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RECONSTRUCTION OF WINDSIM FLOWFIELDS BASED ON PROPER ORTHOGONAL DECOMPOSITION METHOD

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ABSTRACT

The placement of wind turbines in a wind farm, which is called micro-siting, is a crucial task regarding the maximization of the energy production in a wind farm. In this study, a novel method developed to improve the micro-siting process. The method correlates the atmospheric flow field solutions obtained from CFD, based on Proper Orthogonal Decomposition (POD) along with observation data. POD calculates dominant characteristics of the artificial solutions of the flow field. Then, it reconstructs real flow field using dominant features and observation data..

INTRODUCTION

Industrial wind energy production is derived from a large number of turbines installed in a wind farm, where the wind resource is available and sustainable. Once the macro-siting of a wind farm is made, the placement of individual wind turbines on the farm, which is known as micro-siting, becomes the main challenge. The fundamental objective of a macro and micro siting of a wind farm is to maximize the energy production while minimizing the unit cost of energy [Amon, 2016]

Micro-siting of the Wind Farms

Micro-siting deals with the specific properties of a wind turbine and the magnitude and direction of the wind speed, which is affected by any obstruction in the wind field and terrain features. For a successful micro-siting a satisfactory high resolution flow-field analysis with current CFD tools and a proper topographical modeling are necessary [Ahmet, 2015]. Field measurements and accurate CFD simulations of wind fields may be used together for the reconstruction of atmospheric flow fields [Dhunny, 2017]. Local winds are often monitored for a year or more, and different sectors numerical solutions are performed for high-resolution digital elevation model (DEM) data, in order to construct detailed wind resource maps of whole flow field [Sevine, 2017].

Figure 1 shows wind speed contours of a complex terrain. In a wind farm, wind turbines are placed the locations where the wind speed is high. In micro - siting process, the reason why the wind field

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solved is that the power gained from the wind(P_{wind}) is related to the cube of the wind speed (V^3).

$$P_{wind} \propto V^3$$

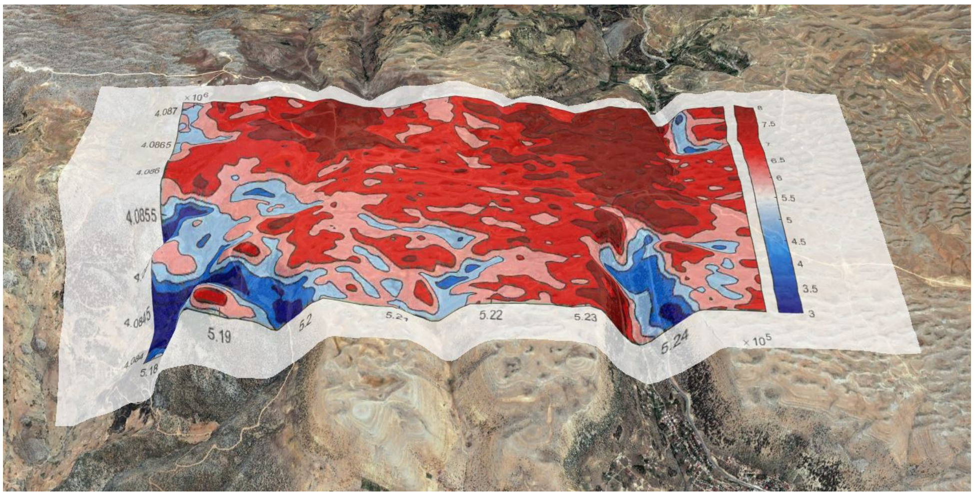


Figure 1: Wind farm micro-siting, wind resource map of Mut/Mersin

Micro-siting with WindSim

WindSim is used for designing wind farms to construct more profitable wind farms. In general, it is used by wind resource and energy assessors, meteorologists, academic institutions and so on. The software helps to optimize park layouts by identifying turbine locations with the highest wind speeds -but with weak turbulence- to maximize production. WindSim software is a solution based on CFD that combines numeric processing and 3D post processing [WindSim, 2017].

For the WindSim solution process, firstly terrain model is generated based on digital elevation models, roughness maps and user inputs such as height above ground, height distribution factor number of cells in the z-direction and so on. Secondly, artificial wind fields are obtained for 12 sectors, based on the terrain model created using RANS equations and k-epsilon turbulence model [Sevine, 2017]. Each sector solutions are obtained from different CFD cases with different wind direction, hence sectoring process is a computationally costly considering at least 12 different sectoral input with a fine grid [Ahmet, 2015].

WindSim works in modular approach for each step:

- Terrain
- Wind Fields
- Objects
- Results
- Wind Resources

Terrain module: produces a 3D model of the terrain around specific wind farm based on digital elevation and roughness data. The factors that affect the wind flow on the terrain can also be modeled such as forested areas and human made structures and so on.

Wind Fields module: produces the wind database. The module simulates how the terrain affects local wind conditions regarding speed-ups, direction shifts, and turbulence. Various physical and numerical models exist in the WindSim.

Objects module: is used for positioning turbines and for climatologies. For this study only climatology data is provided for this module. Wind speed and direction are generally obtained from a meteorological measurement tower (met-mast) in a wind farm, and those data are stored for at least one year to make a valid and successful wind farm siting. WindSim takes these statistical measurement data for at least one point in the wind farm, and corrects artificial wind field solutions based on these statistical data.

