Fast response simulator for flow over a complex terrain: A case study

Balram Panjwani[1], Berit Floor Lund[2], Kjersti Røkenes[2], Mihaela Popescu[1] and Jon Samseth[1]

[1]SINTEF Material and Chemistry, Trondheim Norway

[2]Kongsberg Renewables Technology, Trondheim, Norway

Introduction

Loss in power production from wind turbines and structural loading experienced by the wind turbines depends on the unsteady wake not only due to wind turbines but also due to other obstacles such as hills and adjacent buildings. Main focus of the research so far have been modelling of wake due to other wind turbines and there have been very limited studies on the effect of complex terrain on the overall power production from the wind turbines. The flow over terrain is very complicated due to it unsteady and highly turbulent nature. Most of the wind farms in the Norway are located in those areas where local topography is very complex. It is extremely important to know the wind field in order to reliably predict the approaching wind on the wind turbines. A most accurate way to estimate behaviour of such flow is to perform experiments on the full scale wind farm; however performing such experiments on the full scale is very expensive procedure. The other approach is to use mathematical models for predicting the flow over rough terrain, which can be divided into two types: "prognostic" and "diagnostic" models. Prognostic models are based on the solution of time dependent mass, momentum and energy conservation equations and the solution of the full set of equations is computationally demanding task. These models are run for few cases due to their complexity and cost and coupling of these models with forecasting tools is a challenge. On other hand the diagnostic model is mainly based on the principle of mass conservation in which divergence is eliminated in a flow field and these models are called mass-consistent model. Here a simulator for prediction of the flow over a complex terrain based on the mass consistent approach is developed. The simulator consists of pre-processor, solver and post processor algorithm. The focus of the present work was not to develop each model from scratch but use the existing models for understanding the interaction between complex terrain wake and the wind turbines wake.

Approach

First step for obtaining the flow over a terrain is pre-processing which includes geometry generation, geometry cleaning, creation of computational box, creation of the mesh and initial field generation. Second step is solver and third and final step is post processing of the results. Among these steps the pre-processing step is very crucial and final results depends on this. The wind flow solver accepts grids with high quality and therefore the pre-processing of the geometry needs special attention.

A typical terrain geometry used for wind flow simulation is shown in Figure 1. The mass consistent simulations require a computational box around the terrain geometry (see Figure 2). It is not a challenge to create a computational box around the terrain but the resulting geometry (Consisting of box and terrain file) which is shown in Figure 2.

The second step of the simulator was solver which includes the mass consistent model. The mass consistent model is essentially based on the numerical solution of the steady state three-dimensional continuity equation for the mean wind. The momentum equation is not solved explicitly but the effects due to momentum sink and source will be included in the initial flow field. The theoretical basis for this type of model was developed by Sasaki[1,2] using variational analysis. Mass consistent model have been modified and updated during the last several decades. Sherman[3] and Ross[4] applied mass conservation to an analysis of atmospheric flows over complex terrain. Detailed literature reviews on mass-consistent models over complex terrain have been provided by Ratto[5]. In the present work a mass consistent model developed by G. Montero et.al. [6,7] have been used. The theoretical development of mass consistent model is provided here.

The continuity equation

$$\vec{\nabla}.\vec{\mathrm{u}} = 0 \tag{1}$$

The objective function is

$$E(\vec{\mathrm{u}}) = \int [\alpha_1^2(\widetilde{u} - u_0)^2 + (\widetilde{v} - v_0)^2 + \alpha_2^2(\widetilde{w} - w_0)^2]\, d\Omega \tag{2}$$

Where velocity u_0 , v_0 and w_0 are initial conditions and it can be obtained either from the experimental measurements or other theoretical methods. The constants α_1 and α_2 are the Gauss precision moduli. Following function is derived and essential component in the mass consistent model is the minimization of the following function.

$$E(\vec{\mathrm{v}}) = min\left[E(\vec{\mathrm{u}}) + \int \phi \vec{\nabla}.\overrightarrow{\mathrm{u}d\Omega}\right] \tag{3}$$

$$u = u_0 + \lambda_1 \frac{\partial \phi}{\partial x}; v = v_0 + \lambda_2 \frac{\partial \phi}{\partial y}; w = w_0 + \lambda_3 \frac{\partial \phi}{\partial z}; \lambda = [\lambda_3,\ \lambda_3\ ,\ \lambda_3] \tag{4}$$

The Lagrange multipliers technique with equation (4) is used to minimize the equation (3), whose minimum leads to form the Euler-Lagrange equation.

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial x^2} = -\frac{1}{\lambda}\left(\frac{\partial u_0}{\partial x} + \frac{\partial v_0}{\partial x} + \frac{\partial w_0}{\partial x}\right) \tag{5}$$

A Dirichlet boundary condition for open or flow-through surfaces and Neumann boundary condition for the terrain was employed.

