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WHITE PAPER

2024 Northern American Wind Map

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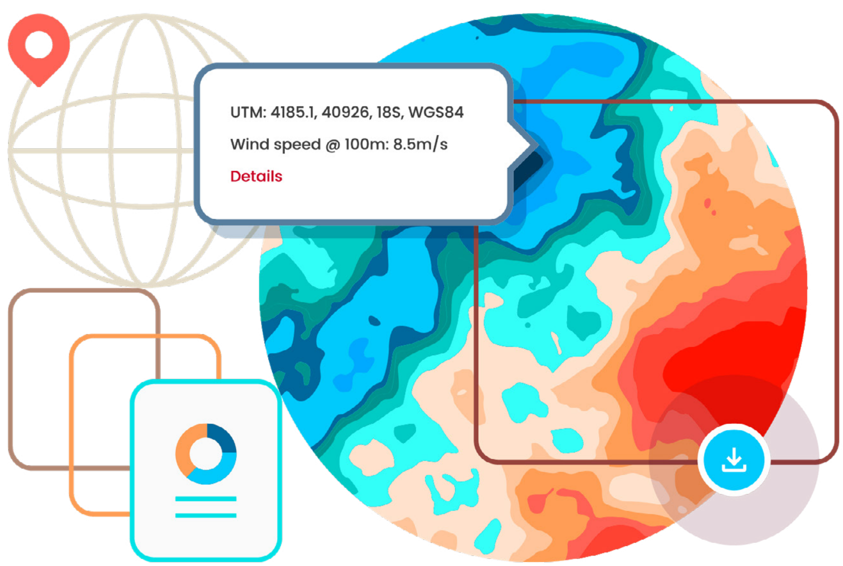
Authors:
Philippe Beaucage — Lead Research Scientist
Yagnesh Yakkala — Research Scientist
José Vidal — Product Manager
Reviewer: José Javier Ripa — Head of Product Management.



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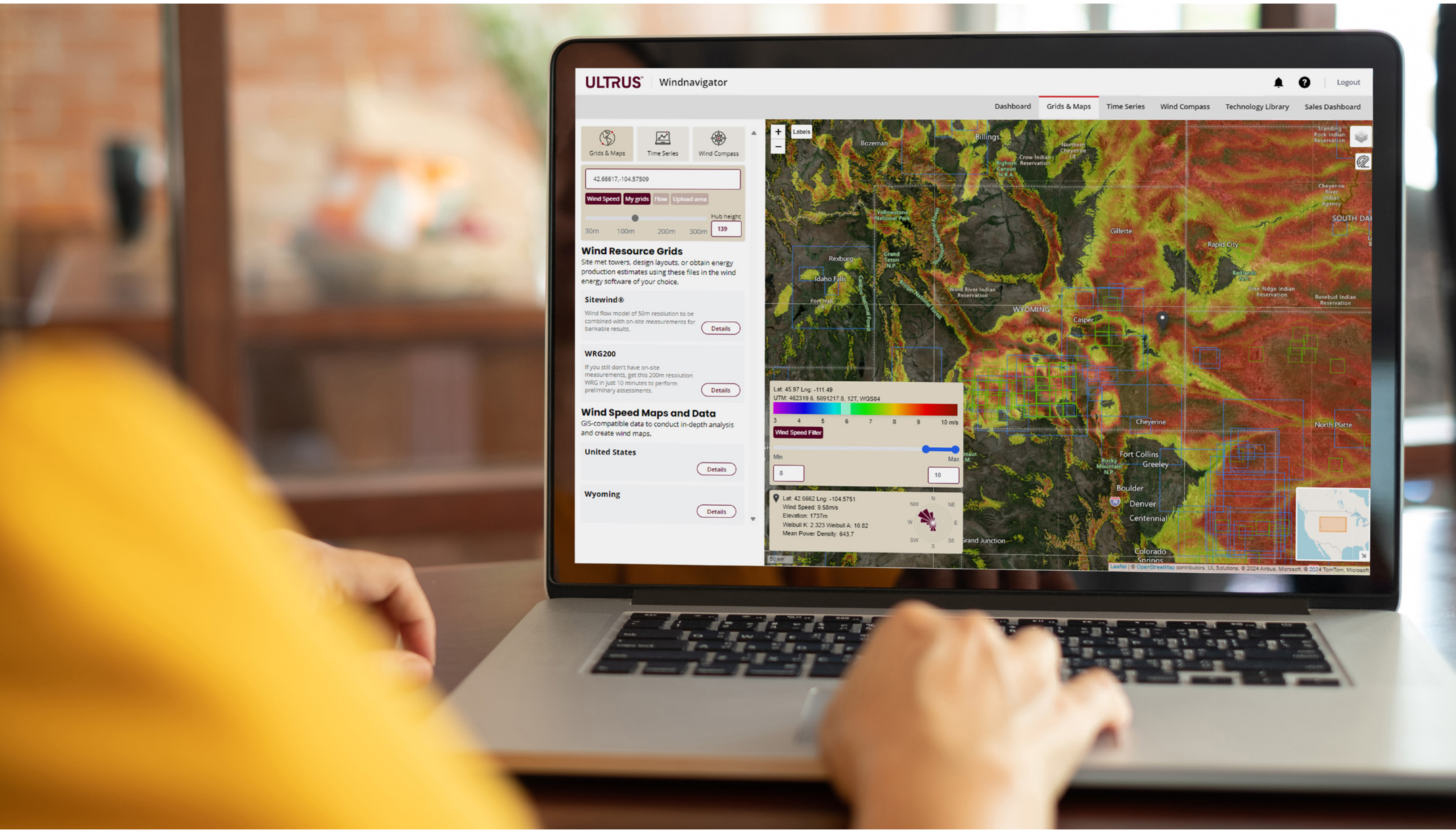

