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ATMOSPHERIC TURBULENT FLOW SOLUTIONS COUPLED WITH A MESOSCALE WEATHER PREDICTION MODEL

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Abstract. *Atmospheric turbulent flow solutions coupled with a mesoscale meteorological weather prediction software are obtained on terrain fitted high resolution computational grids using FLUENT as a CFD tool. The terrain topology of interest, which may be obtained in various resolution levels, is accurately modeled using unstructured grids. The widely used meteorological weather prediction software WRF is used to provide unsteady boundary conditions for the CFD solution domain. Due to difference of mesh structure and resolution, the coupling procedure is challenging. As an addition to previous works, improvements over the coupling procedure are done by using modified boundary conditions to match the ground surfaces of both low resolution WRF data and FLUENT flowfield. Unsteady boundary conditions are implemented through the User Defined Functions developed for FLUENT. The main objectives of this study are to overcome the challenges of the coupling of the solvers and to obtain unsteady, turbulent atmospheric flow solutions accurately using low resolution atmospheric weather prediction models for spatially and time varying boundary conditions and high resolution Navier-Stokes solutions over topographical terrains.*

1 INTRODUCTION

Accurate predictions of unsteady rural and urban atmospheric flow fields have a wide range of usage such as micro-site selection for wind farms and pollution tracking, each of which are of current research topics with several examples in literature[1, 2, 3].

As wind farms consisting of a large number of wind turbines have a high initial investment cost, wind farm siting must be given a significant importance[4, 5]. Low resolution wind energy potential atlases have the necessary statistical information for macro-siting of wind farms but lack the precision for the micro-siting. Therefore; high resolution, more accurate wind field information may be needed for micro-siting in order to improve the power output of a wind-farm.

Bowen(2004)[6] in a Risø-R Report states that Botta et al (1992)[7], Bowen and Saba (1995)[8], Reid (1995)[9] and Sempreviva et al (1986)[10]'s experience in the operation of commercial wind farms (Lindley et al., 1993[11]) has confirmed that effects from the local complex terrain on the site characteristics of each turbine have a significant influence on the output (and perhaps even the viability) of a wind energy project.

F.J.Zajackowski et.al.[12] compares Numerical Weather Prediction Models (NWP) and Computational Fluid Dynamics (CFD) simulations. They conclude that NWP can take radiation, moist convection physics, land surface parametrization, atmospheric boundary layer physics closures, and other physics into account, but wind flow features finer than 1 km are not captured by the turbulence physics of such models. CFD simulations, however, have proven to be useful at capturing the details of smaller scales due to a finer scale topography, and details around urban features such as high-rise buildings.

In the previous work done by Leblebici et. al.[13], FLUENT is coupled with WRF using the unsteady weather prediction data from WRF as unsteady boundary conditions. As the resolution of the WRF solutions' and FLUENT solutions' are not the same, the ground level of both solution domains does not coincide. To overcome this problem, the regions where the ground level of FLUENT is below the WRF ground level velocity is taken as zero. But this approach may yield in inaccuracies in the atmospheric boundary layer profile.

The objective of this study is to develop a methodology to obtain accurate and turbulent atmospheric flow solutions on high resolution terrain fitted grids to accurately model the boundary layer flow near the ground for a given region coupled with unsteady WRF weather prediction solutions. The main development over the previous study[13] is improved boundary conditions which will be explained in the Method section.

2 METHOD

In this study, a coupled flow solution methodology with an atmospheric weather forecast software, WRF, and a commercial flow solver, FLUENT, is developed. WRF produces a low resolution, unsteady atmospheric weather forecast data, which provides the unsteady boundary conditions for turbulent flow solutions obtained with FLUENT on terrain fitted, high resolution unstructured grids. Also, the accuracy of the boundary conditions are assessed and improved.

The coupling procedure and basic flowchart representing the solution methodology is also given in Figure 1 and Figure 2.

