as the SST model in CFX 11.0 (2007).

The BSLRS and SSGRS models inherently account for the turbulent anisotropies, theoretically making these models more suited for ABL simulation.

2.4. The mesh parameters

Close to the rough wall, many of the flow variables are changing rapidly, and it's imperative that any mesh attempts to consider these high gradients. Thus an inflation layer, which is highlighted in the Fig. 3, is used over the ground surface of the domain which consists of a number of prism shaped elements that are thin in the vertical direction, and much more substantial in the longitudinal and cross wind directions. Mesh face spacing is also used to concentrate cells close to the whole surface of the domain. These mesh face spacing set a minimum cell size over the face, and impose an expansion factor so that the cells gradually increase in size up to the main domain parameters, hence preventing large changes in cell size, which would reduce the accuracy of the simulation.

Mesh sensitivity tests have been performed evaluating all important parameters of the mesh. At the surface the length of the elements, the expansion factor and the radios influence were evaluated. Influence of the size of the global element and number of layers, height of the fist element and expansion factor of the inflation were also analyzed. The expansion factor of the inflation elements was set to guaranty a smooth transition from the prismatic elements to the tetrahedral core. Table 2 shows the details of four meshes that exemplify the mesh sensitivity test. The size of the global element, 100 m, is the same for these meshes because this parameter had no significant influence on the results. Figure 3 shows details of mesh 3.

Table 2. Mesh details

	Inflation Parameters			Surface element	Number of	Number
Mesh	Nº Layers	1st Node Height (m)	Expansion Factor	Length (m)	Elements	of Nodes
1	10	2	1.172	25	8300152	2013343
2	30	2	1.050	25	11541001	3652107
3	30	0.1	1.165	25	11568695	3657106
4	30	0.1	1.165	15	21434070	8258295

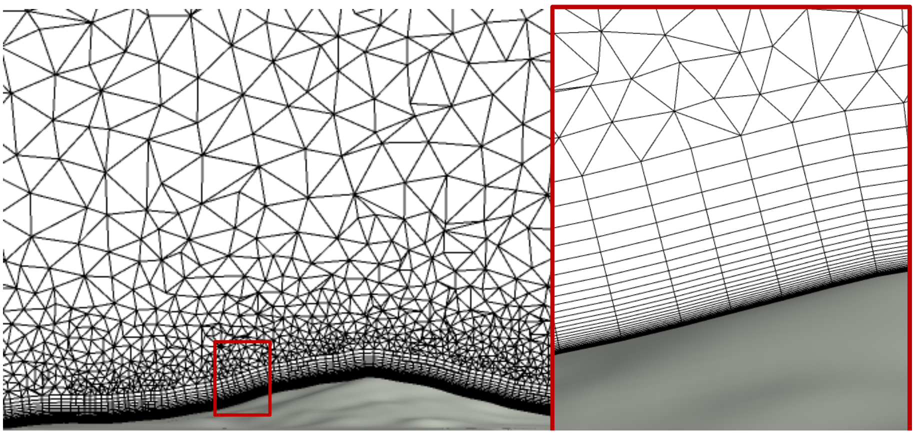

Figure 3. Mesh 3 details at Askervein hill

Mesh sensitivity study was performed using the RNGKE turbulence model using the boundary conditions described in section 2.2. Figure 4 shows the result of the mesh sensitivity test in the form of Speed-up Ratio, calculated according to Eq. 6, and normalized turbulence kinetic energy (k/k_{ref}) along the lines A-A and AA-AA, shown in Fig. 1, at 10 m height above the surface of the hill. The reference turbulence kinetic energy (k_{ref}) was obtained from the inlet profile at 10 m above ground.

