PROJECT REPORT

Wind Resource Maps of Northern New England

Prepared for
The Connecticut Clean Energy Fund
The Massachusetts Technology Collaborative's
Renewable Energy Trust
Northeast Utilities

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Under Subcontract to
AWS Scientific, Inc.

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SUMMARY

This report presents the results of a wind mapping project conducted by TrueWind Solutions, LLC, for Connecticut Clean Energy Fund, the Massachusetts Technology Collaborative's Renewable Energy Trust, and Northeast Utilities, under subcontract to AWS Scientific, Inc. Using its MesoMap system, TrueWind has produced maps of mean wind speed at 30, 50, 70, and 100 m height and of mean wind power at 50 m height, on a 200 m grid covering Vermont, New Hampshire, and Maine. The maps indicate that the windiest sites in the region are found mainly in the hills and mountains of all three states, as well as coastal areas and offshore.

The report also describes the validation of the maps carried out by TrueWind Solutions and the National Renewable Energy Laboratory (NREL). Comparison of the preliminary map with data from 33 wind-monitoring stations, extrapolated to a height of 50 m, resulted in an estimate of the map root-mean-square error of about 0.4 m/s, or 6%, with zero bias. After review by NREL, it was decided that no changes in the maps were warranted before their final release.

The following sections present the maps and describe the validation process and results. For background information on the MesoMap system and mapping methodology, see Addendum 1. For guidelines on using the maps, see Addendum 2.

WIND MAPS

Maps 1-3 show the predicted mean wind speed across northern New England at heights of 30 m, 50 m, and 70 m above the effective ground level.[1] Maps at other heights have been delivered separately. Seventy meters is a typical tower height for the current generation of large wind turbines of 750 KW to 2 MW rated capacity, though towers may be taller; thirty meters is a typical height for small turbines of up to 50 KW rated capacity. Map 4 shows the predicted mean wind power in the NREL standard wind resource classes. This map is especially useful for comparison with the previous map of the region published in the national wind atlas.[2]

The mean speed and power describe different aspects of the wind resource, and both can be useful in different ways. The mean speed is the easiest for most people to relate to and is consequently the most widely used. However, it does not directly measure the power-generation potential in the wind. Some experts regard the mean wind power, which

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[1] In dense forest, the effective ground level is the canopy height, which is estimated to be 2/3 the height of the treetops. Thus if the average tree height is 15 m (45 ft), the effective ground level is about 10 m (30 ft), and a map height of 50 m corresponds to a height of 60 m above ground.

[2] *Wind Energy Resource Atlas of the United States* (Department of Energy, 1986).

depends on the air density and the cube of the wind speed, as a more accurate indicator of the wind resource when assessing wind project sites. Generally speaking, commercial wind power projects using large turbines require a resource with a mean speed of at least 7 m/s or mean power of at least 400 W/m^2 (NREL class 4). Small turbines are designed to operate at lower wind speeds than their larger cousins, and they may be viable at mean speeds (at 30 m height) as low as 5-6 m/s (NREL class 2 to 3).

The wind maps show that the best wind resource is concentrated in two areas: offshore and mountaintops. Offshore winds in northern New England are predicted to be quite strong, especially off the Maine coast, with mean speeds at 50 m ranging from 7 to 8.5 m/s (NREL class 4-6) within 20 km of the main shoreline. Some exposed peninsulas and islands are predicted to have a moderate resource of 6-7 m/s. Moving inland, the wind resource quickly diminishes because of the high surface roughness created by the extensive forest cover. If New England were, like the Great Plains, mostly open farmland, mean wind speeds would be at least 1 m/s higher.

Farther inland, mountain ranges have the most important influence on the resource. Valleys by and large have a very low mean wind speed and power. Many mountaintops, particularly along the high mountain ranges of western Vermont, north-central New Hampshire, and western Maine, are predicted to have mean wind speeds exceeding 9 m/s (NREL class 6-7). These points are high enough to be exposed to the very strong winds that occur aloft, particularly in winter. There may also be some acceleration of the westerly and northwesterly winds over ridges with a favorable north-to-south and northeast-southwest orientation.

It should be emphasized that the mean wind speed or power at a site may differ substantially from the predicted values if there are differences in the elevation, exposure, or surface roughness compared to that assumed by the wind mapping system. The map estimates were developed using 1:100,000 scale topographical and land cover data from the US Geological Survey. The accuracy of these data should be verified in areas where wind projects are being considered. See Addendum 2 for guidelines on the use of the maps.

