500-01-009

New Wind Energy Resource Maps of California

FINAL REPORT

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Indutrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

What follows is the final report for the Wind Resource Mapping Project, [number], conducted by TrueWind Solutions. The report is entitled New Wind Resource Maps of California. This project contributes to the Renewable Energy program.

For more information on the PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/research/index.html, or contact the Commission's Publications Unit at 916-654-5200.

EXECUTIVE SUMMARY

This report describes a wind-mapping project conducted by TrueWind Solutions for the California Energy Commission. Using the MesoMap system, TrueWind has produced maps of mean wind speed and power for a range of heights above ground on a 200 m grid. TrueWind has also produced data files of the predicted frequency, mean speed, and energy by direction and seasonal mean speed and power. The new wind maps provide the most complete and detailed picture of California's wind resources produced to date. They should assistance both companies and individuals seeking to identify prospective sites for small and large wind energy systems.

The MesoMap system consists of an integrated set of atmospheric simulation models, databases, and computers and storage systems. At the core of MesoMap is MASS (Mesoscale Atmospheric Simulation System), a numerical weather model which simulates the complete physics of the atmosphere. MASS is coupled to a simpler wind flow model, WindMap, which is used to refine the spatial resolution of MASS to account for the local effects of terrain and surface roughness. MASS simulates weather conditions over the region for 366 historical days randomly selected from a 15-year period. When the runs are finished, the results are input into WindMap for the final mapping stage. In this project, the MASS model was run on a grid spacing of 2 km, and WindMap on a grid spacing of 200 m.

The preliminary wind maps produced by MesoMap were thoroughly validated by TrueWind Solutions in collaboration with NREL and independent consultants. The validation process used data for 262 stations from a wide variety of sources, including airports, ocean buoys, and towers instrumented specifically for wind resource assessment.

The validation concluded that the initial wind speed estimates at 50 m height, before any adjustments, were accurate to within a standard error of 0.4-0.6 m/s, or 6% to 8%. Qualitatively, the preliminary maps presented a an accurate overall picture of the wind resource, but tended to underestimate winds in certain well-known wind corridors and to overestimate winds on mountaintops. We believe that the most important source of error is the finite grid scale of the MASS simulations, a consequence of the size of the state and limitations of budget and schedule, which resulted in an inability to fully resolve passes through mountains or the blocking of low-level winds by mountain ranges.

Following the validation, the wind maps were adjusted to improve the agreement with the data, and the revised maps were reviewed once more. We avoided adjusting the maps for specific points, but rather attempted to correct for clear patterns of error occurring over sizable regions. The speed adjustment ranged from a decrease of up to 15% to an increase of up to 25%. Most adjustments were around 5-10% in either direction.

The report concludes with some recommendations for further research. The main recommendations are: (1) High-resolution mapping of promising areas to better resolve mountain blocking and channeling effects and consequently to improve the accuracy of the wind resource estimates; (2) research to improve methods of simulating the stable nighttime boundary layer and its effects on wind speeds at the hub height of turbines; (3) the development of an improved data base of land cover and surface roughness throughout the state; and (4) a new program of measurement of winds at or near the hub height of large turbines using tall towers, sodar, and other tools.

ABSTRACT

The MesoMap system has been used to produce new wind energy resource maps and data bases for the State of California on a 200 m grid. The wind resource maps confirm the locations of several major wind resource areas, but also point to the existing of new areas that may not be widely known. An objective validation process, carried out using data from over 260 sites throughout the state and advice from independent consultants, concluded that the preliminary wind resource estimates were accurate to a standard error of 0.4-0.6 m/s (6-8%). Adjustments to the maps were subsequently made to improve the match to the data. The adjustments included increases in the predicted resource within some known wind resource areas, and reductions along some mountaintops and in some coastal areas. The finite grid scale of the model is suspected of being the main cause of the observed errors. The project has resulted in the most accurate current assessment of wind resources in California at a scale suitable for identifying promising sites for wind energy projects. Several topics for further research are suggested to help improve the accuracy of the maps in promising resource areas.

1. INTRODUCTION

Just as the growth of the petroleum industry in the early 20th century depended on the discovery of new oil fields by prospectors and wildcatters, the growth of the modern wind energy industry – and its ability to meet growing energy needs – depends on the discovery of new sites having a useful wind resource. California, in fact, has extensive experience with wind resource assessment, having conducted some of the first such studies in the world in the late 1970s and early 1980s, which resulted in large wind installations in Altamont Pass, Tehachapi Pass, and several other areas. These studies produced a picture of California's wind resources which served the state remarkably well through the 1990s.

Great strides in computers and the development of new wind resource mapping tools and methods have now made it possible to update and refine California's wind resource maps. These new techniques have the potential to place vastly more – and more accurate – information in the hands of the public, enabling anyone from major developers to individual enthusiasts to identify prospective sites for wind energy systems. Of course, mapping is just the first stage of the siting process. Promising sites identified in maps must be confirmed through field assessments and monitoring; and other hurdles such as permitting and environmental impact assessments must be overcome. Nevertheless, the availability of more detailed wind resource information should accelerate the siting process and enable more people and companies to participate in it.

The objective of this project was to create a new wind resource maps and data bases of California, using advanced computer tools, at the highest possible spatial resolution. The wind resource data were to be produced in format that could be imported and used in a Geographcial Information System (GIS). The project had the additional objective, in keeping with the PIER programs mandate to support scientific studies, of objectively estimating the accuracy of the maps, and of identifying weaknesses in the method and data which should be addressed through research.

These objectives have been fully met. Using our MesoMap system, which was developed over four years ago, we have produced new maps of California's mean wind speed and power for a range of heights above ground on a 200 m grid. We have also produced data files of the predicted frequency, mean speed, and energy by direction, as well as the seasonal characteristics of the resource.[1] The validation process provided a mechanism for objectively comparing the wind maps against data from a wide variety of sources, and for estimating the map errors, and it allowed for independent review of the maps by leading wind energy consultants and government researchers. The final, published wind maps have been adjusted to reflect the validation findings, and consequently represents the best current estimate of California's wind resources, at a very high resolution.

In the following sections, we describe the MesoMap system and mapping process in detail; how MesoMap was applied in this project; the process by which the initial maps were validated; the validation results and map adjustments; and the final wind maps and data files. We close with some recommendations for further research.

2. DESCRIPTION OF THE MESOMAP SYSTEM

The MesoMap system has three main components: models, databases, and computer systems. These components are described below.

2.1. Models

At the core of the MesoMap system is MASS (Mesoscale Atmospheric Simulation System), a numerical weather model that has been developed over the past 20 years by TrueWind partner MESO, Inc., both as a research tool and to provide commercial weather forecasting services. MASS simulates the fundamental physics of the atmosphere including conservation of mass, momentum, and energy, as well as the moisture phases, and it contains a turbulent kinetic energy module that accounts for the effects of viscosity and thermal stability on wind shear. As a dynamical model, MASS simulates the evolution of atmospheric conditions in time steps as short as a few seconds. This creates great computational demands, especially when running at high resolution. Hence MASS is usually coupled to a simpler but much faster program, WindMap, a mass-conserving wind flow model. Depending on the size and complexity of the region and requirements of the client, WindMap is used to improve the spatial resolution of the MASS simulations to account for the local effects of terrain and surface roughness variations.

2.2. Data Sources

The MASS model uses a variety of online, global, geophysical and meteorological databases. The main meteorological inputs are reanalysis data, rawinsonde data, and land surface measurements. The reanalysis database – the most important – is a gridded historical weather data set produced by the US National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR). The data provide a snapshot of atmospheric conditions around the word at all levels of the atmosphere in intervals of six hours. Along with the rawinsonde and surface data, the

[1] The data files are provided separately on a CD-ROM.

reanalysis data establish the initial conditions as well as updated lateral boundary conditions for the MASS runs. The MASS model itself determines the evolution of atmospheric conditions within the region based on the interactions among different elements in the atmosphere and between the atmosphere and the surface. Because the reanalysis data are on a relatively coarse, 200 km grid, MASS is run in several nested grids of successfully finer mesh size, each taking as input the output of the previous nest, until the desired grid scale is reached. This is to avoid generating noise at the boundaries that can result from large jumps in grid cell size. The outermost grid typically extends several thousand kilometers.

The main geophysical inputs are elevation, land cover, vegetation greenness (normalized differential vegetation index, or NDVI), soil moisture, and sea-surface temperatures. The global elevation data normally used by MesoMap were produced by the US Geological Survey in a gridded digital elevation model, or DEM, format from a variety of data sources.[2] The US Geological Survey, the University of Nebraska, and the European Commission's Joint Research Centre (JRC) produced the global land cover data in a cooperative project. The land cover classifications are derived from the interpretation of Advanced Very High Resolution Radiometer (AVHRR) data – the same data used to calculate the NDVI. Both land cover and NDVI data are translated by the model into biophysical parameters such as surface roughness, albedo, and emissivity. The nominal spatial resolution of all of these data sets is 1 km. Thus, the standard output of the MesoMap system is a 1 km gridded wind map. However, much higher resolution maps can be produced where the necessary topographical and land cover data are available.

2.3. Computer and Storage Systems

The MesoMap system requires a very powerful set of computers and storage systems to produce wind resource maps at a sufficiently high spatial resolution in a reasonable amount of time. To meet this need TrueWind Solutions has created a distributed processing network consisting of 94 individual Pentium II processors and 3 terabytes of hard disk storage. Since the days simulated by a single processor are entirely independent of other days, a project can be run on this system up to 94 times faster than would be possible with any single processor. To put it another way, a typical MesoMap project that would take two years to run on a single processor can be completed in just one week.

2.4. The Mapping Process

The MesoMap system creates a wind resource map in several steps. First, the MASS model simulates weather conditions over 366 days selected from a 15-year period. The days are chosen through a stratified random sampling scheme so that each month and season is represented equally in the sample; only the year is truly random. Each simulation generates wind and other weather variables (including temperature, pressure, moisture, turbulent kinetic energy, and heat flux) throughout the model domain, and the information is stored at hourly intervals. When the runs are finished, the results are

[2] The US Defense Department's high-resolution Digital Terrain Elevation Data set is the principal source for the global 1 km elevation. Gaps in the DTED data set were filled mainly by an analysis of 1:1,000,000 scale elevation contours in the Digital Chart of the World (now called VMAP).

compiled into summary data files, which are then input into the WindMap program for the final mapping stage. The two main products are usually (1) color-coded maps of mean wind speed and power density at various heights above ground and (2) data files containing wind frequency distribution parameters. The maps and data may then be compared with land and ocean surface wind measurements, and if significant discrepancies are observed, adjustments to the wind maps can be made.

2.5. Factors Affecting Accuracy

In our experience, the most important sources of error in the wind resource estimates produced by MesoMap are the following:

- Finite grid scale of the simulations
- Errors in the topographical and land cover data bases
- Errors in assumed surface properties such as roughness

The finite grid scale of the simulations results in a smoothing of terrain features such as mountains and valleys. For example, a mountain ridge that is 2000 m above sea level may appear to the model to be only 1600 m high. Where the flow is forced over the terrain, this smoothing can result in an underestimation of the mean wind speed or power at the ridge top. Where the flow is blocked by the mountains, on the other hand, the smoothing can result in an overestimation of the resource, as the model understates the blocking effect. The problem of finite grid scale can be solved by increasing the spatial resolution of the simulations, but at a cost of far more computer processing.

Errors in the topographical and land cover data can create additional problems in the simulations. While elevation data are usually reliable, errors in the size and location of major terrain features nonetheless occur from time to time. Errors in the land cover data occur more often, usually because of misclassification of aerial or satellite imagery. It has been estimated that the global 1 km land cover database used in the MASS simulations is about 70% accurate. Where possible, more accurate and higher resolution land cover databases are used in the WindMap stage of the mapping process to correct such errors. In the United States, a 30 m gridded Landsat-derived land cover database is used; a similar 250 m database, called CORINE, is available for Western Europe.

Even if the land cover types are correctly identified, there is uncertainty in the surface properties that should be assigned to each type, and especially the vegetation height and roughness. The forest category, for example, encompasses many different varieties of trees with varying heights and density, leaf characteristics, and other features that affect surface roughness. Likewise, an area classed as residential may consist of a scattering of single-story dwellings or a large number of tall apartment buildings. Uncertainties like this can be resolved only by acquiring more information about the area through aerial photos or direct observation. However this is often not practical if (as in this project) the area being mapped is very large.

3. IMPLEMENTATION OF MESOMAP FOR THIS PROJECT

The standard MesoMap configuration was used in this project. MASS was run on the following nested grids:

First (outer) grid level: 30 km
Second (intermediate) grid level: 8 km
Third (inner) grid level: 2 km

The 8 and 30 km grids covered the entire state. At the third grid level of 2 km, the region was broken up into five overlapping grids. The grid setup is shown in Map 1.

At the WindMap stage, high-resolution topographical and land cover data were used to obtain a final grid spacing of 200 m. The elevations were taken from the USGS 3-arc-second gridded topographical database of the United States, while the land cover classifications were from the USGS 30-meter gridded data set derived from Landsat imagery. Both data sets were resampled to 200 m; the elevations were resampled using bilinear interpolation, which smoothes the terrain, whereas the land cover data were first filtered to identify the most frequent land cover class within a 200x200 m area, then resampled using a nearest-neighbor algorithm. The elevation map is shown in Map 2, the land cover map (reclassified into a few representative categories) in Map 3.

Table 1 lists the categories in the land cover data base and the surface roughness values (in meters) initially assigned to them. The values chosen were judged to be typical for each land cover class. However, the actual roughness may vary a lot within a class (except water). The roughness may also vary by season because of changes in vegetation height and leafiness as well as snow cover.

Table 1. Land Cover Classifications and Surface Roughness

Class	Description	Roughness (m)
11	Open Water	0.001
12	Perennial Ice/Snow	0.001
21	Low Intensity Residential	0.3
22	High Intensity Residential	0.75
23	Commercial/Industrial/Trans	0.01
31	Bare Rock/Sand/Clay	0.01
32	Quarries/Strip Mines/Gravel Pits	0.1
33	Transitional	0.1
41	Deciduous Forest	0.9
42	Evergreen Forest	1.125
43	Mixed Forest	1.125
51	Shrubland	0.05
61	Orchards/Vineyards/Other	0.05
71	Grasslands/Herbaceous	0.01
81	Pasture/Hay	0.01
82	Row Crops	0.01
83	Small Grains	0.01
84	Fallow	0.01
85	Urban/Recreational Grasses	0.01
91	Woody Wetlands	0.66
92	Emergent Herbaceous Wetlands	0.1

From our experience mapping the Pacific Northwest, we were concerned that the roughness on high forested mountaintops might be substantially lower than that shown in the table because trees tend to become shorter and more widely spaced with increasing elevation and exposure to the wind. We developed a tentative model of the variation of forest roughness with elevation, similar to that used in our Northwest work, which depended on knowing where the tree line is. (The tree line is the elevation at which trees substantially disappear on high mountain slopes.)

However, the results, we concluded, were unsatisfactory, as the adjustment led to a substantial increase in the predicted wind resource on mountaintops, whereas it was concluded in the validation (as described in the next section) that the wind resource on mountaintops was generally overestimated. Consequently, the roughness adjusment was dropped in the final maps. It is clear that the question of tree height and density and their effect on the wind resource deserves further study.

4. VALIDATION PROCEDURE

The validation was carried out in cooperation with NREL and consulting meteorologists using data from a large number and wide variety of sources. The participating meteorologists are listed below:

- Jack Kline, Consulting Meteorologist
- Ed McCarthy, WECTEC
- Ron Nierenberg, Consulting Meteorologist
- Richard L. Simon, Consulting Meteorologist

Each consultant provided data from his own sources, both proprietary and public, and NREL and TrueWind also contributed data. A standard spreadsheet table format was followed. The table included the station name, source of data, location, anemometer height, recorded mean speed, period of record, and comments about the site such as local land cover, if available. The locations of the data points are shown in Map 5.

