DTU Library

How fine is fine enough when doing CFD terrain simulations

Sørensen, Niels N.; Bechmann, Andreas; Réthoré, Pierre-Elouan; Cavar, Dalibor; Kelly, Mark C.; Troen, Ib

Published in:
Proceedings of EWEA 2012 - European Wind Energy Conference & Exhibition

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Sørensen, N. N., Bechmann, A., Réthoré, P-E., Cavar, D., Kelly, M. C., & Troen, I. (2012). How fine is fine enough when doing CFD terrain simulations. In *Proceedings of EWEA 2012 - European Wind Energy Conference & Exhibition* (pp. 1167-1172). European Wind Energy Association (EWEA).

How fine is fine enough when doing CFD terrain simulations

Niels N. Sørensen[1], A. Bechmann[1], P.-E. Réthoré[1], D. Cavar[1], M. C. Kelly[1], I. Troen[1]
[1] Department of Wind Energy, DTU Wind Energy, Frederiksborgvej 399, P.O. Box 49, 4000 Roskilde.
nsqr@risoe.dtu.dk

Abstract

The present work addresses the problem of establishing the necessary grid resolution to obtain a given level of numerical accuracy using a CFD model for prediction of flow over terrain. It is illustrated, that a very high resolution may be needed if the numerical difference between consecutive refinements should be of the order of one percent for all flow directions. For the present terrain case, resolution in the order of 1 billion grid points is needed.

Keywords: Computational Fluid Dynamics, Terrain, Siting, Grid Refinement.

1 Introduction

In the past, several studies have been performed comparing linearized flow models like the WAsP code with Computational Fluid Dynamics (CFD) codes, with respect to accuracy for complex terrain. Often these CFD computations are performed on insufficient coarse meshes of less than a million grid points, and only limited effort is spent to assure grid independence with very moderate grid refinement, [1], [2]. Even though, CFD methods are becoming wide spread in the wind community, there is still a high degree of skepticism about these methods, and whether a unique solution can be obtained.

The recent Bolund Blind Comparison, illustrated that consistent results could be obtained by different groups using different CFD models for the flow around Bolund, [3, 4]. Even though the Bolund Hill is complex, the complexity of the terrain is limited to a relatively small area of 200 m$\times$ 200 m embedded in very simple surroundings. For the Bolund case, it was illustrated by the Risø-DTU group that decently grid independent results could be obtained with as little as 300.000 points, see [5].

For actual complex terrain, where not only the target area of interest is complex, but the target area itself is surrounded by complex terrain, the requirement for grid independence may be quite different.

The present study is an investigation of the necessary grid requirement for a full scale complex terrain using a second order accurate CFD model, in order to reduce the numerical difference between consecutive grid levels to a given level. The chosen terrain is a complex site in Portugal just north of the $40°$N, close to the city of Porto, see [6]. In the present work, the computations are focused around the mast 06 at the center of the target area. In the present work no comparison with meausrements is performed, instead the numerical accuracy is evalueated based on a series of computations performed with different grid resolution.

2 Code description

The in-house flow solver EllipSys3D is used for all computations. The code is developed in cooperation between the Department of Mechanical Engineering at the Technical University of Denmark and The Department of Wind Energy at Risø-DTU, see [7, 8] and [9]. All computations performed in the present work, are done under the assumption of neutral flow conditions. In the present work the turbulence in the boundary layer is modeled by the $k-\epsilon$ eddy viscosity model of Launder and Spalding [10], with constants calibrated for atmospheric conditions as described in the work of Sørensen see [9] and [11]. The code has previously been shown to have second order accuracy, in agreement with the formal order of accuracy of the applied discretization, see e.g. the report of Sørensen [12].

3 Terrain processing, computational grid and boundary conditions

When modeling complex terrain, several decisions must be taken about the computational domain and the boundary conditions (bc's) applied at the external faces of the domain. As the flow at a given point will be influenced by the terrain that surrounds the point within a given radius, one needs to decide how much of the surrounding terrain should be included in the computations. Secondly, the vertical extend of the domain must be considered in order not to disturb the solution.