$$\text{Speed-Up Ratio} = \left(U_{10}/U_{ref}\right) - 1 \qquad (6)$$

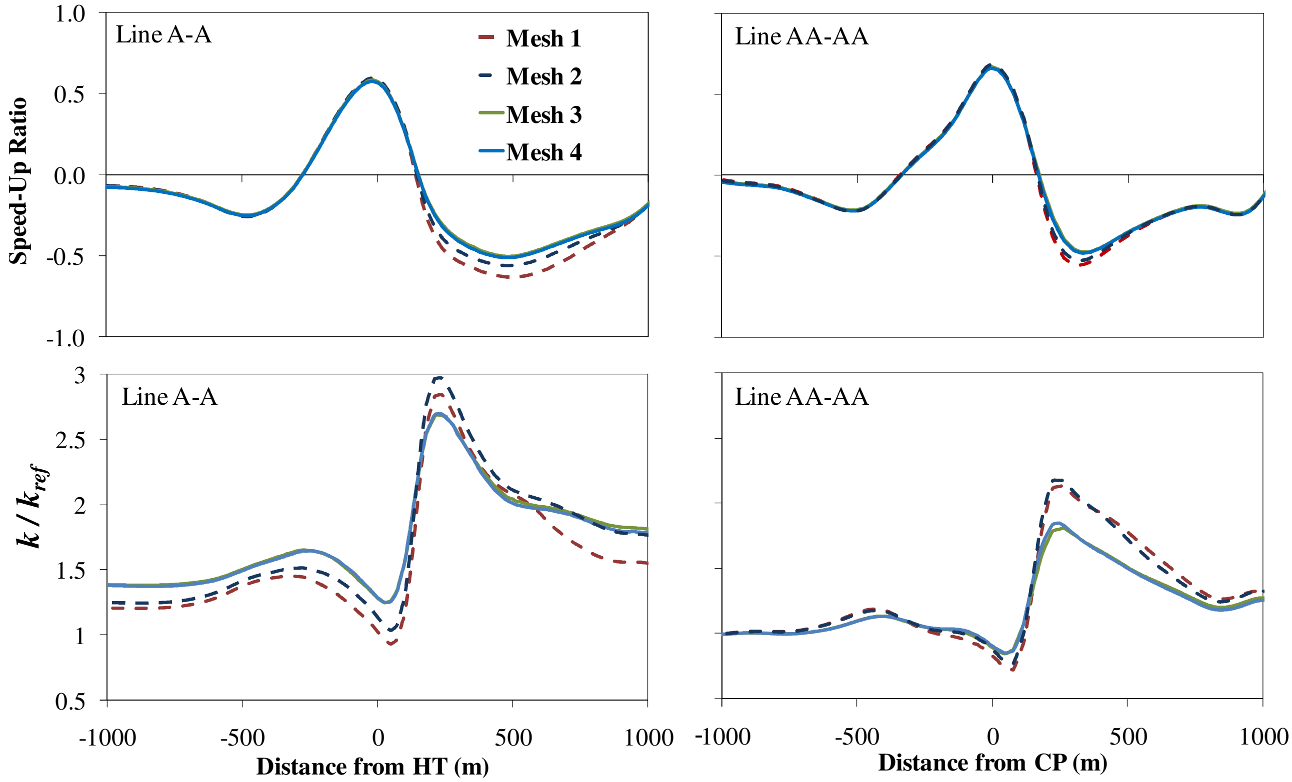

Figure 4. Mesh sensitivity study at Askervein hill

Results show that meshes 3 and 4 have little differences for the compared variables even though mesh 4 is more than 100% bigger than mesh 3 in terms of number of nodes. This results indicate that, for the tested model, mesh 3 is the most appropriate, as it give almost the same results with a computational effort much smaller. The figure also shows that the increase in the vertical refinement of the mesh near the ground has a critical effect on the ABL simulation accuracy.

3. RESULTS

Figure 5 compares the Speed-Up Ratio (Eq. 6) results obtained by the evaluated turbulence models with the field measurements made along the lines A-A and AA-AA, shown in Fig. 1, 10m above the ground. Results for line A-A show that all models perform similarly upstream the HT, but all models fail to predict the measured speed-up at HT. However at the lee side of the hill the RNGKE model results diverge from the experiment, the SSGRS model shows a good agreement, the BSLRS model shows a reasonable agreement and the SST models falls in between with an overall qualitative agreement. Results for line AA-AA show little differences between model predictions with a good qualitative agreement for most points up and downstream CP as well as at CP it's self.

