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WIND POTENTIAL ESTIMATIONS BASED ON UNSTEADY 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 to estimate the wind potential 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. 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 is to obtain unsteady, turbulent atmospheric flow solutions accurately using a low resolution atmospheric weather prediction model for spatially and time varying boundary conditions and a high resolution Navier-Stokes solution over topographical terrains to estimate daily wind power potential density.

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].

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[3; 4]. 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)[5] in a Risø-R Report states that Botta et al (1992)[6], Bowen and Saba (1995)[7], Reid (1995)[8] and Sempreviva et al (1986)[9]'s experience in the operation of commercial wind farms (Lindley et al., 1993[10]) 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.[11] compares Numerical Weather Prediction Models (NWP) and Computational Fluid Dynamics (CFD) simulations. They conclude that NWP can take radiation, moist convection physics, land

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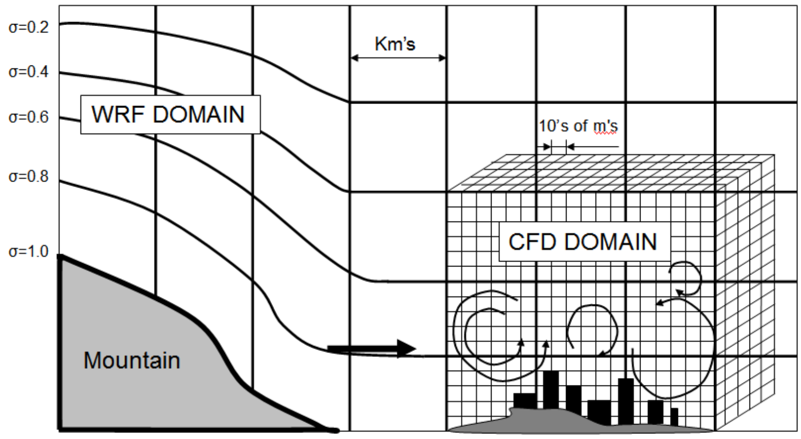

Figure 1: Coupling WRF with Fluent

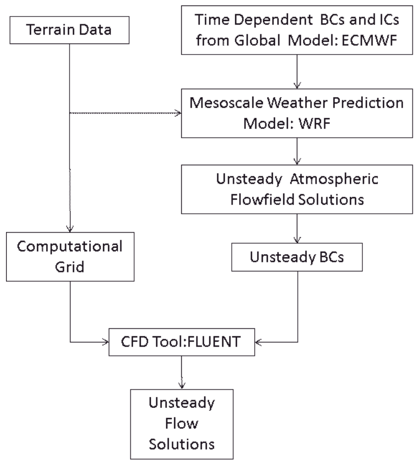

Figure 2: Flowchart

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 proved 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.

Weibull probabilty distribution function is a widely known statistical distribuiton function which is used for wind velocity distributions among other things such as reliability engineering, manufacturing and delivery times in industrial enginnering and so on. In this study, weibull distributions along with windrose patterns is obtained for regions of interest.

Wind power density is basically kinetic energy of the wind passing through a unit area per unit time. It is a useful parameter for the determining the location of a wind turbine. For this study, average wind power density at a specific heigth above the ground level is obtained.

The objective of the present study is to estimate wind power potential density distribution for a day at a specific height above the ground level and obtaining wind power related parameters such as weibull distributions, scale and shape parameters for specific locations using turbulent, unsteady, WRF coupled FLUENT solutions. To do so accurately, interpolation errors due to difference in the resolution of WRF (low resolution) and FLUENT (high resolution) must be minimized. This is achieved by shifting the ground level in WRF solution to the same level of the Fluent domain, which is explained in detail in the following section.

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. The accuracy of the coupled boundary conditions are also assessed and improved. Using these solutions, wind power energy density at a specific height above ground level and weibull distributions and windroses are obtained at specific locations.

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 [12]. WRF uses an η based coordinate system instead of an orthogonal Cartesian coordinate system. The vertical coordinate, η, is defined as:

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

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.