WRF is a fully compressible, Eulerian, η-coordinate based, nest-able, non-hydrostatic, numerical weather prediction model with a large suite of options for numerical schemes and parametrization of physical processes [14]. WRF uses an η based coordinate system instead of an orthogonal Cartesian coordinate system. The vertical coordinate, η, is defined as:

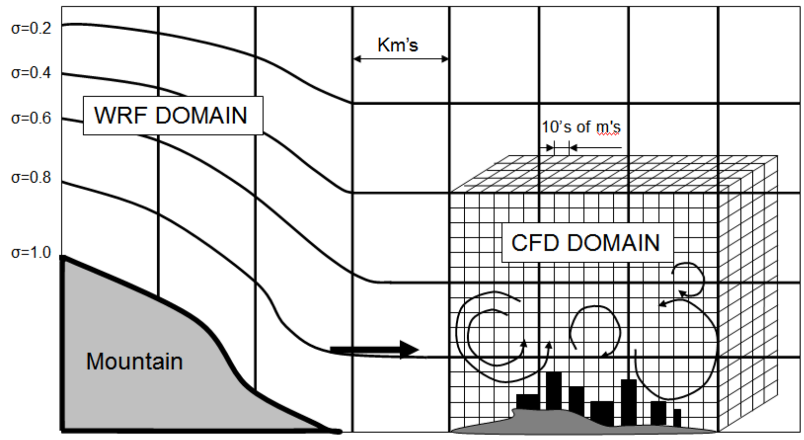

Figure 1: Coupling WRF with FLUENT

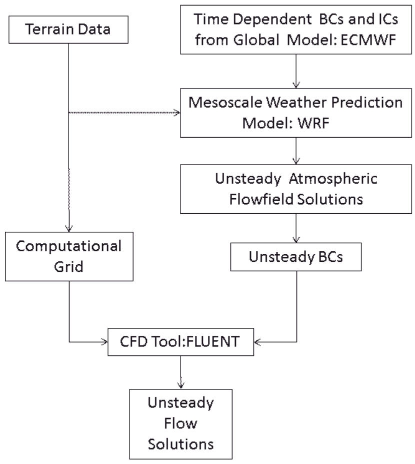

Figure 2: Flowchart

$$\eta = \frac{p - p_{ht}}{p*} \tag{1}$$

and pressure perturbation $p*$ is simply

$$p* = p_{hs} - p_{ht} \tag{2}$$

where p is pressure, p_{hs} is surface pressure, and p_{ht} is the pressure at the top of the model. As seen in Figure3, the η coordinate system causes a poor representation of the surface topography.