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1. Introduction

The 2024 Northern American wind map released on UL Solutions' ULTRUS™ Windnavigator Resource Data and Maps software is a major update to the original map which dates from 15 years ago. The 200-m resolution mean wind speed maps are created with UL Solutions' proprietary wind flow modeling system consisting of a coupled mesoscale and microscale model. The model outputs are subsequently fine-tuned with wind measurements from UL Solutions' large database of met stations. The new wind map not only provides more accurate data and at higher heights (up to 300 m) but also leverage the latest advancements in wind modeling technology, offering enhanced insights when analyzing and prospecting greenfield sites and assessing competing projects. More specifically, the enhancements designed to help wind developers make more informed decisions include:

- Expanded met data coverage
  - 2.5 times more observations compared to the original map
  - Includes met data from longer periods of record and higher measurement heights
  - More representative and spatially diverse met data in Northern America
- Enhanced wind map heights
  - Wind maps now available up to 300m, accommodating taller turbines
- Improved wind modeling and accuracy
  - Based on the latest mesoscale modeling and reanalysis dataset

This report describes the methods and models behind the 2024 Northern American wind map.

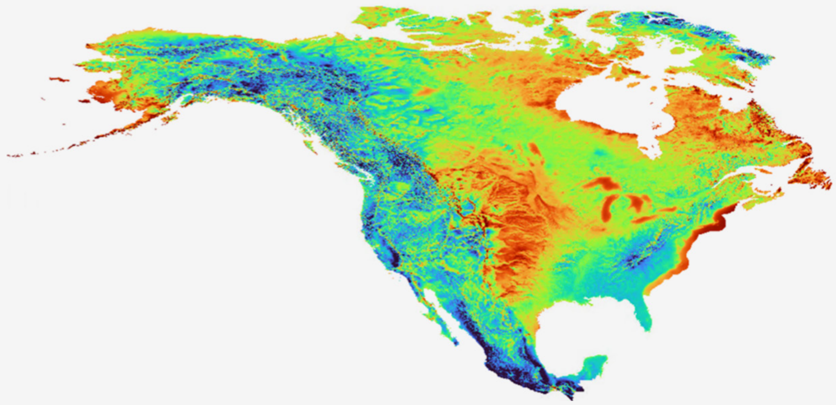

Figure 1.1: Northern American mean wind speed map at 100 m a.g.l.