The mathematical formulation in the mass-consistent model is a Poisson equation for the Lagrange multiplier (see equation 5). Accuracy and speed of the model relies on the solution algorithm employed for the solving the Poisson equation. Some of common algorithm are Gauss–Seidel (GS), strongly implicit procedure (SIP) , the alternating direction implicit (ADI), and the conjugate gradient (CG). In this work, a nonsymmetric variant of the classical Conjugate Gradient method, BICGSTAB is employed for solving the passion equation[6,7] . The speed of the simulation can be increased with the help of multigrid approach[8].

Main body of abstract

The initial flow field is generated from a meso scale model and meteorological data on site. The accuracy in these sources will affect the accuracy of the initial field. Additionally, the initial field does not account for the local wind ward and leeward effects due to hills and obstacles, since the mass consistent model does not solve the momentum equation. To account for these terrain effects in the initial field, a method proposed by Röckle[9] has been utilized. This method gives a representation of the 1) displacement zone in its upwind side, (2) cavity zone in its lee side, (3) wake zone downwind to the cavity zone due to obstacles in the initial field, as shown in Figure 3.

To elaborate this wind flow simulation studies were carried out. In Case-1 the initial field does not account for obstacle effects and in Case-2 these obstacles effects were accounted by modifying the initial field. The initial fields over a small hill accounting for obstacles effects and not accounting for obstacles effect are shown in Figure 4 and Figure 5. A mass consistent solution of Case-1 and Case-2 is shown in Figure 6 and Figure 7. The mass consistent model for Case-1 without windward and leeward wake effects shows velocity reduction on the wind ward and leeward side of the hill and velocity acceleration on the topside of the hill (see Figure 5). The results indicate that the mass consistent model is qualitatively able to predict some of the effects such as windward, leeward and roof effect on the top side of the hill. Circulation zones mainly behind the hill are however not possible to capture with mass consistent model. The accuracy of the prediction again depends on the initial flow field. Röckle[14] proposed windward and leeward wakes only for the box type (rectangular, square shapes) of obstacles. There are not many well established correlations for windward and leeward effects for the hills and complex terrain. The correlation proposed by Röckle over modified to account for these effects. One of the future objectives of the current activity is to obtain such correlation for the hills and obstacles using computational fluid dynamics or from the available measurements over hills. These correlations will be used for generating the initial field.

A mass consistent model was employed for the more complex terrain as shown in Figures 1 and 2. Different set of tools were used for generating the initial mesh files needed for the mass consistent model. The accuracy of the simulation improves with finer meshes, however this will increase the computational cost. Mesh of the geometry is shown in Figure 8. Mass consistent simulations were obtained for two initial fields. A constant uniform initial velocity field was used everywhere in one case, hereafter named Case-3 and velocity field interpolated from the station data were employed in another case, hereafter named as Case-4. Since there are only few station data points' available, horizontal interpolation in only one plane, parallel to the ground, is carried out. Vertical interpolation is performed using values from the horizontal plane. Atmospheric boundary layer profile accounting for stability of atmosphere is used for constructing the vertical interpolation. The mass consistent results for Case-3 and Case-4 are shown in Figure 9 and Figure 10 respectively. Variations in the flow field due to the terrain can be observed in both the cases. Mass consistent model was able to capture some of effects as mentioned earlier even with uniform constant field (see Figure 9), however, the flow field will never be constant and therefore the initial field was modified to account for atmospheric boundary layer profile. Results further improve for Case-4 where a low velocity field was observed on the windward side of the hill and acceleration of the wind was observed on the top side of the hill. The interpolated results of Case-4 do not account for the windward and leeward wake effects and it will be accomplished in future work.

Conclusion

Simulator for estimating the wind over a complex terrain is developed. Major hurdles associated with preprocessing are discussed. Mass consistent simulations were carried out for a simple hill with and without windward and leeward wake effects. The accuracy of the mass consistent model depends on the initial condition. Finally mass consistent simulations were performed for a complex terrain for two different initial conditions. The initial condition interpolated from the station data show a better flow distribution around the terrain.