Results module: is the module where the inspection of flow variables such as wind speed, directional shifts, the turbulent intensity is done. The results of the wind fields at specific heights above ground and the wind sectors could be analyzed.

Wind resource: map is established by weighting the wind database against measurements by interpolation. The wind resource map is the basis for the energy optimization.

Objectives

The main purpose of this study is to reconstruct unknown flow fields based on Proper Orthogonal Decomposition Method using artificial flow fields obtained by CFD and real meteorological observation wind data.

METHOD

In this study atmospheric flow solutions obtained from WindSim are used together with the Proper Orthogonal Decomposition (POD) method for the reconstruction of the wind fields over wind farms. The numerical flow solutions are artificial because they are steady-state solutions. As the nature of the wind is unstable, those solutions are non-realistic; therefore, they needed to be corrected using some real observation data.

In general, the wind fields over wind farms are reconstructed based on the yearly statistical observation data obtained from the met-mast tower located in the wind farm along a year. Primary challenge for the reconstruction is the usage of the statistical data. While WindSim uses some interpolation techniques for this process, our aim is to develop a novel method based on POD.

Proper Orthogonal Decomposition (POD)

The proper orthogonal decomposition (POD) is a powerful and elegant method for data analysis aimed for the modal decomposition of an ensemble of functions, such as data obtained in the course of experiments or numerical simulations [Liang , 2002]. The POD method is currently used for various applications, such as inverse design problems, face recognition, communication,data compression, derivation of reduced order models and so on [Sevine, 2017]. For example, [Sirovich, 1987] obtains the face portraits by providing only some part of the faces based on a method of snapshot technique. The method of snapshots technique can be used for the determination of the dominant POD modes for large problems like CFD which requires substantial memory and computational cost. [Mu, 2016; Ni, 2016]. As the POD method requires dataset, the artificial sectoral solutions are used as snapshot vectors and the dataset $[X]$ is created using directional velocities (u, v, w).

$$[X]_{m\times n} = \begin{bmatrix} u_{1,1} & u_{1,2} & \cdots & \cdots & u_{1,nsnap} \\ u_{2,1} & u_{2,2} & \cdots & \cdots & u_{2,nsnap} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ u_{nnode,1} & u_{nnode,2} & \cdots & \cdots & u_{nnode,nsnap} \\ v_{1,1} & v_{1,2} & \cdots & \cdots & v_{1,nsnap} \\ v_{2,1} & v_{2,2} & \cdots & \cdots & v_{2,nsnap} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ v_{nnode,1} & v_{nnode,2} & \cdots & \cdots & v_{nnode,nsnap} \\ w_{1,1} & w_{1,2} & \cdots & \cdots & w_{1,nsnap} \\ w_{2,1} & w_{2,2} & \cdots & \cdots & w_{2,nsnap} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ w_{nnode,1} & w_{nnode,2} & \cdots & \cdots & w_{nnode,nsnap} \end{bmatrix}$$

u,v,w : velocity components at x, y and z direction
*nnode : Number of nodes (3*nnode = m)*
nsnap : Number of snapshots (nsnap = n)

The data set $[X]$ can be expressed in terms of orthogonal vectors and singular values (Singular Value Decomposition, SVD).

$$[X]_{m\times n} = [U]_{m\times m}[S]_{m\times n}[V]^T_{n\times n}$$

$[U]$ and $[V]$ are POD basis vectors, and $[S]$ is the singular value matrix.

Original data can be reconstructed in terms of basis vectors $[U]$ and the POD coefficients ω.

$$[X]_{m\times n} = [U]_{m\times m}[\omega]_{m\times n} \quad where \quad [\omega]_{m\times n} = [S]_{m\times n}[V]^T_{n\times n}$$

$$\vec{X}_i = [\vec{U}_1\omega_{1,i} + \vec{U}_2\omega_{2,i} + \cdots + \vec{U}_m\omega_{m,i}] \quad ; \quad i = 1, 2, ..., n$$

The reduced form of a reconstruction may be obtained smaller number of modes:

$$\tilde{\vec{X}}_i = [\vec{U}_1\omega_{1,i} + \vec{U}_2\omega_{2,i} + \cdots + \vec{U}_k\omega_{k,i}] \quad , \quad k << m$$

POD coefficients may also be evaluated for a small number of given control points, $\vec{X}_{l_{point},i}$ (e.g. wind mast data points).

$$(\omega) \rightarrow \tilde{\omega}_i \ , \ i = 1, 2, ..., k \ \ (unknown\ coefficients)$$

$$[U]_{red}\tilde{\vec{\omega}} = \vec{X}_{l_{point},i}$$

$$\tilde{\vec{\omega}} = [U]_{red}\backslash\ \vec{X}_{l_{point},i}$$

l_{point} *: Known (given) solutions*

Based on the proper coefficients $\tilde{\omega}'s$ wind field is reconstructed as follows:

$$\tilde{\vec{X}}_i = [\vec{U}_1\tilde{\omega}_{1,i} + \vec{U}_2\tilde{\omega}_{2,i} + \cdots + \vec{U}_k\tilde{\omega}_{k,i}]$$

RESULTS

For this study, computations are done for the complex terrain around Mut Province in Mersin/Turkey where several wind farms are located. The location is around middle part of the Taurus Mountains. Taurus Mountains, Turkish Toros Dalari, mountain range in southern Turkey, a great chain running parallel to the Mediterranean coast [Brittanica, 2014]. The computational domain is created on the ground which is $3.5km \times 7km$ in the northing and easting directions (Figure 2).
The results of this study will be mentioned for the following sections:

- WindSim solutions
- Reconstruction of the wind fields by POD
- Comparison with WindSim reconstruction

WindSim Solutions

For the WindSim simulations METUWIND's WindSim license is used which is the version of 6.2.0 .