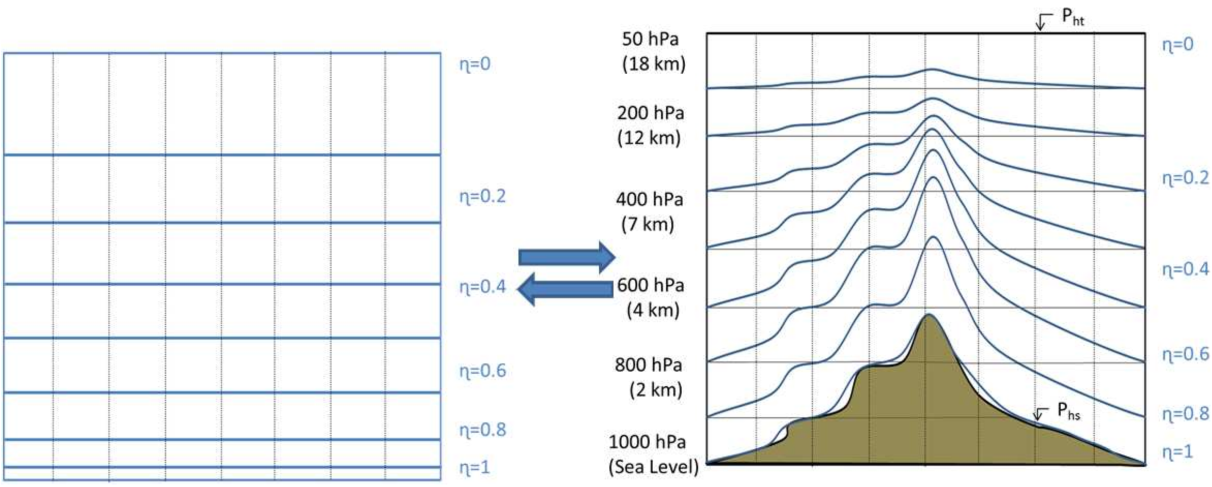

Figure 3: η Coordinate system

Some of the major difficulties in computing turbulent flow solutions using computational fluid dynamics tools are obtaining and utilizing the unsteady boundary conditions and obtaining the regional high resolution topographical data.

In this study, unsteady WRF solutions are first obtained over the geographical domain of interest. The local terrain data is downloaded automatically from UCAR (University Corporation of Atmospheric Research) server via WRF. The time dependent initial and boundary conditions for the WRF solution is obtained from ECMWF (European Centre of Medium Range Weather Forecast). The unsteady boundary conditions needed for the FLUENT solution at its domain boundaries, which fall into the larger scale WRF domain, are then extracted from the WRF solution at 5 minute time intervals.

In computational grids for FLUENT solutions, the high resolution terrain topography is generated using the data obtained from ASTER GDEM Worldwide Elevation at 1.5 arc-sec resolution ($\approx$ 30 meter). The vertical and horizontal grid resolution on the ground for the terrain fitted unstructured grids is about 20 meters. These grids also resolve the atmospheric boundary layers and stretch up to about 2000 meter altitude.

It should be noted that WRF has a horizontal resolution of 1km and a vertical resolution of about 50m on the ground which stretches rapidly. In addition, as shown in Figure4 the surface boundaries in the WRF and FLUENT domains differ significantly mainly due to the high resolution topographic data used in the generation of the FLUENT domain, and due to the η coordinate system employed in WRF.