References

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Figures

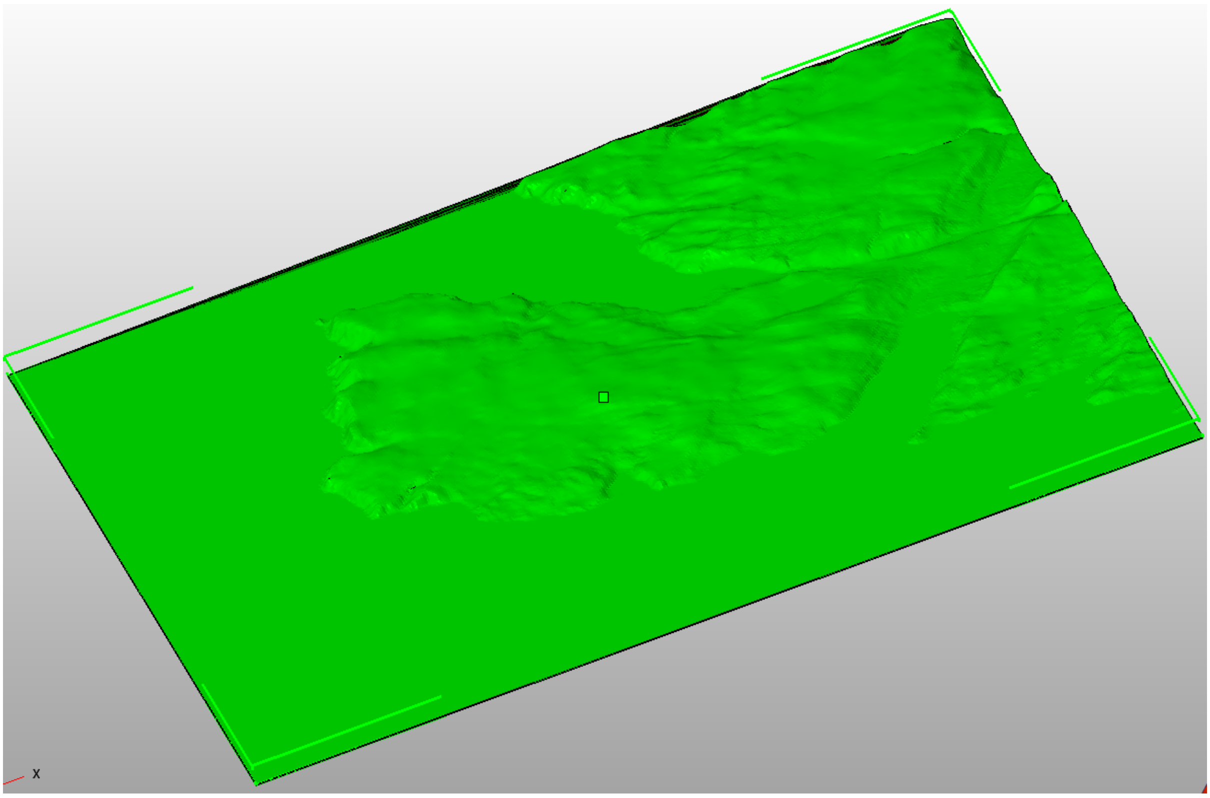

Figure 1: Geometry of the complex terrain

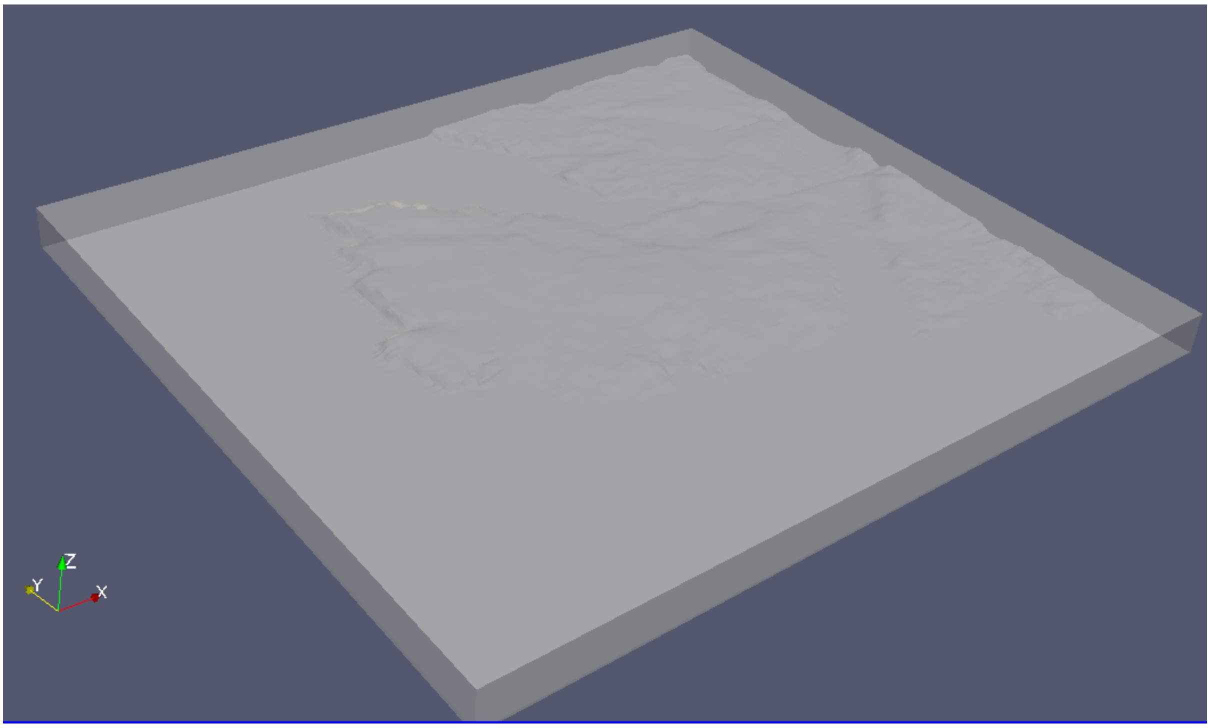