TrueWind then analyzed the data in the following steps:

1. The spreadsheets from the various consultants were combined into one master spreadsheet. Duplicate stations were identified and eliminated. In a few cases it was necessary to reconcile conflicting estimates for the same station, either by picking what seemed to be the more credible of the estimates, or taking the average.
2. Station locations were then verified and adjusted, if necessary, by comparing the quoted elevations and station descriptions against the elevation and land cover maps. Where there was an obvious error in position, the station was either moved to the nearest point of correct elevation, or if a suitable location could not be found, it was eliminated. Position errors of up to 1 or 2 km arose quite often in the older and less well-documented data sets.
3. The observed mean speed and power were extrapolated to a common reference height of 50 m using the power law. Where possible, the measured shear exponent for the site was used. In most cases, however, the shear exponent had to be estimated; we generally followed the advice of the consultants concerning the shear at stations they were familiar with. The estimated shear exponent on exposed ridges and mountaintops ranged from 0.05 to 0.14; in open plains or

broad valleys, from 0.14 to 0.16; and in deep, sheltered valleys, 0.16 to 0.20. Offshore, a value of 0.10 was used. Exceptions were made where it seemed likely the station was either unusually sheltered or the wind was strongly influenced by channeling, compression over a ridge, or acceleration down a slope.

4. The error margin of each data point was then estimated as a function of two factors: the tower height and the number of years of measurement. The tower height enters the equation because of uncertainty in the wind shear. The measured shear exponents reported by the consultants varied with a standard deviation of about 0.07. Absent information about the sites, this could be interpreted as the standard error. However, we assumed that knowing something about the site and relying on the expertise of the consultants would reduce the variance by 50%, implying a standard error in the shear estimates of about 0.05. Where shear data were available, we assumed an error margin of 0.03 between the top anemometer and the map height; the same applied to all offshore data.

   The period of measurement is significant because, even if a site is monitored for a year or more, the resulting mean speed may not be representative of the long term. A rule of thumb in the wind industry is that one year of measurement will result in a mean speed that is within 10% of the long term mean with 90% confidence. This can be translated into a standard error of 6% for one year of data. We assumed that interannual variations are normally distributed, so that the standard error goes down in inverse proportion to the number of years (or, if climatologically corrected, the number of years of the long-term reference).

   The two uncertainties were then combined in a least-squares sum as follows:

$$(2)\quad e=\sqrt{\left(\left(50/H\right)^{0.05}-1\right)^2+\left(\frac{0.06}{\sqrt{N}}\right)^2}$$

   where H is the height of the anemometer and N the number of years of measurement. For example, if the mean speed for a 10 m tower with a two-year record was 6.6 m/s, and the estimated shear was 0.14, then the estimated 50 m speed was 8.3 m/s with a standard error of 9.4%.

   The true error margin may be substantially larger than that given by this equation for certain older and less well-documented data sets because of a lack of information about local site characteristics, equipment type, calibration, tower shadowing, and other factors. On the other hand, the error margin in the major wind resource areas is probably somewhat smaller.

5. The predicted wind speed and power at each station's position were then extracted from the raw (unvalidated) maps. At first we did this using an automated GIS extraction routine, but we found that this resulted in frequent errors because of slight offsets in station locations and in the topographic and land cover data. Instead, we examined each point and extracted the most reasonable map value by hand. This necessitated a certain amount of judgement, but we think it is more reliable than using an automated process.

6. Next, the predicted and measured/extrapolated speed and power were compared, and the map bias (map speed or power minus measured/extrapolated speed or power) was calculated for each point. Stations with especially large discrepancies (compared to the data error margin) were examined closely. In a few cases, the stations were eliminated. The decision to drop a station was made for one of the following reasons: (a) the observed mean speed or power appeared to be grossly inconsistent with other data for similar locations in the region; (b) the data recovery percentage was very low (below 50%); and (c) the location of the station was in serious doubt. Most of the stations that were excluded were short towers with unknown site characteristics and little other documentation.[3]
7. The bias was then displayed in a scatterplot and on a bias map. A scatterplot allows the quick identification of outlying points and reveals the overall quality of the match between prediction and measurement. A bias map, on the other hand, is useful for revealing spatially correlated error patterns. If a cluster of stations have similar errors in sign and magnitude, it is more likely to reflect a real problem in the map than if the errors appear randomly distributed.

5. QUANTITATIVE VALIDATION RESULTS

Table 1 summarizes the results of the validation for wind speed. We did not compile comparable statistics for power because most of the stations did not have power data, and TrueWind did not analyze the power as closely as the speed. The table lists the number of non-duplicate stations received, the number retained after excluding questionable data, the root-mean-square (RMS) discrepancy, and the estimated model error.

Table 2. Validation Summary

Non-Duplicated Stations	Stations Retained	RMS Discrepancy	Estimated Model Error
279	262	0.76 m/s (11.1%)	0.51 m/s (7.4%)

The model error is calculated by subtracting (in a least-squares sense) the data error margin from the RMS discrepancy:

$$(3)\quad e_{MODEL} \approx \sqrt{e_{TOTAL}^2 - e_{DATA}^2}$$

This equation assumes that the model and data errors are both normally distributed and independent of one another. The model error is a more realistic estimate of the accuracy of the map as it accounts for the fact that some of the apparent discrepancy between the map and data is caused by errors in the data.

[3] Three buoys were eliminated because they appeared to duplicate other buoys in the station list but the reported mean speeds were 0.5-1 m/s higher. The three buoys, numbered 740124, 740134, and 740144, were all from the DATSAV data base.

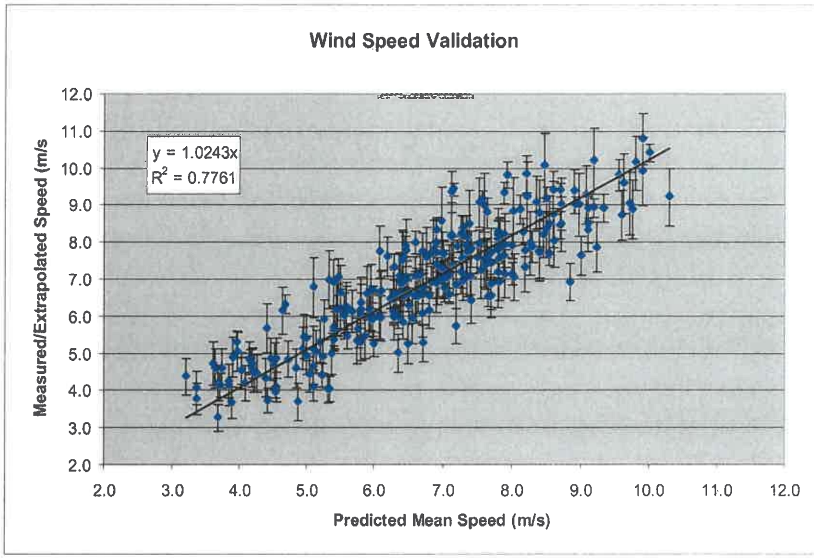

Figure 1. Scatter plot of predicted and measured/extrapolated mean wind speeds at 50 m height for 262 stations. Vertical error bars reflect uncertainty in the extrapolated data due to limited tower heights and periods of measurement.

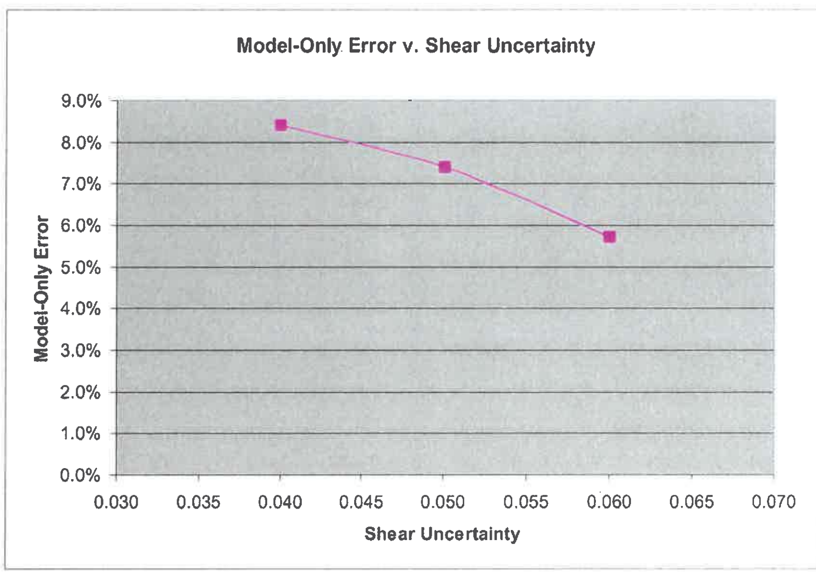

Figure 2. The relationship between the estimated model error and the uncertainty in wind shear. The more uncertainty there is in the shear, the smaller the portion of the discrepancy between the map and data is attributable to the model.

The scatterplot in Figure 1 compares the predicted and measured-extrapolated mean wind speeds at 50 m height. The error bars were calculated with Equation 3. The linear trend line, which is forced through the origin, indicates that the predicted speed has little overall bias (about 2% on average) and explains 78% of the variance in the measured/extrapolated speeds; in addition, the bias does not vary significantly with speed.

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Figure 2 shows that the estimate of the model error is quite sensitive to the assumed uncertainty in wind shear. If the average uncertainty is actually 0.06 at most stations, rather than 0.05, the estimated model error drops to 5.7% (0.4 m/s); if the uncertainty is 0.04, the estimated model error increases to 8.4% (0.6 m/s). This sensitivity reflects the fact that most of the 262 towers in the data set were less than 20 m in height. The real uncertainty in shear probably varies widely, however. In the major wind resource areas it may be lower than average, whereas in remote locations where little other data has been collected, it may be higher.

6. QUALITATIVE OBSERVATIONS AND SOURCES OF ERROR

The main qualitative observations we received from the consultants can be summarized as follows:

- Essentially all known high-wind areas have been identified; however, the predicted mean winds at these sites have generally been under-predicted, with the exception of Tehachapi Pass.
- Low-wind areas have been generally predicted correctly by the map.
- Some high-wind areas have been predicted by the map, but there is no hard data to confirm their existence. The areas include most notably zones east of the Sierra Nevada in Kern County, from Inyokern to Haiwee.
- The mountain-top resource along the coast and in the northern interior may be somewhat overestimated, although the data are weak and the errors very location-dependent.
- Offshore winds are generally well represented, but there is a tendency for the model to overestimate the near-shore resource in the far north, and to underestimate it in the far south.

While there is no single cause of model errors, the most important single factor is probably the finite grid scale of the MASS simulations. This could explain, in large part, both the underestimation of the wind in the main wind corridors and the overestimation of the wind on some mountaintops.

For a finite-element model like MASS to be able to fully resolve mountain passes and wind corridors, it is necessary for the width of the pass to be spanned by at least six grid cells. (Although WindMap runs at a much higher resolution than MASS, its simplifies equations do not permit the simulation of channeling through passes.) This criterion was not met in several instances; San Gorgonio Pass, for example, is about 6-10 km wide whereas each MASS grid cell was 2 km. In addition, where there is significant acceleration down a slope because of warm valley temperatures, the zone of acceleration must be wide enough to meet the same criterion. This requirement was probably not met in Pacheco Pass. The effect of grid scale on the simulation of flow through mountain passes is illustrated in Figures 3 and 4.

Grid scale is equally important in the ability of the MASS model to predict blocking by mountain ranges. California has unusually weak upper-air winds compared to the rest of North America. The most energetic flows actually occur within several hundred meters of

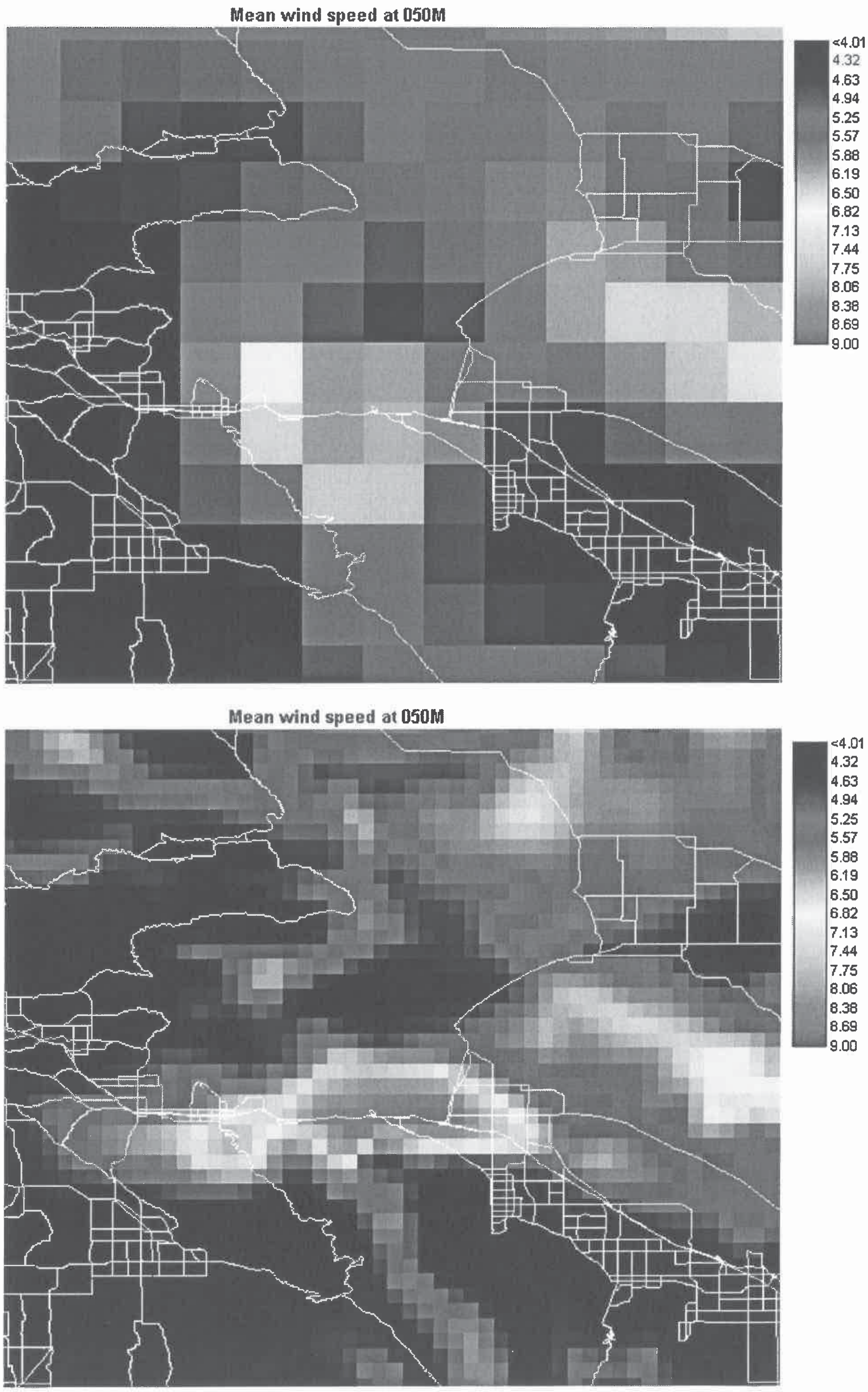


Figure 3. Effect of MASS grid scale on simulated winds through San Gorgonio Pass. In the 8 km simulations (top), the pass is barely visible in the two green grid cells in the middle. At 2 km, the channeled winds are much stronger, reaching and average of nearly 9 m/s. Even so, the pass is spanned across its throat by only 4 to 5 grid cells, implying that the flow through the pass is not fully resolved and would become stronger at higher resolution.

