4.2 MESOSCALE MODELING AS A TOOL FOR WIND RESOURCE ASSESSMENT AND MAPPING

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1. INTRODUCTION

The rapid growth of the wind energy industry in the past decade, both in the United States and elsewhere, has led to the development of new techniques for the systematic identification and evaluation of candidate wind project sites. One of those techniques is mesoscale modeling. A familiar tool of weather forecasting, mesoscale modeling offers a number of advantages for wind resource assessment, such as the ability to simulate, with reasonable accuracy, complex wind flows in areas where surface measurements are scant or non-existent. TrueWind Solutions has developed one such mesoscale modeling technique, which is marketed under the trademark MesoMap. MesoMap has been used in the past five years to create wind resource maps of about half of the United States as well as other parts of the world. Through TrueWind's internal efforts and a public/private partnership with the National Renewable Energy Laboratory (NREL), the accuracy of the method has been assessed by comparing estimates with data from nearly 1000 surface stations. The typical root-mean-square model error, after accounting for uncertainty in the data, has been found to be 5-7% of the mean speed at 50 m. This is a useful level of accuracy, but improvements are still desirable because of the cubic relationship between the energy available in the wind and speed. The intensive validation effort has identified several common sources of model error. This paper discusses three of the most important: surface roughness parameterization, atmospheric stability in the lower boundary layer, and the mesoscale model resolution. Strategies for researching and mitigating these issues are discussed.

2. BACKGROUND

The successful development of wind energy requires a thorough understanding of the wind resource – in effect, an accurate climatology of the wind at a high spatial resolution. In the early years of the wind industry – the 1970s and 1980s – such assessments were done mainly using field techniques, combined with a practical understanding of large scale wind patterns and the effect of topography on wind flow. While often very effective, these techniques suffered from a lack of transferability; expertise in one region did not always translate into expertise in another.

During the 1980s and 1990s, a variety of computer modeling techniques emerged. Several involved equilibrium microscale wind flow models, the most prominent example being the Wind Atlas Statistical Package, or WAsP, developed by the Risoe National Laboratory of Denmark based on the theory of Jackson and Hunt (1975). This model creates a wind map and climatology of a region using data from a single reference mast. It and its cousins (MS-Micro, WindMap, and others) are best suited to estimating the wind resource in areas of simple to moderate terrain slopes at distances of up to tens of kilometers from the reference mast (Bowen and Mortensen, 1996; Walmsley, Troen, Lalas and Mason, 1990).

In the 1990s, the National Renewable Energy Laboratory (NREL) developed a "computer mapping system" that uses upper-air wind data from balloon soundings and various mathematical relationships between the wind and topography to estimate the wind resource over large regions at a grid scale of 1 km (Schwartz, 1999; Schwartz and Elliott, 2001). This method produced some of the first detailed wind resource maps of states in the United States (Vermont, North and South Dakota, and Illinois) as well as other countries (the Philippines and Mongolia, among others).

By the late 1990s, mesoscale modeling techniques were beginning to emerge as a major focus of research. One of the first was the KAMM-WAsP method developed by Risoe. This method uses the KAMM mesoscale model to simulate a representative number of static "cases" sampled from a distribution of upper-air wind statistics (Frank, Rathmann, Mortensen, and Landberg, 2001). The output of the model, at a typical grid scale of 2-5 km, is used to drive WAsP, which produces wind resource estimates at a much higher resolution.

TrueWind Solutions developed its own mesoscale modeling approach, MesoMap, in the late 1990s, with funding from the New York State Energy Research and Development Authority (NYSERDA), the US Department of Energy (DOE), and private sources (Brower, Bailey, and Zack, 2001). Aside from the different models used (described below), a key distinction between MesoMap and KAMM-WASP is that MesoMap's mesoscale model is run in a dynamic mode with the energy equations. This allows the development of non-equilibrium mesoscale flows (sea breezes being an obvious example) within the model domain.