VALIDATION

The preliminary wind maps were produced without reference to any surface wind measurements. To assess their accuracy, we compared the 50 m map with measurements from 33 towers in the region. The data came from a variety of sources, including airports, offshore buoys and platforms, and wind measurement programs from the 1980s and 1990s.[3] Table 1 compares the predicted and measured speeds (the latter extrapolated to 50 m). Where direct shear measurements were not available, the wind shear exponent was estimated from information about the site. Offshore and coastal stations as well as mountaintops were assumed to have a lower shear than stations in forested valleys.

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[3] Data from airports were obtained from the national wind atlas. More recent airport data were judged less suitable because of the limited period of measurement using ASOS equipment installed in the mid 1990s. Offshore buoy and platform data were obtained from the NOAA National Buoy Data Center.

Table 1. Comparison of Predicted and Measured/Extrapolated Speeds at 50 m

Station	*State*	*Height (m)*	*Speed (m/s)*	*Shear Exponent*	*Speed at 50m (m/s)*	*Map (m/s)*	*Bias (m/s)**
Limestone/LOR	ME	4	3.3	0.25	6.2	5.9	-0.4
Caribou/Mun	ME	9	5.0	0.15	6.4	6.2	-0.2
Millinocket	ME	13	3.2	0.25	4.5	5.0	0.5
#5 Mtn	ME	24	10.9	0.05	11.3	10.0	-1.3
Coburn	ME	12	9.9	0.10	11.4	11.1	-0.3
Tumbledown Mtn	ME	15	9.0	0.10	10.2	10.8	0.6
Caribou	ME	27	10.3	0.10	11.0	10.7	-0.3
Kibby Mtn	ME	21	10.4	0.10	11.3	10.8	-0.5
Kibby Mtn South	ME	21	7.6	0.15	8.7	7.9	-0.8
Kibby Range	ME	27	9.2	0.10	9.8	9.0	-0.8
Snow Mtn	ME	18	9.4	0.10	10.4	10.5	0.1
Old Town/DEWI	ME	6	2.8	0.25	4.7	5.3	0.6
Colebrook	NH	40	4.9	0.78	5.8	6.1	0.2
Balsams	NH	30	7.8	0.20	8.6	8.6	0.0
Bangor/Int	ME	6	3.2	0.17	4.6	6.3	1.7
Burke Mtn.	VT	23	8.8	0.10	9.5	8.6	-0.9
Berlin	NH	40	5.0	0.30	5.3	6.0	0.6
Burlington	VT	6	3.9	0.17	5.6	5.4	-0.2
Augusta/State	ME	14	4.7	0.25	6.4	6.1	-0.3
Walker Mtn.	NH	40	5.0	0.30	5.3	5.5	0.1
Montpelier	VT	14	3.6	0.20	4.7	4.9	0.2
Brunswick	ME	5	3.2	0.25	5.8	6.0	0.2
Grandpa's Knob	VT	37	7.2	0.15	7.5	7.0	-0.5
Portland/Int	ME	6	3.9	0.17	5.6	6.1	0.5
Lebanon	NH	12	2.2	0.25	3.1	4.2	1.0
Mt. Sunapee	NH	40	9.2	0.15	9.5	9.0	-0.5
Concord	NH	6	3.1	0.20	4.7	4.3	-0.4
Stratton Mt.	VT	46	11.4	0.05	11.5	11.3	-0.2
Portsmouth	NH	10	4.1	0.17	5.4	5.7	0.3
Manchester/GR	NH	3	3.1	0.17	5.0	5.1	0.1
Mt. Mansfield	NH	11	11.1	0.05	12.0	11.2	-0.8
Buoy 44007	Offshore	5	4.9	0.14	6.8	7.6	0.7
Matinicus Rock	Offshore	17	7.9	0.12	9.0	8.5	-0.5
Average					7.4	7.4	0.0
Standard Deviation							0.6 (8%)
Standard Error							0.4 (6%)

*The bias is the map speed minus the measured/extrapolated speed. Values do not always agree with those calculated directly from the table because of rounding.

The same data are presented as a scatter plot in Figure 1. The error bars show the average uncertainty margin of about 6% that was assigned to the measurements. This uncertainty reflects two main factors: the unknown wind shear between the top anemometer and the 50 m map height; and the number of years of measurement.

