EVALUATION OF THE OPERATIONAL MULTISCALE ENVIRONMENT MODEL WITH GRID ADAPTIVITY (OMEGA) FOR USE IN WIND ENERGY POTENTIAL ASSESSMENT IN THE GREAT BASIN OF NEVADA

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1. INTRODUCTION

In order to further assess the wind energy potential for Nevada, the accuracy of a computational meteorological model, the Operational Multi-scale Environment model with Grid Adaptivity (OMEGA), was evaluated by comparing data collected from a wind monitoring tower near Tonopah, Nevada with simulation results.

At this time, the state of Nevada imports almost all of its energy from outside of the state; however, lawmakers in Nevada have required that the state produces 20% of its energy from renewable sources by the year 2015 (Nevada Revised Statutes 704.7801 - 704.7828). Therefore, Nevada must begin to develop its renewable energy sources such as wind, solar, and geothermal. Out of the 50 states, Nevada ranks 21st in wind energy generation potential, however it has not meaningfully developed this potential. As of 2009, Nevada had not developed one megawatt of wind energy generation. As compared to the surrounding states, Nevada is far behind. Oregon has developed 1758 MW, Utah has developed 223 MW, Idaho has reached 147 MW, Arizona has 63 MW, and California has 2798 MW (NREL 2010).

Wind power is highly dependent on the speed and direction of the wind and the consistency of both these quantities at wind turbine heights and locations. Prediction of winds and other weather phenomena in western Nevada can be very difficult due to the complex topography of the Sierra Nevada Mountains and Carson Range in the west, and the basin and range in the east. Topographic forcing plays a dominant role in the development and modification of mesoscale flows in regions of complex terrain, like Tonopah, especially at the level of wind turbine blade heights (~80 m). In order to determine the wind potential for the state and the most appropriate locations for wind turbine placement, meteorological models that predict the wind must be able to accurately represent and account for terrain features and simulate topographic forcing with accuracy.

At present, wind estimates for Nevada have been developed using standard meteorological models and observations. For example, AWS Truewind, in conjunction with the National Renewable Energy Laboratory (NREL) has created a high-resolution dataset (windNavigator) containing detailed wind resource data for points spaced 200 m (650 ft) apart throughout the United States developed through running atmospheric models and observations (from http://www.awstruepower.com). Other studies of wind resources for Nevada and the United States have been performed using standard meteorological models and observations (e.g., Belu 2009). Standard operational meteorological models use grid structures made up of equidistant squares to cover the simulated land area. Two common operational meteorological models, the Weather Research and Forecasting model (WRF) and Pennsylvania State University – National Center for Atmospheric Research Mesoscale Model (MM5) use a square grid system with nesting available (Grell 1995, Michalakes 2004). Grid nesting allows for higher resolution over areas of interest without the computational costs of increasing the resolution over the entire grid. However, in these models, in any given domain, all grid cells are the same resolution regardless of the underlying topography.

Unlike other operational atmospheric models, OMEGA incorporates an unstructured triangular horizontal grid which allows for increased flexibility and accuracy in characterizing areas of complex terrain (Bacon 2000). OMEGA is the first operational atmospheric model to use an unstructured, adaptive triangular grid in the horizontal. OMEGA's triangular grid incorporates technology developed for computational fluid dynamics which was developed to create grids over irregular surfaces such as urban landscapes (Bacon 2000). For some applications, these unstructured grid techniques are recognized as more efficient and accurate than approaches using structured grids (Bacon 2000).

Aside from model performance, other factors may impact the ability of a model to forecast wind effectively. For example, in Mass et al. (2002), the authors questioned whether increasing horizontal resolution led to more skillful forecasts of precipitation, temperature, and winds. The authors found that increasing resolution only helped improve forecasts statistically up to a point; 12 km horizontal resolution provided increased skill over 36 km forecasts, however 4 km forecasts generally did not significantly improve over 12 km. However, 4 km forecasts developed more realistic mesoscale structures than the larger resolution simulations (Mass 2002). The limits on forecasting ability may be due to the quality of initial and boundary conditions put into the model or dependent on the time of initialization.