2. Methodology for wind resource mapping

The Northern American wind map was created using UL Solutions' coupled mesoscale numerical weather prediction (NWP) model and a microscale model to estimate the wind resource. UL Solutions has extensive experience running NWP models such as MM5, MASS, ARPS and WRF over the last four decades. In the late 1990's, UL Solutions and the Danish Technical University (DTU) independently pioneered a method to couple a mesoscale NWP model with a microscale wind flow model. They are respectively known as MesoMap or SiteWind (Brower 1999) and KAMM/WAsP (Frank and Landberg 1997) systems. Over the years, the coupled mesoscale-microscale modeling system has become the preferred approach for generating mean wind speed maps over large regions (e.g. AWST 2012, Dörenkämper et al. 2020, Davis et al. 2023).

Figure 2.1 provides an overview of the wind mapping process. While a robust wind flow modeling system is key to creating an accurate wind resource map, a large database of good quality wind monitoring stations is just as important. The wind measurements are used to anchor the model outputs to ground truth. The last step when creating wind resource maps is to adjust the mean wind speed maps to wind measurements from met stations.

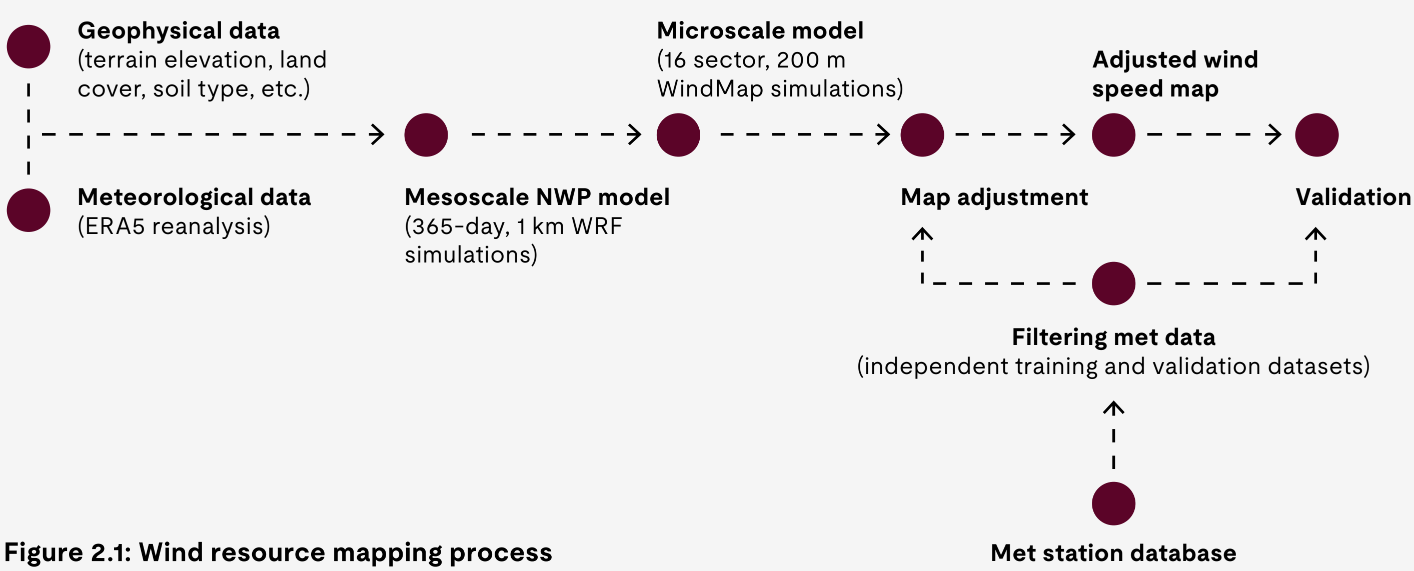

Figure 2.1: Wind resource mapping process

2.1 Wind Flow Modeling

The UL Solutions wind flow modeling system is a combination of two atmospheric models: a mesoscale numerical weather prediction (NWP) model and a microscale wind flow model. The mesoscale model simulates weather conditions for a representative meteorological year (365 days sampled from a recent 15-year period) on a horizontal grid of 2.5 km. The microscale model then refines the wind fields from the mesoscale model to capture the local influences of topography and surface roughness changes at a resolution of 200 m.

