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Validation of New Wind Resource Maps

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VALIDATION OF NEW WIND RESOURCE MAPS

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Background

The National Renewable Energy Laboratory (NREL) recently led a project to validate updated state wind resource maps for the northwestern United States produced by a private U.S. company, TrueWind Solutions (TWS). The independent validation project was a cooperative activity among NREL, TWS, and meteorological consultants. The independent validation concept originated at a May 2001 technical workshop held at NREL to discuss updating the *Wind Energy Resource Atlas of the United States* (Elliott et al., 1987). Part of the workshop, which included more than 20 attendees from the wind resource mapping and consulting community, was dedicated to reviewing the latest techniques for wind resource assessment. It became clear that using a numerical modeling approach for wind resource mapping was rapidly gaining ground as a preferred technique and if the trend continues, it will soon become the most widely-used technique around the world. The numerical modeling approach is a relatively fast application compared to older mapping methods and, in theory, should be quite accurate because it directly estimates the magnitude of boundary-layer processes that affect the wind resource of a particular location. Numerical modeling output combined with high resolution terrain data can produce useful wind resource information at a resolution of 1 km or lower. However, because the use of the numerical modeling approach is new (last 3–5 years) and relatively unproven, meteorological consultants question the accuracy of the approach. It was clear that new state or regional wind maps produced by this method would have to undergo independent validation before the results would be accepted by the wind energy community and developers.

At the time of the workshop, the Windpowering America Program (Flowers and Dougherty, 2001) was actively supporting the acceleration of wind energy development in the Northwest and the production of updated wind resource maps for that region. The participants agreed at the workshop that the Northwest would become the pilot project for a validation effort. Everyone understood that, while the main emphasis of the validation project would be to produce the best wind maps possible, we would need to keep to a fairly tight schedule. This meant that any technical issues that arose during the process had to be resolved quickly and that research on these issues, though important, would not be part of the validation process.

Validation Overview

State and regional maps to be validated during the project included Montana, Idaho, Washington, Oregon, northern California, Wyoming, and Bonneville Power Administration (BPA) service areas in Nevada and Utah. Production of the maps was supported by the U.S. Department of Energy through NREL, BPA, and numerous other Northwest sponsors. Northwest SEED (Sustainable Energy for Economic Development) and the Northwest Cooperative Development Center coordinated the local sponsors.

The five meteorological consultants NREL chose to be part of its team for the Northwest validation included Bob Baker of PacifiCorp Power Marketing; Ron Nierenberg and Richard Simon, consulting meteorologists; John Wade of Terranova Energy Corporation; and Stel Walker of Oregon State University. These consultants were chosen based on their expertise, their experience with wind resource assessment in this region, and because some of them had access to proprietary measurement data that could prove to be quite valuable for the validation. The proprietary data issue could have been a serious roadblock to a comprehensive validation, but thanks to the efforts of the consultant team, much of these data were used to help produce the final wind resource maps.

NREL developed spreadsheets to score the validations for each state. Each spreadsheet contained entries for wind monitoring station locations and elevation, anemometer measuring heights, period of record, measured wind speed and power density, wind speed and power adjusted to map height, the map estimates of speed and power, and any qualitative comments the validators wished to make. Qualitative comments included any special circumstances about a particular monitoring station or special wind resource knowledge about a certain area. NREL requested that the spreadsheet be filled out as completely as possible and that essential monitoring station metadata and adjusted measured and mapped wind speeds be included in the final version. The validators also had the option to include a general geographic description of the station location rather than a specific latitude and longitude for proprietary data. The consultants then sent the spreadsheets to NREL and TWS for review. The results formed the basis for adjusting the preliminary wind maps.

Mapping and Validation Approach and Results

The approach for developing the final wind resource maps included three steps: 1) modeling and production of the preliminary maps by TWS; 2) review and validation of the preliminary maps by NREL and meteorological consultants; and 3) revision of the maps as needed for development of the final maps.