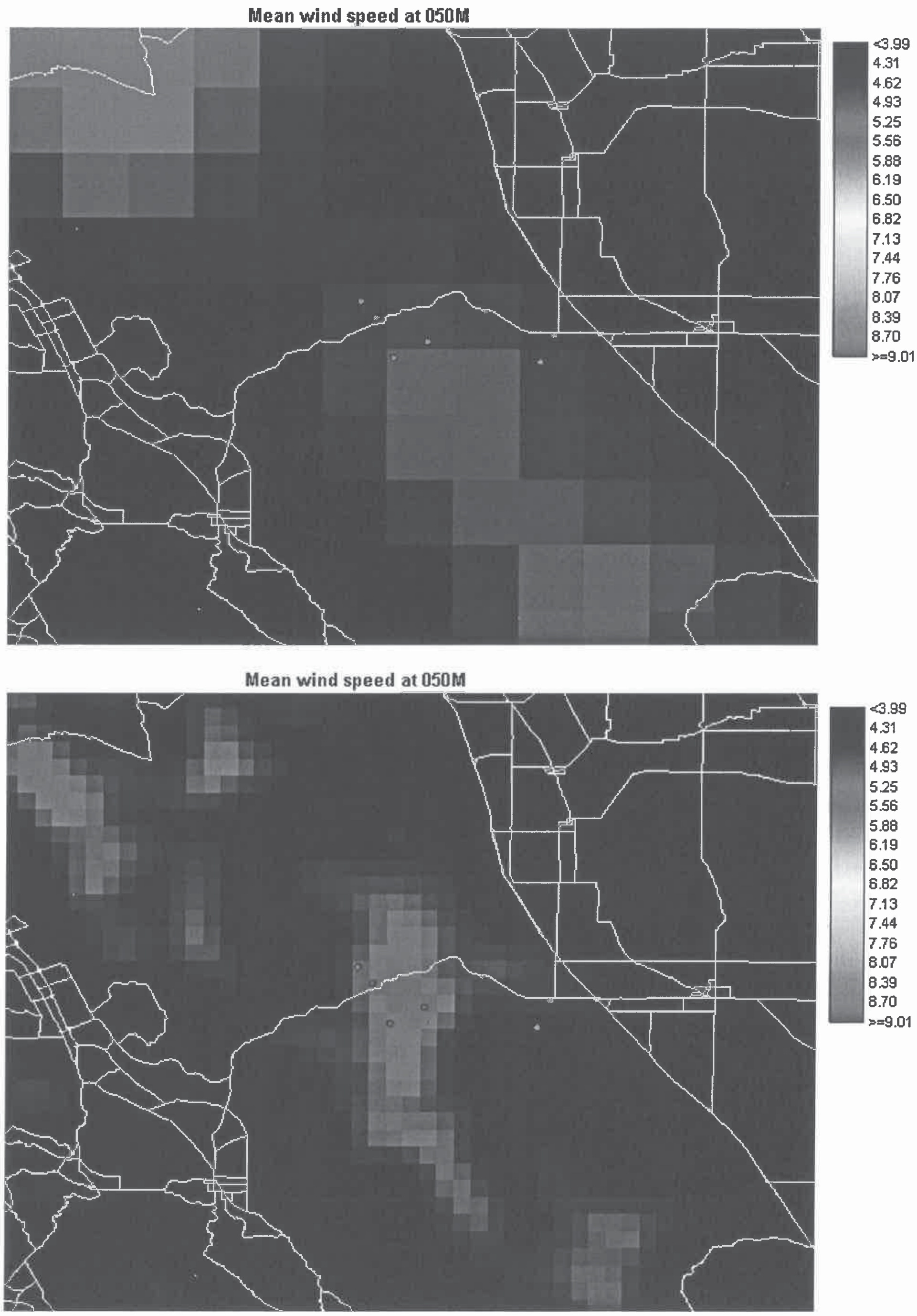
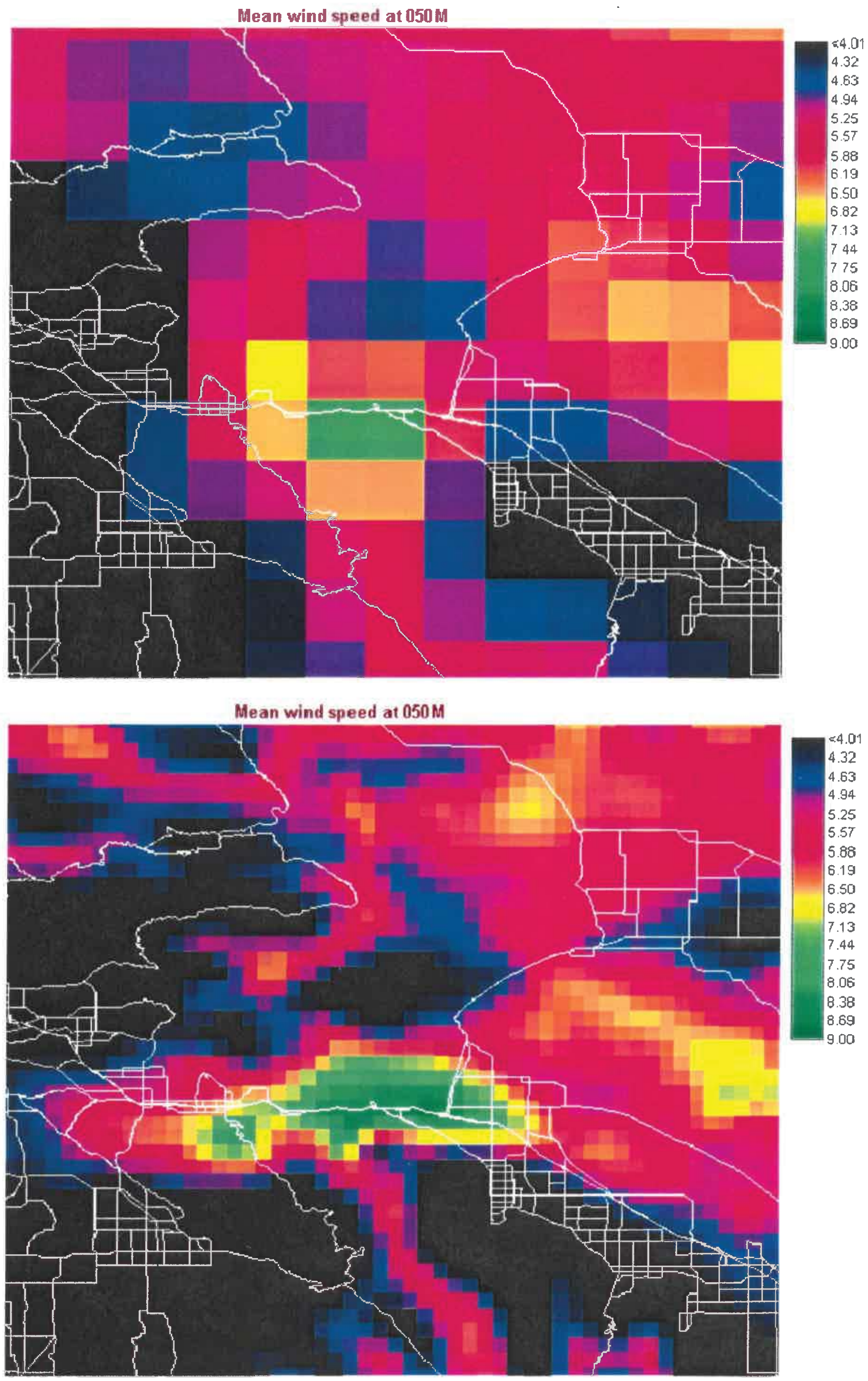


Figure 4. Effect of MASS grid scale on simulated winds through Pacheco Pass. In this instance, the pass is almost entirely missed at the 8 km scale, but it appears more strongly at the 2 km scale (red area in the middle). However, the acceleration zone is only 3-4 grid cells wide – not enough to develop the full strength of the flow.



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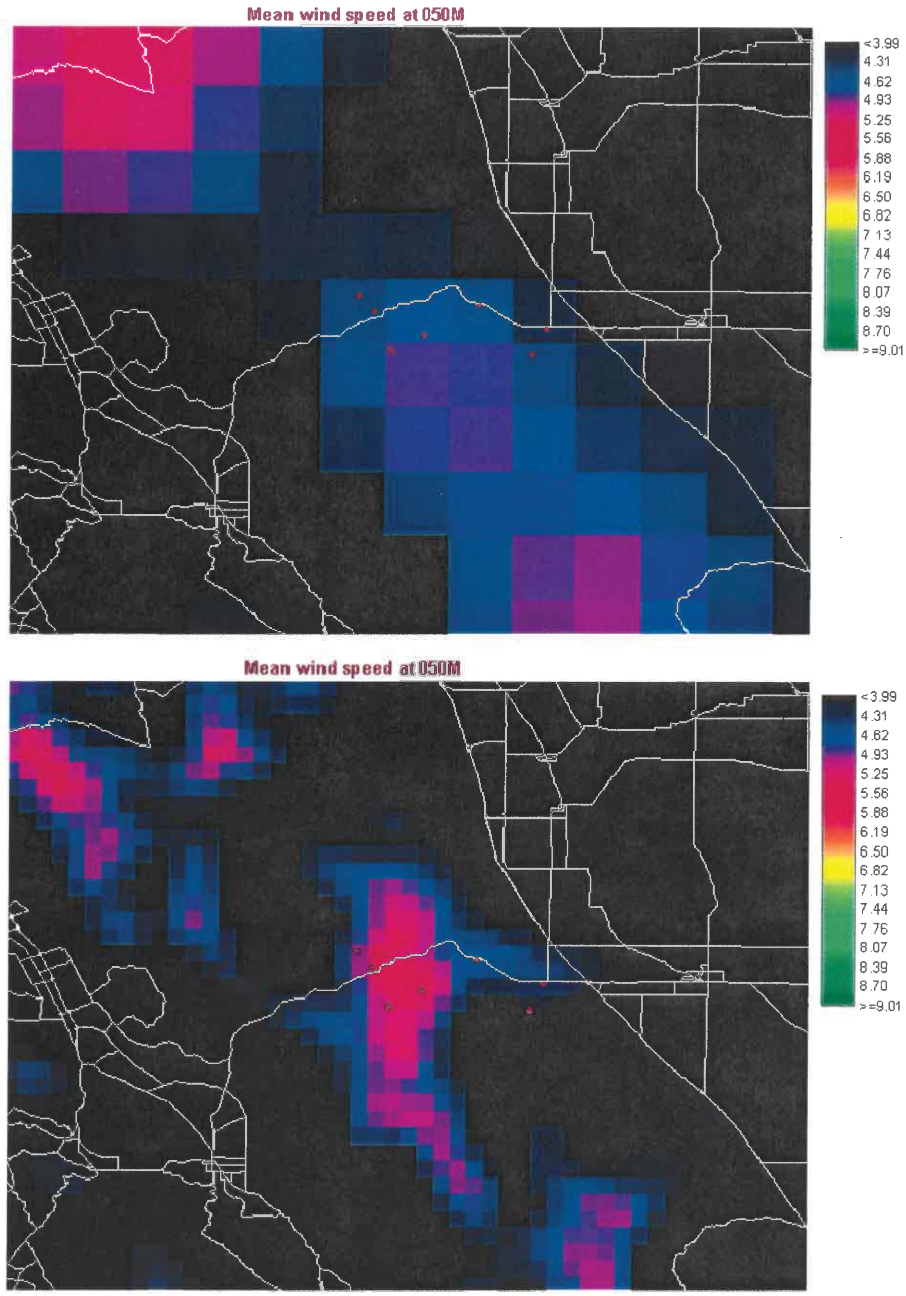

Figure 4. Effect of MASS grid scale on simulated winds through Pacheco Pass. In this instance, the pass is almost entirely missed at the 8 km scale, but it appears more strongly at the 2 km scale (red area in the middle). However, the acceleration zone is only 3-4 grid cells wide – not enough to develop the full strength of the flow.

the surface and can therefore be blocked rather easily by higher mountains. This is one of the main reasons why California's wind resource is concentrated in passes and corridors – there are few other paths for the low-level winds to reach the desert interior. At the 2 km scale of the MASS simulations, however, mountain ranges are smoothed out to some degree and may not, as a result, rise high enough to fully block the flow. Not only can this weaken the flow through the passes, it can result in an overestimation of the mountaintop winds. In high-resolution tests performed by TrueWind, mountain-top speeds in some locations dropped by 1 m/s or more compared to the 2 km simulations of this project.

The vertical, rather than horizontal, resolution appears to be a factor in the ability of the model to accurately simulate intense, low-level winds, such as those found in Solano County and the Montezuma Hills. The standard MASS configuration has 25 layers from the surface to the top of the atmosphere, with the first layer at 10 m and the second layer at approximately 30 m height above ground. We have tested the model with additional layers near the surface, and the result was that the simulated 50m wind speed in Solano County, the Montezuma Hills, and Altamont Pass increased by 4-6%.

An addition issue is the treatment of the thermally stable (nocturnal) boundary layer. In some valleys, as well as near the coast, it appears that the model may allow too much energy to be transferred through the nocturnal boundary layer to the surface. This may help explain why the model overestimated the extent of the wind resource south of Tehachapi Pass. A stable layer is frequently established at night in the desert valley downwind of the pass, preventing strong winds aloft from reaching the surface. Whether because of grid scale or some other reason, the MASS model appears to underestimate this effect.

The depth and persistance of the nocturnal boundary layer is equally important in understanding the rather high predicted wind resource in the valley to the east of the Sierra Nevada range near Little Lake and Haiwee. On the one hand, MASS may have overestimated the near-surface wind because of the difficulty of accurately simulating the deep stable boundary layer which is frequently established there. On the other hand, it is possible that the scant 10 m measurements and tree-flagging observations taken in this area have missed a very promising wind resource because the strong winds do not reach such a low height very often. We would not be surprised if measurements taken at turbine hub height revealed a much different picture than the sporadic winds observed at ground level. The effect of the nocturnal boundary layer on the wind energy resource in such situations is, consequently, a subject deserving much more research.

The effect of unreliable and undocumented data – beyond that accounted for in the estimated data error margin – must also be considered. The exact location and surroundings of many of the stations used in the validation were unknown. A simple problem such as the placement of a 10 m tower in the shadow of trees or buildings, or slightly below a mountain peak, could affect the observed wind speed by much more than the assumed error margin. Other sources of uncertainty include the anemometer type, calibration, and slope and offsets, as well as the degree of analysis and interpretation applied to the data.

We are particularly skeptical of data indicating a very low wind resource on several forested mountaintops, especially in northwestern California. In the absence of good site documentation, we suspect that several of these stations were heavily influenced by trees. Research using sodar – a technique for measuring wind profiles to heights of 100 m and more – shows that, on broad forested peaks, there can be an abrupt transition in the boundary layer from low winds near the surface to stronger winds aloft. Where such a transition occurs, both tree flagging observations and measurements taken from short towers may fail to detect the presence of a useful wind resource at a height accessible to wind turbines.

7. ADJUSTMENTS TO THE WIND MAPS

After reviewing the validation results and comments by the consultants, TrueWind proposed several adjustments to the wind map and submitted the adjusted map to NREL and the consultants for final review. This resulted in a few additional minor changes, which are incorporated in the maps presented here.