Figure 2: Geometry of the complex terrain with computational box

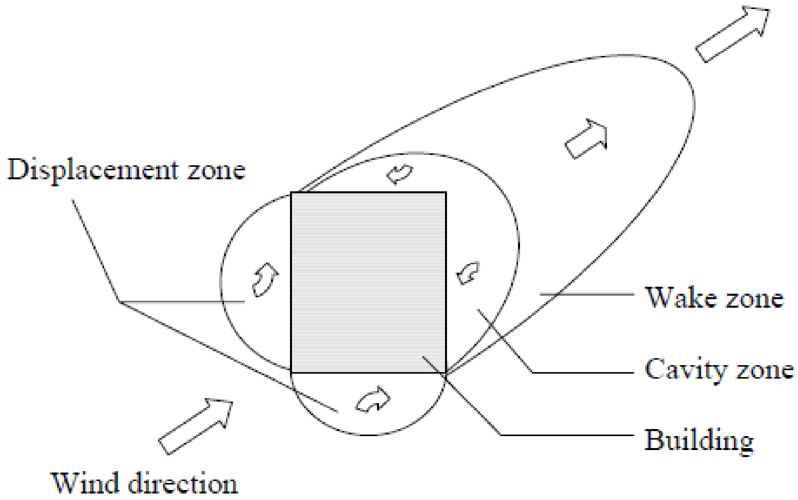

Figure 3: Windward and leeward wakes around the obstacles proposed by Röckle **.**