3. THE MESOMAP SYSTEM

The MesoMap system has several major components. First, there are the models: a mesoscale atmospheric simulation model (MASS) and a mass-

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conserving wind flow model (WindMap). MASS is similar in many respects to the MM5 family of mesoscale models, but is a commercial program developed by MESO, Inc., a co-owner of TrueWind (Manobianco, Zack and Taylor, 1996). In mapping projects, MASS normally operates at a scale of 1-3 km. WindMap is based on the NOABL program, which was developed in the 1970s and 1980s for wind resource studies and subsequently updated by Brower & Company (Sherman, 1978; Brower, 1999). Starting with an initial mesoscale wind field (provided, in this case, by MASS), it finds a solution that conserves mass at the microscale. It normally operates at a grid scale of 100 to 200 m, which is roughly comparable to the spacing between turbines in wind projects.

The second major component is a distributed computer processing system consisting of 94 Pentium III and IV processors connected in a network. It is the parallelization of the mapping process that makes it possible to produce high-resolution maps using this technique in a reasonable amount of time. A typical MesoMap project requires two CPU-years of processing, but can be completed on this system in about a week.

Global meteorological data bases (reanalysis, surface, and rawinsonde) and geophysical data bases (topography, land cover, vegetation greenness, sea temperatures, snow cover, soil moisture) make up the third component. The reanalysis data, which are produced by the National Centers for Environmental Prediction (NCEP), provide a three-dimensional snapshot of global weather conditions every 6 hours over the past several decades on a 2.5 degree grid. Along with rawinsonde and surface data, they provide the initial conditions for the MASS simulations, and they provide updated lateral boundary conditions. The topographic and land cover data are essential, of course, to properly simulating interactions between the atmosphere and land or ocean surface.

The mapping process begins by defining several grids around the area to be mapped. The largest is typically more than 2000 km wide, with a mesoscale grid spacing of 30 km. Within that large grid there are usually two or three levels of nested grids, each covering a smaller area at higher resolution, with the last extending perhaps 200-400 km at a grid scale of 1-3 km. The mesoscale model then simulates weather and wind conditions throughout the area at all levels of the atmosphere for 366 days randomly sampled from a 15 year period. The three-dimensional output of the model (including wind, temperature, pressure, and other parameters) is stored every hour of simulated time, resulting in a total of 8784 samples at each grid point.

The results of the mesoscale simulations are then summarized in data files containing gridded wind rose and Weibull statistics at 11 levels above the surface. These files are input into the Windmap model. Windmap, in effect, perturbs the MASS wind field to account for differences in the topography and land cover as seen by Windmap and MASS.

4. VALIDATION PROGRAM

MesoMap has been applied in the past several years to mapping wind resources in nearly 30 states of the United States as well as in almost 30 other countries. The successful application of MesoMap is in part the result of an unusual public/private collaboration between TrueWind and NREL, with support from the US Department of Energy's Wind Powering America

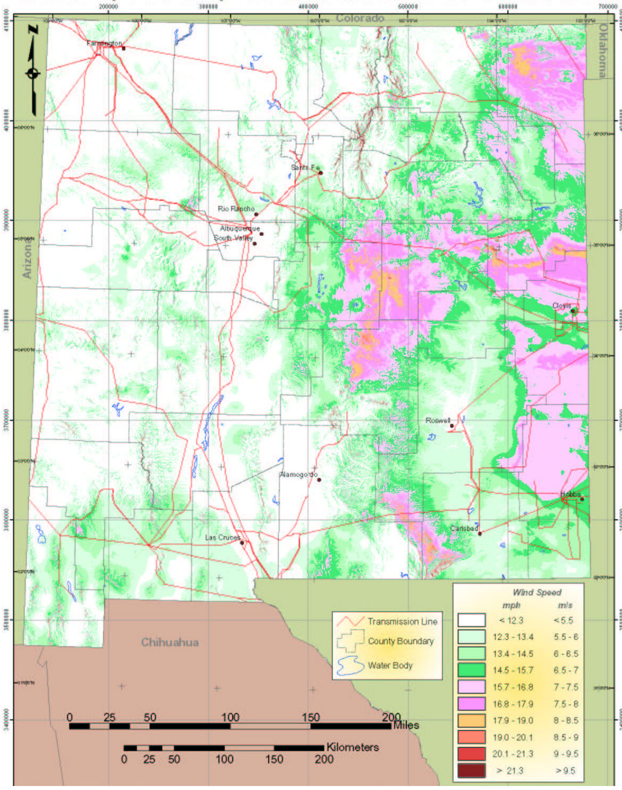

Figure 1. Annual average wind speed map of New Mexico created using MesoMap.