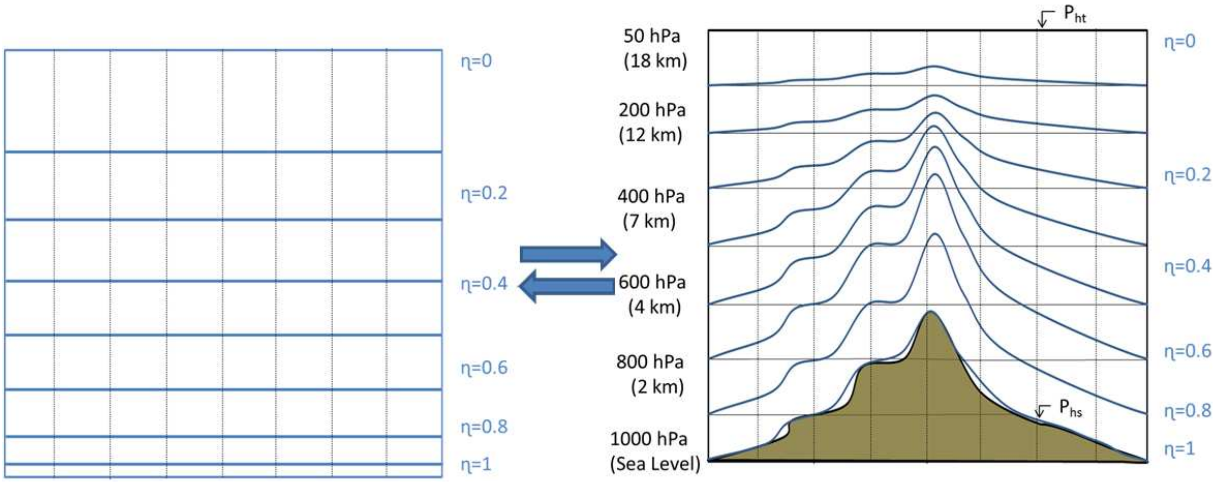

Figure 3: η Coordinate system

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, which is a product of METI and NASA, 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 Figure 4 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.

Due to the difference in grid and ground surface resolution in WRF and Fluent solution domains (Figure 4), interpolation failures may be observed in the application of coupled boundary conditions for Fluent solutions. In this study the ground level of WRF domain is locally shifted to the same level of the Fluent domain and the interpolation in the vertical direction is performed.[13]

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.

After the unsteady solutions are carried out, a terrain fitted surface which is at specific height above the ground level is generated and velocity magnitude data on this surface are obtained in 10 minute intervals.

Wind energy flowing through a volume A is basically:

$$E = \frac{1}{2}mv^2 = \frac{1}{2}(Avt\rho)v^2 = \frac{1}{2}At\rho v^3, \tag{3}$$

So wind power can be expressed as:

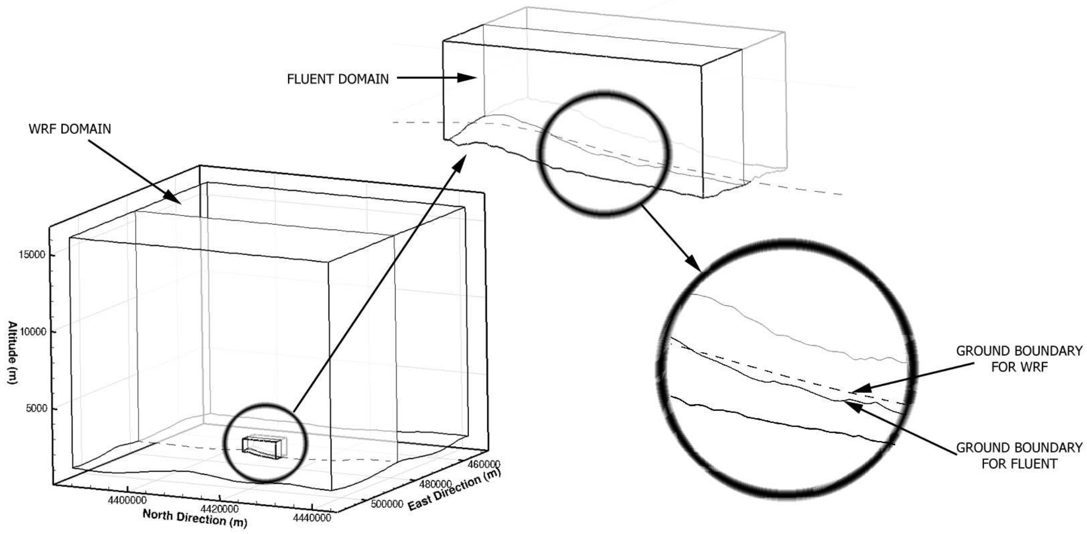

Figure 4: WRF and Fluent solution domains and close-up views

$$P = \frac{E}{t} = \frac{1}{2} A \rho v^3. \tag{4}$$

A more meaningful parameter that can be used for any type of wind turbine is power density which is:

$$PowerDensity = \frac{P}{A} = \frac{1}{2} \rho v^3. \tag{5}$$

For getting the average power density for a day, velocity magnitude data taken at 10 minute time intervals are integrated and divided by 24 hours.

Weibull probabilty distribution function is a widely known statistical distribuiton function which is used for wind velocity distributions. For the wind velocity distribution case, it represents the probabilty (or frequency) of wind speed.

Weibull distribution function can be given as:

$$f(x; \lambda, k) = \frac{k}{\lambda} \left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} \tag{6}$$

where λ is the scale factor, k is the shape factor and x is the wind speed for the case which will be examined in this study.

For the interpretation of these parameters it can be said that λ is related to the most probable wind speed and; k is related to the shape and width of the distribution. Low values of k indicates a scattered distribution whereas high values of k indicates clustered distribuiton around λ value.

Furthermore, Weibull distributions and wind rose patterns for 3 points, 2 of which are the hotspots for potential wind power density are acquired using the data mentioned above.

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. Using these solutions, wind power energy density at 100 meters above ground level are obtained. Also, Weibull distributions and wind rose patterns for 3 points seen in Figure 6, 2 of which are the hotspots for wind power potential density are acquired.

Nested WRF solutions are first obtained for a 24 hour period, within a parent domain of 3 km horizontal resolution and a nest of 1km resolution around METU campus in Ankara. The solutions were done for the date 15.06.2011 starting from 00:00 GMT 0. 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.

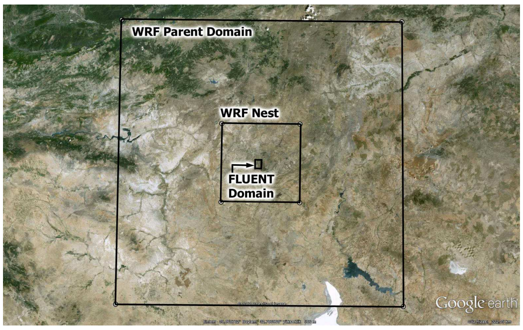

Figure 5: Borders of WRF nests and Fluent solution domain

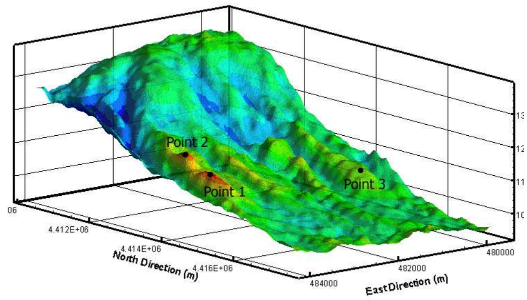

Figure 6: Location of the Wind Power Potential Density Hotspots and Control Point

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 24 hour period first with WRF, and then with Fluent on terrain fitted unstructured grids in a coupled fashion with the WRF solution.

As mentioned earlier, the ground levels of WRF and Fluent domains do not match exactly due to the difference in grid resolutions and interpolation failures can be observed. In this study, the ground levels are equated by shifting the WRF ground level locally before interpolating boundary conditions.