Figure 5 indicates where the adjustments were made. The adjusted speed is calculated by multiplying the initial (raw) speed or power by one plus the adjustment factor. The adjustment is assumed to be the same for all heights and seasons. In reality, the map error may vary with both season and height above ground, but since the data were not validated on a seasonal basis or at different heights, we assumed the adjustment would be the same.

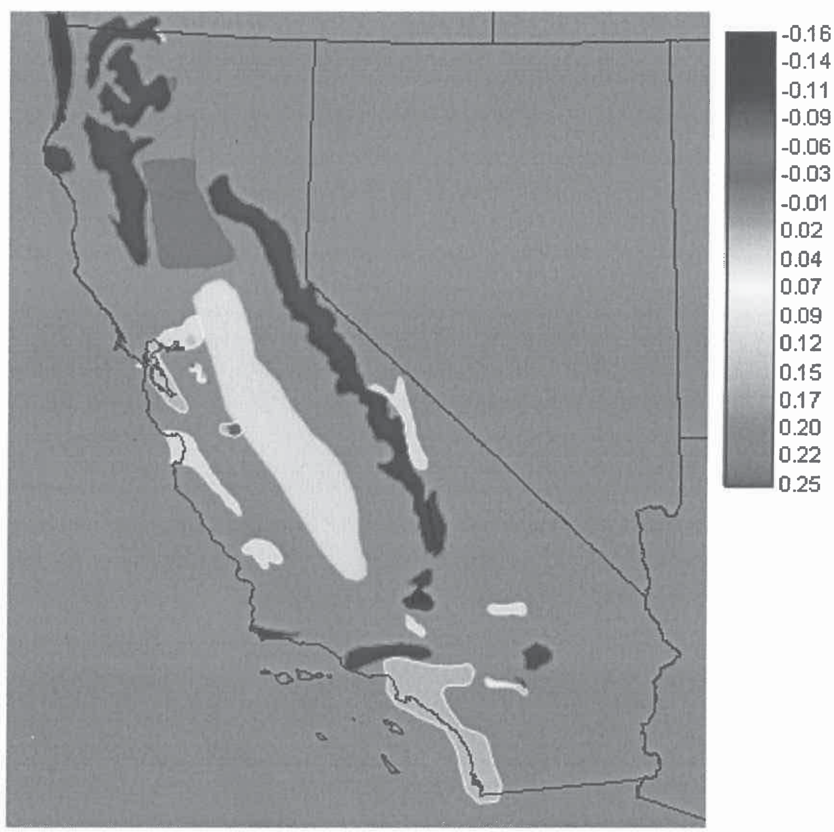

Figure 5. Wind speed adjustment factor. The final wind speed equals the initial (raw) model output multiplied by one plus the adjustment factor. The red color covering most of the region shows where there was no adjustment.

We are, in particular, somewhat skeptical of data which indicate a very low wind resource on several forested mountaintops, especially in northern California. In the absence of good site documentation, we suspect that several of these stations were heavily influenced by trees. Research using sodar – a technique for measuring wind profiles to heights of 100 m and more – shows that, on broad forested peaks, there can be an abrupt transition in the boundary layer from low winds near the surface to stronger winds aloft. Where such a transition occurs, both tree flagging observations and measurements taken from short towers may fail to detect the presence of a useful wind resource at a height accessible to wind turbines.

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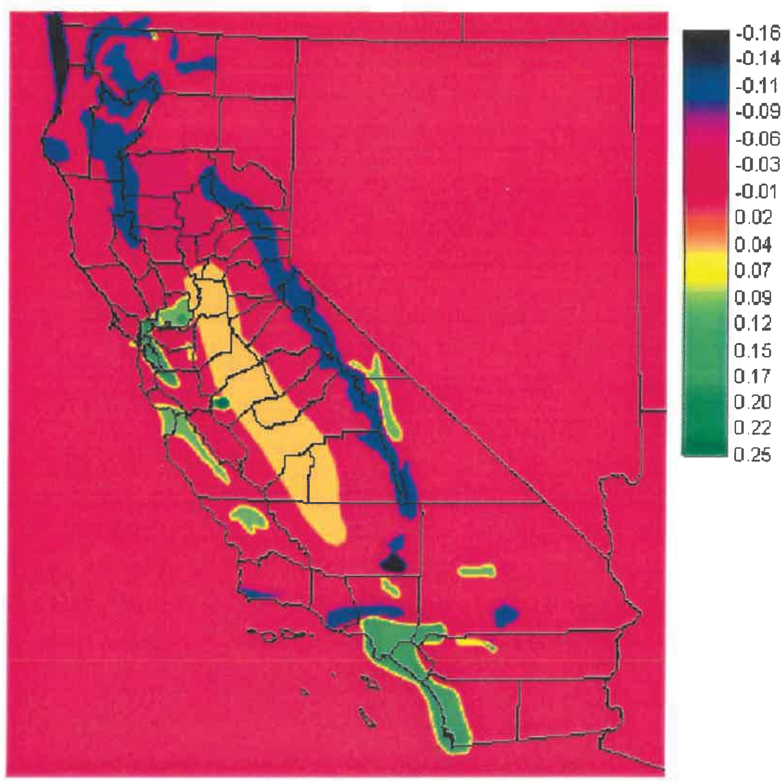

Figure 5. Wind speed adjustment factor. The final wind speed equals the initial (raw) model output multiplied by one plus the adjustment factor. The red color covering most of the region shows where there was no adjustment.

The speed adjustment ranged from a decrease of up to 15% to an increase of up to 25%. Most adjustments were around 5-10% in either direction. Downward adjustments occurred along the coast of extreme northern California, in parts of the Tehachapi area where the outflow from the pass extended too far into the valley, in Owens Valley around Little Lake (because of an absence of data confirming the good resource there), and along mountaintops in northern California and coastal southern California. Upward adjustments were made within the San Joaqin valley and in certain coastal valleys, in Owens Valley near Bishop, in San Francisco Bay, and in several of the main wind resource areas.

Since we had much less wind power data than wind speed data, we decided not to attempt a separate wind power adjustment for each part of the state. Instead, we examined the relationship between the wind power and speed discrepancies for the 71 stations for which we had both types of data.

Figure 6 plots the power adjustment that would be needed to eliminate the discrepancy between the map and data at each point as a function of the corresponding speed adjustment. It is significant that the line passes very nearly through zero; this suggests that the predicted wind speed frequency distribution is, on average, neither too broad nor too narrow. At the same time, the slope of the line, 2.1, is much less than the expected value of 3.0 (based on the cubic relationship between power and speed).

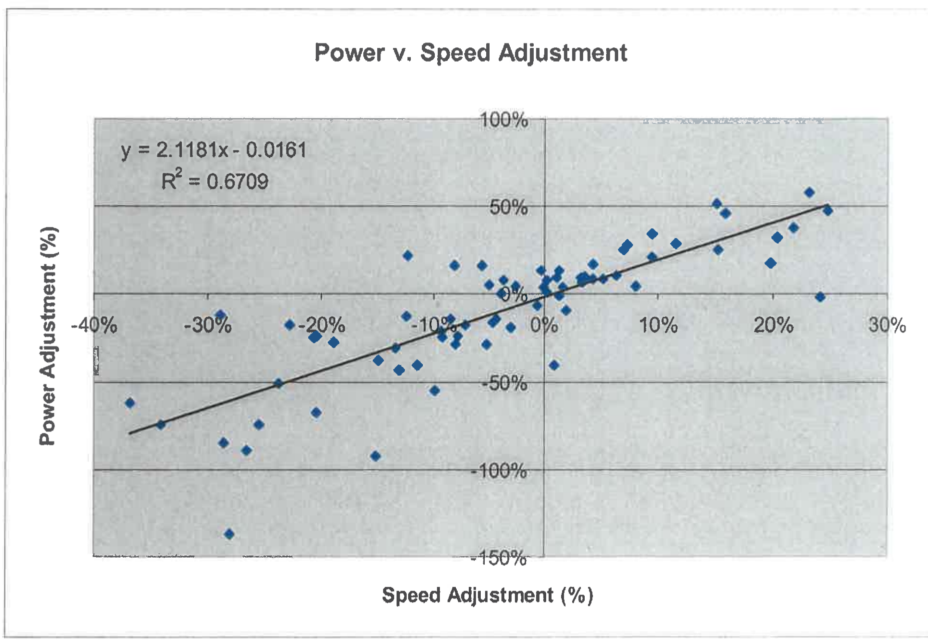

Figure 6. Adjustment in map power needed to eliminate the discrepancy with observations, as a function of the adjustment in map speed.

Why are the wind power errors smaller than expected? We speculate that the nocturnal boundary layer may play a part. Where the predicted speed is too high, it may often be because the model underestimates the effect of a stable boundary layer in reducing the nighttime wind. If so, that would make the actual frequency distribution broader than the

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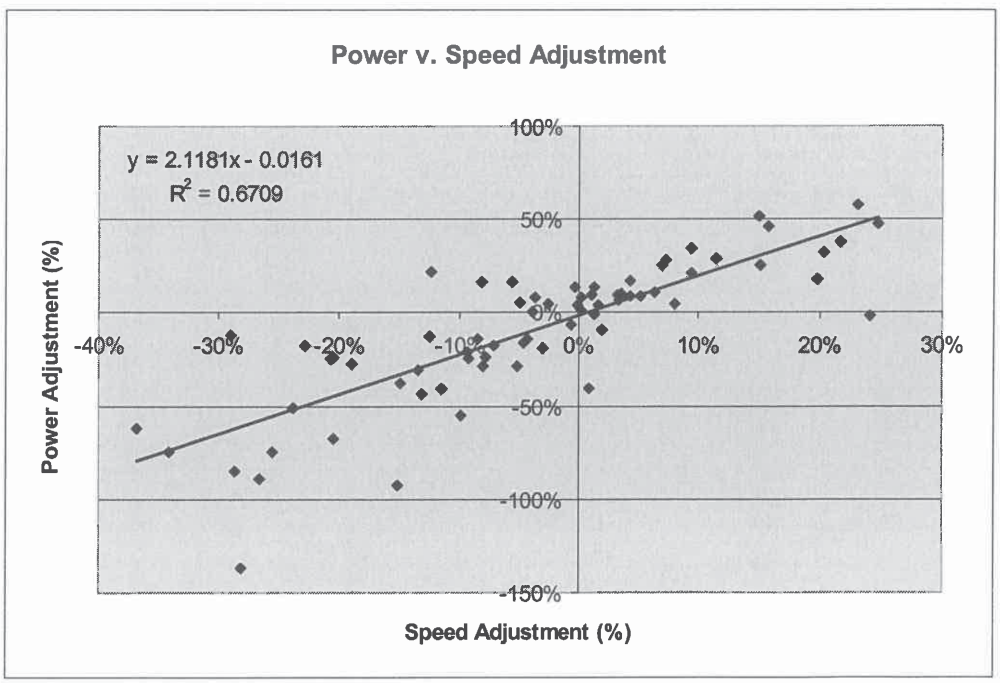
Since we had much less wind power data than wind speed data, we decided not to attempt a separate wind power adjustment for each part of the state. Instead, we analyzed the relationship between the wind power and speed discrepancies for the 71 stations for which we had both types of data, and applied that relationship to convert the wind speed adjustment into a wind power adjustment.

Figure 6 plots the power adjustment that would be needed to eliminate the discrepancy between the map and data at each point, as a function of the corresponding speed adjustment. It is significant that the line passes very nearly through zero; this suggests that the predicted wind speed frequency distribution is, on average, neither too broad nor too narrow. At the same time, the slope of the line, 2.1, is much less than the expected value of 3.0 (based on the cubic relationship between power and speed).



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Why are the wind power errors smaller than expected? We speculate that the nocturnal boundary layer may play a part. Where the predicted speed is too high, it may often be because the model underestimates the effect of a stable boundary layer in reducing the nighttime wind. If so, that would make the actual frequency distribution broader than the model predicts, and the wind power somewhat higher for the same mean speed; and that would, in turn, reduce the apparent error in power compared to what would be expected from a strict cubic relationship. Conversely, where the model underestimates the mean speed, the cause may often be a low-level jet which makes the nighttime or morning wind comparatively strong; this would make the power appear somewhat low for the speed, and therefore also reduce the apparent power error. This idea is supported by the fact that the slope of the power v. speed adjustment for buoys is 2.5, whereas it is 2.0 for the inland stations; stability effects are much smaller offshore because ocean temperatures remain relatively constant throughout the day and night.

Based on this analysis, we set the wind power adjustment factor equal to 2.1 times the wind speed adjustment factor.[4] No separate wind power adjustment map is shown.

8. FINAL WIND MAPS

Maps 6-9 show the final mean wind speed at 30, 50, 70, and 100 m, and Map 10 the final mean wind power at 50 m. The map height is relative to the effective ground level. In dense forest, the effective ground level is the canopy height, which is typically about 2/3 the height of the tree tops. For example, if the tree height is 15 m (45 ft), the effective ground level is about 10 m (30 ft), and a map height of 50 m therefore corresponds to a true height of 60 m above ground. A CD-ROM containing GIS-compatible wind resource data files, both seasonal and annual, is provided separately. Instructions for the use of the data are provided on the CD-ROM and in Appendix II.

Easily the most noticeable aspect of the map is the high concentration of the wind resource in just a handful of areas. The well known ones – Solano, Montezuma Hills, Altamont Pass, Tehachapi Pass, and San Gorgonio Pass – are easily seen. However the wind resource around Tehachapi Pass appears to be more extensive than is perhaps generally known (except by wind energy consultants). Good winds are found on the ridges on either side of the pass, on the slopes down into Antelope Valley, and possibly in sections of Owens Valley around Little Lake and Haiwee. The latter area, which has not been monitored, deserves further study. Another promising wind resource area lies at the border with Mexico: the mountain pass at Jacumba and its eastern slopes. The predicted wind power is especially high – NREL class 6 and 7.

Aside from these standouts, the wind resource is rather mixed in the rest of the state. The eastern California desert is predicted to have quite good winds in places, particularly on hills and mountains rising sharply from the desert floor; channeling around and between some of these terrain features may also result in localized areas of moderately good wind, for example, near Daggett. The low coastal mountains between San Luis Obispo and Santa Barbara offer another potential opportunity, with predicted wind speeds of 7-8.5 m/s in places along the ridgeline. Similar ridgelines can be seen elsewhere along the coastal range; and of course, some of the much higher mountains of the Sierra Nevada have good winds as well. However many of these areas will not be suitable for wind

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[4] An exception was made in the Montezuma Hills, where the ratio of power to speed adjustment was 3.

projects because they are in parks or national forests, or they are valued for scenic and other reasons.

The land area in different wind speed and power bands is shown in Table 3. The total land area of the state is 158,339 sq. mi. at the map grid scale. The figures give a rough indication of the technical potential of wind energy in the state. For example, one might assume that an average of 15 MW of wind capacity could be installed on each square mile of suitable windy land. (The actual density depends on many factors, including the type of terrain, directionality of the wind, and size and efficiency of the turbine.) Then, assuming a hub height of 70 m, about 28,000 MW could theoretically be installed at sites where predicted mean wind speed is at least 7.5 m/s.

Table 3. Land area in each wind speed or power band, in square miles.

Height (m)	Mean Speed (m/s)						
	<4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	>8.5	
30	105161	38555	11136	2644	621	221	
		<5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5
50		134716	17695	4583	1016	257	72
70		125374	24488	6593	1471	331	83
100		114033	32208	9524	2058	415	100
	NREL Wind Power Class						
	1	2	3	4	5	6	7
50	120187	25130	7826	2749	1200	849	397

Maps 11 and 12 depict the seasonality of the wind speed and power. Different parts of the state have much different seasonal characterics. In the state as a whole, summer tends to have the least wind, whereas frequent storms and passing weather fronts make the winter season windier, both on mountain peaks and in the southern desert. However, spring and summer favor stronger winds through the main wind corridors, especially Altamont and Pacheco passes, because of the intense heat generated in the desert.

