Wind Farm Uncertainty Reduction by High-Resolution Mesoscale Wind Flow Modeling

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INTRODUCTION

This work describes the accuracy of V-Bar's high-resolution mesoscale modeling platform when estimating the long-term mean annual hub-height wind speed for wind farms. Our studies encompass wind projects with a diverse range of topographic complexity. The mesoscale modeled wind speeds are compared directly to long-term mean annual hub-height wind speed estimates from meteorological towers within the modeled domain. We review mesoscale wind flow model performance in simple terrain, moderate terrain, and complex terrain.

For a given wind farm project area we define terrain complexity as follows:

1. **Simple** – topographic elevation variation of less than or equal to 25 meters
2. **Moderate** – topographic elevation variation of > 25 to less than or equal to 75 meters
3. **Complex** – topographic elevation variation of more than 75 meters

We present mesoscale modeling residual difference statistics in the following categories:

I. **Mean Absolute Difference**: the mean absolute values of the differences between the mesoscale model prediction of hub-height wind speed and individual on-site met tower observations

II. **Project Standard Deviation:** model results versus more than two on-site met towers within a project, standard deviation is calculated on a project basis

RESULTS SUMMARY: It is shown that for mesoscale modeling at high resolution, the mean absolute deviation of wind flow modeling from met tower estimates averages 1.3% for simple terrain, 1.9% for moderate terrain, and 3.4% for complex terrain. It is shown that for high-resolution (200 m horizontal grid spacing) mesoscale modeling in complex terrain, the mean absolute deviation of wind flow modeling from met tower estimates has 40% less deviation than found when 600 m horizontal grid spacing is used.

MODELING TECHNIQUE

These results are derived from mesoscale modeling over a domain at the project scale (say, 25 x 25 km to 100 x 100 km) and with full physics resolution (or "horizontal grid spacing") at turbine side-by-side spacing scale (300 m or less) for V-Bar client wind farms. The results are down-scaled, using shear extrapolation, to a topographic resolution of either 10 meters or 30 meters. The long-term mean annual wind speed results have been bias corrected ***en masse***, based on the mean bias of the model results to the estimated on-site met tower wind speeds at hub-height. This technique preserves the modeled wind flow patterns, which represent the fundamental ability of this independent wind flow modeling technique to reproduce realistic wind speed patterns, while shifting the pattern to reflect measured wind speeds. As a result, the residual error, or the residual difference between the modeled wind speed and the measured met tower wind speed, can be used to help quantify the remaining uncertainty in the wind flow pattern. When sufficient meteorological towers are present within the domain, the standard uncertainty, or wind flow modeling error, can be quantified for use in estimating site P-values.

Mesoscale modeling is a highly-recognized atmospheric modeling technique used to forecast meteorological variables (e.g. wind, pressure, temperature, humidity, precipitation) within any geographical area. The modeling is performed by computationally solving a set of non-linear equations which represent the evolution of atmospheric state. Other modeling techniques used in the wind industry are often linear or lack the physics (e.g. moisture, atmospheric stability, solar radiation) required to simulate natural weather conditions. Mesoscale-modeling was also found to be the most accurate method, overall, for predicting long-term wind resource patterns in the first AWEA wind flow modeling comparison of linear, CFD, mesoscale, and other techniques. The results of that study were presented by V-Bar at the Wind Resource and Project Energy Assessment Workshop in 2013.

Mesoscale models were first created in the early 1970's, were greatly modified and advanced at elite atmospheric science universities in the 1980's, and have been extensively utilized and improved as computing power has allowed greater physical detail to be addressed. Some relevant references that document the work by Poulos and Kumar are listed at the end of this document, and we will provide them upon request. Many consultants and companies in wind energy use mesoscale models for a variety of purposes, including wind flow modeling of the long-term mean annual wind speed, wind mapping over states/countries/continents, virtual reference station data creation, and real-time wind farm production modeling, among many other uses. V-Bar's principals have been using advanced mesoscale modeling and computational fluid dynamics (CFD) techniques since 1989.