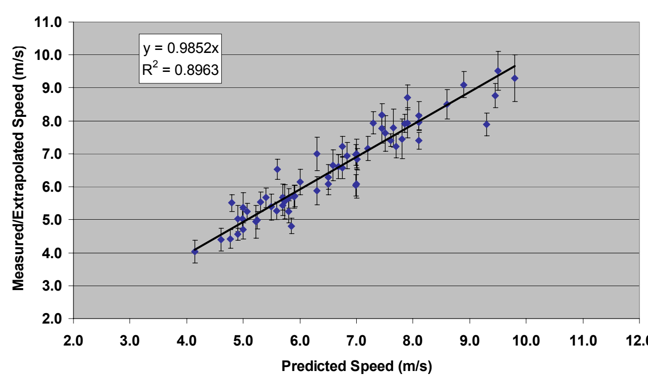

Figure 2. Estimated and measured long-term mean wind speeds at 59 stations in New Mexico. The data have been extrapolated to a reference height of 50 m.

initiative. Recognizing the critical importance of verifying the accuracy of the maps and making corrections, if necessary, NREL has provided both data and meteorological expertise, which have greatly bolstered TrueWInd’s own validation efforts.

Figure 1 shows a typical wind speed map produced by MesoMap, this one of New Mexico. Figure 2 shows the corresponding validation results, here represented as a scatterplot of estimated and measured mean wind speed. Typically, the root-mean-square discrepancy between model and data is 7-10%. After accounting for uncertainties in the data (resulting from limited periods of record, low mast height, and other factors), the rms error ascribed to the model alone usually falls in the range of 5-7%. To place this in perspective, the error margin in a high-quality measurement program is usually 3-4%. (It should be noted that only the mean annual wind speed and power estimates have been validated, not seasonal or diurnal patterns or other aspects of the wind climate.)

Although the typical error in mean wind speed is moderate, it has a considerable impact on wind project feasibility because the energy available in the wind varies as the cube of the mean speed (assuming a fixed speed frequency distribution). A 5-7% rms error in speed implies a 16-22% rms error in available energy. Because wind turbines do not convert all of the available energy to electricity, the rms error in wind turbine output is actually somewhat smaller – about 10-15%. Nevertheless this represents a substantial uncertainty for the financial evaluation of wind projects.

Consequently, it is important to try to determine and mitigate the largest sources of model errors. While in any particular region a variety of factors may be at work, in our experience, three have often been significant: the parameterization of surface roughness, the simulation of the stable boundary layer, and the mesoscale model grid scale.

5. SURFACE ROUGHNESS PARAMETERIZATION

In similarity theory, surface roughness is a property that helps determine the vertical profiles of wind, temperature, turbulence, and other atmospheric parameters. It is represented in the familiar logarithmic-linear formulas by a surface roughness length, in meters, which is related in principle to the height, width, porosity, and average spacing between “rough elements” (such as vegetation and man-made structures) on the land surface. For given conditions of thermal stability, a high roughness induces a greater wind shear and lower wind speed at the surface, whereas a low roughness has the opposite effect. In mesoscale models, the roughness length does not directly determine the vertical profile, but rather influences the flux of energy and momentum between the land and atmosphere at the lowest model level.

A key challenge in producing accurate wind resource maps of large areas is to estimate the surface roughness using remotely sensed data. To do this we make use of a table of common equivalences, drawn from the literature (e.g., Garrat, 1992), between various land cover types (forest, cropland, etc.) and roughness length. In making such estimates, at least three problems can occur:

5.1. Errors in land cover description. Remotely sensed data must be properly interpreted to determine the land cover type. Rather than do such interpretation ourselves, we rely on publicly available land cover data sets. For the mesoscale model, the source is the global 1 km Advanced Very High Resolution Radiometer (AVHRR) data set (Brown, Loveland, Ohlen, and Zhu, 1999). For the microscale model, a 30 m Landsat data set is used in the United States (Vogelmann, Sohl, Campbell, and Shaw, 1998), while a 250 m CORINE data set is available for most of Europe (Fuller and Brown, 1994); for other regions, we usually use the global 1 km Moderate Resolution Imaging Spectroradiometer (MODIS) data set (Hodges, Friedl, and Strahler, 2001).