It should be emphasized that the mean wind speed or power at any particular location may differ substantially from the predicted values, especially where the elevation, exposure, or surface roughness differs from that assumed by the model, or where the model scale is inadequate to resolve significant terrain features. Furthermore, the map height should be interpreted as the height above the vegetation canopy. In dense forests with tall trees, the actual height above ground at which the predicted winds would be observed may be as much as 10-15 m higher than the nominal height.

Detailed guidelines for using the maps and adjusting the wind resource estimates where necessary are provided in Appendix II.

9. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

We have successively used the MesoMap system to predict the wind resource in the State of California at a high spatial resolution. Maps and databases have been produced for several heights above the effective ground level (forest canopy or ground). Aside from confirming the existing of several well-known wind resource areas, the maps point to a number of other promising sites, some already known to wind energy experts, and others, perhaps, previously unsuspected. It is hoped that these indications may lead to new wind reosource projects which will help meet California's future electricity needs.

The preliminary map estimates correlated well with data obtained for 266 towers and extrapolated to a height of 50 m, indicating that the method overall is sound. The scatterplot of measured and predicted wind speed exhibited a strongly linear relationship, with little or no bias, and a r^2 regression coefficient of nearly 80%. The map standard error in speed, without adjustments, was estimated to be between 5.7% and 8.4%, or 0.4-0.6 m/s, depending on the assumed uncertainty in the wind shear of the tower data. This level of error is comparable to the uncertainty in one year of data taken at 50 m height, with no climatological adjustment. Based on the validation, the preliminary maps were adjusted in places by amounts ranging from 5-25% (10-50% in power). The end result, we believe, is more accurate than the validation statistics indicate; however this cannot be established independently without additional data.

While the maps produced in this project have been shown to be quite accurate, we have identified a number of shortcominings in the method and data used and recommend additional research and data collection to address these. Specifically,

1. High-resolution modeling of selected areas. Certain aspects of California's unusually complex wind regime, such as blocking by coastal mountains and channeling through narrow passes, could not be modeled very accurately at the 2 km grid scale of the MASS simulations. Higher resolution model runs could help refine the wind resource estimates in promising areas.
2. Analysis of boundary layer issues. The stability of the nighttime boundary layer can have a major impact on the wind resource in areas such as the California desert, by suppressing valley winds and enhancing winds on bluffs, for example; and yet it poses a significant modeling challenge. A focused program of research on improved methods for simulating the stable atmosphere could substantially improve the accuracy of the wind map in areas of promise of wind development.
3. Improved definition of land cover and surface roughness. Uncertainty in the height and density of trees, among other aspects of land cover, greatly increases the uncertainty in wind resource estimates on forested ridgelines and other locations. There is undoubtedly much data and human expertise on the types and characteristics of California's forests and land cover types which could not be brought to bear in this project. A study to synthesize such information and apply it to wind energy assessment is recommended.
4. Measuring the wind aloft. Most of the towers which provided data for the validation of the maps were less than 10 m in height. Lack of knowledge of the wind shear consequently introduced a large uncertainty in the wind resource at the

hub height of wind turbines. New measurements using taller towers in promising yet unexplored areas are certainly needed. However, even the current generation of 50 m towers do not reach the hub height of modern turbines, which is typically 70 or 80 m, let alone the tops of their blades, which may reach 130 m. Sodar, a tool for measuring the vertical wind profile to heights of 200 m or more, can provide valuable additional information at a moderate cost. In addition to exploring the wind resource at a particular site, sodar could be very useful in validating and refining models to simulate the boundary layer, with benefits in other areas being mapped.

APPENDIX I: GUIDELINES FOR USE OF THE MAPS

The following may be useful guidelines for interpreting and adjusting the wind speed estimates in the maps, especially in conjunction with the accompanying CD-ROM. The CD-ROM allows users to obtain the "exact" wind speed value at any point on the map, and it also provides the elevation and surface roughness assumed by the model, which are needed to apply the adjustment formulas given below.

1. The maps assume that all locations are free of obstacles that could disrupt or impede the wind flow. "Obstacle" does not apply to trees if they are common to the landscape, since their effects are already accounted for in the predicted speed. However, a large outcropping of rock or a house would pose an obstacle, as would a nearby shelter belt of trees or a building in an otherwise open landscape. As a rule of thumb, the effect of such obstacles extends to a height of about twice the obstacle height and to a distance downwind of 10-20 times the obstacle height.
2. Generally speaking, points that lie above the average elevation within a 200×200 m grid cell will be somewhat windier than points that lie below it. A rule of thumb is that every 100 m increase in elevation will raise the mean speed by about 0.5 m/s. This formula is most applicable to small, isolated hills or ridges in flat terrain.
3. The roughness of the land surface – determined mainly by vegetation cover and buildings – up to several kilometers away can have an important impact on the mean wind resource at a particular location. If the roughness is much lower than that assumed by the mapping system, the mean wind speed will probably be higher. Typical values of roughness range from 0.01 m in open, flat ground without significant trees or shrubs, to 0.1 m in land with few trees but some smaller shrubs, to 1 m or more for areas with many trees. These values are only indirectly related to the size of the vegetation; they are actually scale lengths used in meteorological equations governing the structure of the boundary layer.

   An approximate speed adjustment *in the direction of the roughness difference* can be calculated using the following equation:

$$\frac{v_2}{v_1} \approx \frac{\log\left(500/z_{01}\right)}{\log\left(h/z_{01}\right)} \times \frac{\log\left(h/z_{02}\right)}{\log\left(500/z_{02}\right)}$$

   v_1 and v_2 are the original and adjusted wind speeds at height h (in meters above the effective ground level), whereas z_{01} and z_{02} are the model and actual surface roughness values (in meters). As an example, suppose the land cover data used by the model showed an area to be forested in all directions with an estimated roughness value of 1 m, whereas in fact the land was fairly open in all directions with an estimated roughness value of 0.1 m. For $h = 65$ m, the above formula gives

$$\frac{v_2}{v_1} \approx \frac{\log\left(500/1\right)}{\log\left(65/1\right)} \times \frac{\log\left(65/0.1\right)}{\log\left(500/0.1\right)} = 1.13$$

implying the model wind speed should be increased by about 13%.

This formula assumes that the wind is in equilibrium with the new surface roughness above the height of interest (in this case 65 m). When going from high roughness to low roughness (such as from forested to open land), the clearing should be at least 1 km wide for the benefit of the lower roughness to be fully realized. However, when going from low to high roughness, the reduction in wind speed may be felt over a much shorter distance. For this and other reasons, the formula should be applied with caution. Where doubts arise, users are urged to obtain the advice of a qualified consulting meteorologist.

APPENDIX II: THE DATA CD-ROM

The CD-ROM accompanying this report contains a free program called ArcExplorer 2, produced by ESRI, which allows users to view, query, copy, and print maps in an interactive environment. This addendum contains basic instructions for using the ArcExplorer program and associated maps and data bases. For detailed instructions, see the ArcExplorer on-line help file or visit www.esri.com/software/arcexplorer/index.html. The CD-ROM contains additional data files not used by ArcExplorer which may be imported into ArcInfo, ArcView, or other GIS programs. These files are described at the end of this addendum.

All coordinates in the data files are in meters referenced to the Universal Transverse Mercator coordinate system, zone 11, WGS84 datum.

9.1. Using Arcexplorer

STEP 1. SYSTEM REQUIREMENTS AND INSTALLATION

The first step is to install the ArcExplorer program on your system. According to ESRI, the maker of ArcExplorer, ArcExplorer 2 works on Windows 98/2000/NT operating systems. However, users report that it also works on Windows 95 and Windows Me operating systems. Because of the large data files, it is recommended that you have at least 128 MB of RAM.

Execute the program called ae2setup.exe found on the CD-ROM root directory. The setup program will guide you through the rest of the process. The data files can be left on the CD-ROM, but if you have room, you should copy the data directories to your hard disk. That will give you much faster performance.

STEP 2. OPENING THE PROJECT

Start ArcExplorer either by clicking on the icon that was placed on your Desktop (if you chose that option during installation) or by choosing Start - Programs - ESRI - ArcExplorer.

Choose File - Open and navigate to the CD-ROM or to the directory where you placed the files. Open the project file (extension: AEP).

NOTE: The file may take several minutes to load, especially from CD.

STEP3. FINDING YOUR WAY AROUND THE MAIN SCREEN

After ArcExplorer finishes loading the project, you should see the main window with a color wind map resembling the maps presented in this report. You may adjust the shape of the window to fit the map by dragging on its corners or sides. Notice that below the main map the X and Y position of the mouse pointer (in meters in UTM or state plane coordinates) is shown, along with the scale of the map and a scale bar.

A small Overview Map may be visible in the lower left corner of the main window. As you zoom in on an area in the main map, you will see a red rectangle on the Overview which shows where you are.

MAP LAYERS

Look to the left of the map window. Here you see a legend with the names of each of the map layers (also called themes). Not all of the layers are visible on the map when you first open the project. Some will appear only when you zoom sufficiently far into the map. Typically the first two layers have _ROSE and _MAIN in their names. They are described below:

<u>XX_ROSE</u>. This layer contains wind rose data including the frequency, mean speed, and percent of total wind energy from each of 16 directions (starting due north clockwise around the compass). The points are displayed only at high magnification (see below for instructions on changing the magnification).

<u>XX_MAIN</u>. This layer is the main wind resource database. It contains the mean annual speed, wind power, and Weibull frequency distribution parameters. The points are displayed only at a high magnification.

Most of the other layers contain overlays such as rivers, roads, and county or state boundaries. The last few layers are bitmap images (called something like SPD50.BMP) which is used as a color backdrop for the other layers. The color bands are defined in 0.5 m/s increments; for a legend, see the maps provided at the end of this report.

Now look along the top of the main window where a number of icons are visible. Aside from Open, Close, Save, and other standard functions, several useful tools are found here. To find out what each one does, hold the mouse pointer over the icon for a couple of seconds and a description will appear.

Starting from the left on the second row of icons, verify the locations of the following tools: Zoom to Active Theme, Zoom In, Zoom Out, Identify, and Measure. Following is a brief description of each:

<u>Zoom to Active Theme</u>. This tool is very useful for restoring the map to its full (initial) size after zooming. A theme (map layer) is activated by clicking on its name in the legend on the left.

<u>Zoom In and Zoom Out</u>. These tools function just like they do in many other programs. After selecting the tool, the mouse looks like a magnifying glass. Each click of the magnifying glass within the main map increases or decreases the scale by a factor of two. If you click and drag the magnifying glass over an area, you will zoom directly to that area.

Pan (hand tool). This tool allows you to move the map around by clicking on it and dragging in any direction. You can also navigate by clicking on the red rectangle in the overview map and dragging it where you want to go. This can be especially useful when you are at high magnification.

Identify. This tool is used to get more information about features you select on the map. You will find it most useful for querying the wind speeds and other data in the MAIN and ROSE layers. To use the tool, first select a map layer by clicking on the name in the legend on the left. Then click on the icon and the mouse pointer will change to an "i" with a circle around it. Click on a feature in the selected map layer and a data table will appear. If features are close together, the data table may contain entries for several of them.

Measure. This tool is used to measure distances on the map. To use it you will first have to select a measurement unit (kilometers, meters, miles, or feet) by clicking on the small arrow to the right of the icon. After selecting the tool, click on the map at one point and drag to another and the distance "as the crow flies" will be displayed.

STEP 4. ZOOM AND DATA TABLES

Select the Zoom In tool and click several times anywhere on the map. Or you may find it easier and quicker to select a zoom area by clicking and dragging the pointer to form a rectangle. In any case, once the scale becomes small enough, a number of blue points and red circles should appear. Each point represents one data point in the MAIN layer. The circles represent points in the ROSE layers.

First select the MAIN theme by clicking on its name in the legend to the left of the map. You will notice that as you pass the mouse over the points in the map, a number will appear next to the mouse pointer. This is the mean speed (in m/s) at each point.

Now select the Identify tool and click on one of the points. A data table will appear showing the exact X and Y coordinates (in meters UTM), the latitude and longitude in decimal degrees, the elevation and roughness assumed by the model (both in meters), the mean speed, power, and the Weibull C and k factors. At first the field names will be listed in a mixed-up order. Click on the word Field at the top of the list and the field names will be alphabetized.

Close the data table and select the ROSE layer. Click on a circle and alphabetize the data table. The fields labeled FREQ 1...FREQ16 correspond to the frequency (in percent) from each direction of the compass. The fields SPEED 1...SPEED16 are the mean speeds for each direction (normalized to the average), and the POWER 1...POWER16 fields are the percent of total energy for each direction.

Note that in a 16-sector wind rose, each sector corresponds to the following direction ranges (in degrees from north):

Sector	*Degree Range*
1	348.75 - 11.25
2	11.25 - 33.75
3	33.75 - 56.25

4	56.25 - 78.75
5	78.75 - 101.25
6	101.25 - 123.75
7	123.75 - 146.25
8	146.25 - 168.75
9	168.75 - 191.25
10	191.25 - 213.75
11	213.75 - 236.25
12	236.25 - 258.75
13	258.75 - 281.25
14	281.25 - 303.75
15	303.75 - 326.25
16	326.25 - 348.75

If you want the data points and circles (or any of the other features) to appear at a different magnification, then go to the magnification level you want using the zoom in and out tools. Right click on the name of the layer and select Set Maximum Scale. If you zoom out from that scale, the layer will disappear. If you prefer to set the display manually each time, then select Remove Scale Factors. Then, to prevent the map layer from displaying at any scale, simply uncheck the box next to the theme name.

The symbols used in the map overlays can be changed by going to Theme Properties. Select a map layer, then choose Tools - Theme Properties from the menu.

STEP 5. SAVING, COPYING AND PRINTING MAPS

Once you have selected an area of interest, you can copy the map to the Windows clipboard or save it as a picture file (bmp or emf format) by selecting commands under the Edit menu. Or you can print it by selecting Print under the File menu.

Be warned that the maps produced directly from ArcExplorer are not of very high quality. To produce a better map, consider saving the wind map as a bmp or emf file and importing it into a graphics program, or using the bitmap images as backdrops in a GIS program such as ArcView, ArcInfo, or Idrisi.

STEP 6. FOR MORE INFORMATION

If you have questions about the ArcExplorer program, please see the on-line documentation under the Help menu, view the ArcExplorer manual in PDF format on the CD-ROM, or visit http://www.esri.com/software/arcexplorer/index.html. For help with or information about the data base or any other aspect of the wind maps, send an e-mail to mbrower@truewind.com.

9.2. Other Data Files on the CD-ROM

The other data files on the CD-ROM contain additional information or are in different formats for different applications. The directories are as follows:

BMP. This directory contains the bitmap images used as a backdrop in ArcExplorer. The BMP files are accompanied by ESRI "world files" which provide geographic referencing when used in a compatible program such as ArcView.

CSV. The files named XX_MAIN.CSV are comma-delimited databases containing, for each grid point, the X and Y coordinates, latitude and longitude, the assumed (model) elevation and roughness, the predicted wind speed and wind power data at each height, and Weibull distribution parameters C and k at 50 m. The files named XX_ROSE.CSV contain the wind rose frequencies, mean speeds, and percent of energy. There is one file of each type for the annual data and one file of each type for the seasonal data. The XX_MAIN data are on a 200 m grid, the XX_ROSE data are on a 2 km grid. The files can be easily imported into a database program such as Microsoft Access, or they can be used to create Shape files or other GIS overlay files in ArcView or ArcInfo.