During a previous experiment, observational data from the Stone Cabin tower were collected using sonic anemometers at 40, 60, and 80 m above the surface for the period February 9 through March 10, 2007 (Koracin 2007). The observations were then compared to model simulations using the MM5 and WRF models at a number of varying horizontal resolutions: 18 km, 6 km, 2 km, 666 m, and 222 m (Koracin 2007). In this previous research, the MM5 did not improve in forecast skill (root mean square error) with increasing resolution and the WRF only showed an improvement from 18 km to 2 km; the WRF skill stayed the same below 2 km (Koracin 2007).

This project used the OMEGA model to simulate flows in the complex terrain of Nevada to determine the effectiveness of using OMEGA for wind potential studies. Point winds calculated from model results at the Stone Cabin Tower location were compared to sonic anemometer observations from the Koracin (2007) study. Additionally, a number of sensitivity studies were run to determine the effect of horizontal resolution, initial conditions, and time of initialization on model performance.

2. METHODOLOGY

The present research evaluated the ability of OMEGA to reproduce point winds as compared to observational data from the Stone Cabin Tower at 40 m, 60 m, and 80 m above ground level. Model sensitivity to horizontal grid resolution, initial and boundary condition analyses, time of initialization, and terrain dataset resolution were tested. OMEGA was run over three different horizontal grid resolutions with minimum horizontal edge lengths of: 18 km, 6 km, and 2 km. The model was initialized at either 00:00 GMT or 12:00 GMT to determine whether time of initialization affected the simulation. For each resolution, the model was initialized using both the Global Forecasting System (GFS) and North American Regional Reanalysis (NARR) to determine model sensitivity to the resolution and information included in the initial conditions. Each 30-day model run was then analyzed using statistical analysis to determine how the model generated winds compared with the observed winds. The statistical results were then compared with the results from the MM5 and WRF simulations to determine the most appropriate model for wind energy potential studies in complex terrain.

2.1 Observational and Model Setting

The area of interest for this study is the complex terrain of the western United States, in particular the state of Nevada. Nevada is characterized by high mountains and low-lying valleys, or basin and range (Fiero, 1986). Most of the state is part of the Great Basin, parallel north-south aligned valleys and mountain ranges. The valleys are generally elevated desert, of 1200 to 1500 meters above sea levels, and the mountain ranges can reach to 4000 meters (Fiero, 1986). Bordering Nevada to the west are the Sierra-Nevadas, the Carson Range, and the White Mountains.

2.2 Observational Methodology

The immediate area of interest is a cell phone tower (Figure 1) 48 kilometers (30 miles) to the east-northeast of Tonopah, NV. This tower is in a location with complex terrain features, especially to the northwest of the tower.

Figure 1: The Stone Cabin Tower in Nevada.

The tower had both sonic anemometers and cup anemometers installed at heights of 40 m, 60 m, and 80 m above the surface for a total of six instruments (Koracin 2007). At each elevation, cup anemometers were installed off the northern tower leg and 3-D sonic anemometers were installed off the southern tower leg. Sensor mounts were designed to ensure the least amount of tower influence on the wind measurements as possible. The sonic anemometer used was a Campbell Scientific CSAT3 model and sampled 20 observations per second. The cup anemometer and wind direction sensor were an NRG Systems #40C cup anemometer and #200P wind direction vane. The data for the cup anemometers was recorded once every minute. The data from both anemometer types was then averaged over an entire hour, the last 10 minutes of the hour, and the last one minute of the hour in order to create a single value to represent the entire hour.

2.3 Model Methodology

Observations in many areas, particularly in mountainous regions, tend to be sparse and therefore it is useful to use mesoscale models to better understand terrain forced phenomena and atmospheric flow in mountainous regions (Weber and Kaufmann 1998). Using a mesoscale model with fine grid resolution allows a closer inspection of the dynamics of the flow and will provide information about the atmosphere that cannot be determined from observations alone. For this project OMEGA was used to model the synoptic, mesoscale, and microscale dynamics of the area surrounding the Stone Cabin Tower in western Nevada. Bacon et. al. (2000), fully described OMEGA. A number of sensitivity studies were employed to test the relative importance of initial data, terrain resolution, and model resolution in predicting the winds. The simulations from OMEGA were then compared with previously collected observational data from the Stone Cabin Tower.