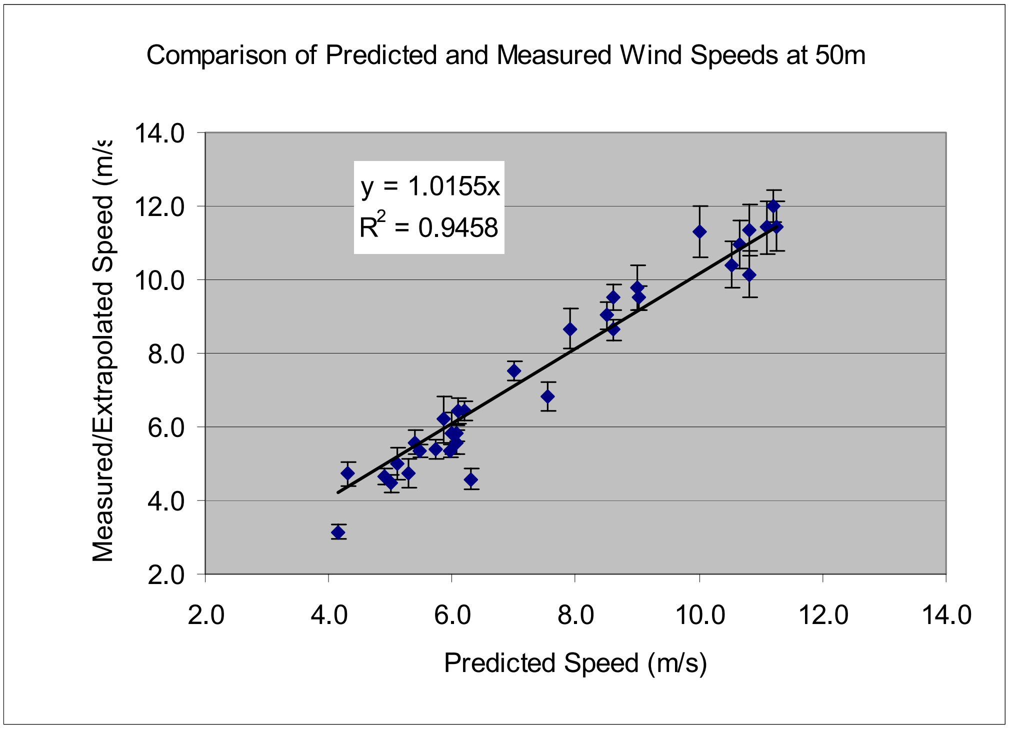

Figure 1. Scatter plot showing predicted and measured/extrapolated mean wind speeds at the 34 stations listed in Table 1. The two outliers at the lower left below the line are Lebanon and Bangor International Airport.

It is evident in both the table and the scatter plot that there is a strong agreement between the model and data. The root-mean-square (rms) discrepancy between the predicted and measured/extrapolated data is 0.6 m/s, or about 8%. After subtracting (in a least-squares sense) the uncertainty associated with the data, we estimate the standard error of the map to be 0.4 m/s, or 6%. On average, the predicted speed has virtually no bias. The r^2 correlation coefficient of 95% indicates that the model was able to explain the vast majority of the variance in observed wind speed.

Two outliers, Lebanon, New Hampshire, and Bangor International Airport, account for nearly half of the standard error. At this point we do not know whether the discrepancy between the map and measurement was caused by a problem with the model, the input data (meteorological or topographical), or some problem with the stations (such as sheltering by buildings or trees). Both are airport stations with relatively short towers. We speculate that in both cases, the model overestimated the localized increase in speed caused by the low roughness of the airport surroundings.

The wind maps were independently reviewed by NREL. Focusing mainly on the wind power, NREL gave a positive review of the map and recommended no changes. Consequently, TrueWind made no adjustments to the northern New England map before its release, except that needed to merge the map with the corresponding maps of southern New England that were released in July 2002.

CONCLUSIONS AND SOURCES OF UNCERTAINTY

The MesoMap system has been used to predict the wind energy resource in northern New England on a 200 m grid. Maps have been produced showing the predicted mean wind speed at 30 m, 50 m, 70 m, and 100 m, and the mean wind power at 50 m, above the effective ground level (forest canopy or ground). The maps indicate that the most favorable winds are found offshore, at exposed points along the coast, and on mountaintops of Vermont, New Hampshire, and Maine.