The unsteady flowfield solutions obtained at 100 meter above ground level are given in terms of veloctiy magnitude contours in Figure 7. Z-coordinate is scaled up by 4 in order to see the effects of topography more clearly. Before the analysis, it is noteworthy to say that the prevailing wind direction for METU campus is North-East meaning the wind blows South-West direction. As seen from Figure 7 general idea that wind speed is higher in high altitude regions may prove to be wrong. It is clear from the Figure 6 that the locations with high wind speed are not where the altitude is high but are usually locations where wind is not blocked by the topography.

As briefly mentioned in introduction and method section, wind power density is basically kinetic energy of the wind passing through a unit area per unit time and can be seen in eqn 5.

For calculation of the mean wind power potential density, flowfield solutions for a day at 10 minute time intervals are taken on a terrain following surface 100 m above the ground level and integrated, yeilding the potential wind energy that can be produced per unit area. Afterwards the results are divided by 24 hours for obtaining the average wind power potential densities (per unit area). Results can be seen in Figure 8. The previously mentioned argument that wind speed is higher in high altitude regions may prove to be wrong, can also be justified from Figure 8. It is clearly seen that the two hotspots for the wind power potential density are not in the highest altitude locations but they are in the locations where the wind is not blocked by terrain and also is locally high altitude. This clearly shows that geometry of terrain may have a more dominant effect than just high altitude in terms of wind power potential.

Windrose patterns and Weibull distributions are examined for the 3 locations two of which are wind power potential density hotspots (Point 1, Point 2) and a control point (Point 3) as mentioned previously. The reason for selecting Point 3 which is considerably at a smooth location is to distinguish the effect of abrupt changes in topography as in Point 1 and Point 2. Results can be seen in Figure 9. X- axis shows the wind speed whereas the Y-axis shows the frequency of occurance of that wind speed for the weibull distributions. For the windrose patterns, polar coordinate R shows the frequency; θ shows the wind direction; and colors show the velocity magnitude. As an example, %17.5 of the day wind blowed in south-west direction %4 of the time with wind speed between 2 and 3 m/s.

It is seen that in all 3 of the points weibull bin data matches weibull fit distribuitons quite fairly. There are jumps around the weibull fits' most probable wind speed for point 1 and point 2; whereas point 3 matches weibull