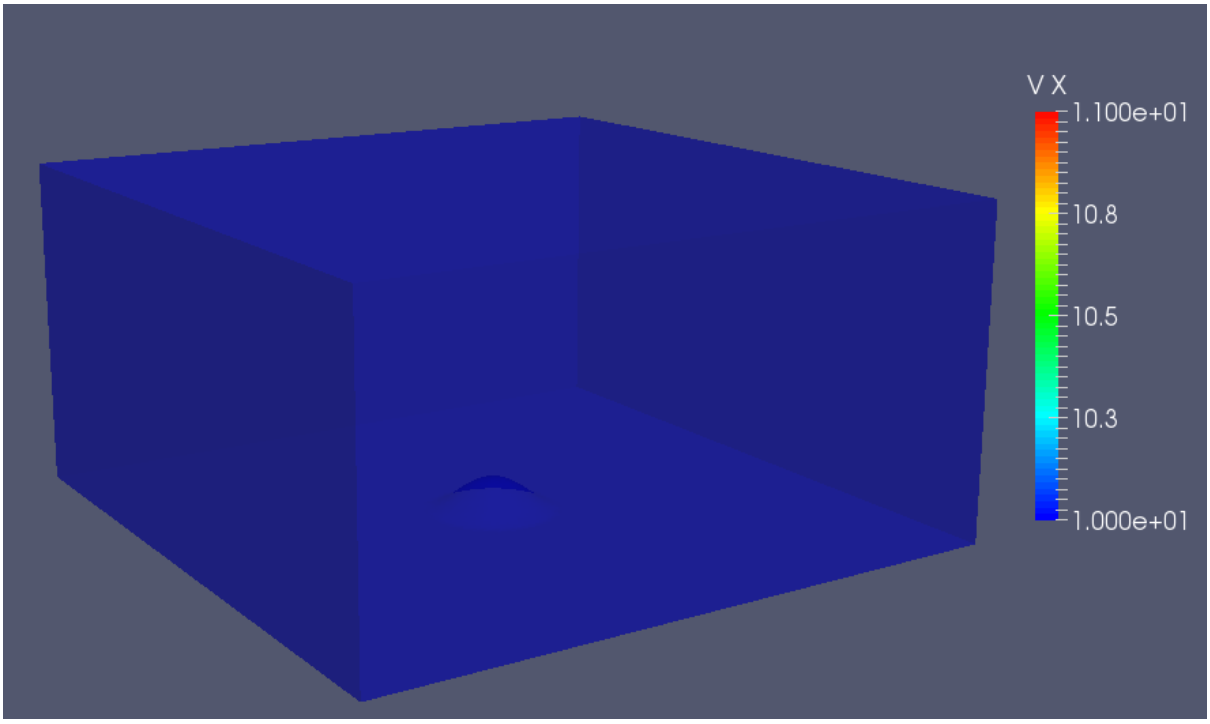

Figure 4: A constant velocity of 10 m/s around the hill

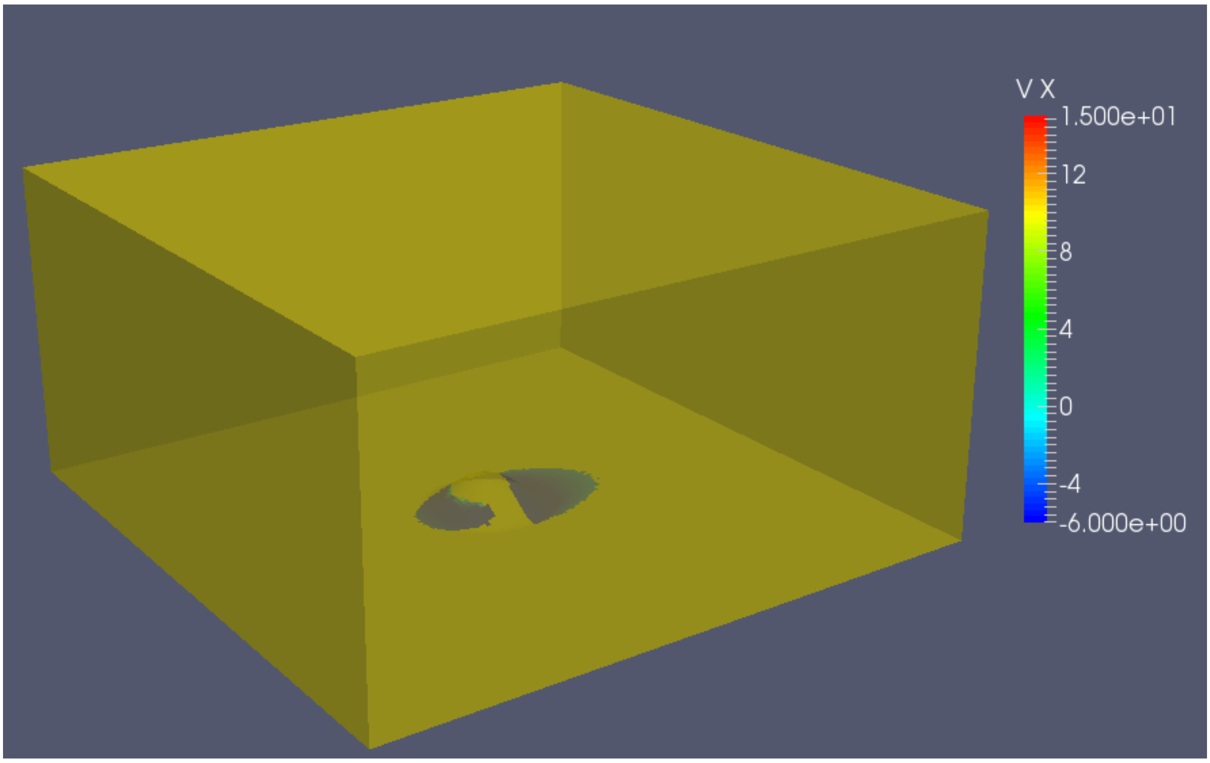

Figure 5: The initial field was modified to account for windward and leeward wake effects