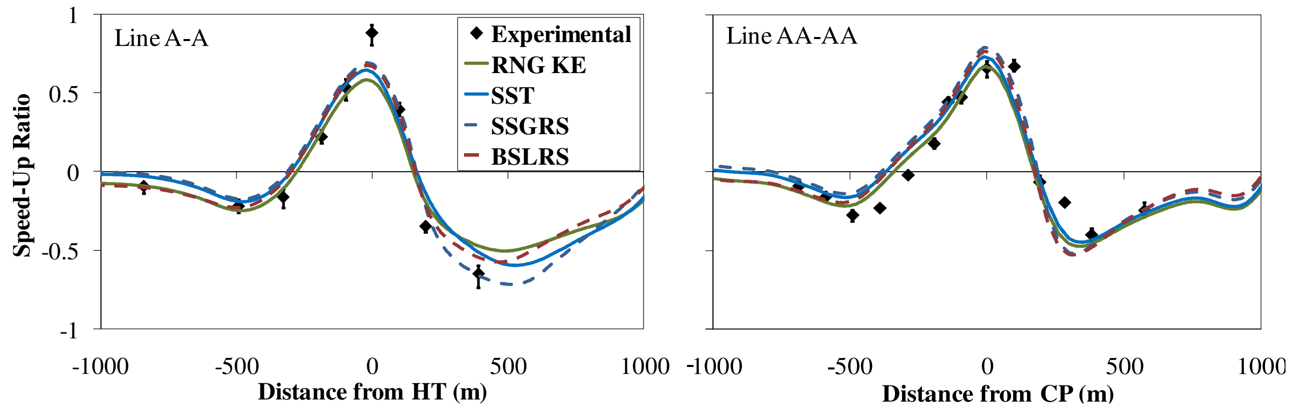

Figure 5. Speed-Up Ratio results at Askervein hill for all evaluated turbulence models

Figure 6 compares the normalized turbulence kinetic energy (normalized by inlet value) results obtained by the evaluated turbulence models with the field measurements. The results from line A-A show major differences between models and experimental results more pronouncedly in the lee region of the hill. Values of turbulence kinetic energy obtained with RNGKE and SST models downstream HT are greatly under estimated when compared to the measurements. The predictions by the SSGRS and BSLRS models agree reasonably better to the experiment especially the last that shows great predictions for all but the two measured points further downstream HT. Although there are no measurements downstream CP, it is expected that turbulence is also amplified in this regions. Analyzing Fig. 6 at line AA-AA it can be also observed a great under prediction of turbulence kinetic energy by the RNGKE and SST models.

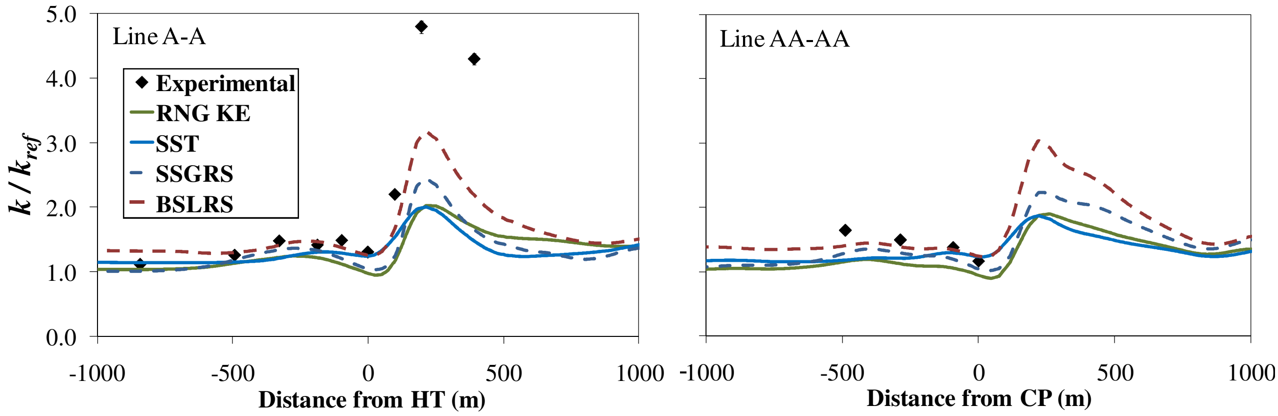

Figure 6. Normalized turbulence kinetic energy results at Askervein hill for all evaluated turbulence models

Figure 7 shows the Speed-Up Ratio at HT obtained using the evaluated turbulence models compared to measured values. The calculated Speed-Up was performed using as reference velocity the theoretical profile provided by Eq. 1. The observed overall qualitative behavior is reasonable predicted by all models above 10 m of HT, however at the lower height the RNGKE and SST model greatly underestimate the Speed-Up Ratio. The SSGRS model had the best agreement to the measurements and the BSLRS model showed a slightly worst prediction.