The maps agree well with available wind measurements extrapolated to the same height. Nevertheless caution should be used in using the maps, especially because the local elevation and surface roughness (land cover) may differ from that assumed by the model. Guidelines provided in Addendum 2 allow the user to make adjustments to the map values where differences appear. Even with such adjustments however, map estimates for any particular location should be confirmed by measurement.

ADDENDUM 1: DESCRIPTION OF THE MESOMAP SYSTEM

The MesoMap system consists of three key components: models, databases, and computer and storage systems. These components are described below.

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 both as a research tool and to provide commercial weather forecasting services. MASS embodies 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 requiring the use of powerful workstations and multiple parallel processors. However, MASS can be coupled to a faster model, WindMap, a high-resolution mass-consistent wind flow model. Depending on the size and complexity of the region and requirements of the client, WindMap may be used to increase the spatial resolution of the MASS simulations.

Databases

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 reanalysis data establish the initial conditions as well as updated lateral boundary conditions for the MesoMap simulations. However, the 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, the MesoMap system 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. 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 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.[4] The US Geological Survey, the University of Nebraska, and the European Commission's Joint Research Centre (JRC) produced the 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, emissivity, and others. 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, although higher resolution maps can be produced if the necessary topographical and land cover data are available. In the United States, the final map resolution typically ranges from 100 m to 400 m.

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 and with a fast turnaround 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 each processor simulates a sequence of days independently from the others, a project can be run on this system 90 times faster than would be possible with any single processor. To put it another way, a typical MesoMap project requiring 2 CPU-years of processing can be completed in a little over one week. The typical project also generates around 500 GB of data.

The Mapping Process

The MesoMap system creates a wind resource map by simulating 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. 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 data files are compiled and summarized in a variety of formats, including most importantly color-coded maps of mean wind speed and power density at various heights above ground and databases containing wind frequency distribution parameters. The results are then compared with available land surface and ocean surface wind

[4] 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).

measurements, and if significant discrepancies are observed, adjustments may be made to the wind maps or the runs may be repeated with a different model configuration.

Accuracy of the Method

TrueWind has compared the MesoMap predictions with high-quality measurements from tall towers in several regions and climates.[5] These comparisons indicate that the standard error in mean wind speed is usually 7% or less once the uncertainty in the data are removed. The errors are usually driven by one or more of the following factors, which are listed in approximate order of decreasing importance:

- Variations in topography and land cover not resolved at the model grid scale
- Errors in the land cover data bases
- Finite sample size
- Errors in the meteorological data

The first is usually the most important. With a sufficiently high resolution at both the MASS and WindMap scales, we have found that the model-only standard error can usually be reduced to around 3-6%. What resolution is "sufficiently high" depends on several factors including the complexity of the terrain and whether there are any land-ocean boundaries within the domain being mapped. Even where a higher resolution is clearly desirable, however, budgetary and schedule considerations may limit our ability to reduce the grid spacing of the model runs.

Errors in the land cover data, and especially the translation to surface roughness, are perhaps the next most common problem. These errors can usually be reduced or eliminated by applying site-specific adjustments to the surface roughness based on field surveys and aerial photography. (The method is described in Addendum 2.)

The finite sample size (366 independent days) introduces an uncertainty margin of, typically, 3-4%. However the uncertainty can be larger where the wind speed frequency distribution is unusually broad – for example, if the wind resource varies greatly by season.

Errors in the meteorological data are probably of little concern in the United States and other developed, but may be significant in developing countries where data collection is relatively sparse.

ADDENDUM 2: 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 ArcReader 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.

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[5] See Michael Brower, Bruce Bailey, and John Zack, "Micrositing with MesoMap," Proceedings of Windpower 2002, American Wind Energy Association (2002).

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 1 m/s. This formula is most applicable to small, isolated hills or ridges in otherwise flat terrain.
3. The roughness of the land surface – determined mainly by vegetation cover and buildings – up to 1-2 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:

$$\frac{v_2}{v_1} \approx \frac{\log\left(300/z_{01}\right)}{\log\left(h/z_{01}\right)} \times \frac{\log\left(h/z_{02}\right)}{\log\left(300/z_{02}\right)}$$