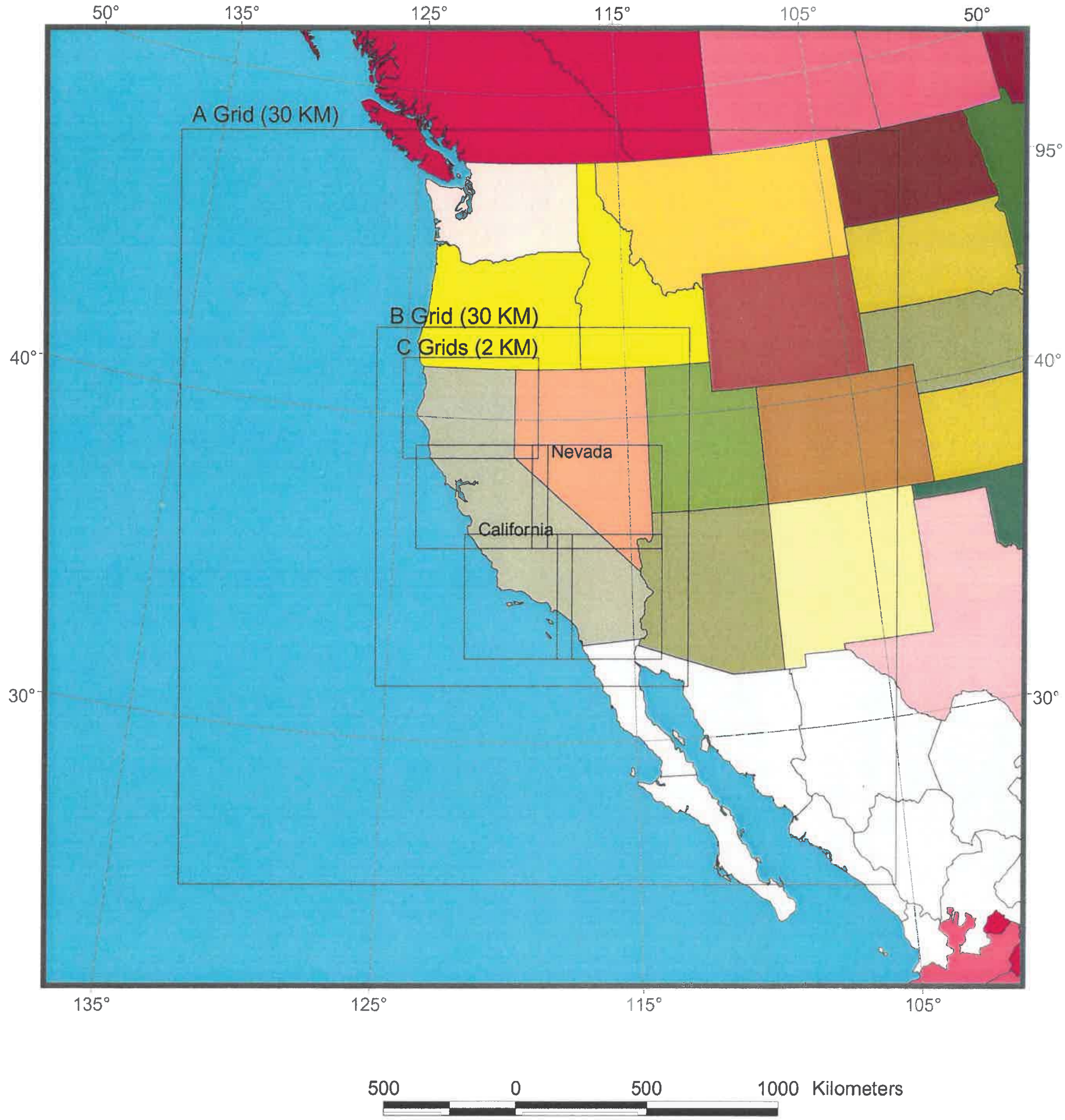
FloatingPoint. The files in this program are ArcInfo-type floating point grid files containing the mean wind speed and power at each height. They can be imported into ArcView or ArcInfo and may be more convenient than using the CSV files. However only annual data are provided in this format.

Raster. These files provide an alternative bitmap-type format for use in compatible GIS programs. The format is recognized by ArcView and ArcInfo. However no wind speed or power data can be read directly from them – they indicate only the wind speed or power class, as shown in the wind maps.

Shape Files. These are the vector overlays used in ArcExplorer. They can be also be used in ArcView and ArcInfo, and they can be imported into many other GIS programs. Included among them are the annual XX_MAIN and XX_ROSE shape files used in the ArcExplorer project included on the CD-ROM.

MAPS

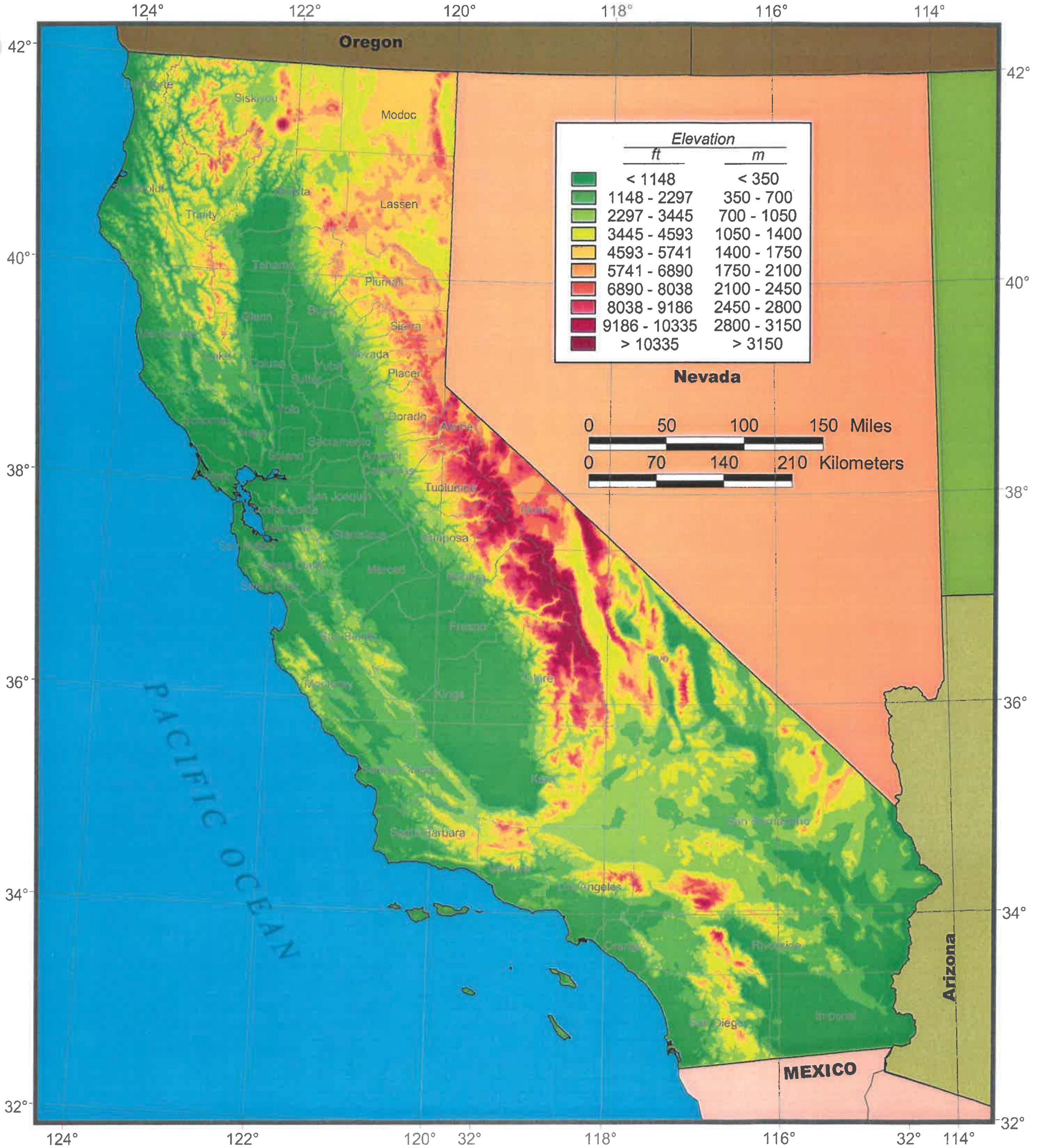
Map 1. Grid Setup for California and Nevada



TrueWind Solutions

Projection: Polar Stereographic

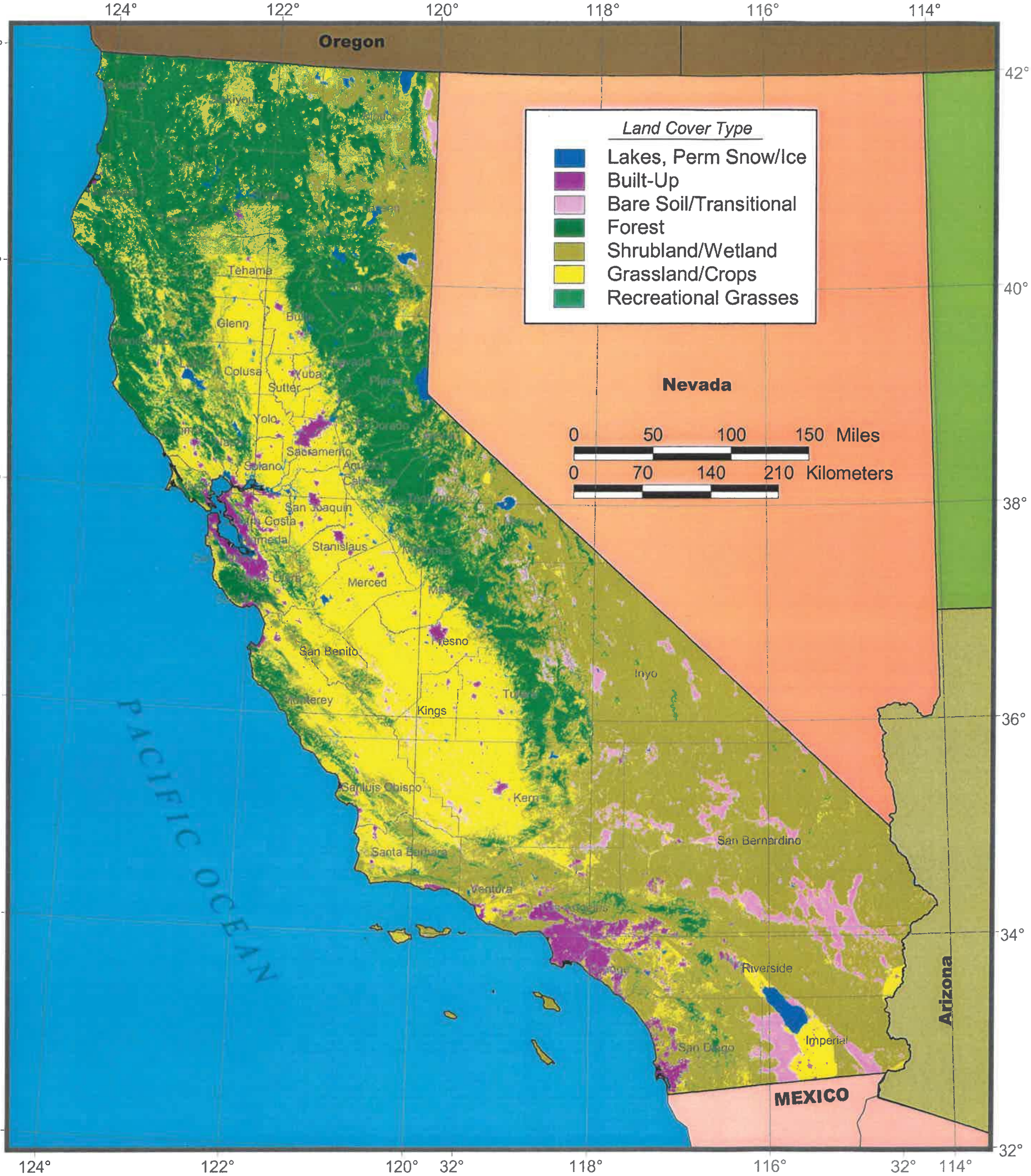
Map 2. Elevation



TrueWind Solutions

Projection: Universal Transverse Mercator (Zone 11)
Spatial Resolution of Elevation Data: 200 m

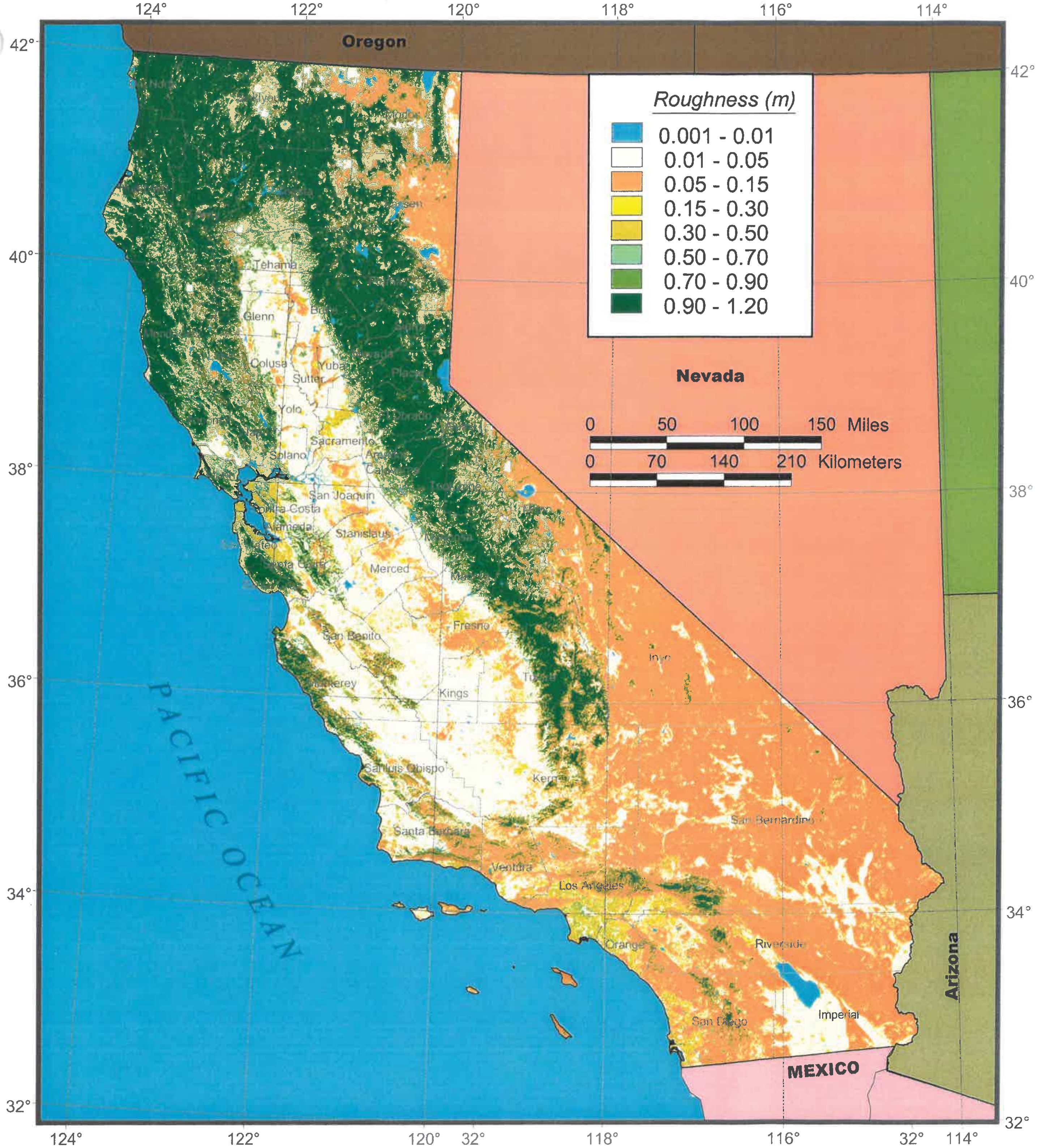
Map 3. Land Cover



TrueWind Solutions

Projection: Universal Transverse Mercator (Zone 11)
Spatial Resolution of Elevation Data: 200 m