MesoMap, the modeling and mapping system employed by TWS, consists of three components: models, databases, and computer and storage systems (Brower et al., 2001). At the core of the MesoMap system is MASS (Mesoscale Atmospheric Simulation System), a numerical weather model used in commercial and research applications. MASS can be coupled to WindMap, a mass-consistent wind-flow model, to increase the spatial resolution of the MASS simulations. The main meteorological inputs for MASS are gridded historical weather data (the Reanalysis database), rawinsonde data, and land surface measurements. The main geophysical inputs are elevation, land cover, vegetation greenness, soil moisture, and sea-surface temperatures. The MesoMap system creates a wind resource map by simulating weather conditions from a large number of days (typically 365 days) selected from a historical period (typically 15 years). For each day in the sample, the wind speed and direction and other weather variables (including temperature, pressure, moisture, etc.) are simulated and stored at hourly intervals over the model domain. When the runs are finished, the data are compiled and summarized to produce maps of mean wind speed and power density (and other statistics) at various heights above ground.

The final MASS simulation output for the Northwest was at a 2.6-km grid resolution. These data were then used in WindMap to improve the final resolution to 400 m. The preliminary maps of mean annual wind speed at heights of 30 and 50 meters above ground and mean annual wind power density at 50 meters above ground produced by TWS were validated. Additional products produced by TWS were not validated due to time and budget constraints. These products included seasonal and diurnal grids of wind speed and power at 50 meters and wind roses (speed and frequency of direction) on a 10-km grid at 50 meters.

Northwest SEED coordinated with the various sponsors and project participants to establish the specific order for production of the different state and area maps for the Northwest. The Idaho maps were produced and validated first, followed by Washington, Montana, Oregon and specific areas of northern California, Nevada, and Utah, and finally Wyoming. The specific areas mapped are shown on the Northwest SEED web site at www.windpowermaps.org. Examples of final wind resource maps are shown here for two states, Washington and Wyoming, in Figures 1 and 2. The classification on the wind power map corresponds to the same seven power classes used in the 1987 U.S. wind atlas and maps more recently produced. Class 4 and above is generally considered good resource for utility-scale applications. The maps also show some other useful information such as major transmission lines and county and tribal land boundaries.

NREL and the meteorological consultants worked to identify and obtain available wind measurement data for use in the validation. Table 1 presents a summary of the wind measurement data used by NREL and the consultants in the validation of the preliminary maps for the states of Idaho, Montana, Oregon, Washington, and Wyoming. Measurement data from additional locations were used for validation of the specific areas of northern California, Nevada, and Utah. In all, data from more than one thousand locations in the region were analyzed and evaluated in the assessment and validation process. Although most of the data were collected at heights at or near 10 meters above ground, there were also substantial data from heights near 30 to 50 meters in some areas, particularly in areas where wind projects have been developed or are being considered. Data from these heights were the most valuable, because these data are at or near the map heights for which the wind resource estimates were generated. The hub-heights of modern wind turbines being installed or planned are often in the range of 70–100 meters, but data from these heights are too sparse to attempt to validate resource maps especially over large areas of complex terrain.

The estimation of the wind shears (change of wind speed and power with height above ground) was a major issue in extrapolating data measured at lower heights to estimates at 30 and 50 meters. These decisions were generally left to the discretion of the expert meteorological consultants who described their adjustment methods. In extrapolating data from airports and other measurement locations estimated to have low roughness, NREL typically used the standard 1/7 power law equation for the vertical adjustment.

NREL and all the consultants validated the wind speed maps. NREL also validated the wind power density maps, except for a few locations where hourly or adequate time series data were not available to estimate the wind power density.

TABLE 1. SITES USED FOR NORTHWEST MAP VALIDATION

Validation Sites by Consultant and State

	ID	MT	OR	WA	WY	Total
Bob Baker	8					8
Ron Nierenberg		10	4	30	9	53
Rich Simon	5	25	39	60	28	157
John Wade	114	106		12		232
Stel Walker (OSU/BPA)	28	26	147	102		303
Total	155	167	190	204	37	753

NREL Validation Sites by Type and State

	ID	MT	OR	WA	WY	Total
Tall Towers (DOE, etc.)		4		3	1	8
Kenetech	4				14	18
Airport	12	21	12	15	18	78
Highway Sites	2	25			16	43
CstGrd/LtHse/Buoy			8	13		21
Forest Service					10	10
Other	16	22	2	3	19	62
Total	34	72	22	34	78	240