As we are going to apply simple equilibrium conditions at the inflow boundaries, logarithmic velocity profiles etc., we need to assure that these are applicable where they are applied. To have equilibrium conditions, we need to assure that the terrain is flat both in the flow direction and in the cross-flow direction. This is similar to what should be done when doing wind tunnel experiments of terrain flow, where the terrain at some given radius needs to be flush with the tunnel floor. In the present work, a tangens hyperbolic function based on the distance from the center of the computational domain is used to accomplish the blending of the actual terrain into a uniform height:

$$f = \tanh\left[\left(\frac{1.6 \times r}{R_{Domain}}\right)^8\right] ,$$

where r is the local distance from the center of the domain, and R_{Domain} is the radius of the computational domain.

In the present work a cylindrical domain is used. The two main reasons for selecting a cylindrical domain are, that the high grid resolution is naturally clustered at the central part of the domain where it is mostly needed, and that the domain is equally suited for flow from all directions. In the central part of the domain a square grid zone is used around the target area, which has a size of 2.4 km$\times$2.4 km. This central region is embedded in a polar zooming grid that places the farfield boundary approximately 14 km from the center of the target area, see Figure 1 and 2. Previous study of neutral flow over terrain, see e.g. the work of [9], has shown that using a domain height of approximately 10 times the change in terrain elevation, should guarantee that the actual domain height is not disturbing the flow solution.

Two meshes are used, one highly refined mesh of 1.2 billion points is used for the most complicated flow direction from west, called Mesh-1 see Table 1. Additionally a moderate fine grid of 300 million points is used to illustrate the dependency of the accuracy of the flow direction, called Mesh-2 see Table 2.

The following bc's are used: At the terrain surface standard atmospheric rough wall conditions are applied, at the inlet part of the outer cylindrical boundary equilibrium conditions (log-law) are applied. At the outlet part of the cylindrical boundary a fully developed assumption is used, implemented as a zero gradient Neumann conditions for all flow quantities except for the pressure. More details about the atmospheric bc's can be found in the paper by Sørensen et al. [13].

For most terrains, grid coarsening in connection with grid independence test will result in implicit smoothing of the terrain, and thereby change to the form drag. In the present work, no procedure is applied to compensate for this dependency of the form drag on grid resolution as well as on explicit smoothing and leveling of the terrain. We would expect, that explicitly changing the surface roughness on coarser grid levels, could to some degree compensate for the implicit smoothing of the grid coarsening. In house work along these lines is performed at present, but is still not concluded.

4 Present Study

The focus of the present paper is not to illustrate how well a CFD code can predict the wind resources in complex terrain, the focus is merely to illustrate what degree of grid resolution it would take for a very complex terrain to decrease the numerical difference between consecutive grid refinements to a given tolerance.

The comparison in the following is based on the difference between the absolute value of the velocity on a given grid level and on the finest level, at 50 meter height above terrain level normalized by the undisturbed velocity at 50 meter height. The results are computed in a target area of 2 km by 2 km around the Mast 06 position. The comparisons are done with respect to the mean, the max and the standard deviation.

The results for the westerly wind direction, which is the most complicated direction to predict, are listed in Table 3. For a grid of 150