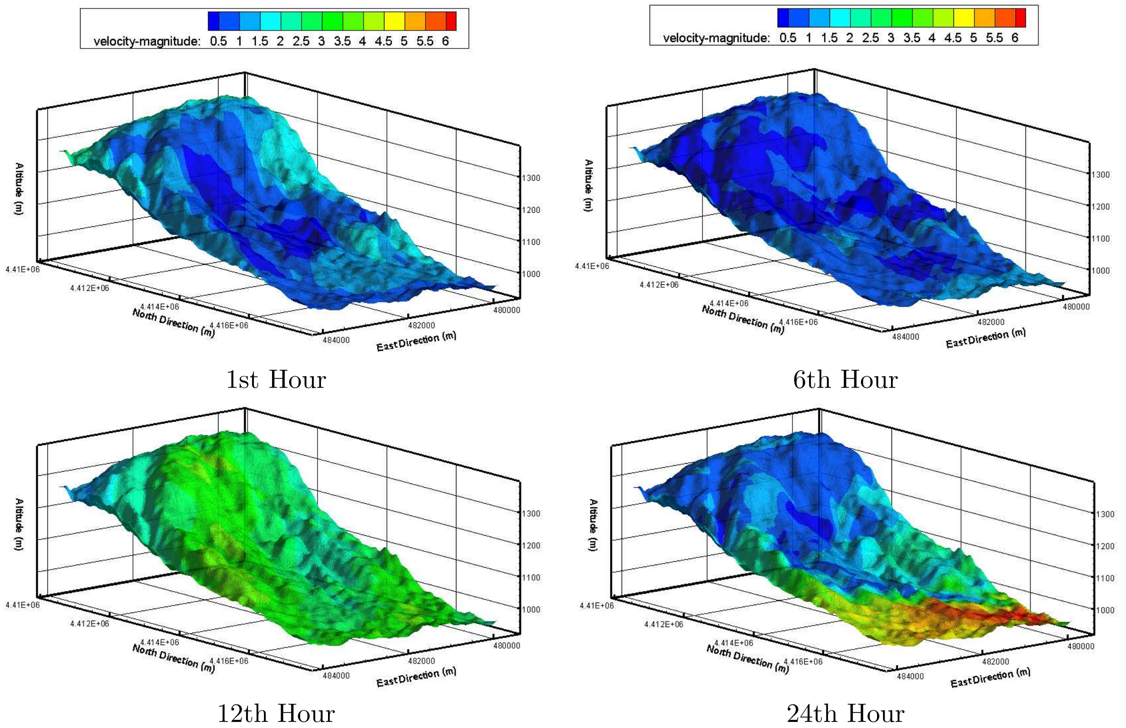

Figure 7: Velocity contours at the 1st, 6th, 12th and 24th hours of the solutions

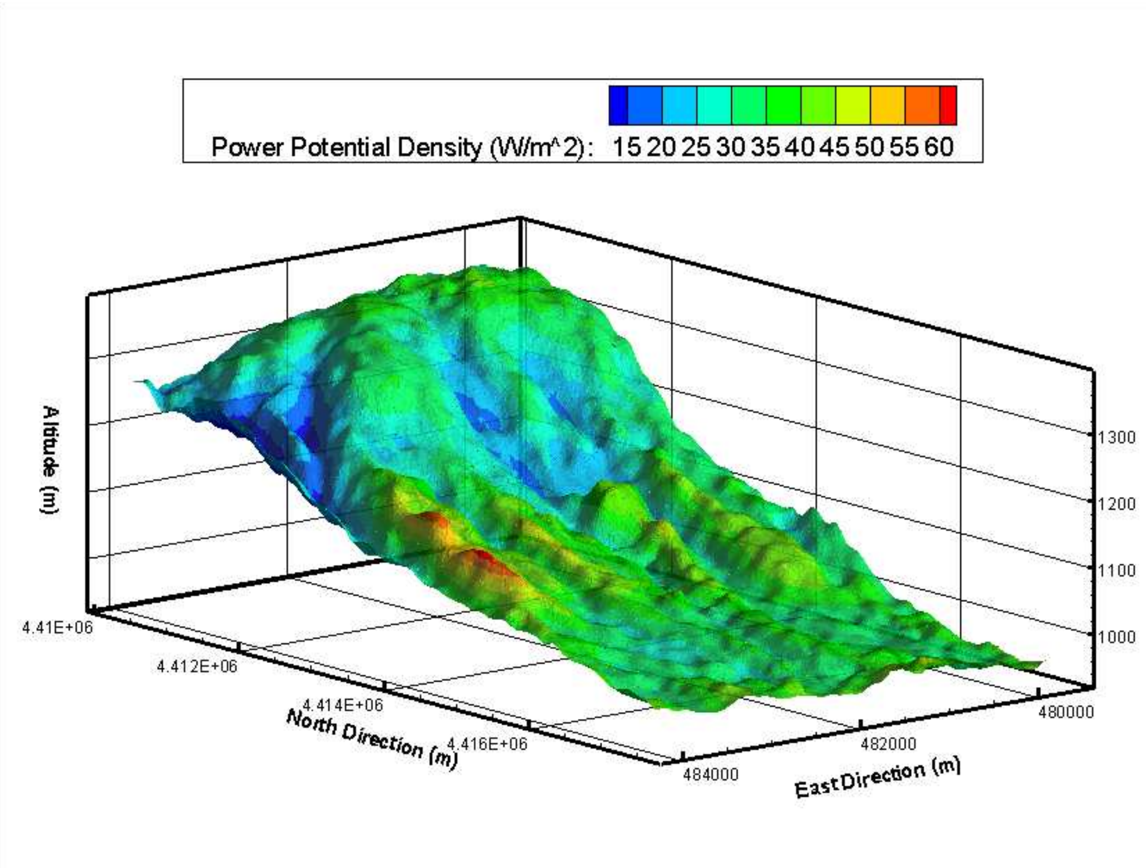

Figure 8: Wind Power Potential Density contours at 100m above ground level

fit better than point 1 and 2. This may be the indication of the effects abrupt changes in the topography on wind velocity bin. As mentioned previously, the prevailing wind direction is North-East for METU campus and results are in agreement. As these Weibull distributions are extracted from a daily data, number of samples for each velocity bin are small. It is thougt that increasing the simulation time, Weibull fit curves may match the velocity bins more precisely.