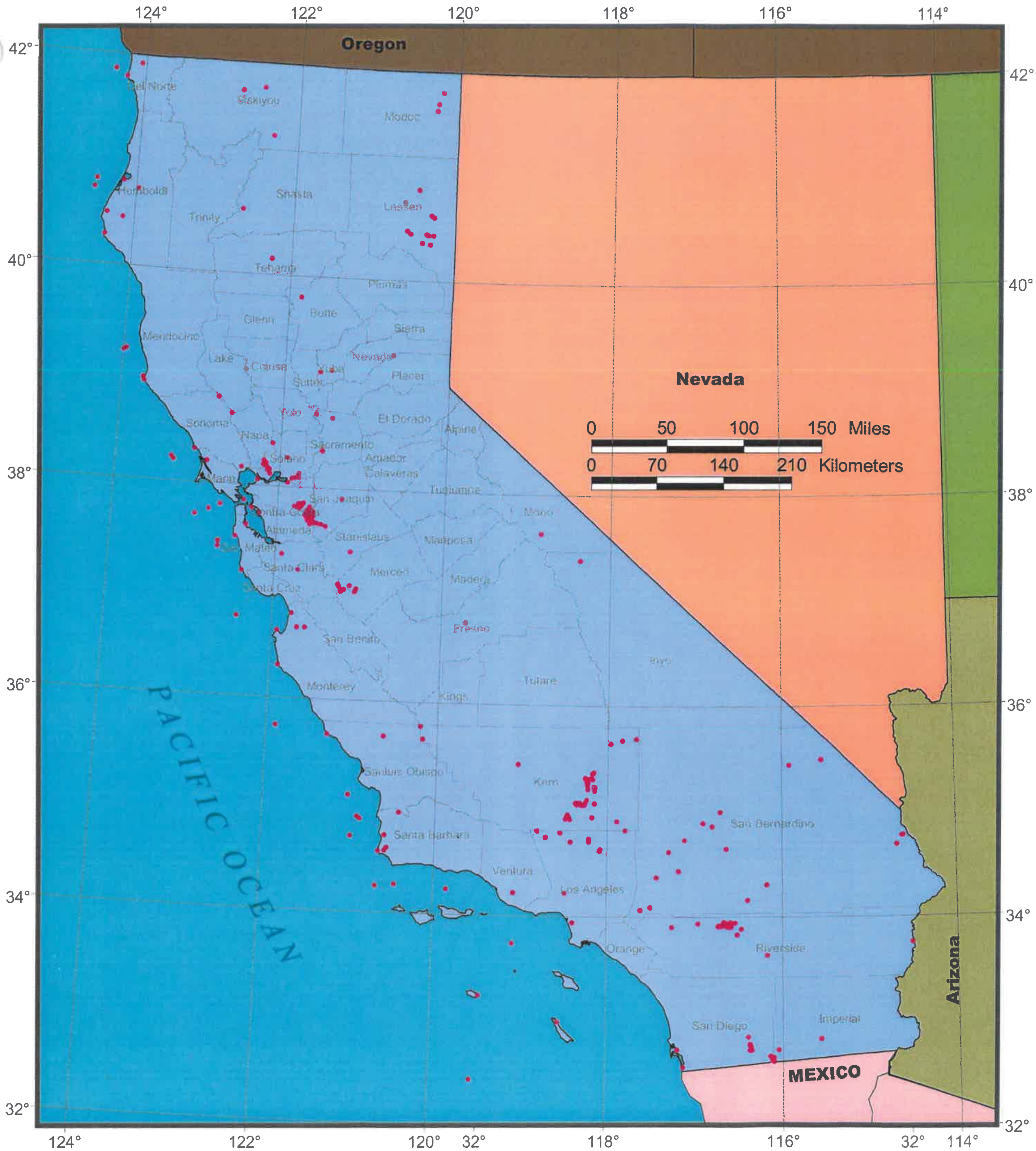
Map 4. Surface Roughness



TrueWind Solutions

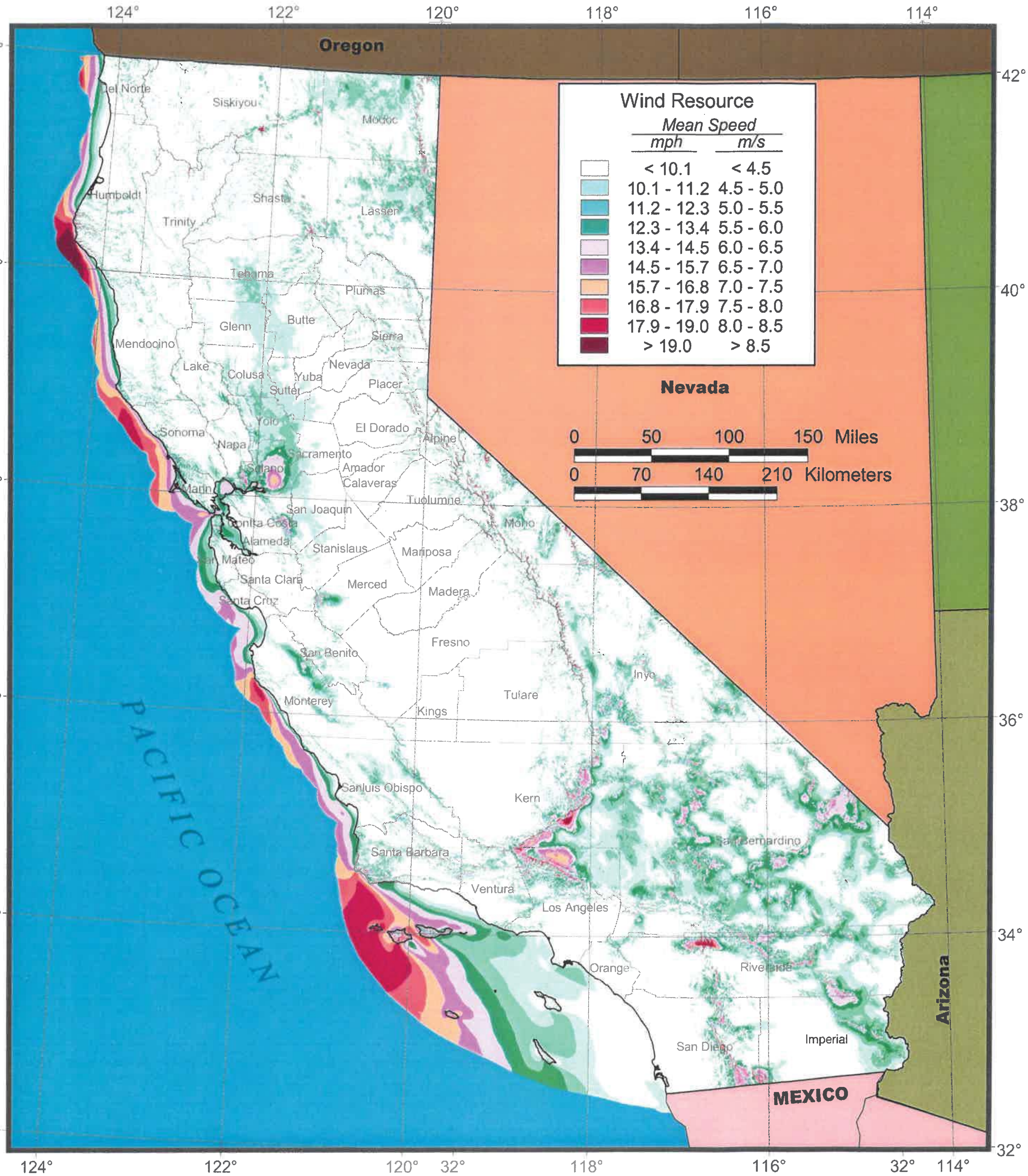
Projection: Universal Transverse Mercator (Zone 11)
Spatial Resolution of Wind Resource Data: 200 m
This map was created by TrueWind Solutions using the Mesomap system and historical weather data. Although it is believed to represent an accurate overall picture of the wind energy resource, estimates at any location should be confirmed by measurement.

Map 5. Validation Sites



TrueWind Solutions

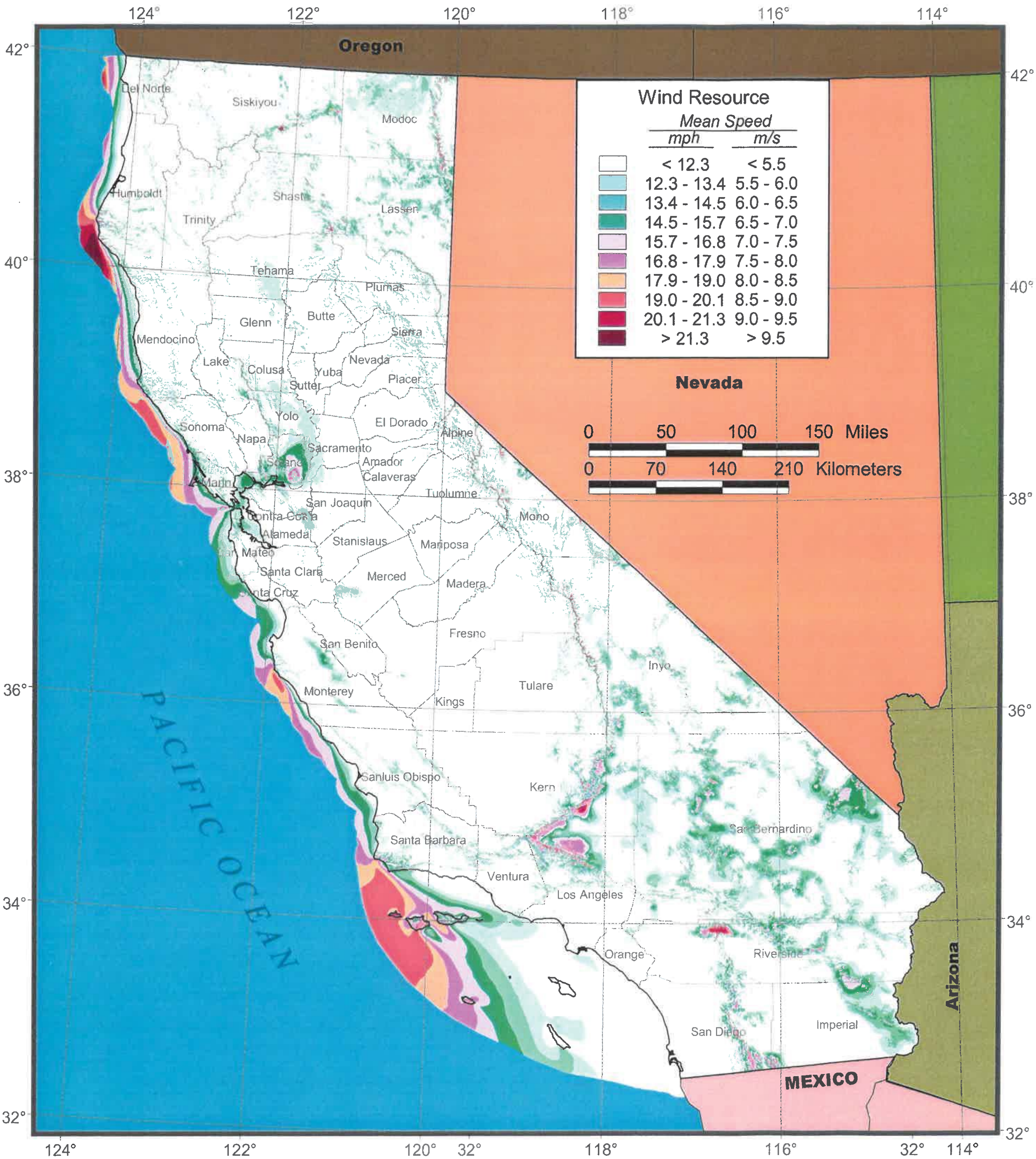
Map 6. Wind Speed at 30 m



TrueWind Solutions

Projection: Universal Transverse Mercator (Zone 11)
Spatial Resolution of Wind Resource Data: 200 m
This map was created by TrueWind Solutions using the Mesomap system and historical weather data. Although it is believed to represent an accurate overall picture of the wind energy resource, estimates at any location should be confirmed by measurement.

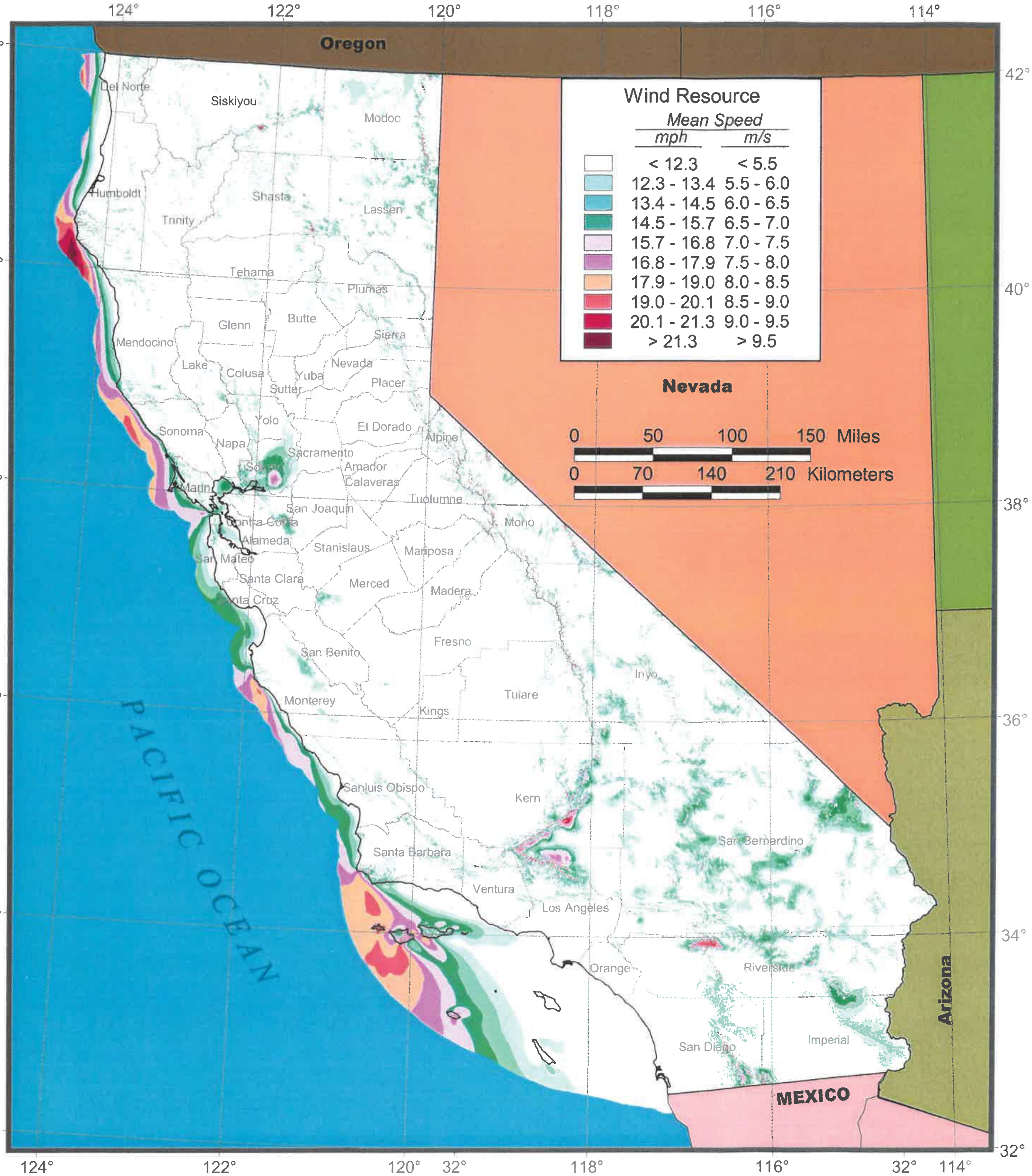
Map 8. Wind Speed at 70 m



TrueWind Solutions

Projection: Universal Transverse Mercator (Zone 11)
Spatial Resolution of Wind Resource Data: 200 m
This map was created by TrueWind Solutions using the Mesomap system and historical weather data. Although it is believed to represent an accurate overall picture of the wind energy resource, estimates at any location should be confirmed by measurement.