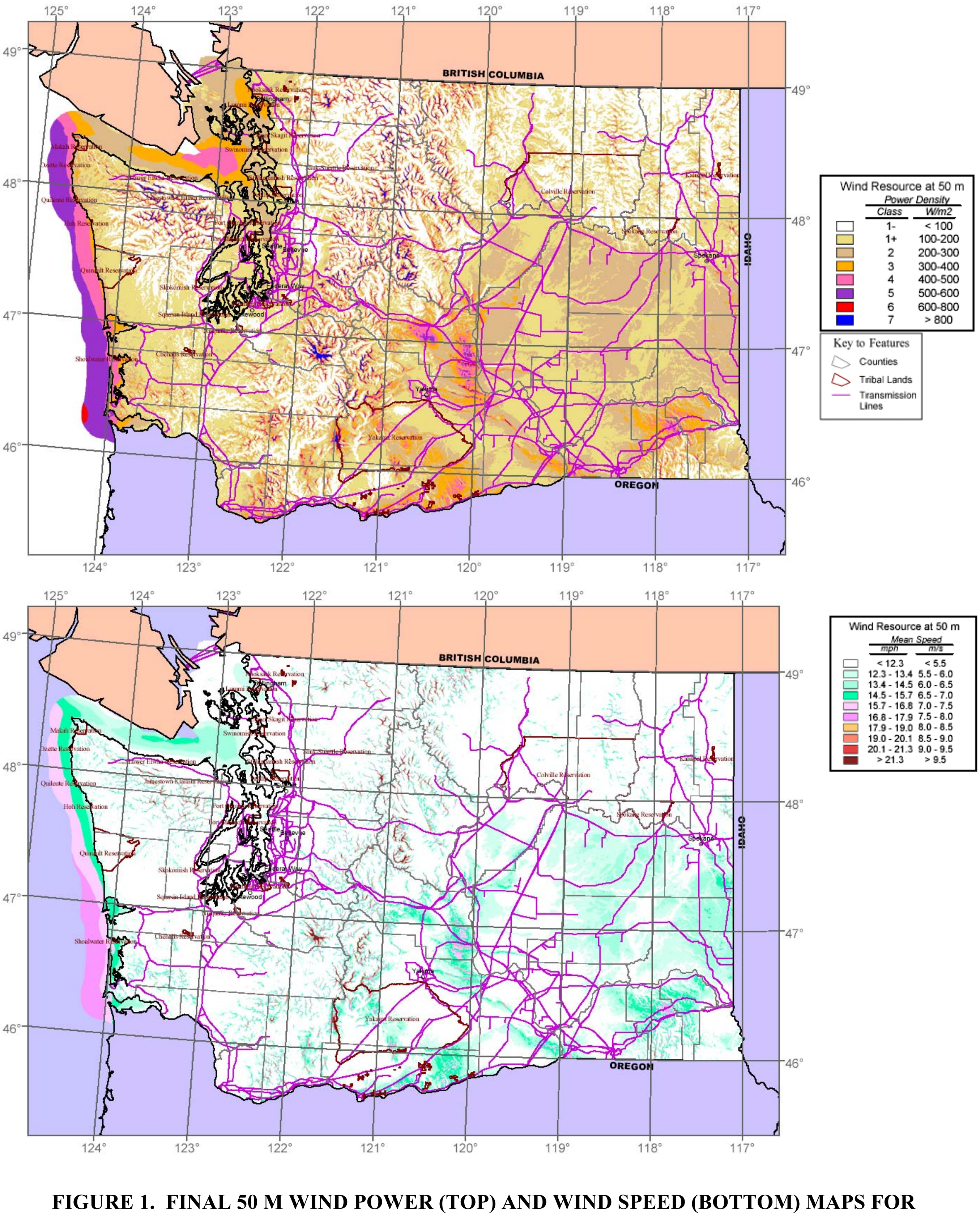