UL Solutions relies on a state-of-the-art mesoscale NWP model, the Weather Research and Forecasting (WRF) model (Skamarock 2004). WRF solves the fully compressible, non-hydrostatic Navier-Stokes equations and includes a complete suite of physics parameterization schemes. Accurate initial and boundary conditions are crucial for NWP simulations. UL Solutions relies on the ERA5 reanalysis, the fifth-generation climate reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). It incorporates weather observations from many thousands of platforms around the world, including surface stations, rawinsonde stations, satellites, aircraft, and others. ERA5 provides hourly data for many atmospheric, land-surface and sea-state parameters on a 0.25-degree resolution grid (~ 30 km resolution). NWP models like WRF are the best tools available to simulate the evolving atmospheric conditions, especially the synoptic scale and mesoscale.

The 2.5-km resolution WRF model outputs are then coupled to the microscale model WindMap which is run with a grid spacing of 200 m. WindMap, developed by UL Solutions, is a mass-conserving model that adjusts an initial wind field, here supplied by WRF, in response to local variations in topography and surface roughness. Thus, WindMap preserves as much information as possible from the mesoscale model fields while adjusting the microscale wind flow to the finer resolution topography and surface roughness maps.

2.2 Wind Observations

A large database of good quality wind observations is crucial to produce accurate wind resource maps. Thanks to UL Solutionss long history providing renewable energy consulting going back to the 1980s, we can rely on approximately 5000 met stations in Northern America, most of them coming from private sources. For this wind mapping exercise, we had roughly 2.5 times more wind observations than for the original map and with longer periods of record and higher measurement heights. UL Solutions' database of long-term mean wind speed observations mostly comes from numerous met masts and remote sensing devices instrumented for wind resource assessment as well as surface weather stations. The met data comes from a wide range of sources, including public, private, and governmental sources. Public data is often available through various state-or-province-level wind resource assessment programs, academic or government-sponsored measurement programs. Privately funded data is often provided by customers of UL Solutions and is used only with permission. Where possible, the mean speeds from short-term measurement programs are adjusted to represent long-term conditions; stations with periods of record of less than one year are not considered. As can be seen in Figure 2.2, a majority of the met stations are in the U.S. and Canada. Approximately 80% to 90% of them come from privately funded wind resource assessments.

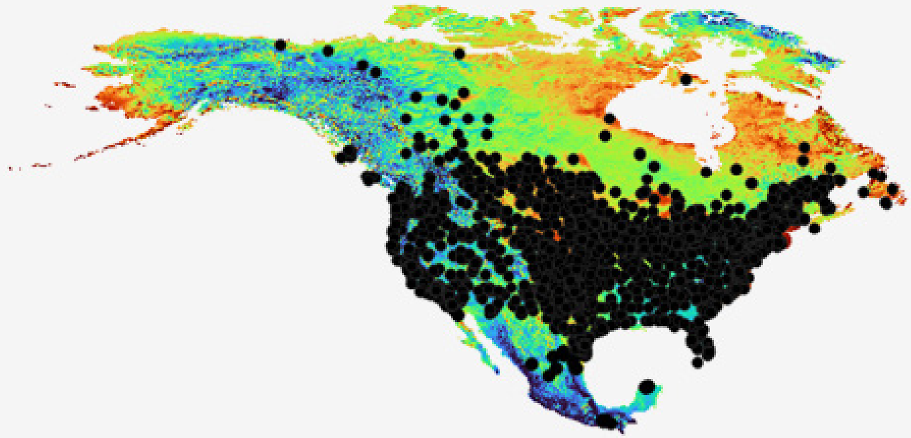

Figure 2.2: Met station database for Canada, U.S. and Mexico.

To minimize the deviation between the mean wind speed map and the measurements, a regional, rather than local, bias correction is preferred (see next section). The met station database is filtered to find the most representative met station within a radius of about 10-15 km. To do so, the met stations were grouped by clusters and one met station per cluster was selected. The most representative met station in a cluster is the one with the longest period of records and highest top measurement height. This filtering allows for the representative met stations to be more equally spaced over the entire region. The other advantage of filtering the met station database is to have enough independent met data for the validation exercise (see Section 3). After filtering, approximately 200 representative met stations were selected in Canada, 700 in the US and 13 in Mexico as shown in Figure 2.3 for a total of 913 representative mat stations.