Mistakes frequently arise in the global data sets because of their relatively coarse resolution. In a systematic ground-truthing of the AVHRR land cover data, it was found that the surface roughness designation based on land cover class was correct about 80% of the time (Defries and Los, 1999). In our experience, the MODIS data are somewhat more accurate than AVHRR, while the Landsat and CORINE data are probably more accurate than either. As far as we know, however, no systematic validation of roughness derived from these other data sets has yet been performed.

5.2. Errors in roughness assignment. Even when the land cover type is correct, it is not always easy to determine the appropriate roughness length. Surface roughness depends on vegetation height and density, among other things, which land cover descriptions say nothing about. Forests can be sparse and deciduous or dense and evergreen, with the roughness length ranging, as a result, from as low as 0.3 m to as high as 2 m. The cropland designation can encompass everything from vast open spaces of wheat to small fields separated by wind breaks, farm buildings, fences, and other structures; in the first instance, the surface roughness length could be as low as 0.02 or 0.03 m; in the latter, it could be as high as 0.1 to 0.15 m. Seasonal variations can be important as well. In winter, snow cover can create a very smooth surface, whereas in the summer and fall when grasses and crops are at their tallest, the roughness is comparatively high.

5.3. Errors in displacement height. Where vegetation is particularly tall and dense, the wind flow can be displaced upwards off the ground. The displacement height is defined as the height at which a logarithmic wind profile reaches zero. A typical estimate of the displacement height is two-thirds of the average

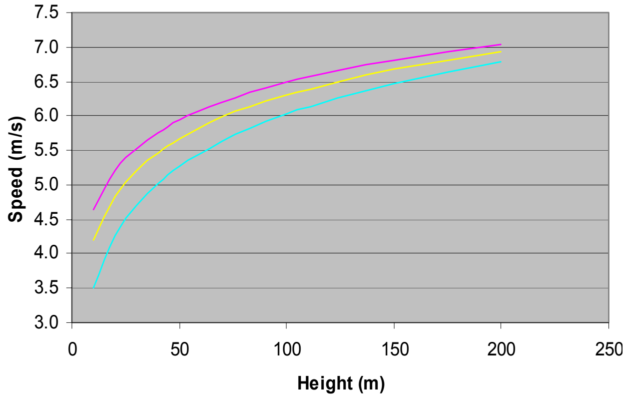

Figure 3. Theoretical vertical wind profiles for three values of roughness length: 0.03 m (pink), 0.1 m (yellow), and 0.4 m (blue), assuming a thermally neutral atmosphere. Similarity theory was used, with the assumption that the wind is unaffected by roughness differences at heights above 500 m.

vegetation height (Garrat, 1992). For densely spaced trees 20 meters tall, according to this rule of thumb, the displacement height would be about 17 m. Such a large displacement can substantially reduce the observed wind speed at typical wind turbine hub heights of 50-80 m. Like roughness, however, it cannot be determined exactly from the land cover designation.

5.4. Roughness corrections at the microscale. The surface roughness at the microscale is often quite different from what it is at the mesoscale – in part because of the higher resolution, and in part because we generally use a different, region-specific land-cover data set for the microscale simulations. Our microscale model, WindMap, must adjust the vertical profile and surface winds to account for the different roughness. Since WindMap lacks the turbulent mixing equations of a mesoscale model, this necessitates some approximations – for example, to describe the rate of growth of the internal boundary layer downwind of a roughness change, or to describe the maximum height to which a different equilibrium roughness will affect the wind.

The wind profiles in Figure 3 illustrate the potential effect of errors in roughness. In this example, changing the roughness from 0.03 m to 0.4 m would cause the estimated mean speed at 50 m to decrease by nearly 1.5 m/s, or 12%. The impact could be even greater – 20% or more – under stable atmospheric conditions.