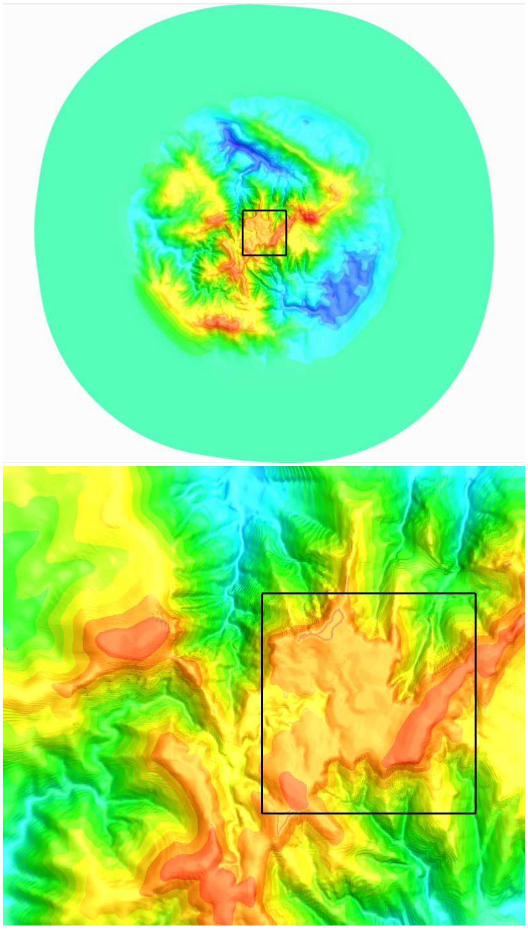

Figure 1: Overview of the Porto terrain, showing the farfield artificial leveling of the terrain, and the 2 km×2 km target area enclosed in the polar domain. The mast 06 is placed at the center of the target area.

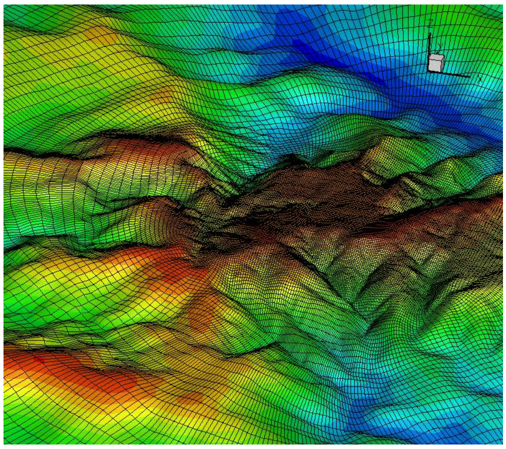

Figure 2: Detail of the computational grid around the target area for Mesh-1, showing the resolution on level-4, or only every 8 cell in each direction.

million points, the mean difference compared to the finest level of 1.2 billion is below 1.4%. For a more manageable grid of 19 million points (level 3), an average difference with the fine grid solution of 3.2 percent is obtained. The max difference from the fine grid solution though, is respectively 9.5% and 16.6% on the level-2 and level-3 mesh. Going to even coarse meshes, which is more comparable with previous available studies, a mean difference of 9 to 15 % should be expected, while the max difference may be as high as 50%.

Using Mesh-2 with 300 million points on the finest level, see Table 2, an investigation of the grid dependence on the wind direction is illustrated. Comparing the North and West direction it is seen that the mean difference may vary with a factor of ten depending on the flow direction, see Table 4. For the max difference similar results are found. This directional dependency clearly indicates that for very complex terrain one would need to make grid dependency studies for all flow directions, in order to have a realistic estimate of the solution quality.

It is important to remember, that the present study only indicates whether the solution is approximately grid independent, or whether we should expect drastical changes in the flow solution with further grid refinement. The study does not tell whether the model is well suited for predicting actual terrain flows.

Having the solution on several grid levels (here five levels), it would be natural to perform Richardson extrapolation [14] or mixed order extrapolation [15] to get a prediction of the infinitely fine solution and the order of the scheme. The Richardson extrapolation fails to give a meaning full answer, as the flow is not every where in the asymptotic range where the solution exhibit a monotonic convergence towards a single value. Similar, using mixed order error analysis based on solution on the four finest grid levels and assuming the solution to contain error terms of first, second and third order, it is clear that the first order term is the dominating term. As second order convergence behaviour of the EllipSys code has previously been illustrated for smooth aerodynamic flows, the failure to reach the asymptotic range is believed to be related to the large range of scales present in complex terrain flow. The lack of asymptotic behaviour is also seen from the variation of the vertical velocity profile

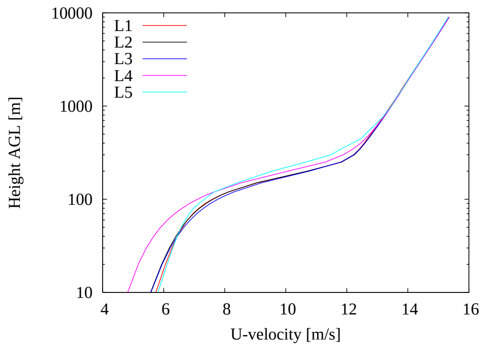

Figure 3: Vertical velocity profiles at the location of Mast-6.

in Figure 3.