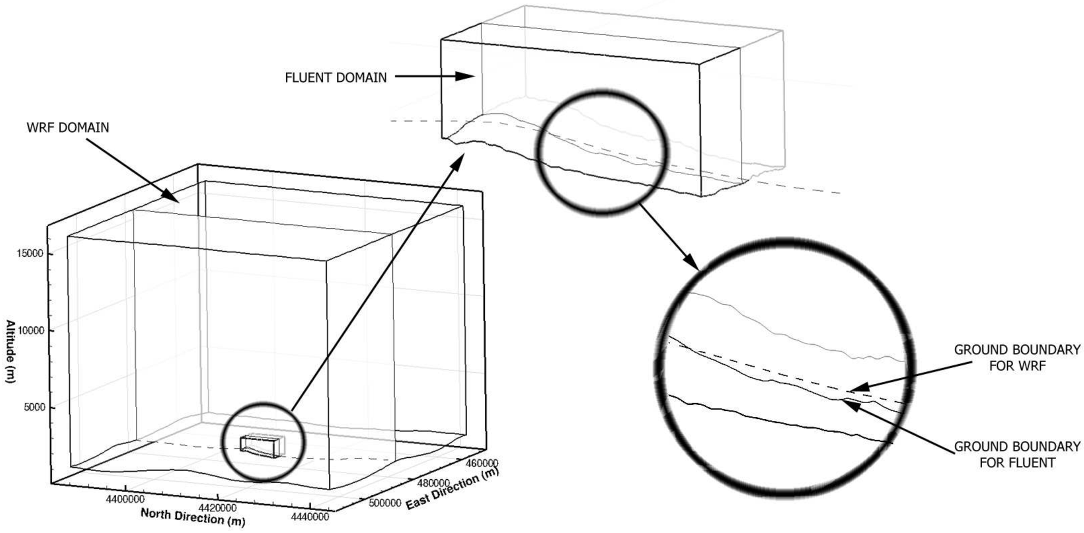

Figure 4: WRF and FLUENT solution domains and close-up views

Due to the difference in resolution boundary condition data from WRF should be interpolated accordingly to the FLUENT flowfield's boundaries. In the previous work [13], the values from WRF are interpolated using a fictious surface at least below the ground level of fluent is generated for the interpolation of boundary conditions at the FLUENT's boundaries. But this method results in zero velocity boundary conditions near the ground level of FLUENT where WRF's ground level is higher. To overcome this problem, vertical distances from the ground are calculated for each of the faces in the boundaries in FLUENT domain and x-velocity, y-veloctiy and z-velocity at these distances above the ground level of WRF domain are taken as boundary conditions.

The unsteady boundary conditions for the FLUENT solutions are interpolated for the outer boundary cells from the WRF solution at every 5 minute, and then linearly interpolated for the time steps between 5 minute intervals by means of User Defined Functions (UDF) within FLUENT. Three UDFs are developed for determining the boundary cells and boundary faces, for reading the appropriate unsteady boundary information data obtained from the WRF solution, and for interpolating the flow variables at the boundary faces.

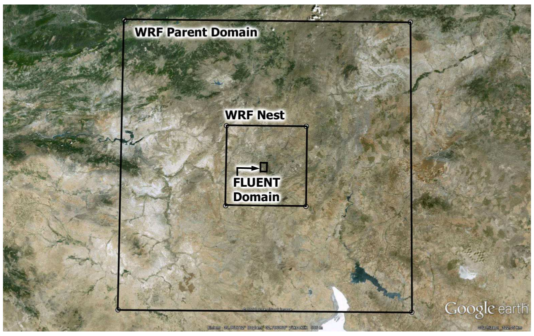

Figure 5: Borders of WRF nests and FLUENT solution domain

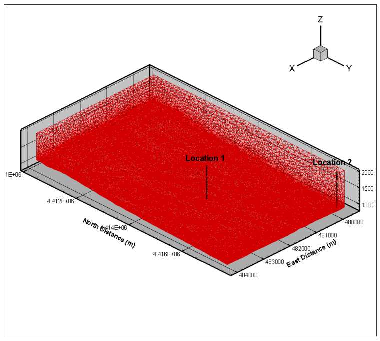

Figure 6: Location of the points on which BL profiles are taken

3 RESULTS AND DISCUSSION

In this study, turbulent atmospheric flow solutions coupled with WRF and the commercial flow solver FLUENT are carried out around METU campus in Ankara/TURKEY on high resolution unstructured grids.

Nested WRF solutions are first obtained for a 12 hour period, within a parent domain of 3 km horizontal resolution and a nest of 1km resolution around METU campus in Ankara. The parent and the nested solution domains, which are of 70x58(horizontal) x 50(vertical) size, are given in Figure 5. Unsteady solutions in the nested domain is saved in 5 minute time intervals, which are used to extract the unsteady boundary conditions for the FLUENT solution.

Gambit is employed to generate computational grids for FLUENT solutions. The high resolution topographic data for the domain of interest is taken from the ASTER-GDEM data set which has a horizontal resolution of about 30 meter. Terrain fitted unstructured grids with vertical and horizontal grid resolution on the ground about 20 meters are generated.

η coordinate system may result in the disturbances due to complex terrain not to be captured. Both the usage of high resolution terrain data and unstructured girds defined in Cartesian coordinate system instead of η coordinate system makes it possible to analyze the flowfield in the vicinity of the ground better especially in complex terrains.

The atmospheric flow solutions over the domain of interest are successfully obtained for a 12 hour period first with WRF, and then with FLUENT on terrain fitted unstructured grids in a coupled fashion with the WRF solution.

As previously mentioned in Method section, ground levels of WRF and FLUENT domains does not match exactly due to the difference in resolution. To overcome the problems this phenomenon may yield for the accuracy of the boundary conditions, distance from the ground is calculated at each face at the boundaries of the FLUENT domain and using this information FLUENT domains ground level and WRF's are matched.