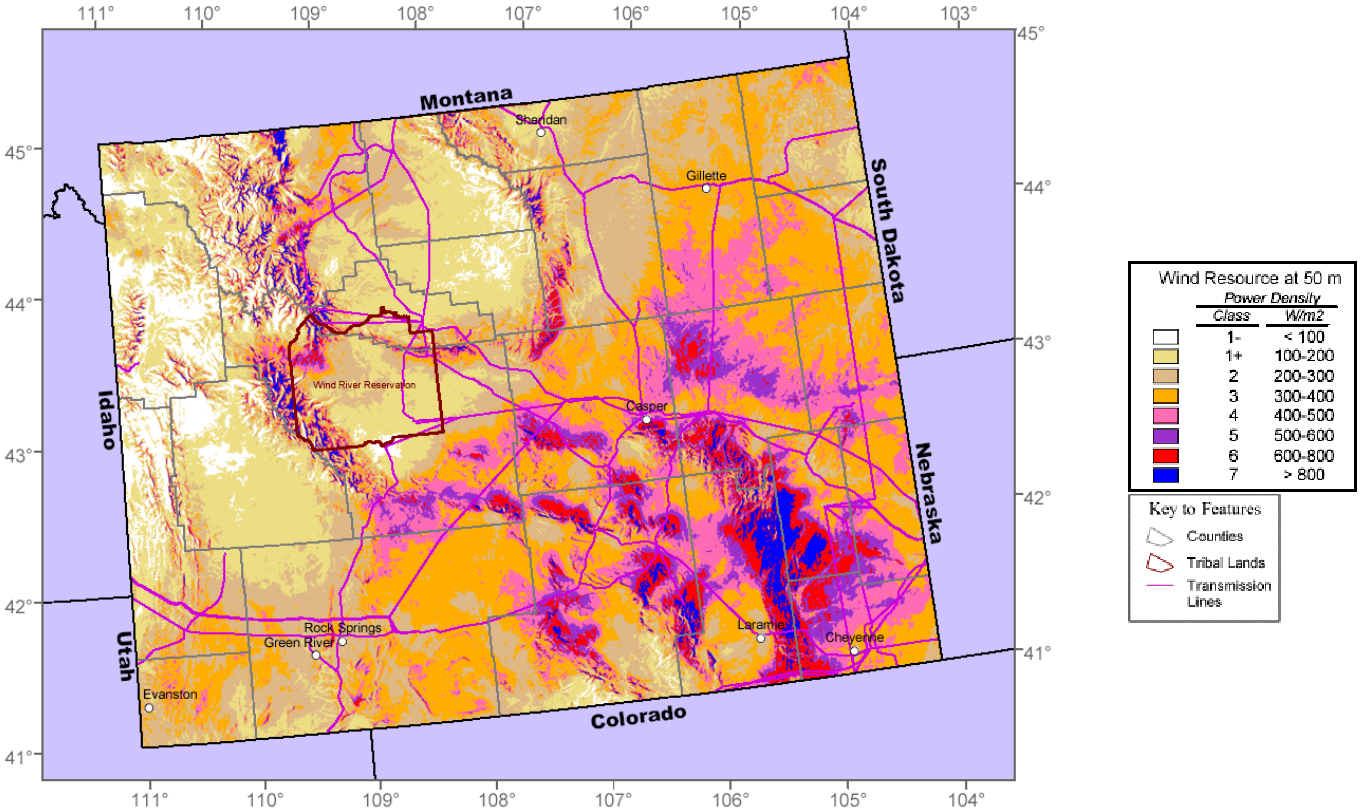