Terrain Module:

In this module, general terrain specifications are entered to the WindSim in terms of terrain extensions, roughness height, height above terrain, number of cells in z-directions and so on. For the terrain extension part, coordinate system is chosen as global which doesn't convert given coordinates to newer one. Later the objects will be defined based on the coordinate system chosen here. Roughness height is specified constant as 0.01, height above terrain is 1000m and number of cells in the z-direction is 30 (Figure 3, 4). The surface resolution is around 38 m and the vertical resolution is tried to be chosen as small as possible, which is less then 5m.

Wind Fields Module:

This module is related with the artificial numerical solution of the wind fields, and boundary conditions, physical models, convergence criteria is specified here. Uniformly distributed 12 sectors are used for the runs (Figure 5). The wind speed above the boundary layer is given as 9 m/s which is reasonable for the Mut province. RNG $k-\epsilon$ is used for the turbulence model, and finally the convergence criteria is 0.001. As a sample solution 0° (north-inflow) sector results are shown in Figure 6 in terms of residual and wind field at 40m above the ground.

Objects Module:

As the purpose of the study is compare a new-developed method POD vs. WindSim interpolation technique, the same climatology data is given for both POD method and WindSim. This data is not obtained from the measurements, it is created from artificial numerical wind field solutions. Reason for creating our own climatology data is for more accurate comparison, because if one-point measurement data is used for climatology it would be impossible to make cross-check for other points on the wind farm. However, using an extracted climatology from the numarical solutions provide a chance to compare whole 3D wind field instead of one point comparison. Therefore, another artifical wind field is solved different sector which is 23° . A point in the wind field is chosen like a met-mast point, the 23° solution at that point is given as climatology data. Then, the purpose is to reconstruct 23° solution using other 12 sector solutions and the data provided for climatology (Figure 7).

Results Module:

The results of the wind field simulations are stored in vertical extension from ground specified in the Wind Field module. The result module extracts 2D horizontal planes from this database. 0° , 90° , 180° and 270° sectoral results of 40m, 60m and 100m are shown in Figures 8 and 9.

Wind Resources Module:

As mentioned in the method section, WindSim makes interpolation using observation data to obtain wind resource maps. For making comparison easier these wind resource map data is converted to MATLAB format and replotted using it (Figure 10).

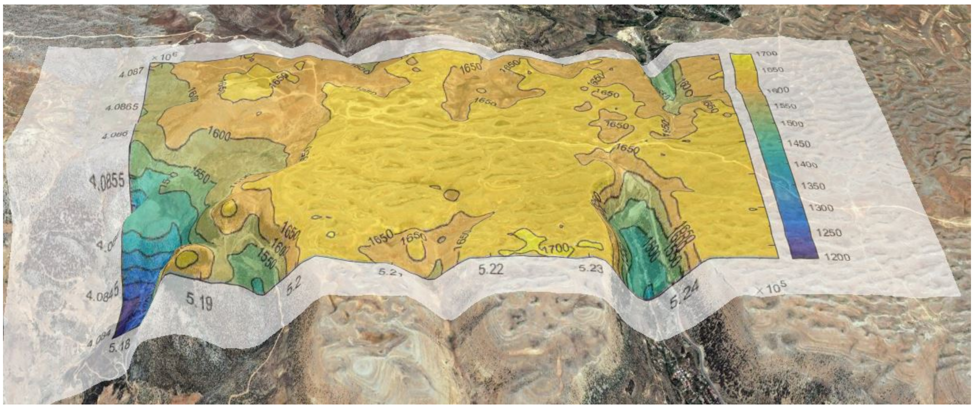
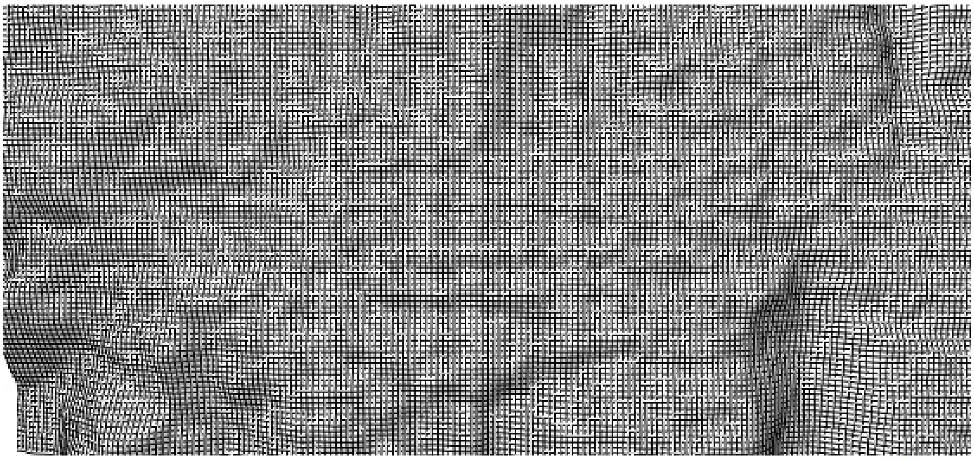
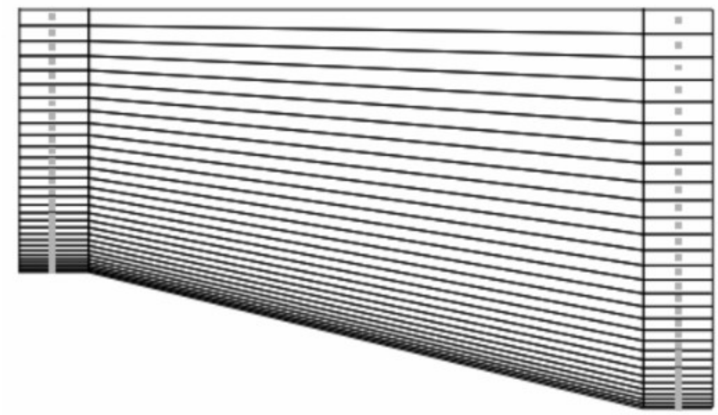