OMEGA is a fully non-hydrostatic, three dimensional prognostic atmospheric model based on a rotating Cartesian coordinate system (Bacon, 2000). The OMEGA model, developed by Science Applications International Corporation (SAIC), is different than traditional mesoscale models because it uses an unstructured, dynamically and statically adaptive grid in the horizontal (Bacon, 2000). The unstructured triangular grid in the horizontal allows for increased flexibility in providing high resolution in areas of complex terrain and allows the model to accurately discretize complex topologies easily by creating meshes for arbitrary surfaces and volumes in three dimensions (Ahmad et. al., 2009, Ahmad et. al. 2005). The grid can also dynamically adapt to follow certain meteorological features such as hurricanes (Bacon, 2000). The unstructured grid used in OMEGA is also highly beneficial for systems where the "breadth of the scales of the physical system is large" (Bacon 2000).

In the horizontal, each grid cell is a triangle, or in 3-dimensions, each grid cell is a triangular prism referenced to a rotating Cartesian coordinate system (Figure 2). The volumetic mesh can be described by: vertexes, edges, faces, and cells. Scalar quantities are defined at the cell centroid whereas vector quantities are defined at the center of the vertically stacked cell faces (Bacon, 2000). In the vertical, all vertically stacked cells (prisms) for any location on the grid possess the same footprint. This is achieved by projection of radials from the center of the earth through the vertices of the surface grid into the vertical and creating vertically stacked grid cells from these vertices (Bacon, 2000).

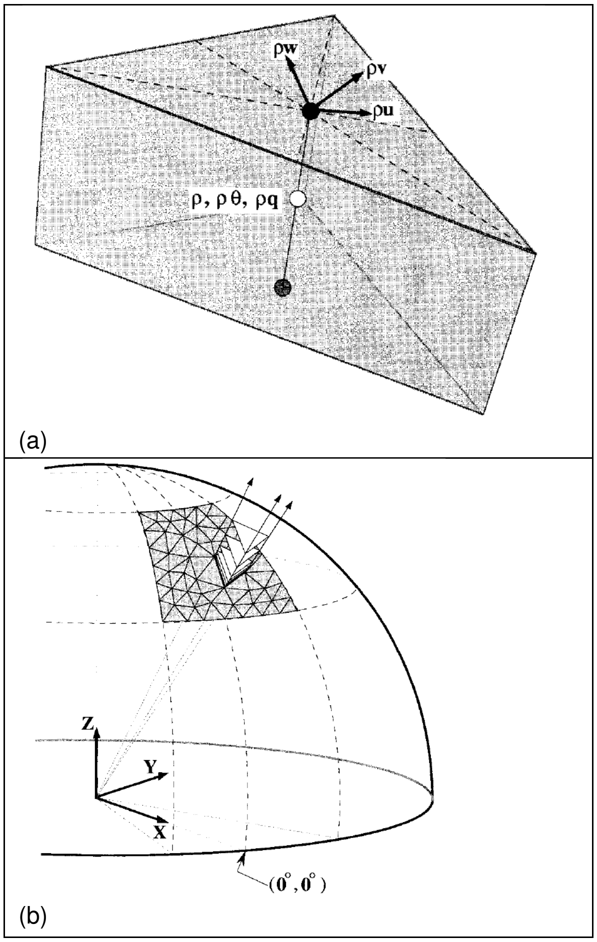

Figure 2: The OMEGA grid (a) element and (b) vertical structure (reproduced from Bacon, 2000).

The number of edges that meet at any vertex is arbitrary. The normal to each face must be calculated in order to calculate fluxes across the face, therefore the grid can be aligned arbitrarily and the grid is naturally separated from the coordinate system. OMEGA uses a rotating Cartesian coordinate system and terrain-following grid. The coordinate system has the origin at the center of the earth, the z-axis passes through the North Pole, the x-axis passes through the equator and prime meridian, and the y-axis is orthogonal to both.

OMEGA implements a finite volume flux-based numerical advection algorithm and a Lagrangian dispersion algorithm (Bacon, 2000). The OMEGA model makes calculations of fluid dynamics using numerical methods to solve the Navier-Stokes equations; these calculations are applied to an unstructured grid in the horizontal and a structured grid in the vertical. The advection, pressure gradient, Coriolis, and buoyancy terms of the momentum equation are all calculated explicitly. The microphysics scheme available in OMEGA is based on the Lin package, the planetary boundary layer is divided into three layers, microphysics is based on an extensive bulk water package (Lin 1983), the cumulus parameterization may be either a modified Kuo scheme (Kuo 1974) or the Kain-Fritsch scheme, and radiation as described previously.