The unsteady flowfields obtained with the previous boundary conditions and improved boundary conditions are shown along with the WRF results in Figure 7 in terms of the velocity magnitude contours and streamlines taken on a horizontal surface at 940m altitude, which is about 30m above the ground. It is observed that in general all the solutions are in agreement in the large scale but FLUENT solutions have a higher resolution of the flowfield as well as the surface topography than the WRF solution as expected. The turbulent flow solutions with FLUENT capture detailed flow features especially at the 3rd and 6th hours of the solution when the wind velocity is relatively low. At the 12th hour, when the wind velocity increases, the computed flowfields are in more agreement. Nevertheless, the velocity magnitudes computed by WRF and FLUENT may still differ at various locations by as much as 50%.

As for the comparison between two FLUENT solutions, it is seen that usage of the improved boundary conditions resulted in capturing a swirl at the 3rd hour whereas in the previous study there was not such a feature and also the flow pattern at 6th hour is somewhat different and seems more realistic. Overall, both FLUENT solutions agrees with each other.

Figure 8 presents the 3-D streamlines over the FLUENT solution domain and the WRF solution domain. Similar to the sectional views in Figure 7, the 3-D views reveals the differences in the resolution of the topography and the flow features. In contrast to the smoother wind fields in WRF solutions, the the FLUENT solutions predict a more complex and a detailed wind field.

For understanding the effects of the change in boundary conditions, boundary layer profiles in the vicinity of the ground (up to 250 meters above the ground level) are plotted in Figure 9 at two different locations. Location 1 (Zone 36 482020E-4414690N in UTM coordinate system) is located about the center of the domain and used to analyze the effects far from the boundaries whereas Location 2 (Zone 36 479800E-4417370N in UTM coordinate system) used to observe the effects near the boundaries as seen in Figure 6.

As seen in Figure 9, at location 2 which is near the boundaries of the FLUENT domain, improvement in boundary conditions resulted in a more realistic boundary layer profiles and also the difference between WRF solution and new FLUENT solutions are smaller compared to the old FLUENT solution. Looking at the boundary layer profiles at location 1, it can be said that the difference in the flowfield solution due to improved boundary conditions is not negligible.

Although the FLUENT solutions are high-fidelity and have higher resolutions in the surface topology and in the solution domain in comparison to the WRF solutions, their accuracy should first be validated with the observation data. It is hard to draw a conclusion about whether improved boundary conditions are better. Nevertheless, increased accuracy near the boundaries may imply that it is so. In addition, the accuracy of the FLUENT solutions may also be established through grid resolution studies. In this preliminary study, higher grid resolutions are avoided due to the fact that FLUENT can not be run in the parallel mode in the presence of UDFs, and serial computations with the total number of cells exceeding 10^7 become prohibitively resource demanding.

4 CONCLUSIONS

In this preliminary study, the unsteady atmospheric flowfields are successfully computed with a commercial viscous flow solver, FLUENT, coupled with a meteorological weather prediction software, WRF. The unsteady boundary conditions for the FLUENT solution are extracted from the unsteady WRF solution. It is shown that the FLUENT solutions on terrain fitted unstructured grids provide high resolution atmospheric flowfields, and are in agreement with the WRF solution globally. As for improving the boundary conditions, it can seen that it increases accuracy with respect to WRF. However, the accuracy of the FLUENT solutions should be assessed first in a grid convergence study, which is the next stage in our research. In addition, all the solutions should ultimately be validated against the atmospheric observation data. The methodology developed is highly promising in micro-siting of wind farms and in accurate prediction of power production of operational wind farms.