While such extreme errors in roughness – equivalent to confusing cropland with forest – are relatively rare and confined to small regions, moderate errors are quite common and can be widespread. A case in point is New Mexico. Initially areas denoted as shrubland in the Landsat data set – including much of southeast New Mexico and valleys west of the Rockies – were assigned a roughness of 0.02 m. After a round of validation, it was concluded that this value was too low, and it was raised to 0.07 m. This led to a reduction of about 5% in the estimated 50 m wind speed.

Our main strategies for addressing such errors are, first, to verify to the extent possible the roughness designations for different land cover types by examining photographs and other information; and second, to acquire more accurate land cover data. The Landsat and CORINE data sets for the United States and western Europe have proven invaluable. Elsewhere, we have adopted the MODIS data for the final stage of mapping, and will eventually replace AVHRR with MODIS for the mesoscale modeling as well.

6. THE STABLE BOUNDARY LAYER

The thermal stability of the atmosphere has an equally important effect on the vertical wind profile and on estimates of the wind resource at a particular height. In a stable boundary layer, the air has negative buoyancy, so that a parcel of air displaced upwards or downwards tends to return to its previous level. As a result, mixing and friction are confined to a shallow layer near the surface, above which the wind increases rapidly. In an unstable atmsosphere, in contrast, momentum is spread by convective mixing more evenly throughout a much deeper boundary layer. This typically raises the wind speed very near the surface and reduces it above.

Mesoscale models like MASS approximate these effects by changing the mixing parameterization depending on the stability class in which the boundary layer falls. The stability class is determined by the predicted potential temperature profile. Although the equations work well most of the time, highly stable conditions pose a particular challenge. Sometimes the model allows more momentum to penetrate the stable layer to the surface than occurs in reality. This results in an overestimation of the wind resource.

Figure 4 illustrates a typical range of overestimation of nocturnal winds using data from Kansas City International Airport, Missouri, and Douglas Bisbee International Airport, Arizona. The problem is mild in the first but much more significant in the second. As these examples suggest, the overestimation tends to be greater where winds are light because highly stable conditions can occur more frequently and persist longer.

The dynamic behavior of the stable atmosphere also presents modeling challenges. Nocturnal jets, for example, are a significant feature of wind climates in parts of the United States. They are caused by the sudden decoupling of friction in the atmosphere that occurs as night falls. That decoupling alters the balance of frictional and Coriolis forces, causing an oscillation in the wind vector. The rebound effect can be pronounced at heights of 50 to 200 m – precisely the zone of importance to large wind turbines. Because of the nocturnal jet, the wind speed is often at a maximum at night in this height range in many locations.

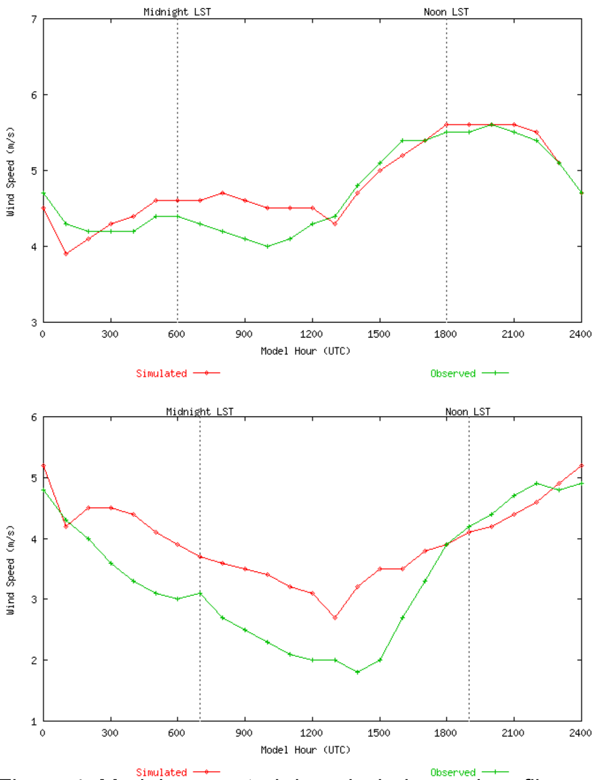

Figure 4. Model-generated durnal wind speed profiles (red) at 10 m height compared with actual profiles (green) at 6 or 10 m height, for Kansas City, Missouri (top), and Douglas Bisbee, Arizona (bottom). The dips in model speed at 0100 and 1300 UTC are caused by data assimilation every 12 hours.