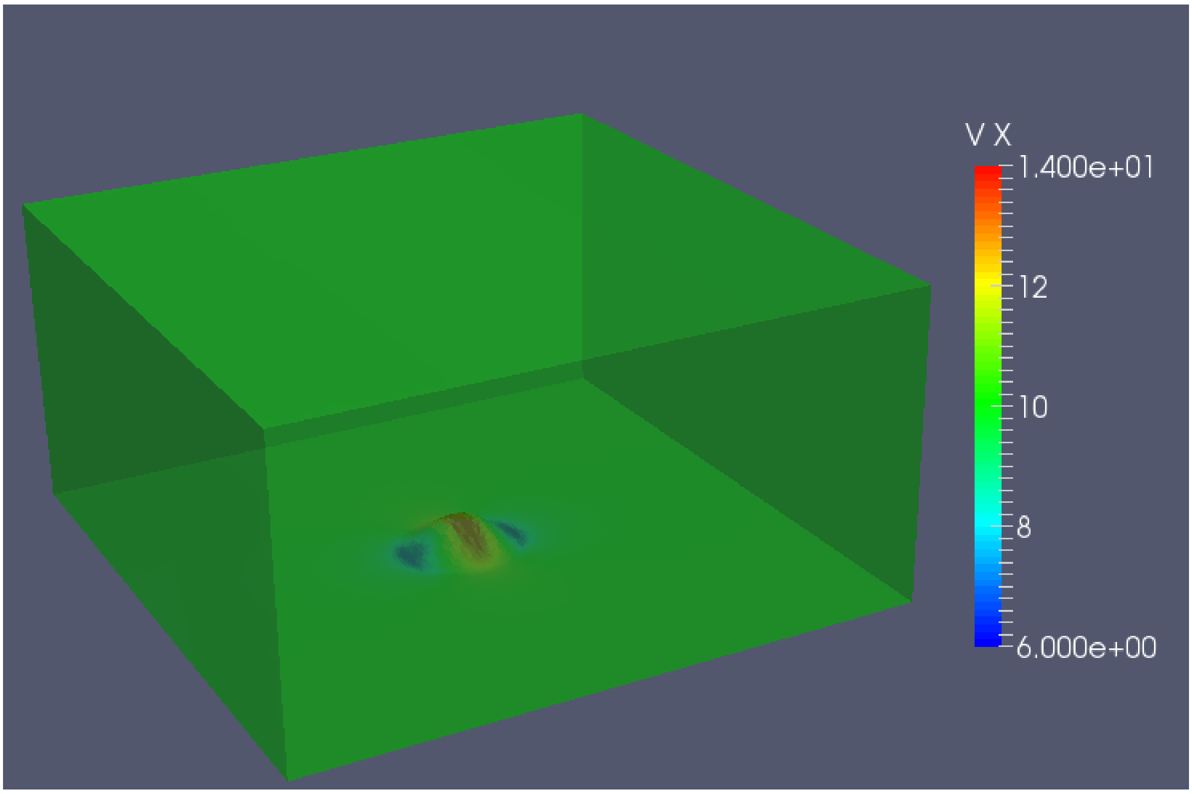

Figure 6: Results obtained from the mass consistent model (Case-1)

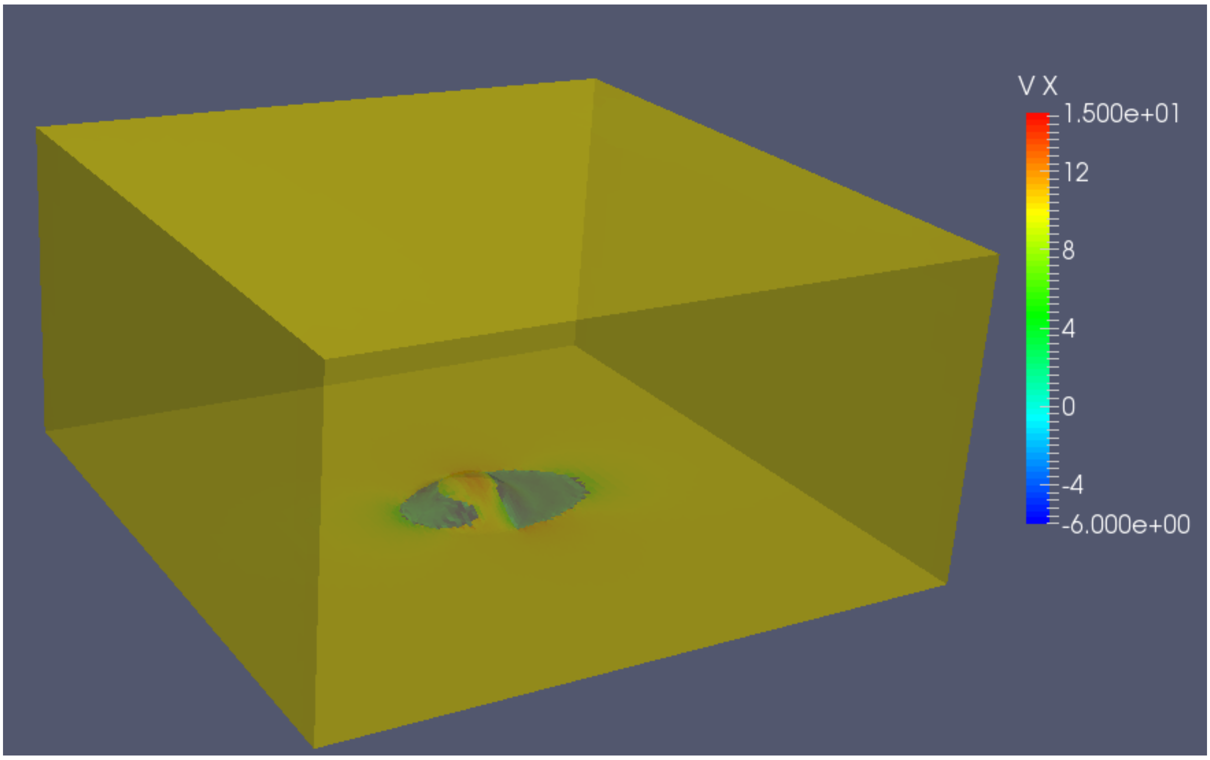

Figure 7: A mass consistent results for case-2 in which windward and leeward wake effects were added (Case-2)