Figure 2: Digital elevation map (DEM) of computational domain, Mut/Mersin



	x	y	z	total
Grid spacing (m)	38.2	38.2	Variable	-
Number of cells	186	87	30	485460

Figure 3: Digital terrain model, grid (xy)



.	1	2	3	4	5	6	7	8	9	10
z-dist. max (m)	3.0	10.0	18.9	29.7	42.3	56.8	73.2	91.5	111.7	133.8
z-dist. min (m)	4.6	15.2	28.8	45.1	64.3	86.4	111.4	139.2	169.8	203.3

Figure 4: Digital terrain model, grid (z)

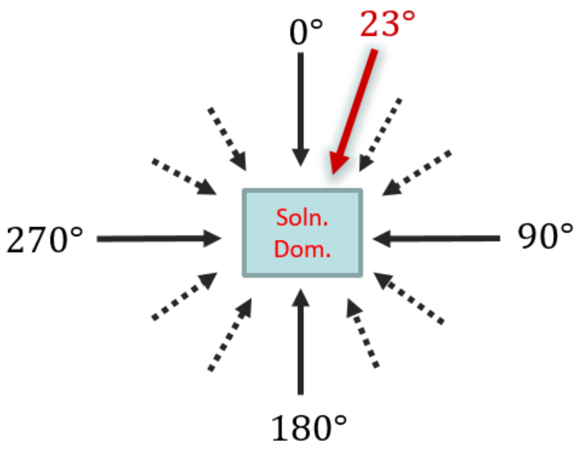


Figure 5: WindSim sectoring scheme

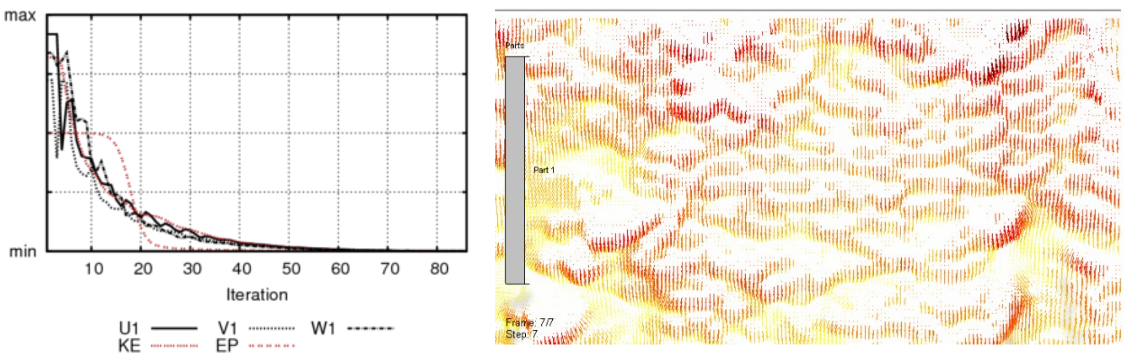


Figure 6: Residual graph and wind field solution for sector 0°

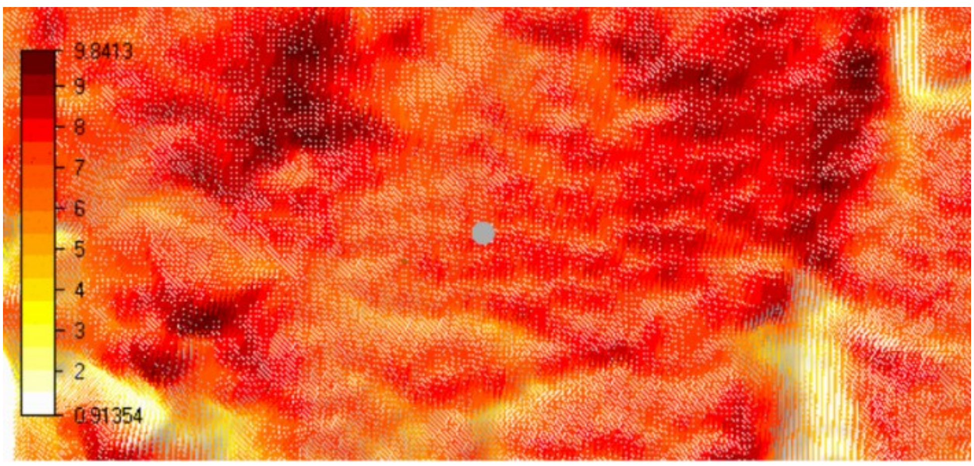


Figure 7: Wind speed 40 meters above ground for 23° sector and climatology station