OMEGA can be configured with higher resolution grid cells in operator designated regions but keep a continuous and variable resolution throughout the domain. The interaction between different spatial scales is achieved implicitly, leading to increased efficiency over models that require a step-down into a finer nested grid (Ahmad 2009). Nested grid models such as the MM5 and WRF require sequential placement of increasingly fine scale grids in areas of focus within the domain. The interaction between multiple nests requires the model to calculate additional time steps for each nested grid and may lead to discontinuous changes of speed between grid nests for propagating waves or reflection of the waves off the nest boundaries (Ahmad 2009). The OMEGA unstructured grid approach avoids the problems inherent in a nested grid method.

2.4 Statistical Methodology

To compare results from OMEGA simulations with both the sonic anemometer observations and MM5 and WRF simulation results a number of statistical and empirical data analysis techniques were applied. Root mean square error (RMSE) and index of agreement (IOA) with the sonic observations were calculated for each 30 day model simulation. Distributions of wind speeds were then created using a Weibull distribution and compared to the distribution of the sonic observed winds. All calculations were performed using MATLAB packages.

Root mean square error is a commonly used measure to estimate the differences between values predicted by a model and observed values. Taking the square root of mean square error yields the RMSE, which has the same units as the quantity being estimated; for an unbiased estimator, the RMSE is the square root of the variance. RMSE is calculated by:

$$RMSE = \sqrt{\sum \frac{(O-E)^2}{n}}$$

where *O* is the observed value, *E* is the estimated or modeled value, and *n* is the number of observation/model data pairs (Wilks 2006).

The index of agreement is a value between one and zero where one represents a perfect fit and zero represents no fit and is defined by the equation:

$$IOA = 1 - \left[\sum \frac{(E-O)^2}{\sum (|E-\overline{O}| + |O-\overline{O}|)^2} \right]$$

where the overbar refers to the mean (Koracin 2007).

The Weibull distribution is a continuous probability distribution with a probability density function ‘f’ defined by:

$$f(x;\alpha,\beta) = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left[-\left(\frac{x}{\beta}\right)^{\alpha}\right]$$

where *x, α, β* are greater than zero (Wilks 2006). The shape parameter, α, indicates the dominance of wind regimes and is generally between one and three (Wilks 2006). When α = 1, a low wind speed regime is indicated and when α = 3, a high wind speed regime is indicated. Where α = 2 is a special case of the Weibull distribution called the Rayleigh distribution, indicating a moderate wind speed regime (Koracin 2007). The scale parameter, β, stretches or contracts the distribution along the x-axis; larger values of β indicate that wind speeds are more spread about the mean whereas smaller values of β indicate a tightly clustered distribution about the mean (Wilks 2006).

2.5 Experiment Design

This project focuses on determining the sensitivity of the OMEGA model to differing initial conditions, time of initialization, and grid resolution.

In order to determine sensitivity to initial conditions, the OMEGA model was initialized with analysis data from the NARR, the GFS, and the RAMS model. The NARR analysis data is on a 32 km horizontal resolution grid with 29 vertical pressure levels. The NARR is comprised of data from the NCEP/NCAR reanalysis, radiosondes, dropsondes, pibals, aircraft, surface pressure and wind observations, cloud drift winds, and precipitation observations and analysis. The GFS analysis data is on a one-degree latitude by one-degree longitude grid (approximately 111 x 111 km for the model area) over the entire globe and contains 64 vertical levels.

OMEGA was programmed to have 40 vertical layers with a top boundary of approximately 100 mb. The vertical resolution of OMEGA can be adjusted to focus on certain areas such as the boundary layer by setting the height of the layer closest to the surface and using grid stretching which effectively packs the vertical layers into the boundary layer. The first layer above the surface in this study was set to 11.9 m with a grid stretching ratio of 1.15 for each subsequent layer.