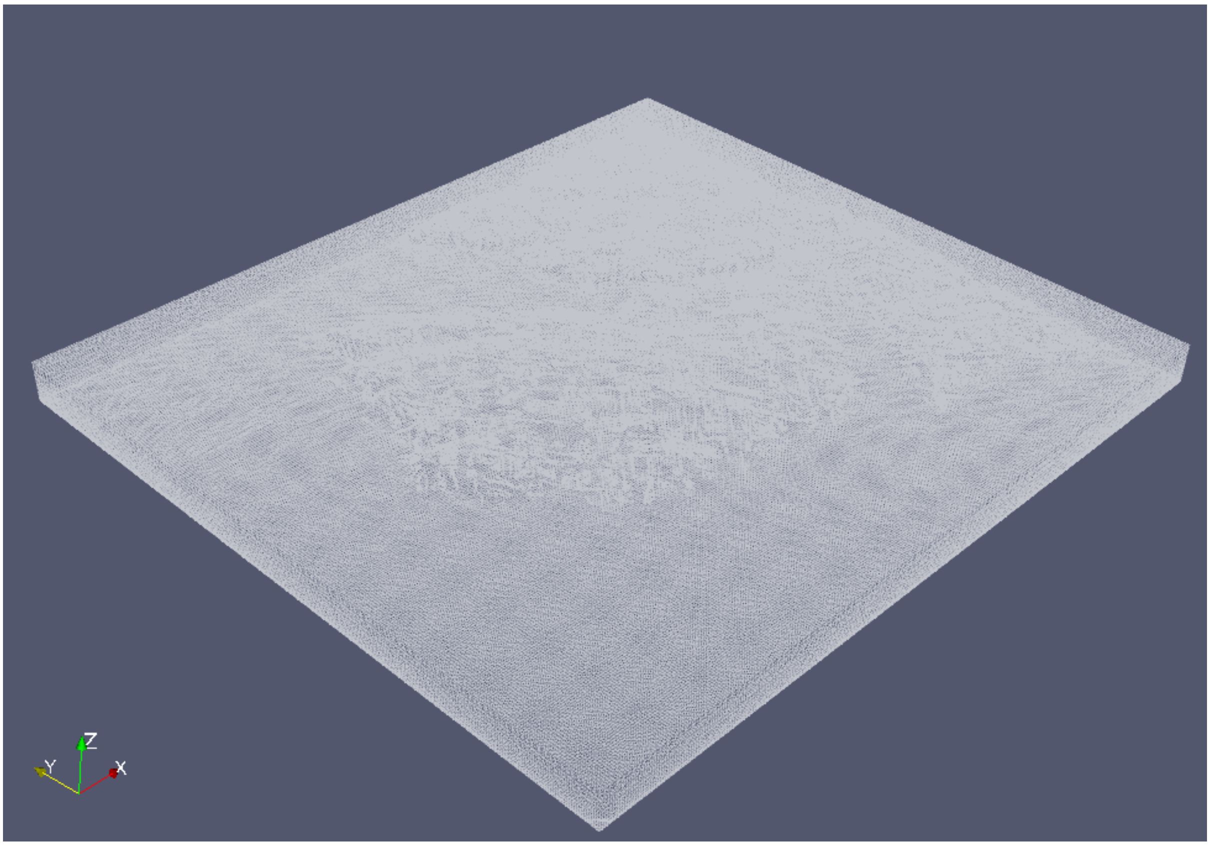

Figure 8: Mesh of the geometry

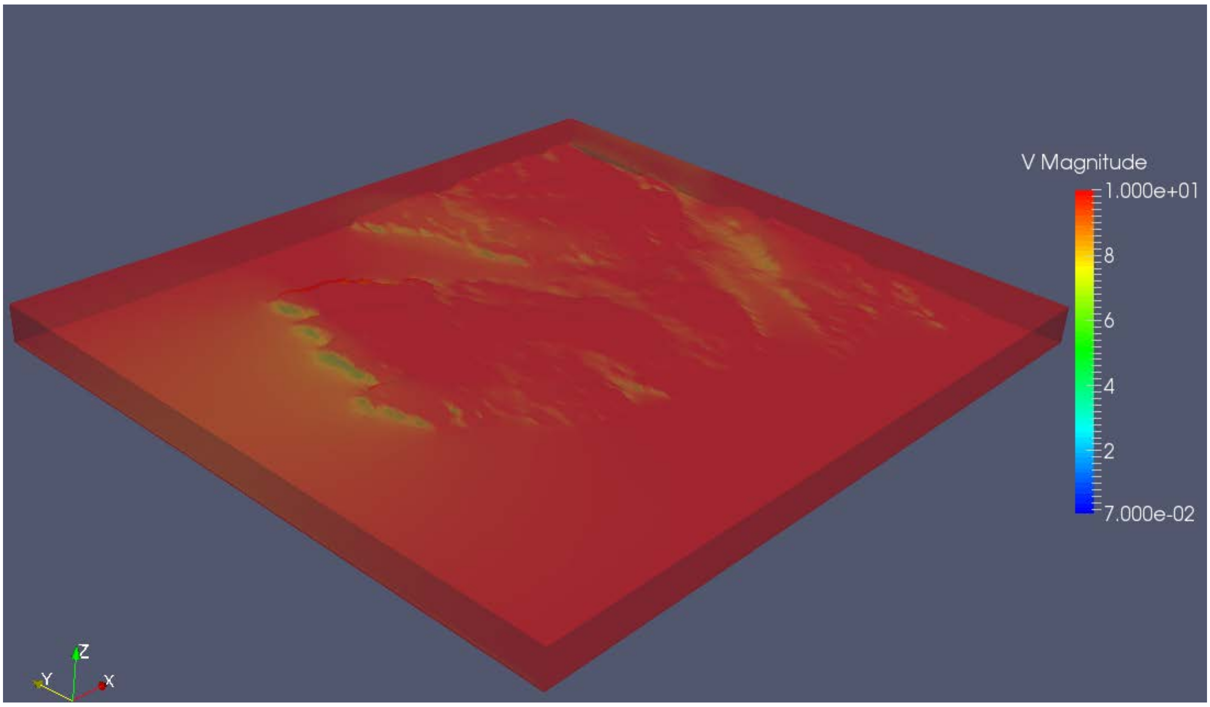

Figure 9: A mass consistent results for the complex terrain where initial field was