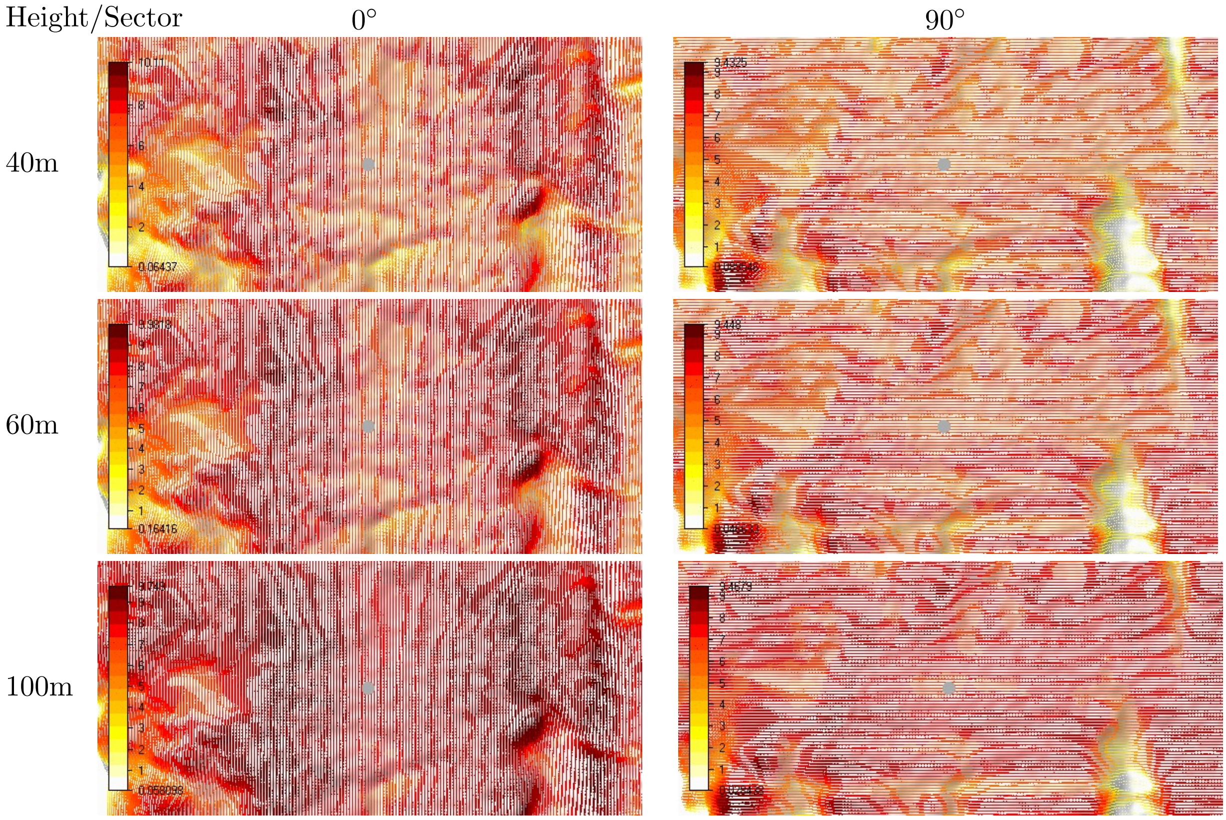


Figure 8: WindSim wind field results, sector 0° and 90°

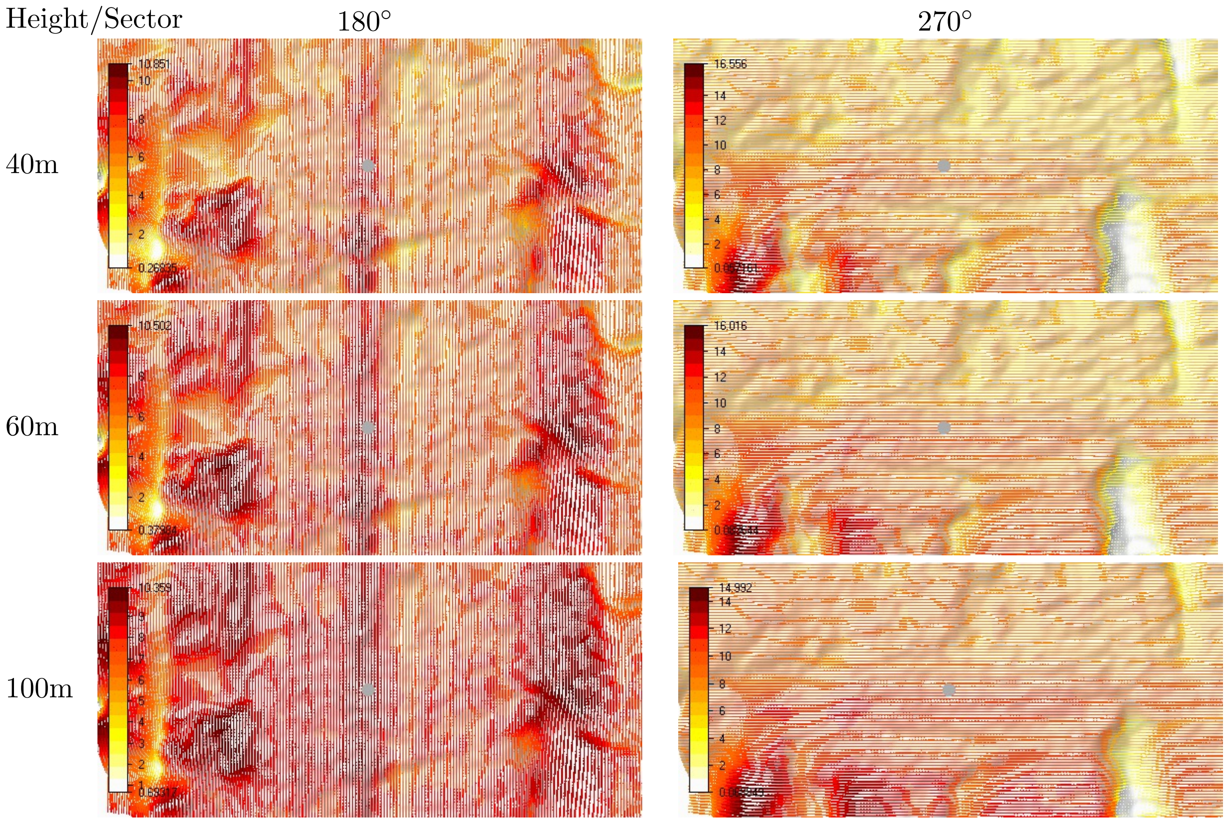


Figure 9: WindSim wind field results, sector 180° and 270°

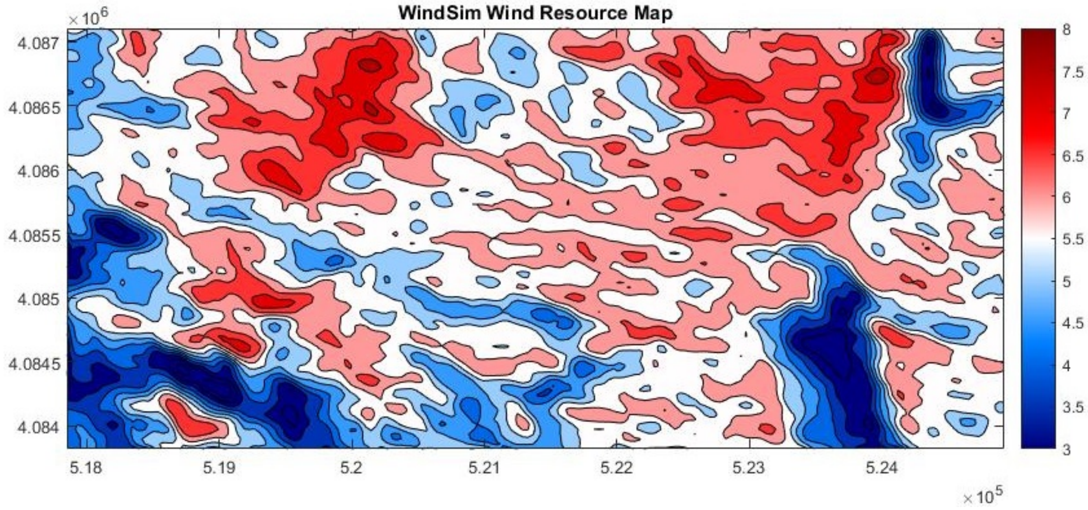


Figure 10: WindSim wind resource map at 40m height

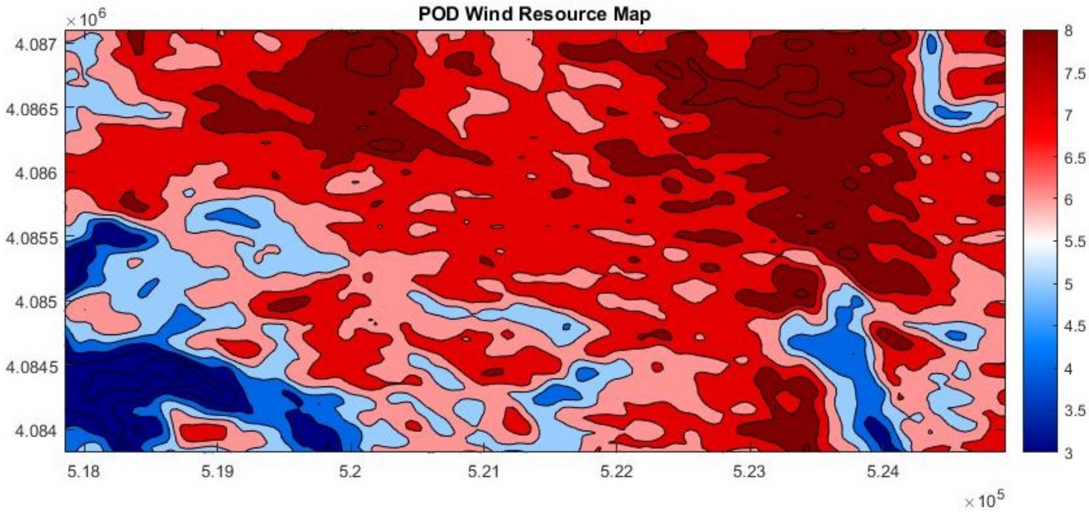


Figure 11: POD wind resource map at 40m height

Reconstruction of the Wind Fields by POD Method

Artificial wind fields obtained from the WindSim are used for the reconstruction of the atmospheric wind fields based on POD method. The purpose is to obtain a similar wind resource map with the one obtained from the WindSim. As done in WindSim, same climatology data is used which is 23° sector solution of WindSim CFD. The result of the POD is shown in Figure 11

Comparison of the Wind Resource Map with Exact Solution

Wind resource maps are obtained from both WindSim and POD method. As mentioned above same numerical solution is used for a climatology data. In Figure 12, 23° sector solution at 40m height shown as WindSim Exact. The purpose is to obtain the exact solution using WindSim and POD method and the comparison of them against exact solution. As it can be seen from the figure most of the parts of the wind farm region POD method catches the exact solution while WindSim underestimates the wind speed for the Mut region. To observe and make further comparison error estimation is done in Figure 13. This error estimation is nothing but the absolute error distributions. While POD method has more blues in the contour plot, WindSim has generally light blue and white areas in the region which means that POD results are more closer to the exact solution.