The OMEGA model was run at three differing horizontal resolutions to determine the utility of increasing horizontal resolution on the ability of the model to forecast wind characteristics in complex terrain. Each grid was increasingly focused on the Stone Cabin Tower location. The model was given a range of edge lengths to allow it to statically adapt to terrain features. The three horizontal domains (18, 6, and 2 km) were created using a minimum edge length and a corresponding maximum edge length equal to one and one-half times the minimum edge length. The lowest resolution used was an 18-27 km edge length over the domain 29.77°N to 46.45°N latitude and 127.34°W to 106.14°W longitude, referred to hereafter as the 18 km domain. For each successive increase in resolution, smaller domains were embedded within the 18 km domain, leading to more domains as the minimum edge length decreased (see Figure 3). For the 6 km minimum edge length grid (6 km grid), the inner grid was created over the domain of 35.98°N to 40.24°N latitude and 119.45°W to 114.03°W longitude with an edge length of 6 to 9 km. The 2 km minimum edge length grid (2 km grid) was formed over the area of 37.10°N to 39.12°N and 118.12°W to 115.36°W with edge lengths of 2 to 3 km.

A number of studies were designed to test the sensitivity of OMEGA to horizontal grid resolution, initial conditions, and time of initialization. Three grid resolutions, 18 km, 6 km, and 2 km (described above), were tested. The model was also initialized using both NARR and GFS analysis data for initialization. Finally, the model was initialized at both 00Z and 12Z for each 36-hour simulation to test sensitivity to initialization time. Twelve total 30-day simulations were performed for this study.

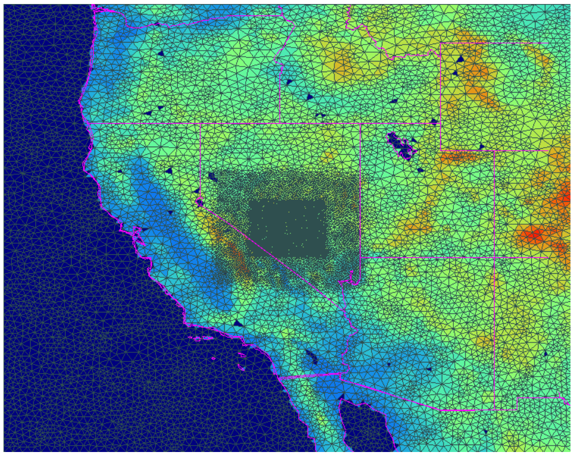

Figure 3: The OMEGA 18 km, 6 km, and 2 km horizontal domains.

3. ANALYSIS

In order to evaluate the performance of the OMEGA model as compared to observations and the two operational models, MM5 and WRF, a number of statistical techniques were applied to the model output. First, the observed point winds at the Stone Cabin tower were compared with OMEGA output at 40, 60, and 80 m above the ground. For each 30-day simulation, a statistical comparison to the observed data was performed including calculation of the RMSE and IOA, scatter plots of both observed and modeled data, and fitting to a theoretical Weibull distribution. Table 1 gives a summary of RMSE and IOA results from each of the 12 different OMEGA simulations.

OMEGA RMSE ranges from approximately 3.1 to 4.2 over all of the simulations and IOA ranges from 0.42 to 0.70. OMEGA appears to better simulate the 40 m winds than those at 60 or 80 m above the ground. It is clear from the statistics that the runs initialized at 00Z have more skill in forecasting winds than those initialized at 12Z. Also, the runs initialized with the GFS consistently outperform runs initialized with the NARR analysis. The most skillful simulations according to RMSE were initialized with the GFS data with a horizontal resolution of 6 km. The most skillful according to the IOA were those initialized with the GFS at 00Z using 2 km grid resolution. The statistical results show that the skill of OMEGA does not vary radically in the vertical for each run.

Runs:		18 km		6 km		2 km	
		00Z	12Z	00Z	12Z	00Z	12Z
GFS							
40 m	RMSE	3.28	3.37	3.29	3.33	3.23	3.47
	IOA	0.66	0.61	0.65	0.63	0.70	0.65
60 m	RMSE	3.45	3.56	3.35	3.38	3.34	3.58
	IOA	0.66	0.60	0.66	0.64	0.70	0.66
80 m	RMSE	4.11	4.08	3.13	3.12	3.38	3.46
	IOA	0.56	0.51	0.67	0.66	0.70	0.67
NARR							
40 m	RMSE	3.25	3.84	3.52	4.02	3.45	4.08
	IOA	0.67	0.43	0.63	0.46	0.65	0.50
60 m	RMSE	3.41	3.98	3.66	4.11	3.55	4.21
	IOA	0.66	0.43	0.62	0.48	0.66	0.51
80 m	RMSE	3.78	4.01	3.25	3.68	3.43	4.11
	IOA	0.60	0.43	0.66	0.51	0.68	0.52

Table 1: Statistical comparison of the OMEGA simulated wind speeds versus the sonic anemometer observed wind speed for twelve 30-day simulations at 40, 60, and 80 m above ground level at Stone Cabin tower.