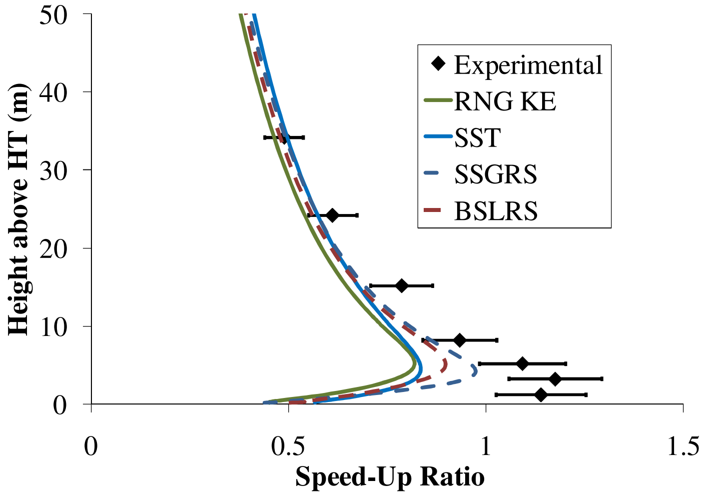

Figure 7. Velocity profile at the Hill Top (HT) of Askervein hill for all evaluated turbulence models

The lower values of y^+ encountered in all the simulations were well above 100. In these conditions, the CFX 11.0 (2007) automatic wall treatment becomes a log-law function very similar to the scalable wall-function. This way, wall-treatment effect was reduced and the results differences were basically due to the modeling of turbulence itself.

Results indicate that better predictions can be obtained using Reynolds Stress based models and that two-equation eddy viscosity models should be avoided when turbulence characteristics of the flow are an important variable to be considered.

The results also show an often observed behavior in RANS ABL simulations that is the under prediction of the HT Speed-Up Ratio and downstream turbulence along line A-A (Kim and Patel, 2000, Castro el al., 2003, Forthofer, 2007, Benchmann et al., 2007). Many possible reasons for these results have been discussed in the past and most have attributed to poor turbulence modeling by RANS models (Benchmann et al., 2007, Lopes el al., 2007). Undheim et al.

(2006) showed that the contour map height spacing used to digitalize the surfaces topology of Askervein hill can greatly influence the obtained results.

To verify the influence of the contour map resolution used on the RANS simulations performed with CFX 11.0 (2007), a new domain was generated using a map with 2 m of height interval resolution instead of 10 m. The new domain was simulated applying the same boundary conditions with the BSLRS and SSGRS model that showed best flow predictability in the previous simulations. As the surface description has enhanced for the new domain the mesh was once more evaluated performing simulations with mesh 3 and 4 to determine the results sensitivity. Figure 8 shows a comparison between topologies generated using both contour maps, it can be observed that many aspects of the hills topology were smoothened by the 10 m contour map.

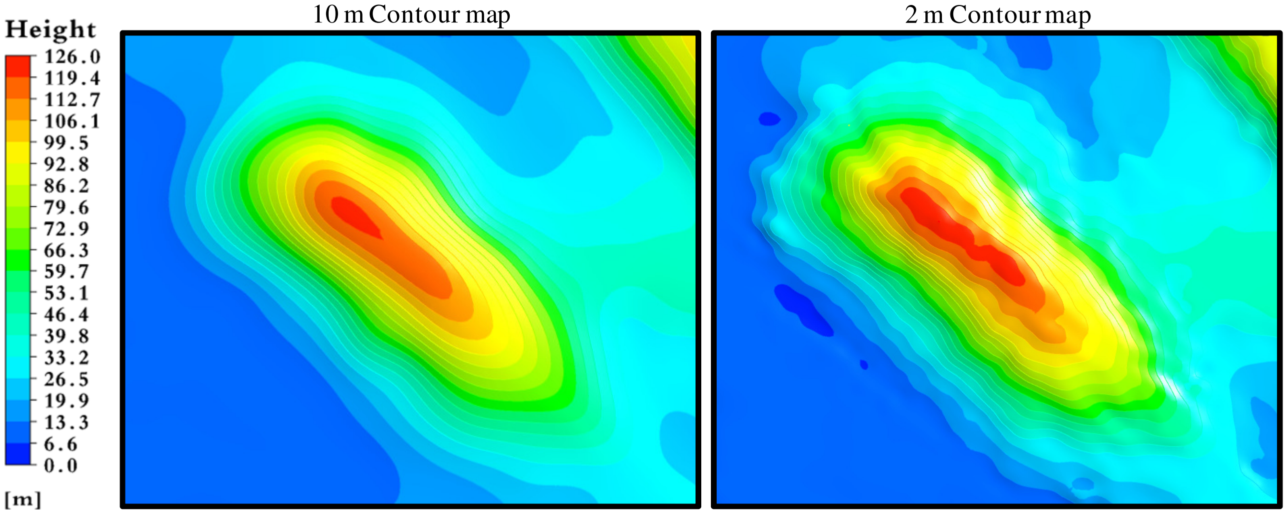

Figure 8. Differences in the simulated topologies of Askervein hill obtained from different resolution contour maps