Scale and Shape parameters of the Weibull distributions for the terrain fitted surface 100m above the ground level are given in Figure 10. It is seen that scale parameter is higher on the south-west parts where wind is not blocked by topographical effects and also where the altitude is low with respect to most of the domain. This is in aggrement with the previous statement about the effects of topography being more important than the effect of altitude on wind power potential. The shape parameter which defines the shape of the Weibull distribution is high on both wind power potential density hotspots meaning the wind speed distribuiton is clustered at the most probable wind speed. Also, the scale parameters are high on both location, indicating these locations (Point 1 and 2) are the most suitable locations for wind turbine placement according to the coupled CFD solutions.

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. However, once the validation is done for this process; it will provide a valuable tool for estimating daily wind power production.

In addition, the accuracy of the Fluent solutions may also be established through grid resolution studies. In this study, the higher grid resolutions could not be performed due to the fact that Fluent can not be run in the parallel mode in the presence of UDFs that change boundary conditions, and serial computations with the total number of cells exceeding 10^7 become prohibitively resource demanding.

CONCLUSIONS

In this preliminary study, the unsteady 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. Using these solutions, wind power energy density at 100 meters above the ground level is obtained. Also, Weibull distributions for 100 meter above the ground level and wind rose patterns for 3 locations are acquired.

Results show that the effect of topography may be more important than just high altitude for wind power potential. Two hotspots for the wind power potential density being in the locations where the wind is not blocked by terrain not in highest altitude locations is a clear indication of this. So, a high resolution terrain following CFD solution is needed for the proper assesment of wind energy. All the results in this study seems consistent with each other. 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.