Observations	**40 m**	**60 m**	**80 m**
Shape	1.724	1.779	1.636
Scale	5.807	6.199	5.371

Table 2: Weibull fit shape and scale parameters for sonic anemometer observations at 40, 60, and 80 m heights above ground level.

Weibull fit statistics for the OMEGA simulations give an idea of how well the simulations are capturing the distribution of wind speeds. Table 2 shows the results of the Weibull shape and scale parameters for the sonic anemometer observations. These parameters can then be compared to the parameters calculated from the OMEGA simulations to determine whether OMEGA is accurately representing the wind distributions. The Weibull fit parameters for the OMEGA simulations ranged from 1.411 – 2.010 for the shape parameter and from 3.821 – 6.377 for the scale parameter, which encompasses the range of sonic anemometer observations. In general, the OMEGA simulations at 2 km and 18 km resolutions give more accurate distributions than those at 6 km (not shown). The 2 km runs performed most skillfully at reproducing wind distributions with average errors of approximately 10% as compared to the fit parameters for the observations, see Table 3.

2 km OMEGA simulation averages	**Shape**	**Scale**
12Z, NARR	1.564	5.372
00Z, NARR	1.636	5.647
12Z, GFS	1.587	5.328
00Z, GFS	1.701	5.907

Table 3: Weibull shape and scale parameters for OMEGA 2 km horizontal resolution runs averaged over all heights listed with initialization times and analyses.

Table 4 summarizes the RMSE averages over all heights for the MM5, WRF, and OMEGA simulations. Comparing OMEGA simulation statistical results with those derived from MM5 and WRF runs, it is clear that OMEGA results are comparable to those from MM5 and WRF. The most direct comparison, NARR initialized runs started at 12Z, shows that the RMSE from OMEGA is comparable to MM5, but WRF is slightly better. OMEGA also does not vary as much in the vertical as either WRF or MM5 (not shown). Again, these results show that initializing at 00Z provides more accurate results than initializing at 12Z. Also, the OMEGA simulations initialized using the GFS analysis provide more skillful wind forecasts than those initialized using the NARR analysis.

Model	Initialization	**18 km**	**6 km**	**2 km**
MM5	NARR, 12Z	3.45	3.97	4.14
WRF	NARR, 12Z	3.54	3.60	3.48
OMEGA	NARR, 12Z	3.95	3.94	4.13
OMEGA	NARR, 00Z	3.48	3.48	3.48
OMEGA	GFS, 12Z	3.67	3.28	3.50
OMEGA	GFS, 00Z	3.61	3.26	3.31

Table 4: Statistical summary of averaged RMSE (over all levels) for MM5, WRF, and OMEGA simulations compared to sonic anemometer observations at the Stone Cabin tower.

Comparing the Weibull fit parameters for the 12Z, NARR initialized MM5, WRF, and OMEGA simulations with the shape and scale parameters for the sonic anemometer distributions, both MM5 and OMEGA outperform WRF (not shown). The WRF shape and scale parameters averaged over all levels showed a percentage difference as compared to the observations of 16 - 35%. The MM5 parameters had a percentage difference of 5 - 28% compared to the observations. The percentage difference between the OMEGA and observed shape and scale parameters was between 9 and 26%.

4. CONCLUSIONS

Using a statistical comparison to sonic anemometer observations taken at Stone Cabin tower for the period 9 February 2007 through 10 March 2007, OMEGA's performance was evaluated and compared with MM5 and WRF. The results of this study show that the OMEGA adaptive grid model has the ability to forecast point winds in complex terrain with accuracy similar to or better than that of MM5 and WRF. Further, it is clear that OMEGA is quite sensitive to time of initialization and the dataset used to initialize the model. In general, the 00Z initialized runs performed more accurately than those initialized at 12Z. Also, the GFS initializations consistently outperformed the simulations initialized with the NARR analysis. In order to determine the wind potential in complex terrain, it appears that it is important to employ varying initialization times and datasets in order to best simulate the wind field.

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