uniform constant field (Case-3)

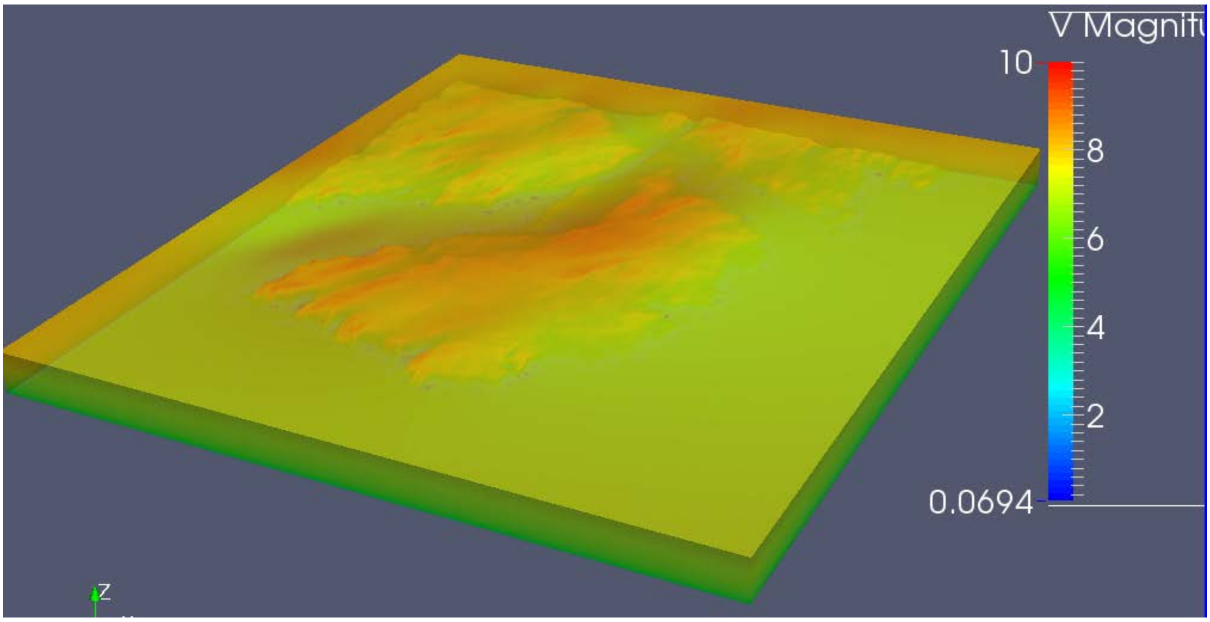

Figure 10: A mass consistent results for the complex terrain where initial field was interpolated from the station data (Case-4)