Another class of stability-related phenomens is mountain-valley circulations, which include katabatic winds. Such flows up and down mountain slopes and through valleys are driven by differential solar heating and nocturnal cooling of the earth's surface. In the absence of strong synoptic forcing, the wind speed is highly sensitive to a variety of factors, such as surface properties that affect the rates of heating and cooling, and the precise depth of the nocturnal boundary layer.

Part of the problem with the simulation of stable conditions is having enough vertical resolution. Often there is a very shallow, highly stable layer (e.g., an inversion) which acts as an effective barrier to mixing. If the model layers are too widely spaced, the simulated barrier may be too weak. The coefficients of the mixing parameterization equations in stable conditions are also rather uncertain, as the experiments on which they are based show a good deal of scatter.

One step we have taken to improve the simulation of the stable atmosphere is to adopt a new method of determining the depth of the stable boundary layer, one based on turbulent kinetic energy (TKE). This has generally reduced the depth of the layer, which has, in turn, increased the shear and reduced the speed at the surface. Based on available wind shear data, the model-estimated nocturnal shear from 10 to 100 m is now quite realistic in most cases. At the same time, the change has increased the intensity of nocturnal jets and katabatic winds, with more mixed results. In some regions, such as the coastal mountain passes of California, the change has been for the better, whereas in others, it has accentuated the tendency towards overestimation.

As a further step, TrueWind Solutions is now engaged in a research effort funded by the California Energy Commission to improve the simulation of winds at a height range of 50-200 m in a variety of climates, and in particular under the stable conditions that occur frequently from night through morning in the California interior. Model simulations will be coordinated with measurements using 100 m masts, sodar profilers, and other instruments.

7. MESOSCALE GRID SCALE

The ability of the mesoscale model to resolve major features of the topography and surface properties (such as coastal boundaries) is of obvious importance to developing accurate wind climatologies. It is the reason TrueWind has invested in a large distributed computer processing system. While the microscale model, WindMap, is able to adjust for simple acceleration over small hills and ridges, it cannot account for channeling, blocking, circulations created by thermal gradients, and other phenomena. Unfortunately, it is difficult to determine, *a priori*, the mesoscale resolution needed to achieve a desired level of accuracy. Certainly, the more complex the terrain, the higher the resolution should be.

Figure 5 demonstrates the effect of mesoscale grid scale on the ability of the model to resolve channeling through a mountain pass – in this case, San Gorgonio Pass, a major center of wind projects that lies between Los Angeles and Palm Springs, California. At 8 km, the pass is barely visible, and the predicted mean speed through it is about 7.5 m/s; at 2 km, the pass is nicely resolved, and the predicted speed is, at maximum, about 9 m/s. In reality, annual mean wind speeds through the pass exceed 9.5 m/s. It is likely that an even smaller grid spacing, such as 1 km, would be needed for the model to develop the channeled winds to their full intensity.

Increasing the mesoscale grid resolution poses practical problems, however. The first is the computer processing required. In a simulation covering a fixed area, the number of grid cells increases inversely with the square of the grid cell size. In addition, to control gravity and sound waves, the model time step must be reduced roughly in proportion to the grid cell size. Thus, there is a cubic relationship between total run time and grid cell size; reducing the size from 2 to 1 km requires a factor of 8 increase in run time.