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Point 1

Point 2

Point 3

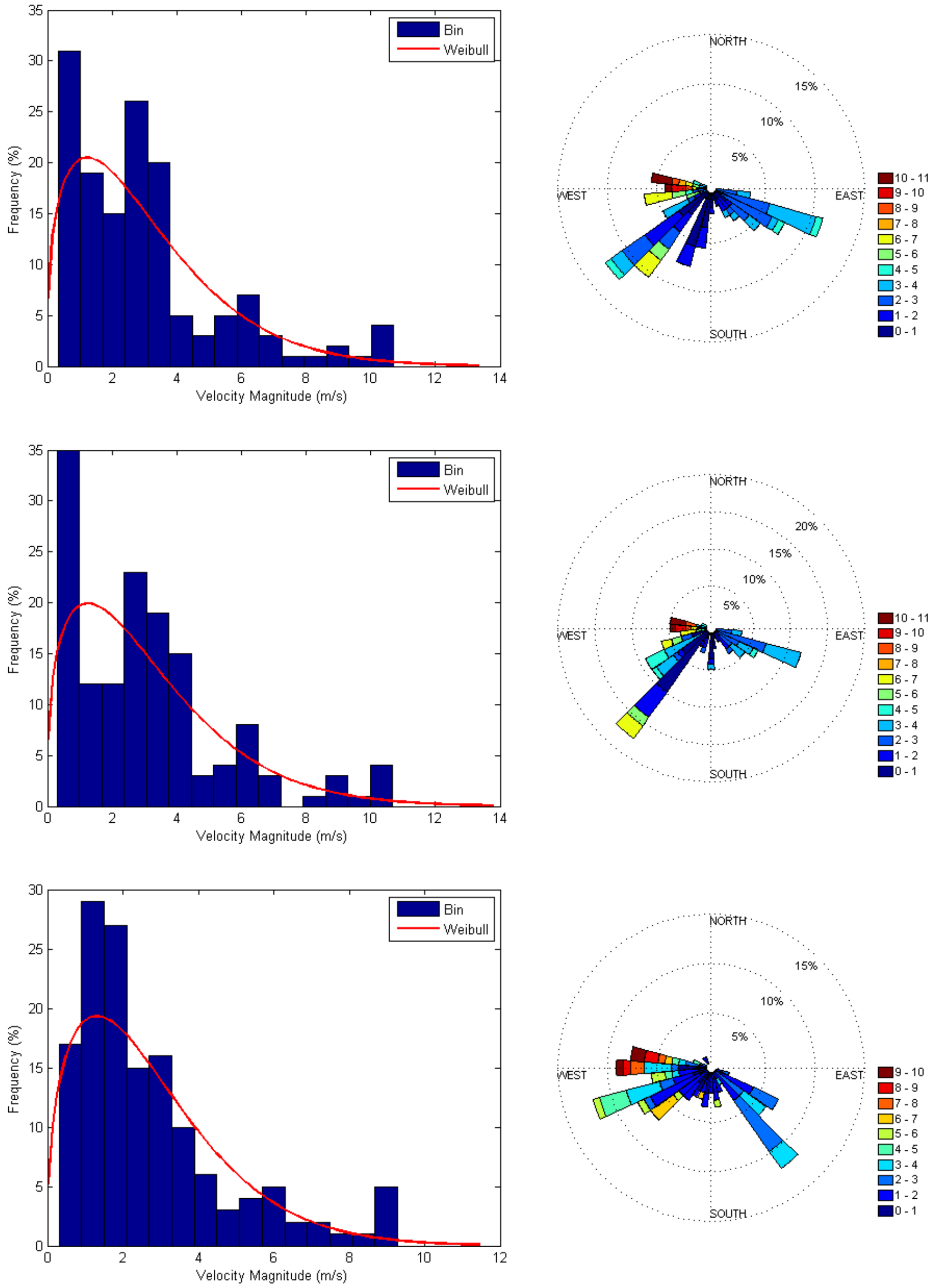
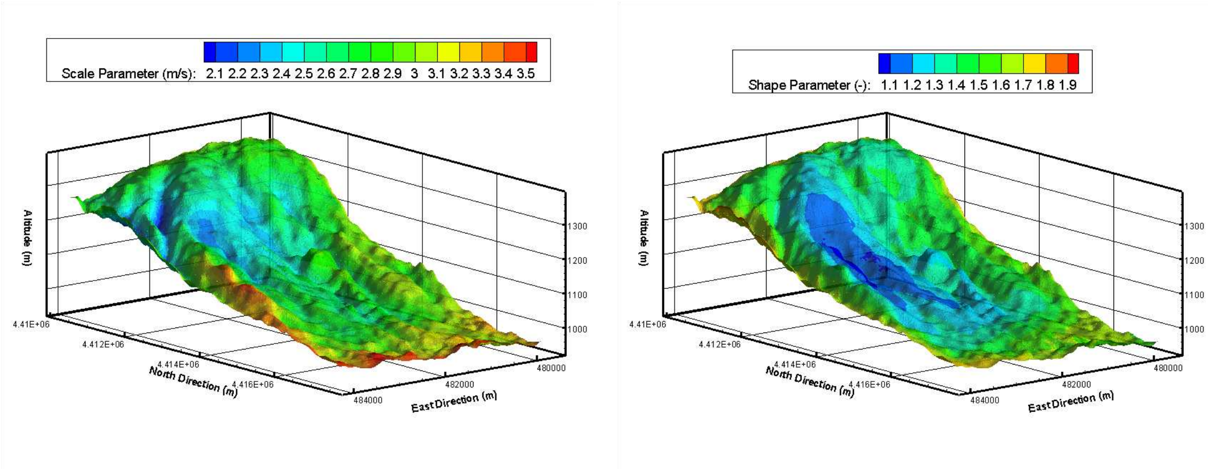


Figure 9: Weibull Distributions and Windrose Patterns for 3 Points in Figure 6



Scale Parameter Shape Parameter

Figure 10: Scale and Shape Parameter Contours at 100m above ground level

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