FIGURE 1. FINAL 50 M WIND POWER (TOP) AND WIND SPEED (BOTTOM) MAPS FOR WASHINGTON



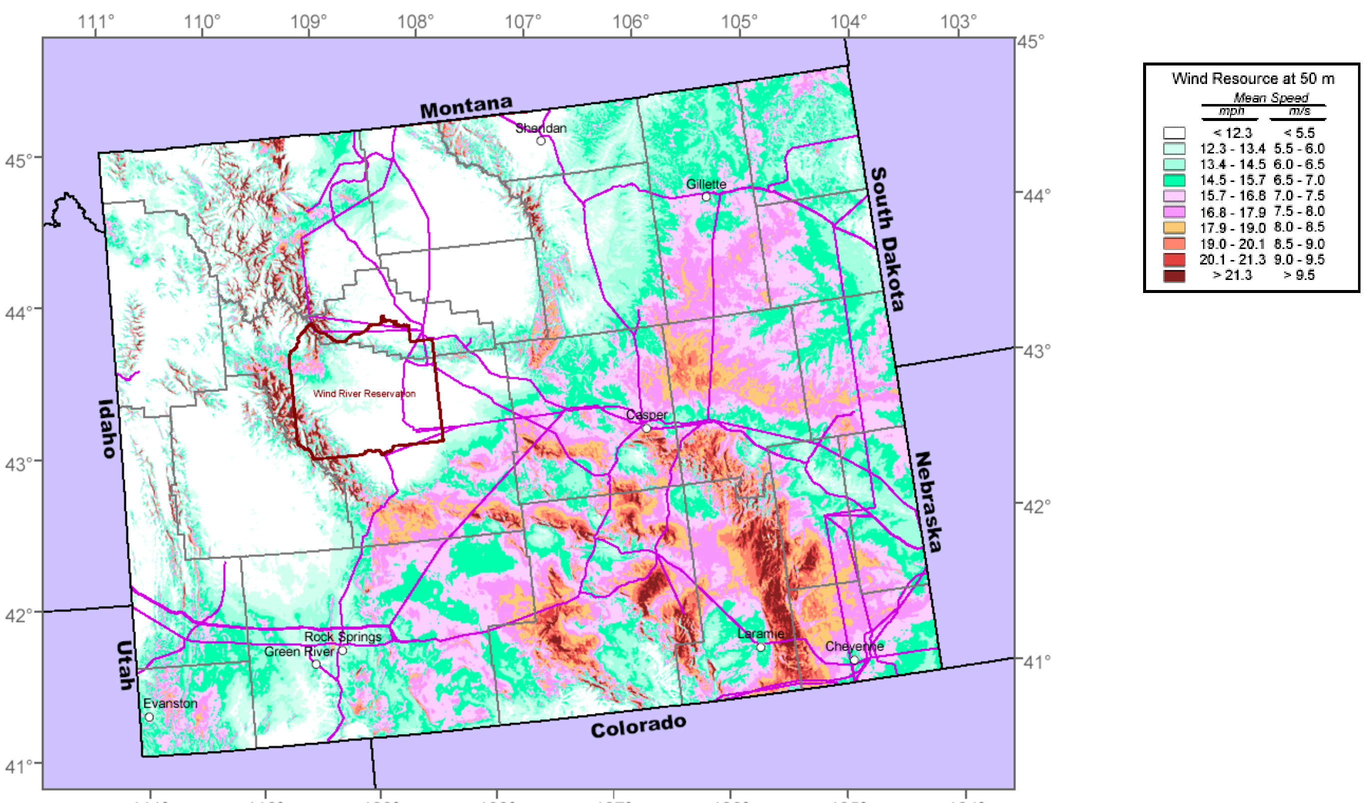


FIGURE 2. FINAL 50 M WIND POWER (TOP) AND WIND SPEED (BOTTOM) MAPS FOR WYOMING

Many sites had inadequate metadata (such as site descriptions and precise information on the location, anemometer height and measurement history), which complicated the use of the data in the validation process. In some cases, attempts were made to obtain more information needed to correct bad location coordinates and other questionable data. For many sites, coordinates were available only to the nearest minute (approximately 1.6 km). Therefore, we developed several strategies for comparing the 400-m resolution map estimates to the measured data, such as averaging the map estimates over larger areas and examining the variability of the 400-m estimates over a larger area. Some consultants made visual estimates of the map estimates due to proprietary issues in performing the validation. This introduced some small errors in the validation because the bins on the wind speed maps are generally 0.5 m/s. Again, we would like to emphasize that the time constraint to complete the review and validation of the maps was a major factor in this project. The objective was to produce the most accurate maps possible given these constraints.

The maps are not intended for micrositing, even though the data resolution is 400 meters. The MASS simulations were on a 2.6-km grid; therefore, the wind resource for small-scale terrain features less than 10 kilometers may not be resolved. The validation was an iterative process among the participants to improve the map estimates, with qualitative as well as quantitative input. As shown in Table 1, a large amount of data was obtained from many sources, and it was a challenging process to analyze the data for more than one thousand locations over a short time period and from such a large complex region. In all, data were identified from almost two thousand locations, but considerable data were discarded from use in the assessment for various reasons. For example, most wind measurement data obtained from the U.S. Forest Service that were collected at 560 remote automated weather stations were determined to be from low measurement heights and obstructed by trees. It was extremely difficult to reliably adjust the measured wind speeds to 50 m heights. Data obtained from more than 140 agricultural meteorological stations collected at heights only 2-3 meters above ground also could not be adjusted to validation heights with any confidence.