5 ACKNOWLEDGEMENT

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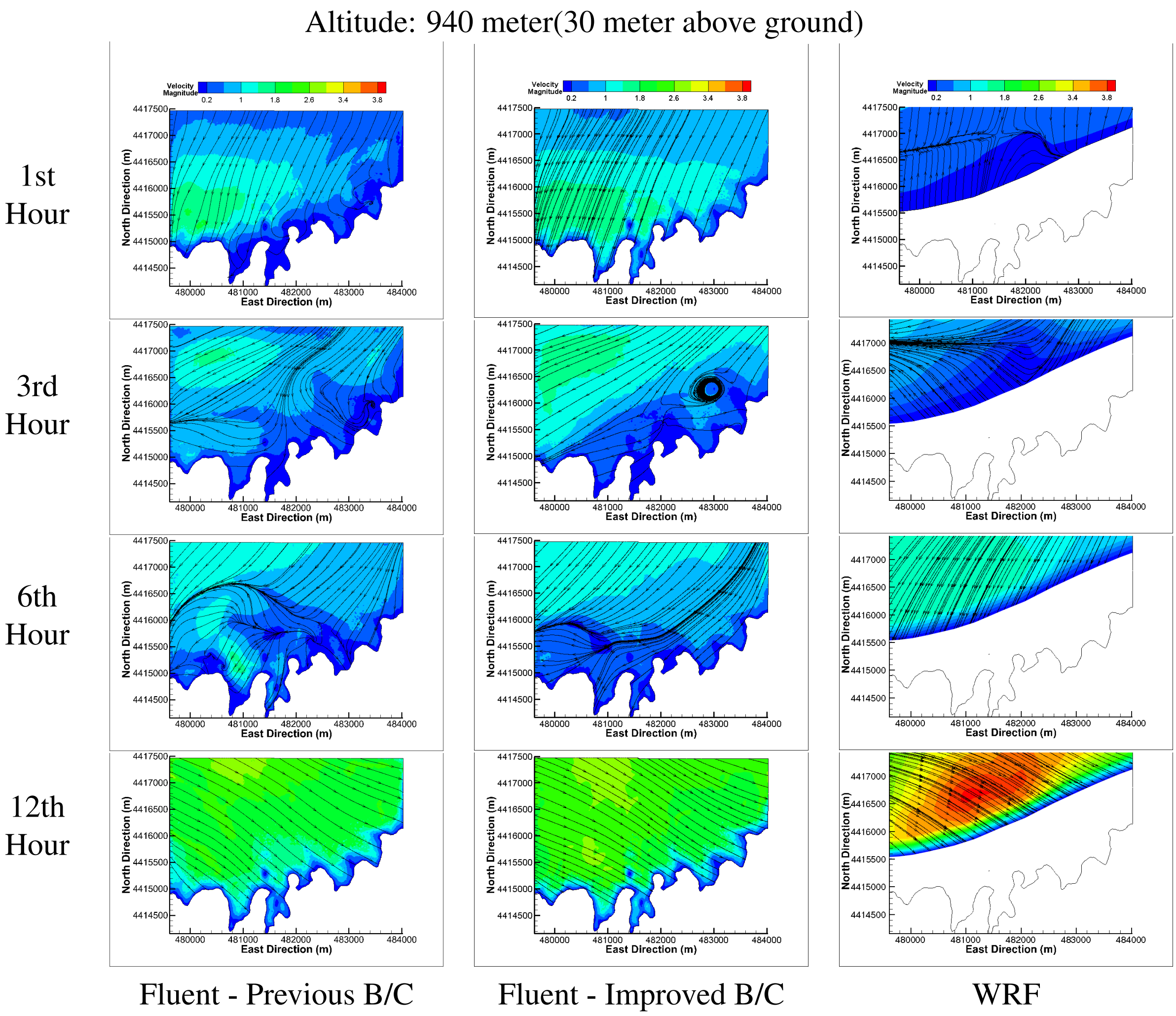