5 Discussion and conclusions

The present study has shown that as expected grid convergent solutions can be obtained by successive grid refinement in terrain simulations. The range of scales involved in siting/terrain computations dictates a very high number of grid points to be truly grid independent. Additionally, the reduction of the difference in the solution is lower than expected from the formal second order accuracy of the applied code, which indicates that even with the very fine mesh, the asymptotic range is not reached due to unresolved features in the terrain.

It is clearly illustrated that the difference between the solution on the different grid levels is highly dependent on the flow direction, which is believed to be correlated to the complexity of the upstream fetch. As a result we conclude that caution should be taken when making resolution studies, and preferable one should carry out studies for all relevant flow direction.

Finally, the present simulations indicate that velocities deviating around 5% from a much finer solution obtained by doubling the grid resolution in all three direction several times, can be obtained with a grid having between 5 and 10 million points for a terrain with a high geometrical complexity. A grid resolution like this should be feasible to use on a small scale multiprocessor machine. Going to much coarser grids of $\sim$ one million grid points, could result in differences of more than 15 percent in mean values and max deviation of more than 40 percent.

Acknowledgements

The work is partially funded by the Danish Council for Strategic Research (DSF), under contract 2104-09-0026, Center for Computational Wind Turbine Aerodynamics and Atmospheric Turbulence and by the Danish Business Innovation Fund. Computations are made possible by the use of the PC-cluster provided by Danish Center for Scientific Computing (DCSC) and the DTU central computing facility.

Table 1: Computational grid parameters for the Mesh-1 configuration, including grid coarsening. All grids levels consist of 576 blocks, have a domain radius of ~ 14 km and a domain height of 9 km.

Grid Level	Nr. Cells $\times 10^{-6}$	Nr. Vertical Cells	Wall Cell Size [m]	Horz. Cell [m]
1	1207	384	0.03	2.3
2	151	192	0.06	4.7
3	19	96	0.12	9.4
4	2.4	48	0.24	18.8
5	.3	24	0.48	37.5

Table 2: Computational grid parameters for the Mesh-2 configuration. All grids levels consist of 144 blocks, have a domain radius of ~ 14 km and a domain height of 9 km.

Grid Level	Nr. Cells $\times 10^{-6}$	Nr. Vertical Cells	Wall Cell Size [m]	Horz. Cell [m]
1	300	256	0.03	4.7
2	38	128	0.06	9.4
3	4.7	64	0.12	18.8
4	0.6	32	0.24	37.5
5	0.07	16	0.48	75.0

Table 3: Comparison of the mean, max and standard deviation of difference in the absolute velocity in percentage of the undisturbed velocity at 50 m height AGL, between the solution on a given grid level and the finest grid level on Mesh-1.

Coarse Grid Level	Mean Diff. in %	Max Diff. in %	Variance in %
2 (151 mill.)	1.4	9.5	1.5
3 (19 mill.)	3.2	16.6	3.0
4 (2.4 mill.)	9.0	22.4	5.8
5 (0.3 mill.)	15.3	50.5	12.0

Table 4: Dependence on flow direction of the mean, max and standard deviation of difference in the absolute velocity in percentage of the undisturbed velocity at 50 m height AGL, between the solution on a given grid level and the finest grid level on Mesh-2.