However, the high quality of some of the new data identified during this project, such as the data collected at highway meteorological sites in Montana and Wyoming, was unexpected and quite useful in the validation. These data provided insight into the wind resource characteristics in many areas of these states.

Proprietary data from the former Kenetech Windpower, analyzed by NREL and Ron Nierenberg, provided valuable information for validation of the map estimates in many areas of the Northwest. The Kenetech data will become available to the public in late summer 2002.

Stel Walker of Oregon State University used an extensive data set with wind measurements from more than 300 locations over many years, much of it from the early 1980s when the BPA funded instrumentation on many sites in the Northwest. These data were recently documented in a report and are available on a CD (Walker, 2001).

The data used by NREL from airports, coast guard stations, lighthouses, and ocean buoys were obtained from the U.S. National Climatic Data Center and had multiyear periods of record. In addition, NREL used wind data from satellite-derived ocean reflectivity measurements collected by the Special Sensor Microwave Imager as part of the Defense Meteorological Satellite Program.

The data used by John Wade for Idaho and Montana were derived from examinations of tree flagging, primarily on ridge crests. Oregon State University and others have developed methods to estimate wind speeds from the degree of tree flagging. The flagged tree data were instrumental in the validation and ultimate revision of the preliminary maps, particularly for ridge crests in forested areas. The general consensus, based on comparison of these data and other meteorological information to the model-derived estimates, was that the initial model resource estimates were generally too low for ridge crests in forested areas. TWS concluded the model estimates were too low because the land cover and surface roughness data used in the model does not account for the height of the trees, which typically decreases with increasing elevation in much of the Northwest region. This conclusion led to a revised modeling technique that reduced the roughness on ridge crests and increased the wind speed and power. This revision improved the results of final maps throughout the Northwest region.

Another model revision resulted from NREL's validation of the wind power density maps and some preliminary maps of Weibull k estimates generated by TWS. We discovered some problems with the values and spatial distribution of the wind power estimates that appeared to be related to some apparent problems with Weibull k estimates. TWS corrected this problem by calculating the power directly from the hourly wind speed simulations, rather than estimating from fitted Weibull k distributions. Further improvement in the model accuracy was achieved by increasing the number of days for the input data, which reduced the sampling errors. The revisions in the model improved the preliminary maps produced by TWS. NREL received preliminary maps of Washington with and without the model revisions. The validation results demonstrated the map with the incorporated revisions was superior to the map based on the original model.

Figure 3 shows the percentage difference in power and speed between the preliminary (after model revisions) and final maps for Washington. In the Columbia Basin of eastern Washington and Puget Sound area of western Washington, the preliminary model results overestimated the wind resource. Atmospheric stability issues were determined to be the primary cause of this error. Under very stable conditions, which are prevalent during much of the colder season when strong winds occur aloft, the downward mixing of the winds is severely restricted and reduces the resource in the basins. The complex interaction between the near surface flow and terrain that the model did not quite estimate accurately was responsible for much of the error in other parts of Washington. It is important to realize that Washington has a complex wind climate and though the preliminary model output data were not perfect, we were impressed by how accurate the model estimates were in many areas, particularly after model improvements were made. Adjusting the model estimates to the desired accuracy based on the validation results and qualitative input generated the final Washington maps. We believe the final maps exemplify the benefit of the validation process and the iterative modeling adjustments made by TWS as a result of the validation.

It became apparent as the validation project continued that it was not easy to predict how well the model would perform for specific states and regions. In most areas, the model performed well in estimating the wind resource. In some specific areas of very energetic resources, particularly some major wind corridors and downslope acceleration areas, the model underestimated the wind resource. Examples of these areas include the vicinity of Medicine Bow and the eastern side of the Laramie Mountains in southeastern Wyoming, and Judith Gap and the Browning areas in Montana. In some regions of the accelerated wind flow such as the Columbia River Gorge in Washington and Oregon, the model depicted the acceleration but did not accurately show the spatial distribution of the wind resource. We believe that for many of these accelerated flow regions, improvements in magnitude and distribution of the wind resource may be achieved through further refinements in the modeling such as running the model at a higher resolution over the local area. TWS has recently begun using the MesoMap system for micrositing assessments (Brower et al., 2002).