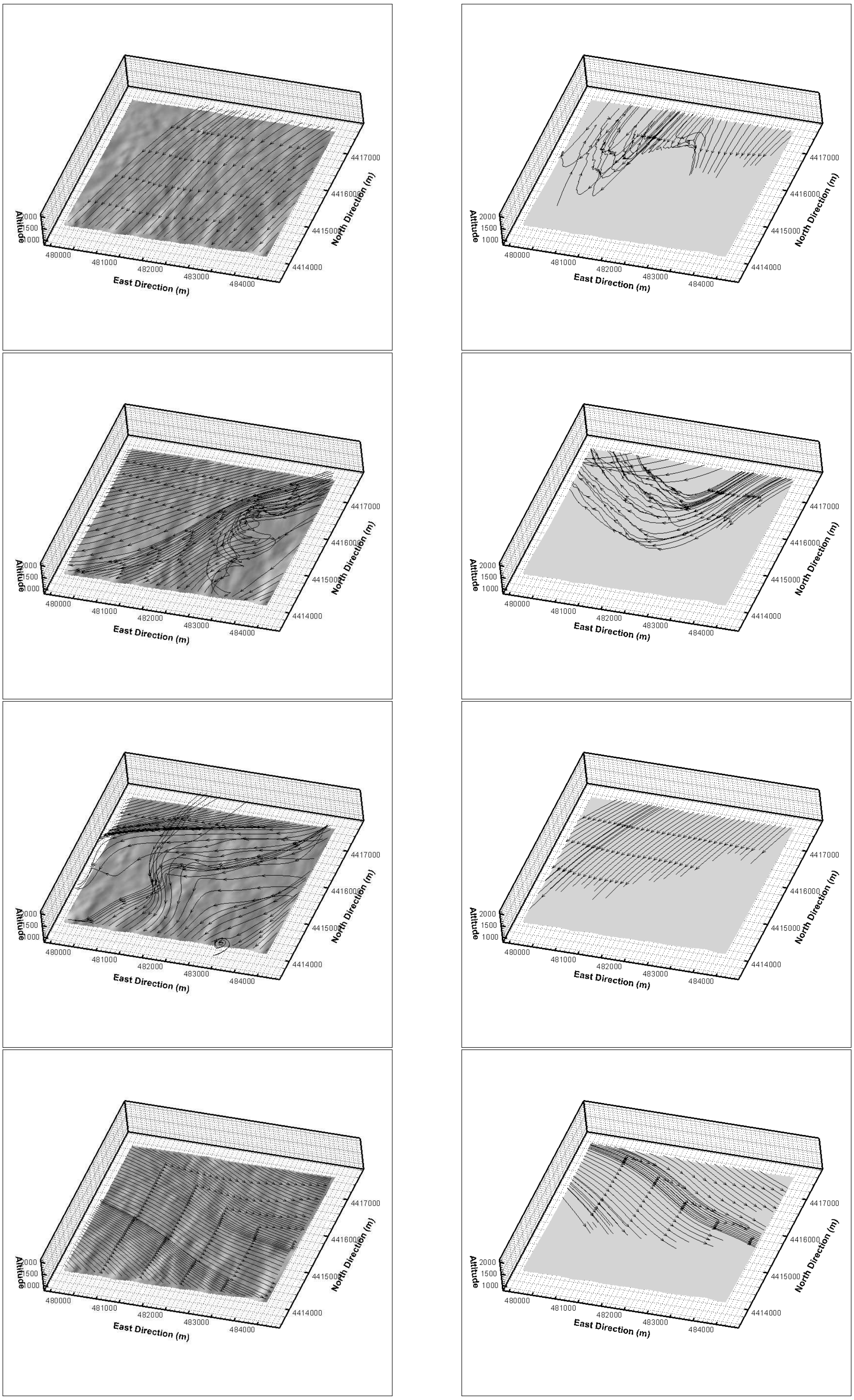
Figure 7: Velocity contours and streamlines at 940m altitude at the 1st, 3rd, 6th, 12th hours of the solutions

1st Hour

3rd Hour

6th Hour

12th Hour



FLUENT solutions

WRF solutions

Figure 8: 3D representation of streamlines about 940 m altitude at the 1st, 3rd, 6th, 12th hours of the solution