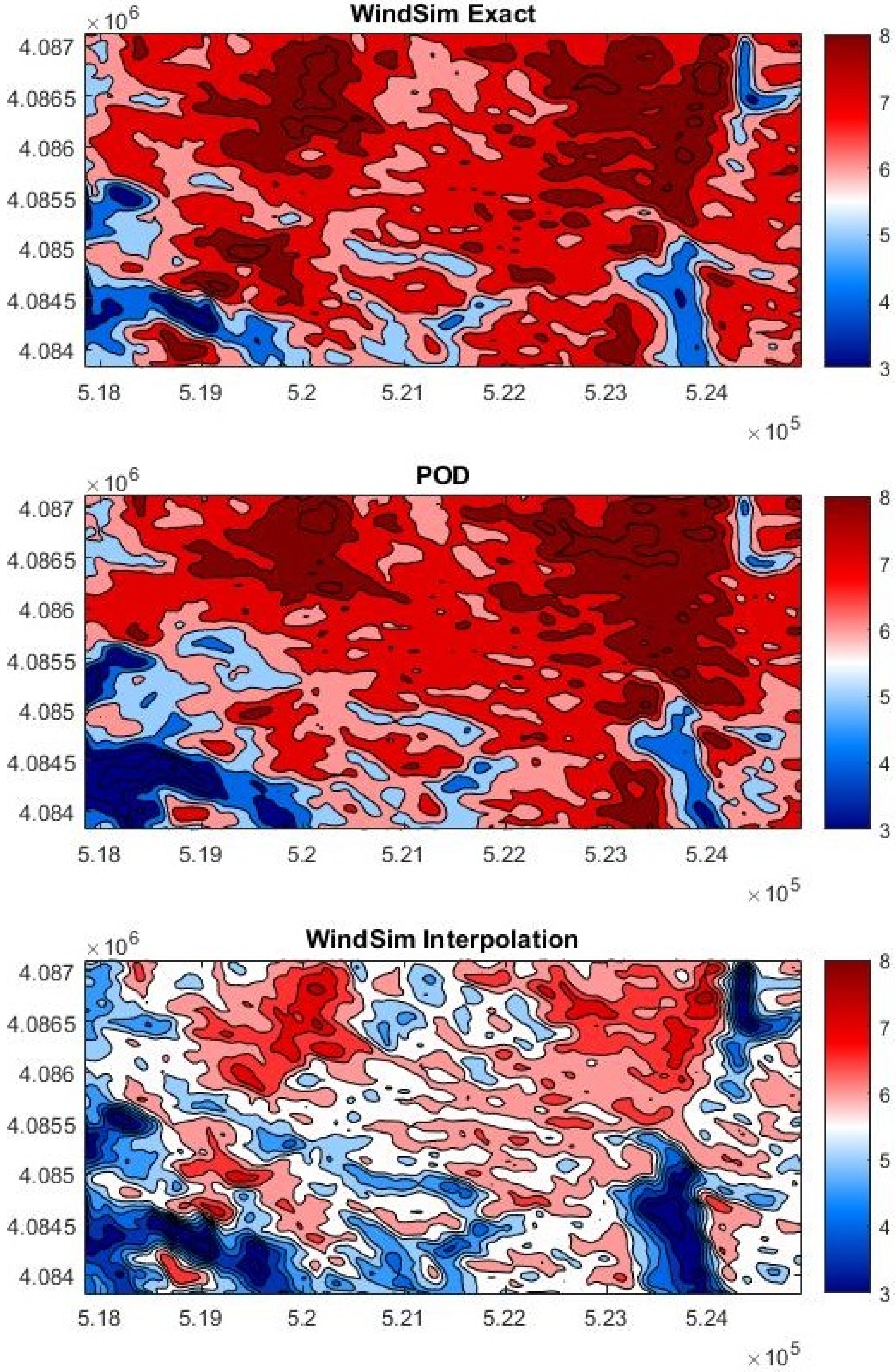


Figure 12: POD wind resource map at 40m height

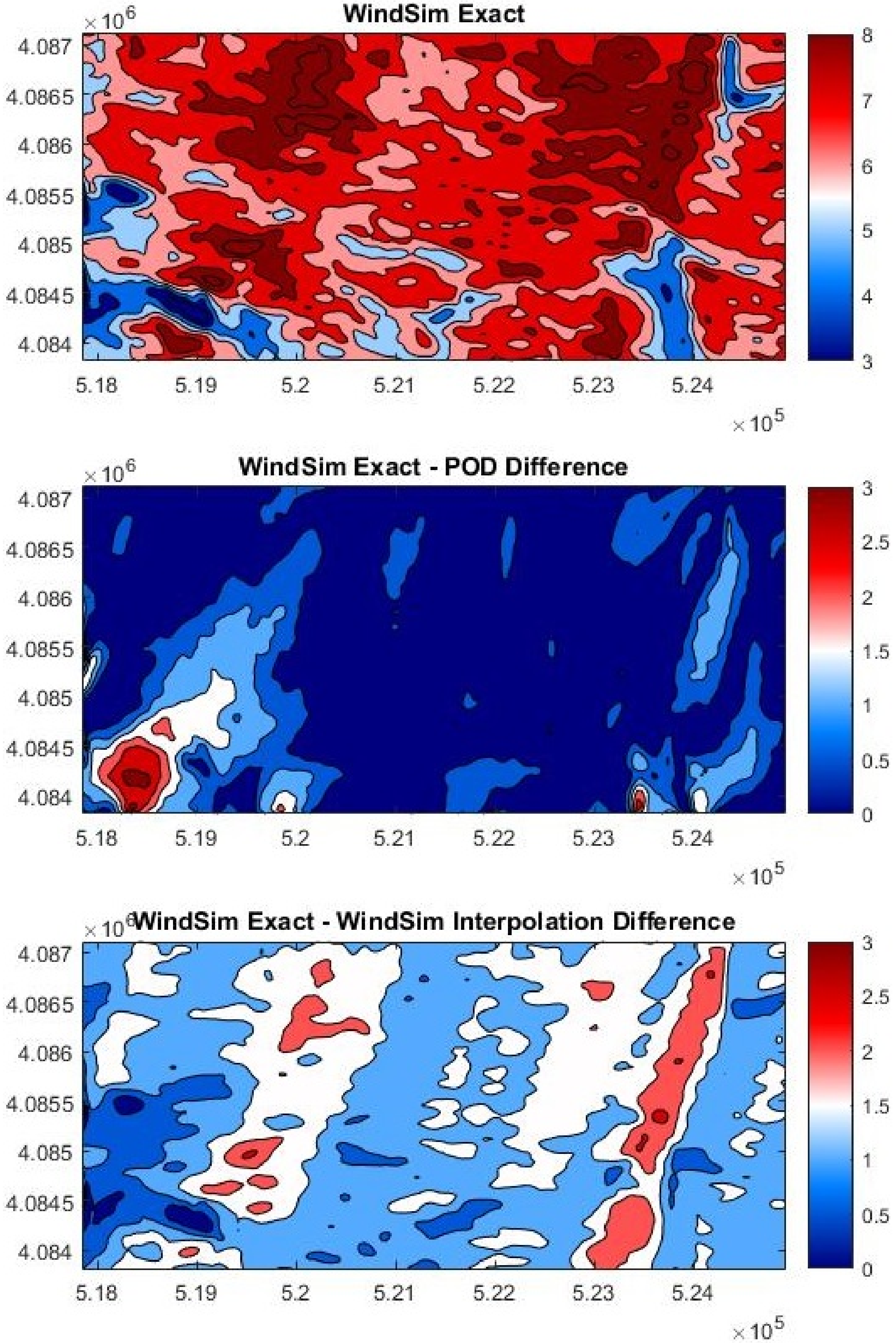


Figure 13: POD wind resource map at 40m height

CONCLUSION

In this study, atmospheric wind fields are solved and wind resource maps are reconstructed based on POD methodology. The reconstruction algorithm is developed and applied to the atmospheric wind fields. It is shown that the POD method successfully captures the dominant characteristics of the sector flow fields, and create a correlation between the solution at grid points within the domain and the dominant flow characteristics. For the validation the results of POD method is compared against WindSim exact solution and WindSim wind resource map interpolation. It is shown that POD method is mostly superior to WindSim interpolation techniques.

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