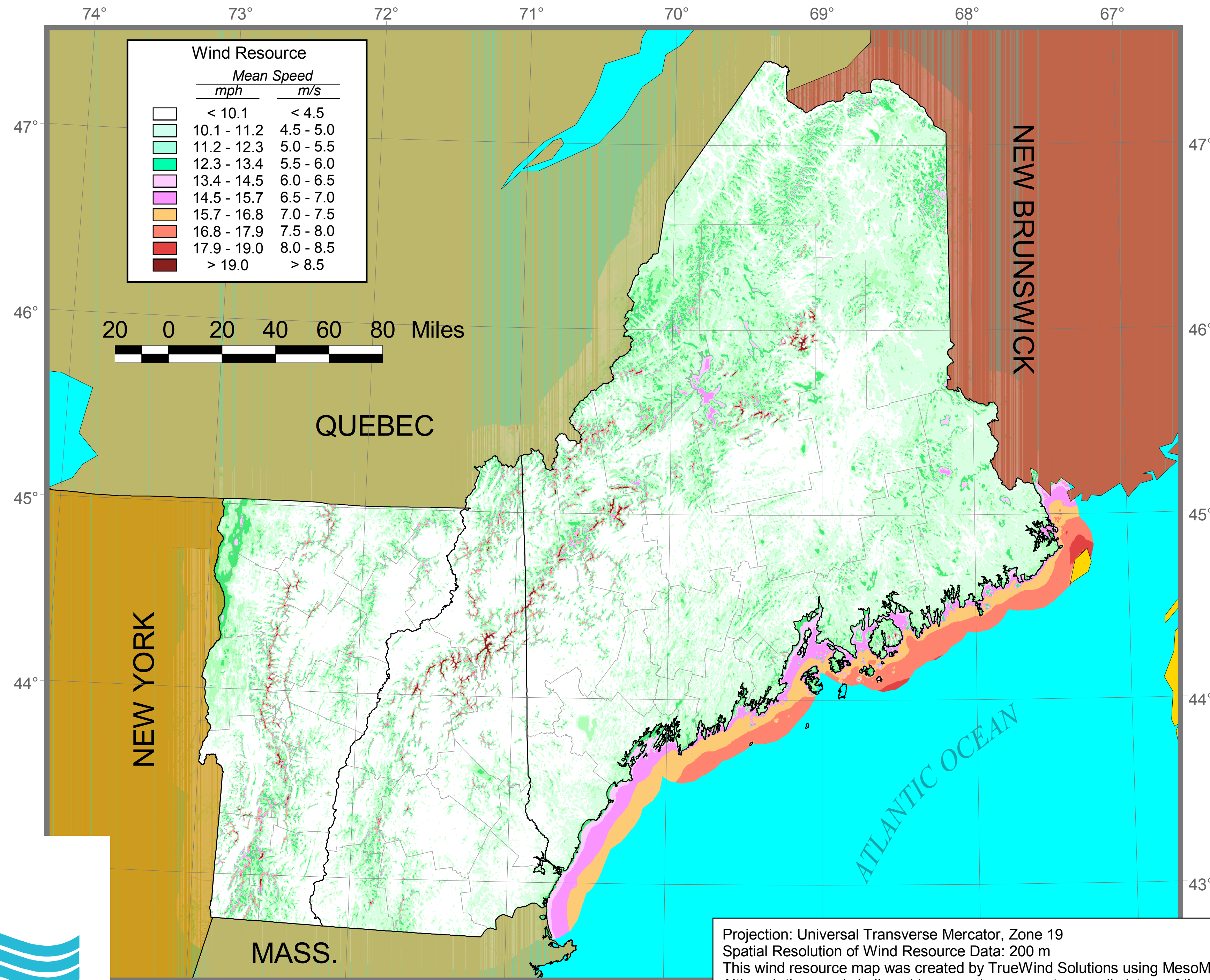
   v_1 and v_2 are the original and adjusted wind speeds at height h (in meters above the effective ground level), whereas z_{01} and z_{02} are the model and actual surface roughness values (in meters). As an example, suppose the land cover data used by the model showed an area to be forested in all directions 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

$$\frac{v_2}{v_1} \approx \frac{\log\left(300/1\right)}{\log\left(65/1\right)} \times \frac{\log\left(65/0.1\right)}{\log\left(300/0.1\right)} = 1.11$$

   implying the model wind speed should be increased by about 11%.

   The formula assumes that the wind is in equilibrium with the new surface roughness at least to 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.