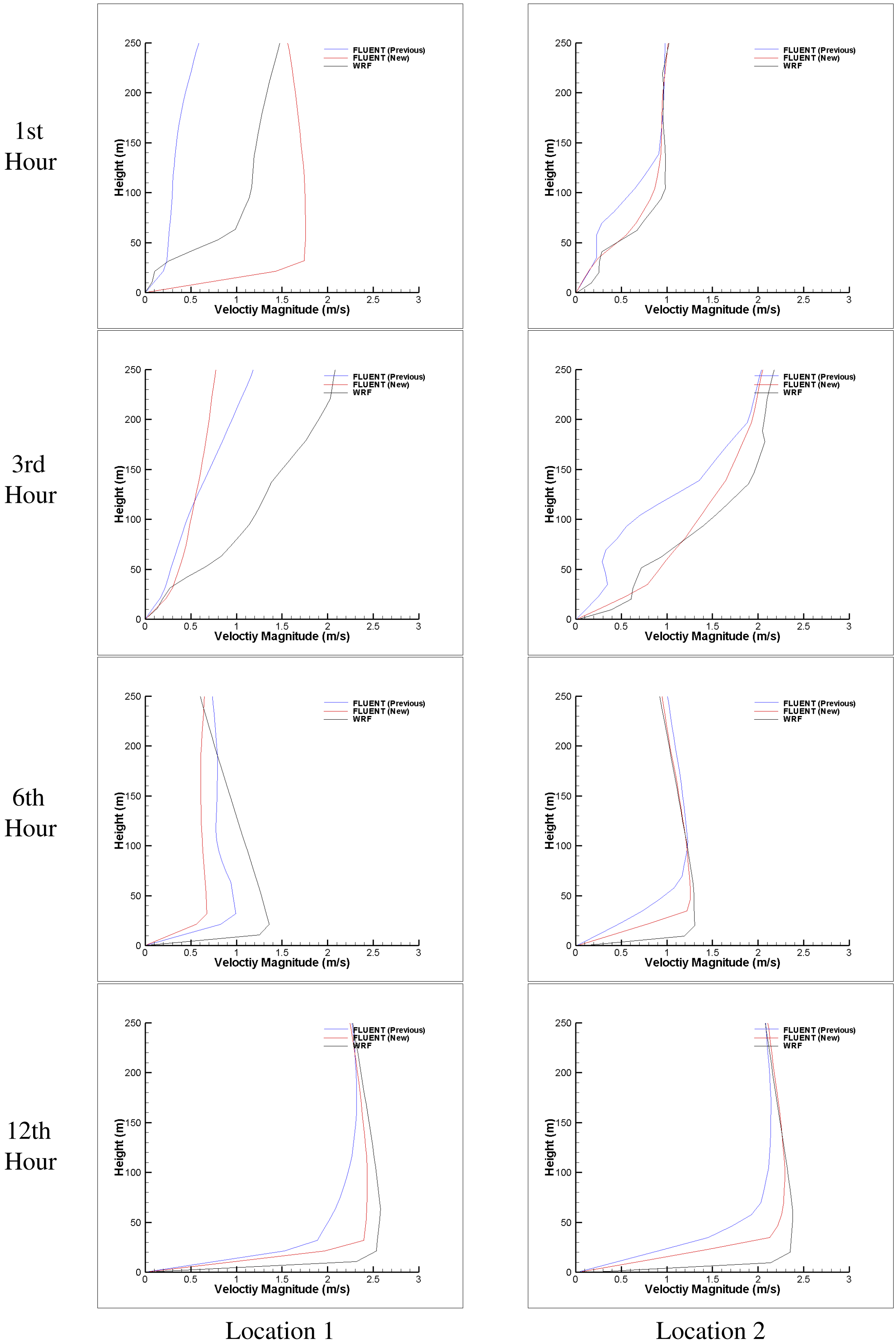


Figure 9: Boundary Layer Profiles at Location 1(right) and Location 2(left) at 1st, 3rd, 6th and 12th hours

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