The V-Bar product uses the state-of-the-science Weather Research and Forecasting (WRF) model (http://www.wrf-model.org/index.php). This product has been specifically designed to improve P50 wind energy production estimates and to reduce the uncertainty of those estimates. When properly applied and objectively compared to on-site wind measurements, the use of mesoscale modeling will generally improve project-specific P-values significantly by reducing wind flow modeling uncertainty.

PROJECTS EVALUATED

The wind energy projects evaluated in this study are in the Americas and span the mid-latitude and subtropical climate zones. The ground cover varies from grassland, to brush-covered, to forested. The topography varies widely, from the simplest U.S. Great Plains topography, to complex terrain of the U.S. Appalachians, to the rolling hills of mid-latitude South America, to 300 m elevation changes in very irregular topography in the high altitude interior Trade Wind zones of northeastern Brazil. In several cases, very narrow ridgelines, of 50-100 m in width, are present. In all cases, the underlying project information is confidential, so only tabular statistics are presented.

CASES STUDIED
Total number of mesoscale modeling cases: 23
Number of simple terrain cases: 5
Number of moderately complex terrain cases: 4
Number of complex terrain cases: 14

METEOROLOGICAL TOWERS STUDIED
Total number of meteorological towers: 124
Number of simple terrain meteorological towers: 29
Number of moderately complex terrain meteorological towers: 27
Number of complex terrain meteorological towers: 68

In all cases the long-term mean annual hub-height wind speed predicted by the mesoscale model for the coordinate of a given met tower is compared to the long-term mean annual wind speed predicted from the data measured at the met tower location (using measure-correlate-predict methods). Model predicted wind speeds for a given met tower coordinate are interpolated bi-linearly between the nearest four modeled grid points (10 meter or 30 meter resolution, with one exception at 90 m resolution, for these cases) at the requisite hub height. The meteorological tower heights vary from 60 meters to 120 meters in height. Hub-heights vary from 80 meters to 98 meters.

WIND SPEED COMPARISON RESULTS

Accuracy assessment model vs. met tower, by terrain complexity, all data:

Terrain Complexity	Mean Absolute Difference (mps)	Mean Absolute Difference (%)	Project Mean* Standard Deviation (%)
All	0.21	2.59	2.17
Simple	0.11	1.28	0.91
Moderate	0.15	1.88	0.92
Complex	0.27	3.43	2.81
Maximum	1.04	13.90	5.91

* excludes projects with two or fewer met towers

Accuracy assessment, model vs. met tower, by raw model grid spacing, before down-scaling, all data:

Grid Spacing (m)	Mean Absolute Difference (mps)	Mean Absolute Difference (%)
200	0.17	2.07
300	0.20	2.39
600	0.33	4.41

Accuracy assessment, model vs. met tower, by raw model grid spacing, before down-scaling, complex terrain only:

Complex Terrain Only Grid Spacing (m)	Mean Absolute Difference (mps)	Mean Absolute Difference (%)
200	0.20	2.66
300	0.26	3.21
600	0.33	4.41

CONCLUSIONS

This study compares mesoscale modeled long-term mean annual hub-height wind speeds to those from 124 tall wind energy project met towers, across terrain of varying complexity.

We conclude that:

1. High resolution mesoscale modeling of long-term mean annual hub-height wind speed is very accurate, with standard deviations of wind flow modeling differences to on-site measurements at met towers in the range of 1% to 3% for the 23 cases studied here. This value is within typical anemometer measurement uncertainty of 3%.
2. Maximum project-wide standard uncertainty of wind flow modeling was 6%, in complex terrain, and with the coarsest model grid spacing studied (600 m).
3. Complex terrain wind flow modeling mean absolute deviations and standard deviations, with values near 3% to 4%, are nearly double the value of those of simple or moderately complex terrain.

During wind project development, this high-resolution modeling platform can help make improved strategic wind farm decisions and reduce uncertainty in wind energy resource assessment estimates.

At financing, wind flow modeling uncertainty can be quantified relative to on-site measurements and, assuming quality of the results is similar to those shown here, can be used to reduce wind flow modeling uncertainty relative to other modeling techniques, leading to improved P-Values.

Future studies will evaluate simulations using model grid spacing under 200 m.

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