Second, as the resolution increases, non-hydrostatic effects become more significant in the simulations. Normally, the atmosphere is very close to hydrostatic equilibrium. However, where rapid vertical

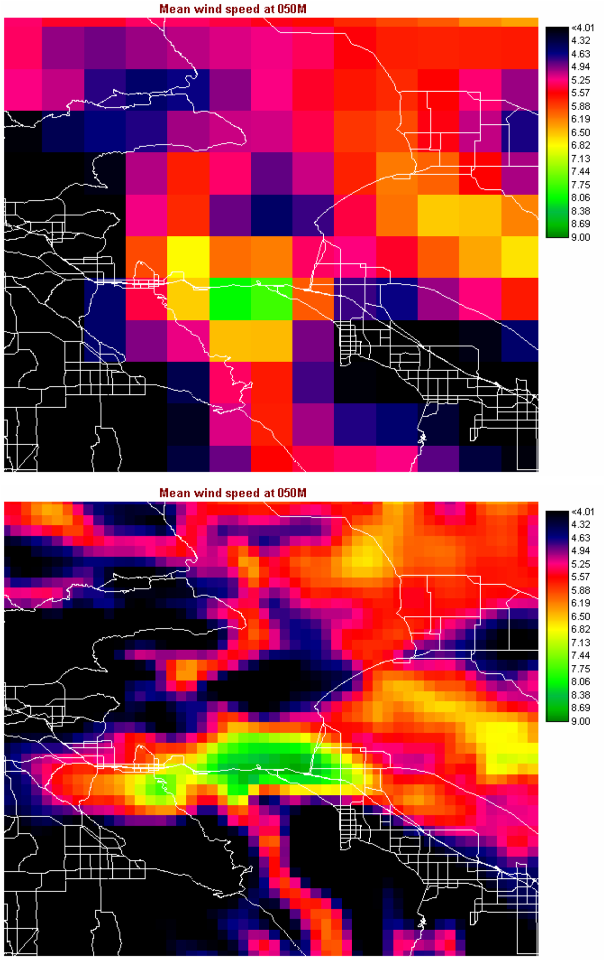

Figure 5. The mean wind speed through San Gorgonio Pass as simulated at 8 km grid scale (top) and 2 km grid scale (bottom).

accelerations occur – such as over a steep mountain ridge or in a thunderstorm – the non-hydrostatic pressure response can be significant. Running MASS in a non-hydrostatic mode entails roughly a 50% increase in run time. One strategy to cope with this is to allow the model to go into non-hydrostatic mode only when the vertical acceleration demands it. This capability has not yet been implemented, however.

Lastly, as the model resolution increases, numerical rounding errors between the finite elements in the terrain-conforming grid used by MASS (and similar models) begin to accumulate and create noise in the simulations. We are presently exploring the limits of the terrain-conforming grid, but expect they will become important in complex terrain at grid scales below about 500 m. Wherever the limit occurs, a change in the coordinate system will be required to achieve further gains in resolution.

Ultimately, as computer power increases, TrueWind plans on adopting a new mesoscale model with a non-conforming grid. One option is the OMEGA model, which was developed jointly by MESO, Inc., and Science Applications International Corp. OMEGA does not use a terrain-conforming grid; instead, the terrain is represented as a lower boundary condition. The model also uses a unique, unstructured, adaptive grid in the horizontal dimension, which allows high resolution to be concentrated on features of interest (such as a mountain pass). This feature has the advantages of improving computational efficiency and eliminating the need for grid nesting.

9. CONCLUSIONS

Mesoscale modeling has been widely applied to wind energy resource assessment. Although it cannot substitute for on-site measurements, it can provide useful information for the identification and preliminary evaluation of wind project sites. In the course of validating wind maps created by the MesoMap system, a number of interesting modeling challenges have been encountered. The first of these, surface roughness parameterization, is being addressed through field verification and the acquisition of better sources of land cover data. The second, the stable boundary layer, has already led to modifications in the formulation of the boundary layer depth in the mesoscale model and is the subject of a coordinated modeling and measurement program in California. The third, mesoscale grid resolution, is being addressed through continuing expansion of TrueWind's distributed computer capability and by employing the mesoscale model in a non-hydrostatic mode. Ultimately, however, the desire to reduce mesoscale grid spacings below 500-1000 m will necessitate switching to a new mesoscale model that does not use a terrain-conforming grid.

9. ACKNOWLEDGMENTS

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