Figure 9 shows the obtained results for the simulations with the new topology. It can be observed that the prediction of the Speed-Up Ratio at HT was greatly enhanced for both models and that the overall prediction behavior of the Speed-Up was enhanced for both models.

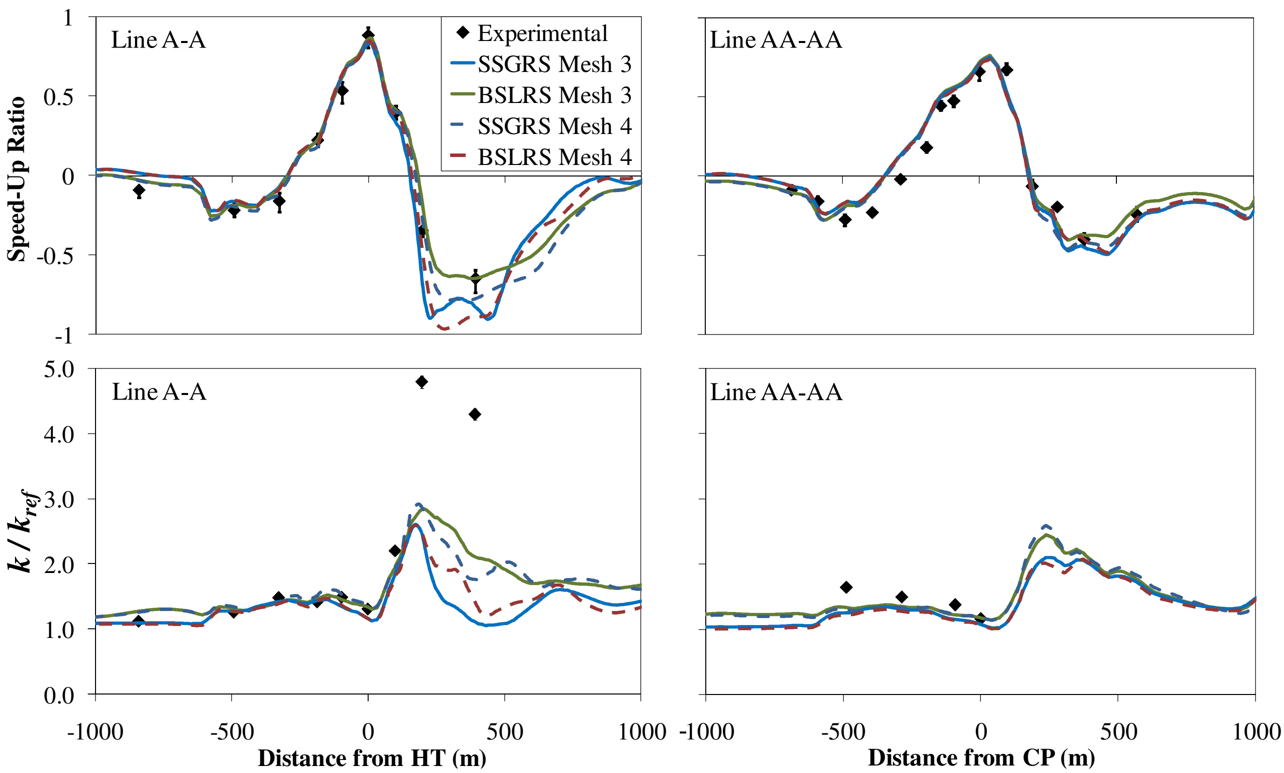

Figure 9. Results for the new topology from contour map with 2 m height resolution

In Fig. 9 it is shown that upstream HT and CP the simulated meshes and models showed little differences between each other, but compared to the previous simulations (Fig. 5 and 6), results show better agreement to the experiments. However, downstream HT the obtained predictions differ both from used meshes and turbulence models. In regards to the mesh it is observed that results with the new topology can still improve with a greater surface mesh refinement.