Coarse Grid Level	Quantity	North	East	South	West
2 (38 mill.)	Mean Diff.	0.3	1.8	0.7	2.7
	Max Diff.	2.4	28.9	10.6	14.4
	Variance	0.2	2.0	0.7	2.7
3 (4.7 mill.)	Mean Diff.	0.6	3.0	1.2	7.9
	Max Diff.	7.9	33.4	22.8	21.5
	Variance	0.7	3.9	1.5	5.2
4 (0.6 mill.)	Mean Diff.	1.4	4.0	1.5	14.6
	Max Diff.	11.2	24.7	24.2	44.7
	Variance	1.3	3.8	1.9	11.0
5 (0.07 mill.)	Mean Diff.	2.4	7.4	2.3	23.8
	Max Diff.	15.5	46.5	30.25	75.2
	Variance	2.0	5.6	2.8	15.4

References

[1] Berge E., Gravdahl A.R., Schelling J., Tallhaug L., and Undheim O. Wind in complex terrain. a comparison of wasp and two cfd-models. In *EWEC 2006 Scientific proceedings*, pages 152–155. EWEC, 2006. Presented at: 2006 European Wind Energy Conference and Exhibition : Athens (GR), 27 Feb.- 2 Mar., 2006.

[2] Schaffner B. and Gravdahl A.R. Wind modeling in mountains. intercomparison and validation of models. In *EWEC 2003*. EWEC, 2003. Presented at: 2003 European Wind Energy Conference and Exhibition : Madrid (SP), 16 - 19 June, 2003.

[3] Andreas Bechmann, Niels N. Sørensen, Jacob Berg, Jakob Mann, and Pierre-Elouan Mikael Rethore. The bolund experiment. part ii: Blind comparison of microscale flow models. *Boundary-Layer Meteorology*, 2011.

[4] Jacob Berg, Jakob Mann, Andreas Bechmann, Michael Courtney, and Hans Ejsing Jørgensen. The bolund experiment, part i: Flow over a steep, three-dimensional hill. *Boundary-Layer Meteorology*, 2011.

[5] Andreas Bechmann. Presentations from the bolund experiment: Workshop 3-4th december 2009. Technical report, Danmarks Tekniske Universitet, Risø¸ Nationallaboratoriet for Bæredygtig Energi, Roskilde, 2010.

[6] Bowen A.J. and Mortensen N.G. WAsP predictions errors due to site orography. Risø-R- 995-(EN), Risø National Laboratory, Roskilde, Denmark, December 2004. In English.

[7] J. A. Michelsen. Basis3D - a Platform for Development of Multiblock PDE Solvers. Technical Report AFM 92-05, Technical University of Denmark, 1992.

[8] J. A. Michelsen. Block structured Multigrid solution of 2D and 3D elliptic PDE's. Technical Report AFM 94-06, Technical University of Denmark, 1994.

[9] N. N. Sørensen. General Purpose Flow Solver Applied to Flow over Hills. Risø-R- 827-(EN), Risø National Laboratory, Roskilde, Denmark, June 1995.

[10] B. E. Launder and D. B. Spalding. The numerical computation of turbulent flows. *Comput. Meths. Appl. Mech. Eng.*, 3:269–289, 1974.

[11] Niels N. Sørensen, Andreas Bechmann, Jeppe Johansen, Lisbeth Myllerup, P. Botha, S. Vinther, and B.S. Nielsen. Identification of severe wind conditions using a Reynolds averaged Navier-Stokes solver. *J. Phys.: Conf. Ser.*, 75:13, 2007. Presented at: International conference: The science of making torgue from wind : Lyngby (DK), 2007.

[12] Niels N. Sørensen. Airfoil computations using the $\gamma - re_{\theta}$¸ model. Technical report, Risø¸ National Laboratory for Sustainable Energy, Roskilde, 2009.

[13] Niels N. Sørensen. CFD modelling of wind turbine aerodynamics. In J.-F. Brouckaert, editor, *Wind turbine aerodynamics: A state-of-the-art*, Lecture Series 2007-05, page 24 p, Rhode Saint Genese, 2007. von Karman Institute for Fluid Dynamics. Presented at: von Karman Institute for Fluid Dynamics lecture series : Rhode Saint Genese (BE), 2007.

[14] I. B. Celik, U. Ghia, P. J. Roache, C. J. Freitas, H. Coleman, and P. E. Raad. Procedure for Estimation and Reporting of Uncertainty Due to Discretization in CFD Applications. *J. of Fluids Eng. ASME*, 130, July 2008.

[15] C.J. Roy. Grid Convergence Error Analysis for Mixed-Order Numerical Schemes. *AIAA JOURNAL*, 41(4):595–604, April 2003.