Technical Mapping Issues

Several interesting technical issues, particularly those relevant to the numerical model wind mapping technique became apparent during the course of the validation. Though it was beyond the scope of this project to study these in detail, it seems likely that these issues will arise again in future mapping projects and that research is warranted. Here is a brief description of these issues.

The first issue is surface roughness and its effect on the mapping results. The most straightforward way to apply surface roughness in a mapping project is to apply a linear relationship for each grid cell. In other

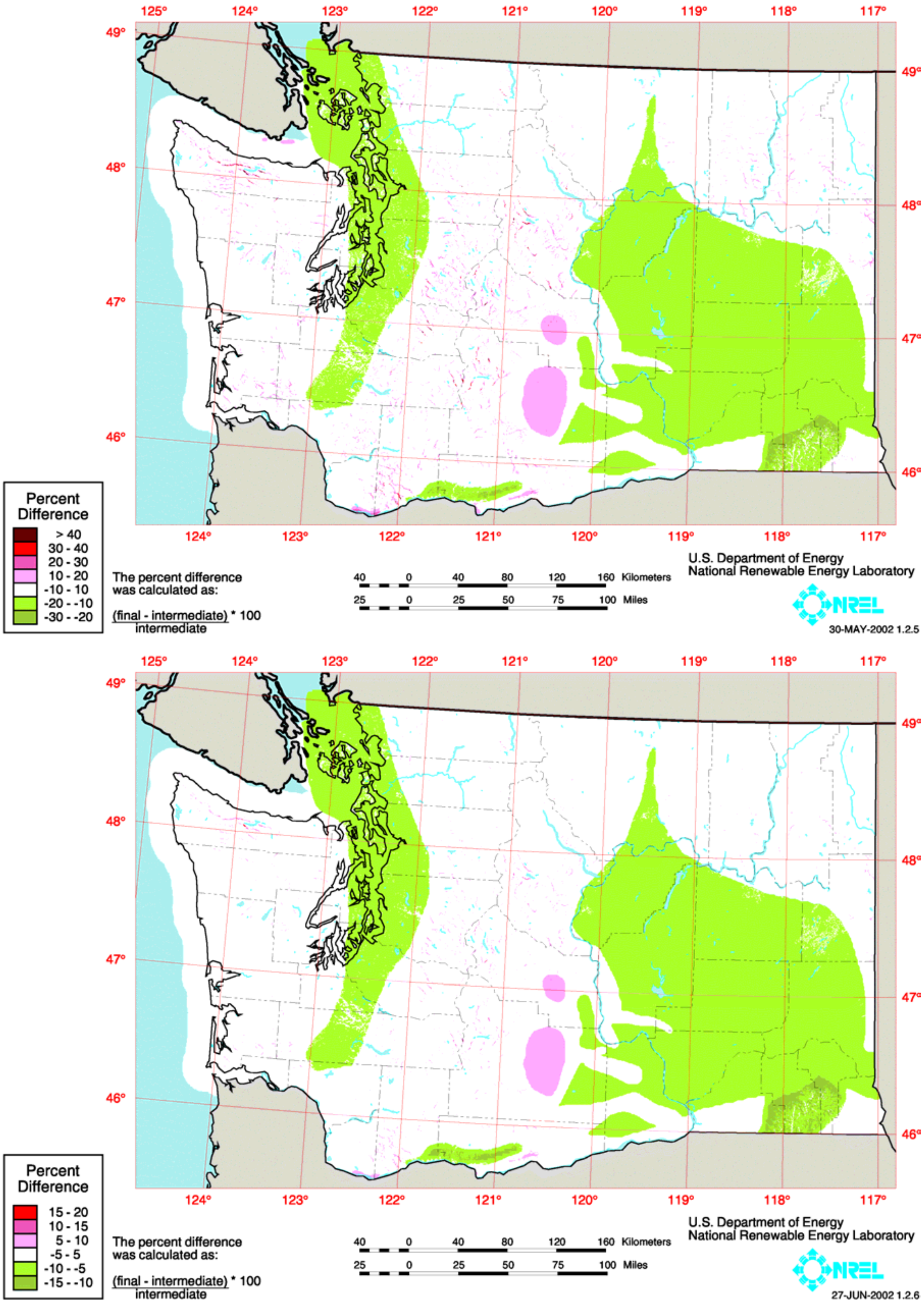


FIGURE 3. PERCENTAGE DIFFERENCE OF WIND POWER (TOP) AND SPEED (BOTTOM) BETWEEN FINAL AND PRELIMINARY MAP (AFTER MODEL REVISIONS)