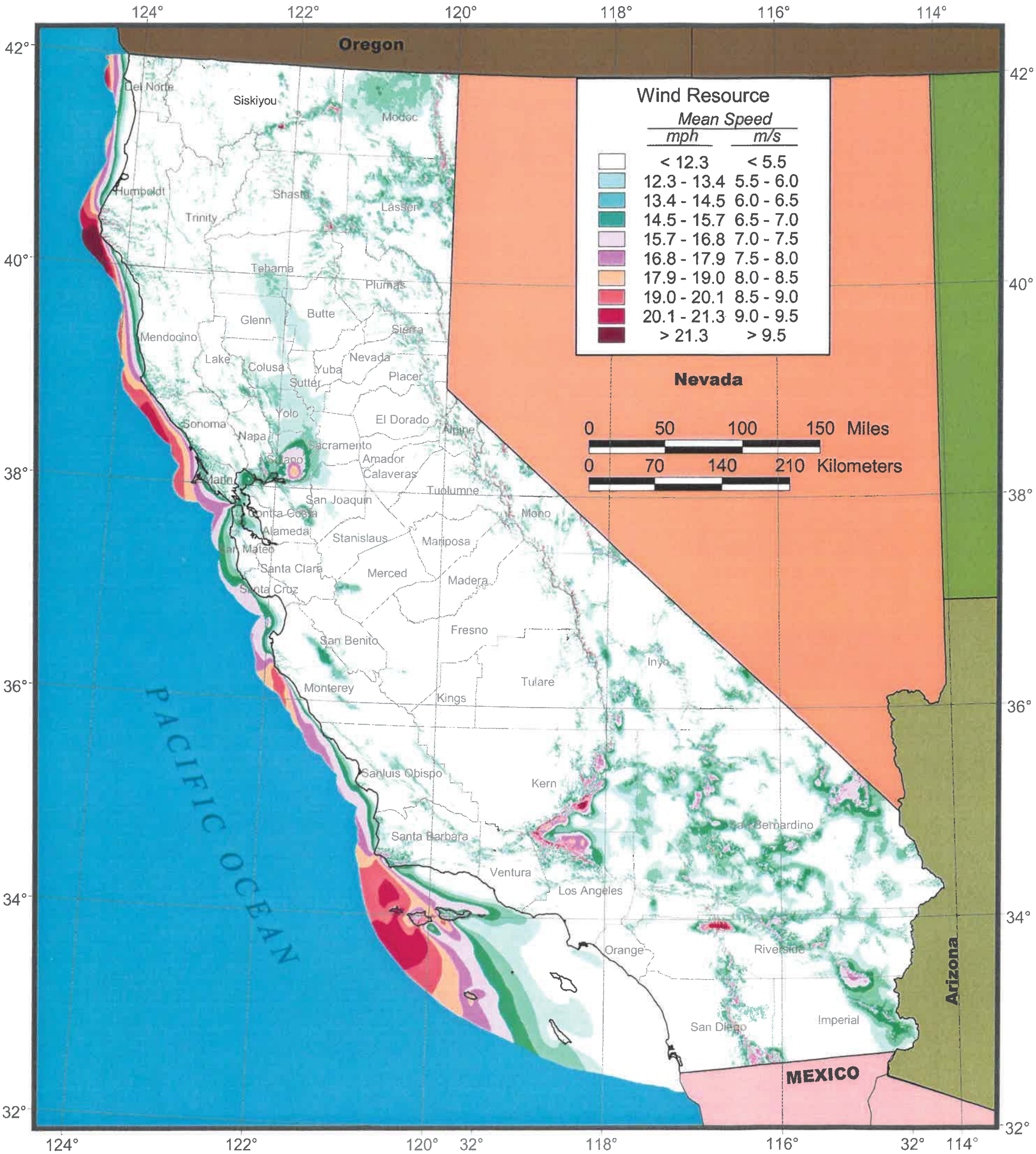
Map 7. Wind Speed at 50 m



TrueWind Solutions

Projection: Universal Transverse Mercator (Zone 11)
Spatial Resolution of Wind Resource Data: 200 m
This map was created by TrueWind Solutions using the Mesomap system and historical weather data. Although it is believed to represent an accurate overall picture of the wind energy resource, estimates at any location should be confirmed by measurement.

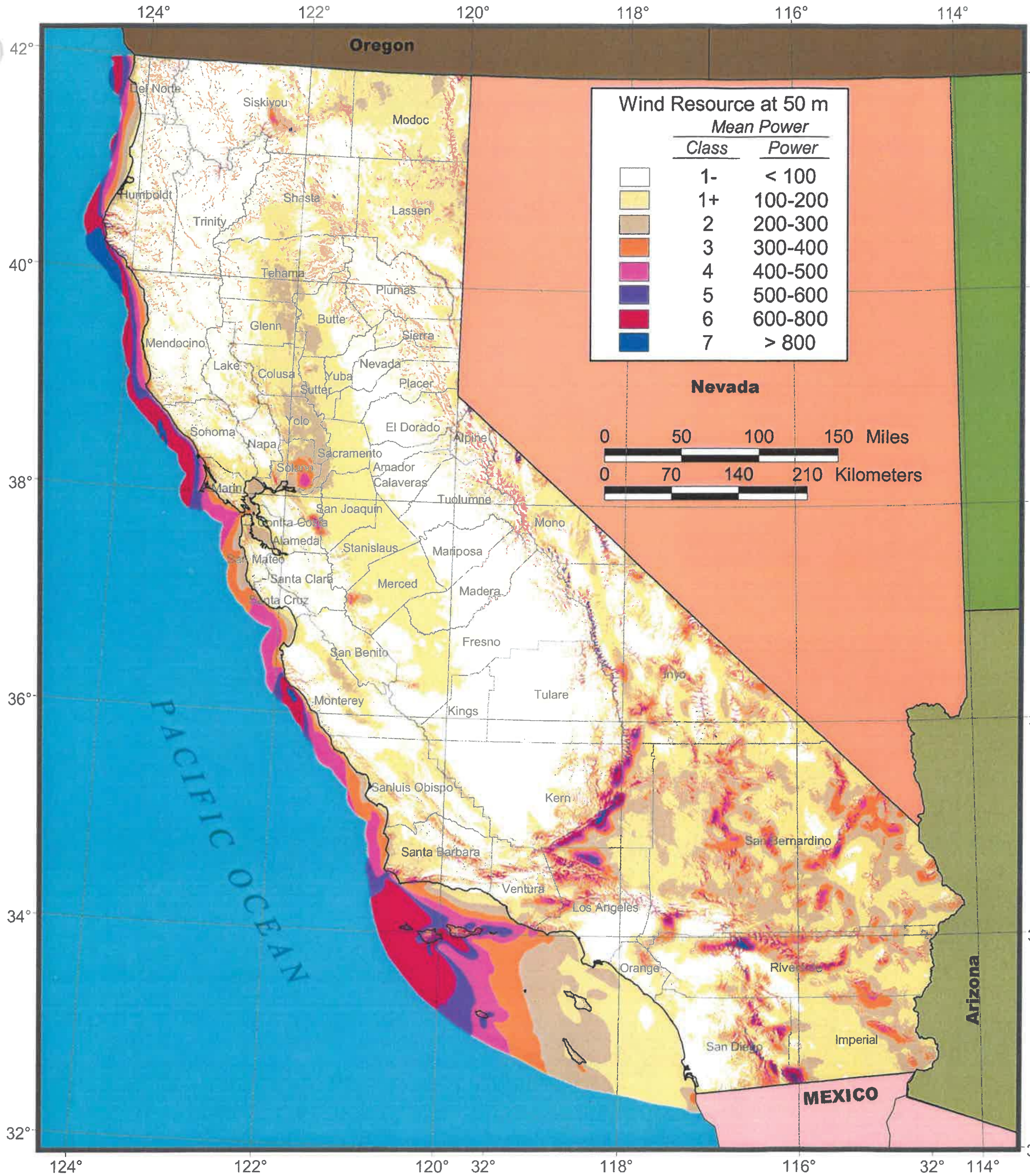
Map 9. Wind Speed at 100 m



TrueWind Solutions

Projection: Universal Transverse Mercator (Zone 11)
Spatial Resolution of Wind Resource Data: 200 m
This map was created by TrueWind Solutions using the Mesomap system and historical weather data. Although it is believed to represent an accurate overall picture of the wind energy resource, estimates at any location should be confirmed by measurement.

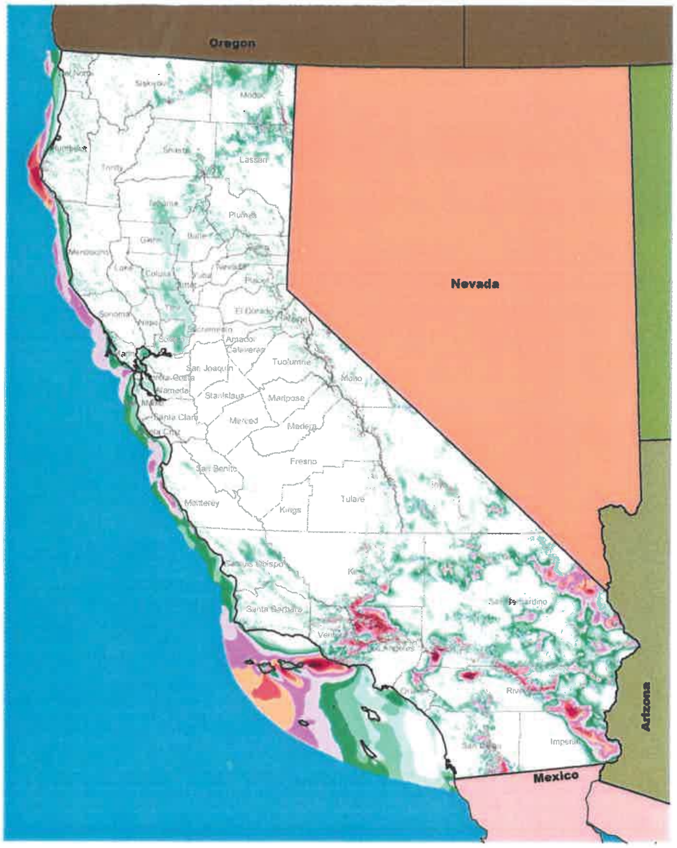
Map 10. Wind Power at 50 m



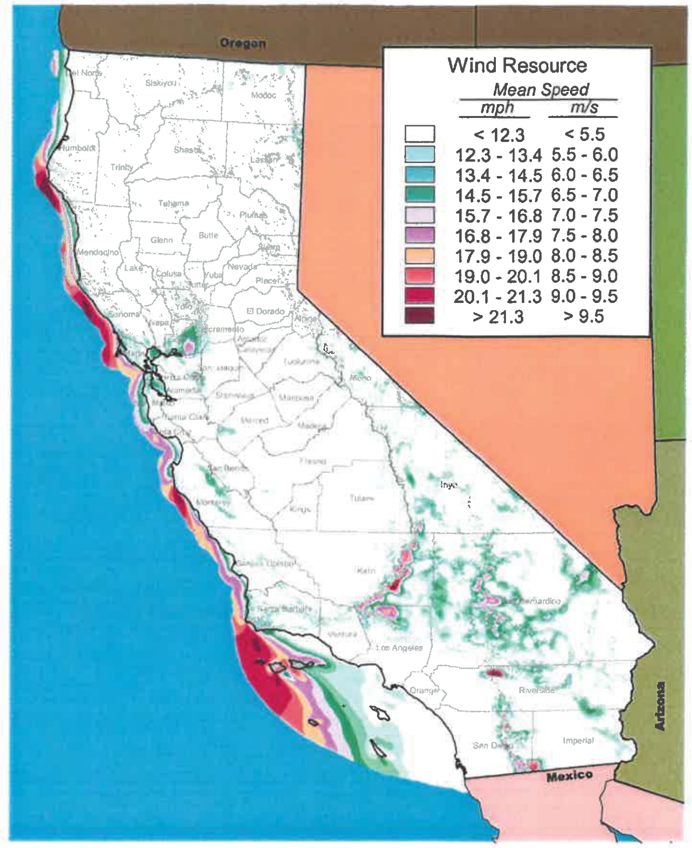
Projection: Universal Transverse Mercator (Zone 11)
Spatial Resolution of Wind Resource Data: 200 m
This map was created by TrueWind Solutions using the Mesomap system and historical weather data. Although it is believed to represent an accurate overall picture of the wind energy resource, estimates at any location should be confirmed by measurement.

TrueWind Solutions

Map 11. Seasonal Wind Speed at 50 m

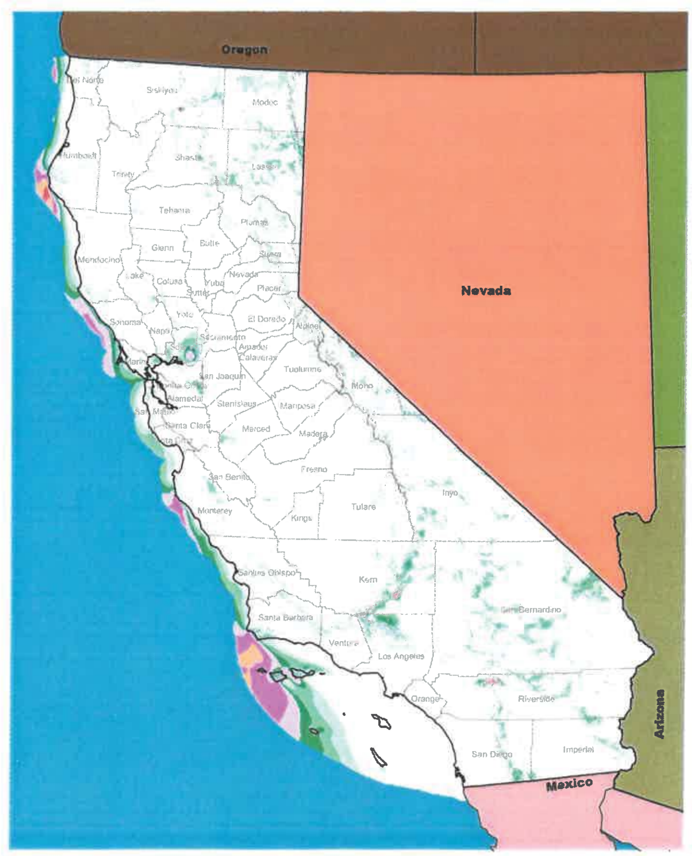


Winter



Spring

Summer



Fall