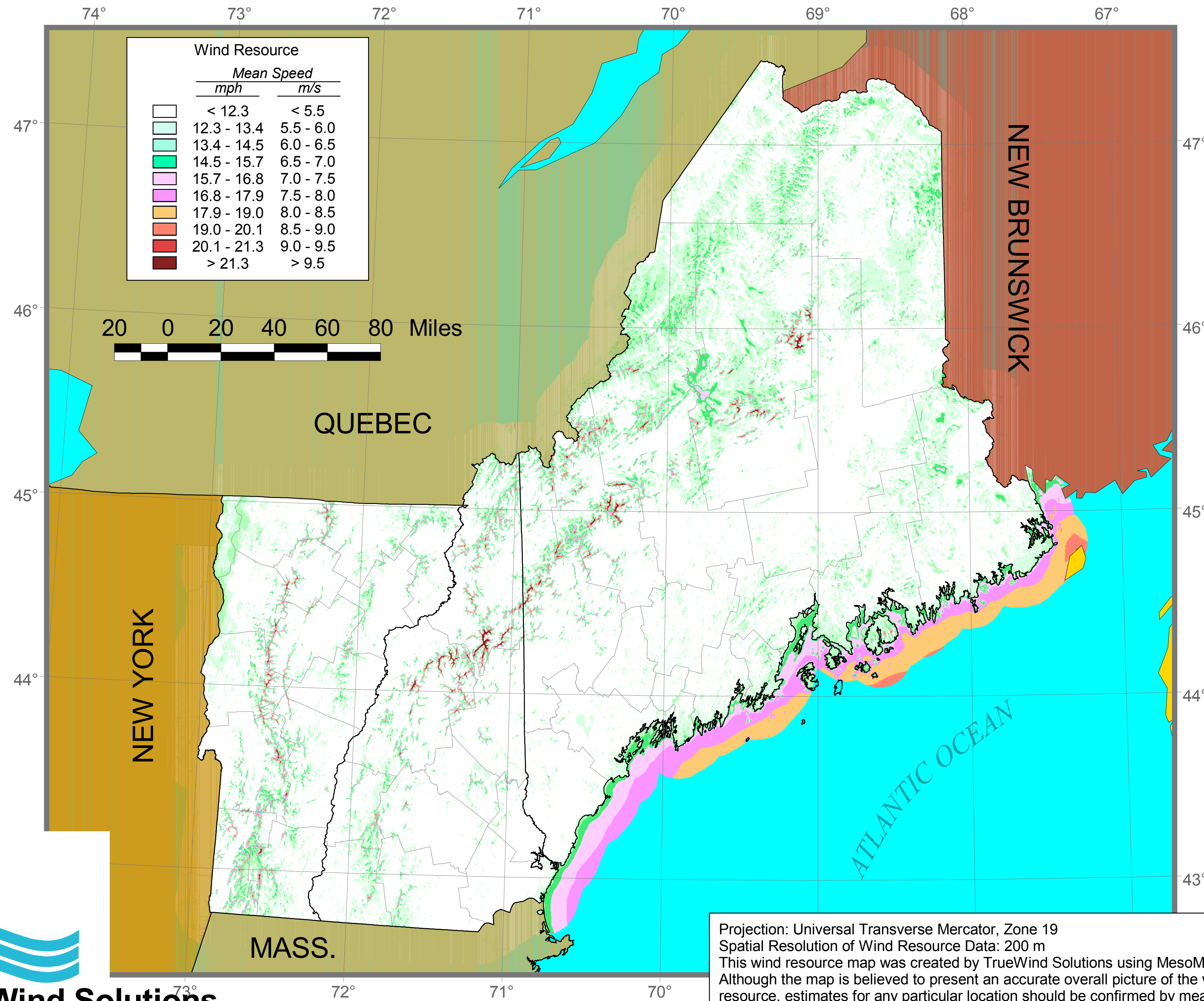
Wind Speed Map of Northern New England at 30 m



Projection: Universal Transverse Mercator, Zone 19
Spatial Resolution of Wind Resource Data: 200 m
This wind resource map was created by TrueWind Solutions using MesoMap.
Although the map is believed to present an accurate overall picture of the wind resource, estimates for any particular location should be confirmed by measurement.
In forested areas, the map height should be interpreted as the height above the canopy.

TrueWind Solutions

Wind Speed Map of Northern New England at 50 m



Projection: Universal Transverse Mercator, Zone 19
Spatial Resolution of Wind Resource Data: 200 m
This wind resource map was created by TrueWind Solutions using MesoMap.
Although the map is believed to present an accurate overall picture of the wind resource, estimates for any particular location should be confirmed by measurement.
In forested areas, the map height should be interpreted as the height above the canopy.