Higher values of negative Speed-Up Ratio can be observed in Fig. 9 at the lee of the hill at line A-A especially for the BSLRS model. Similar results have been observed by Castro et al. (2003) and been attributed to the model that assumes a constant roughness height for the entire hill that, however, may have a smaller roughness near the top. Other observation is that the normalized turbulence kinetic energy agreement was not enhanced by the better resolution of the topology for the two furthest measured point's downstream HT.

Figure 10 shows the Speed-Up Ratio at HT obtained for the simulations with the new topology. Simulations results for both models show excellent agreement to measurements for all points which is a great enhancement from the previous results (Fig. 7).

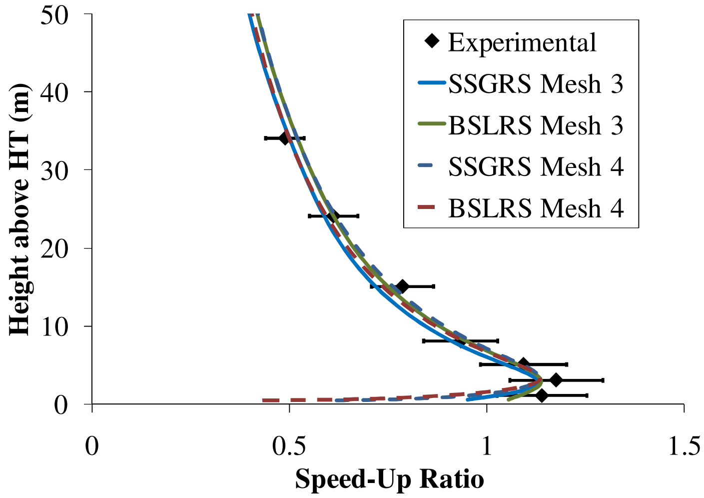

Figure 10. Hill top velocity profiles

Results indicate that better predictions can be obtained using a more refined topological map and that RANS Reynolds Stress based turbulence models are capable of predicting well the Speed-Up at the top of a hill.

4. CONCLUSIONS

The performance of the Reynolds Averaged Navier-Stokes (RANS) turbulence models: RNGKE (Renormalization Group *k-ε*), SST (Shear Stress Transport *k-ω*), SSGRS (Speziale-Sarkar-Gatski Reynolds Stress) and BSLRS (Baseline Reynolds Stress) were evaluate for the simulation of the flow over complex topologies with the commercial CFD code, CFX 11.0 (2007). This study is part of the atmospheric simulation and measurement research program currently underway at the Department of Mechanical Engineering (DEMEC) of the Federal University of Minas Gerais (UFMG).

The Askervein hill (Taylor and Teunissen, 1983, 1985 and 1987) was chosen as the region modeled in this study due to the large dataset available for this region. Experimental measurements of velocity and turbulence were taken along two parallel lines that passed through the hills top and center.

A mesh sensitivity study was performed using the RNGKE turbulence model to assess the best meshing parameters for complex topology simulation. Sensitivity to the number of layers near the surface and height of the first element away from the ground were observed.

Turbulence model evaluation was performed with the optimum mesh. Numerical results of Speed-Up Ratio and normalized turbulence kinetic energy were compared to measured experimental values. The BSLRS and SSGRS models showed the best predictions for the Speed-Up Ratio and turbulence along both evaluated lines, however poor prediction of the Speed-Up at the hill top and turbulence at the lee side of the hill were observed.

The influence of the contour map resolution used on the RANS simulations performed with CFX 11.0 (2007) was verified. A new domain was generated using a map with 2 m of height interval resolution instead of 10 m, default map digitalization resolution. The new domain was simulated applying the same boundary conditions with the BSLRS and SSGRS model. It was observed that Speed-Up predictions were greatly enhanced especially at the hill top were the predicted profile had an excellent agreement to experimental data for both models. Turbulence predictions at the lee side of the hill were not enhanced as much by the topology resolution.

Results in this study showed that simulations performed with CFX 11.0 (2007) on a proper mesh and topological map with a RANS Reynolds Stress turbulence models offer very good velocity predictions very useful in engineering projects.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank Dr. Ove Undheim and his fellows from Ordinance Survey for their kind gesture of providing the digitalized maps of Askervein hill.

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