words, each grid cell is assigned a surface roughness value and the wind resource is reduced by a given amount for that value. In high wind resource areas, this concept may break down because the variation of the surface roughness of the fetch from the prevailing wind direction(s) may override the surface roughness of a particular grid cell. The issue is further complicated by discrepancies among the data sets that can be used to define surface roughness. For example, for Raynolds Pass on the Idaho-Montana border, one data set had the area forested (incorrect) while another set had the region correctly described as grassland. Naturally, given a linear surface roughness relationship the modeled wind resource would be severely underestimated if the "forested" data set were used.

A second issue is whether the physical processes that affect the wind resource are adequately captured in the modeling process. Because important processes can extend over a range of scales (storm-driven pressure gradients to local thermal circulations), there is always a tradeoff between having finer resolution to try and capture as many of these processes as possible and increasing the cost and effort of the mapping project.

Atmospheric stability is another concern. The stability affects the turbulent mixing of momentum and boundary-layer fluxes, important factors in the level of the wind resource at a particular location. The question is whether a mapping technique can adequately capture the effect of atmospheric stability. In the Northwest, this issue is significant because during the winter in the interior and during the summer along the coast the atmosphere is frequently stable. These conditions can affect the vertical profile of the wind resource with lower elevations having less resource and higher elevations having greater resource than would normally be expected given the large-scale wind climate.

Finally, all mapping models need comprehensive meteorological and topographical input data to produce a credible product. However, there are many different forms of these data and the strengths and weaknesses are not easily evaluated. It is quite possible that input derived from a particular source may result in a model producing a more accurate product in some wind regimes than in others, or that a combination of data sources might be the best to use in select wind climates. This is a technical area that deserves further research.

Conclusion

The Northwest validation process produced final wind resource maps of that region noticeably better than those that would have been produced without validation. The validation was successful because of the iterative process among NREL, TWS, and the consultant team. Success can be attributed in part to the considerable high-quality data from the region and the validators' knowledge of the wind resource in this region. Similar validation efforts are underway and are planned for the Mid-Atlantic and the Southwestern United States. The lessons learned from the Northwest validation will enhance the validation efforts for these areas.

Important technical mapping issues mentioned earlier in the paper have become better defined because of the initial validation project. Research into these areas will have a direct bearing on the plan to update the 1987 U.S. atlas. In addition, this project showed that research to evaluate numerical model performance in different types of terrain and wind climates is warranted. Investigations into model performance in wind corridors and downslope acceleration zones, coastal areas, areas with low-level jets, and "choppy" terrain versus ridge-like features will help improve resource maps produced by numerical models.

In summary, the validation of the new wind resource maps has proven to be successful not only in creating high-quality maps but also in showing fruitful paths for wind resource assessment and mapping research.

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References

Brower, M.; Bailey, B.; Zack, J. (2001). *Applications and Validations of the MesoMap Wind Mapping System in Different Wind Climates.* Windpower 2001 Proceedings , Washington, D.C.: American Wind Energy Association, 10 pp.

Brower, M.; Bailey, B.; Zack, J. (2002). *Micrositing Using the MesoMap System.* Presented at the Windpower 2002 Conference, June 2-6 ,2002, Portland, Oregon.: American Wind Energy Association.

Elliott, D.; Holliday, C.; Barchet, W.; Foote, H,; Sandusky, W. (1987). *Wind Energy Resource Atlas of the United States.* DOE/CH 10093-4, Golden, Colorado: Solar Energy Research Institute, 210 pp.

Flowers, L.; Dougherty, P. (2001). *Wind Powering America.* Windpower 2001 Proceedings, Washington, D.C.: American Wind Energy Association, 9 pp.

Walker, S. (2001). *Pacific Northwest Wind Data.* Energy Resources Research Laboratory, Corvallis, Oregon: Oregon State University, 42 pp.

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