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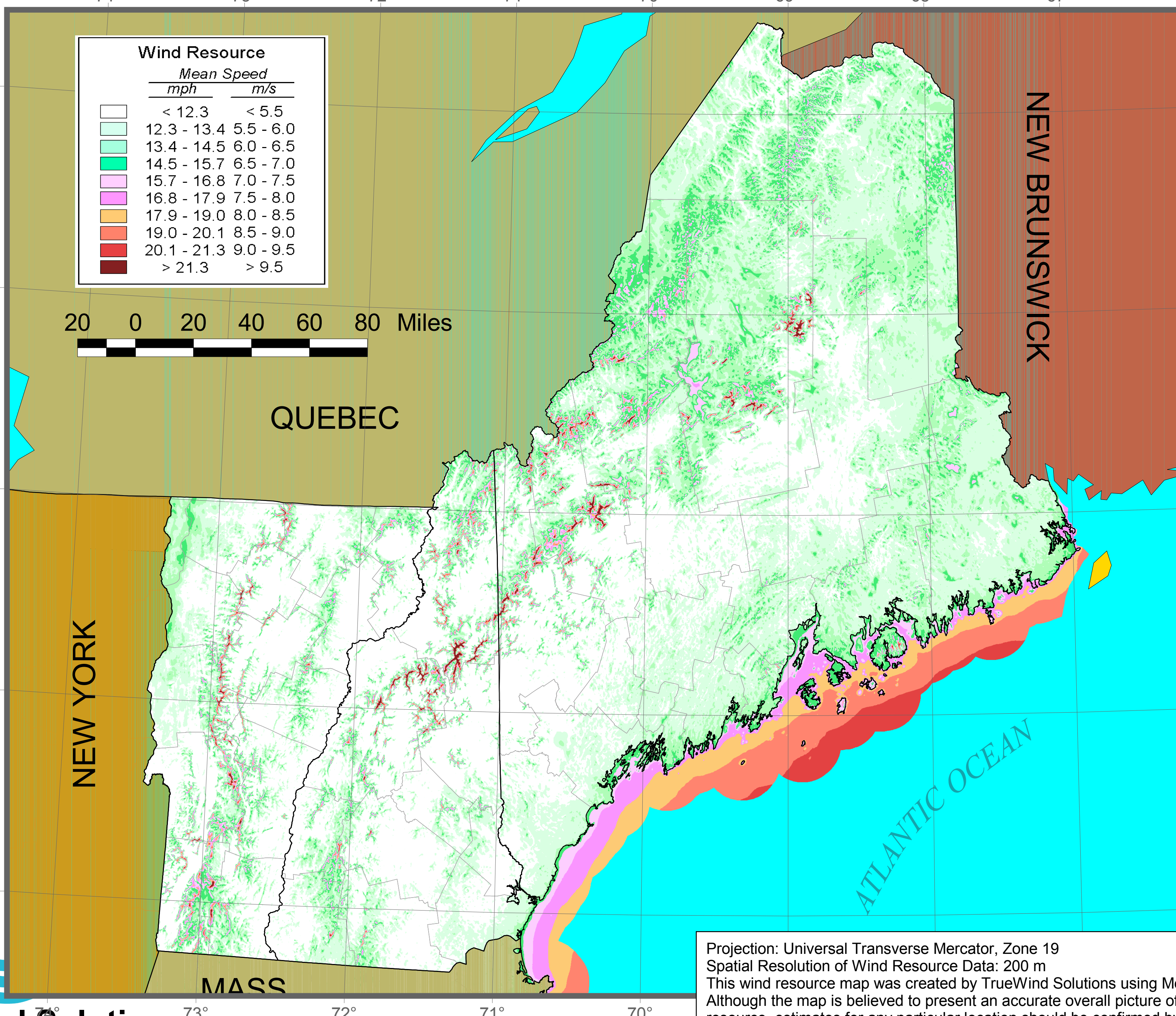
Wind Speed Map of Northern New England at 70 m



Projection: Universal Transverse Mercator, Zone 19
Spatial Resolution of Wind Resource Data: 200 m
This wind resource map was created by TrueWind Solutions using MesoMap.
Although the map is believed to present an accurate overall picture of the wind resource, estimates for any particular location should be confirmed by measurement.
In forested areas, the map height should be interpreted as the height above the canopy.

TrueWind Solutions