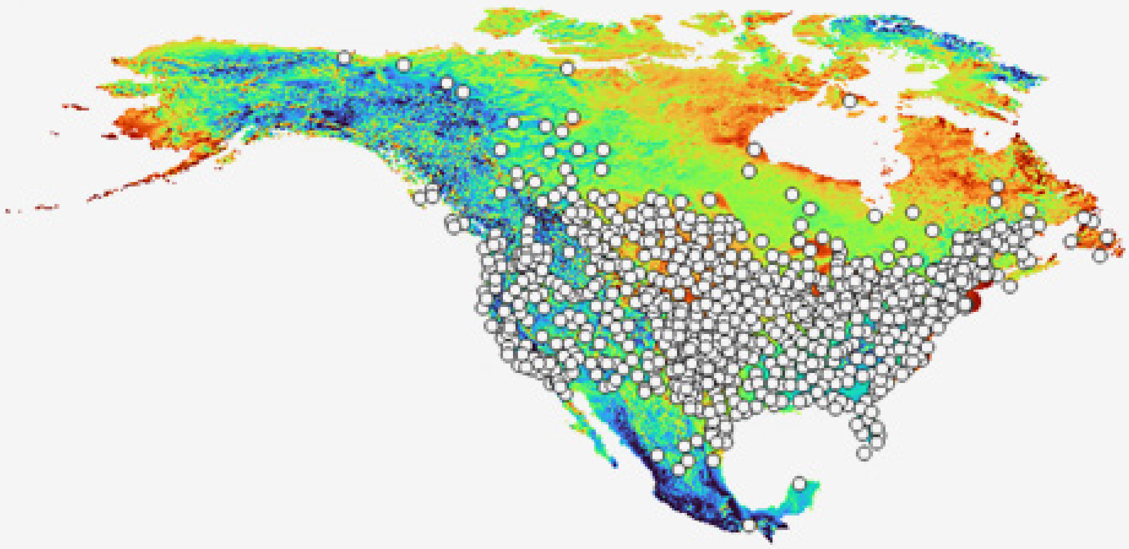

Figure 2.3: Representative met stations in Canada, U.S. and Mexico.

2.3 Map Adjustment

In the map adjustment process, the wind observations in UL Solutions' database serve to reduce the mean wind speed bias of the map. The mean wind speed map is adjusted using the available wind observations. The objective of this map adjustment is to minimize discrepancies between modeled and observed mean wind speeds.

The first step is to calculate the wind speed bias between the raw (unadjusted) wind map and the observed mean wind speed for each met station. An in-house software program interprets the mean wind speed biases at all the met stations to generate a speed bias map. This speed bias map is then applied to the raw (unadjusted) wind map to create the adjusted wind speed map. Given our approach to select one representative met station within a radius of about 10-15 km, we are effectively applying a regional bias correction rather than a local bias correction. A local bias correction generally leads to bull's eye patterns around the measurement locations and may lead to overfitting in surrounding areas without measurements. Instead, the smoother regional bias correction is designed to eliminate spatially correlated biases affecting regions of a significant size, roughly the mean spacing between representative met stations in the U.S. which is 50-75 km. In the end, this map adjustment approach does not eliminate the wind speed bias at every met station. However, it does significantly reduce the mean bias error (MBE) and root mean square error (RMSE) while improving the coefficient of determination (R^2). In fact, the scatterplots in Figure 2.4 demonstrate the advantages of adjusting the raw mean wind speed maps with good quality observations. The error statistics listed for the raw map (top left panel) are satisfactory but are improved by a wide margin when using a leave-one-out cross-validation (center panel), which corresponds to adjusting the raw map with all but one met station at a time in a round robin fashion. It effectively removes the mean bias. Lastly, the adjusted map shows the best error metrics because it is evaluated with the same met data used in the map adjustment. Notice that the RMSE is not equal to 0 m/s and the R^2 is not 1.0 for the adjusted map although it is not that far on the R^2. It is indicative of a regional bias correction as opposed to a local bias correction.

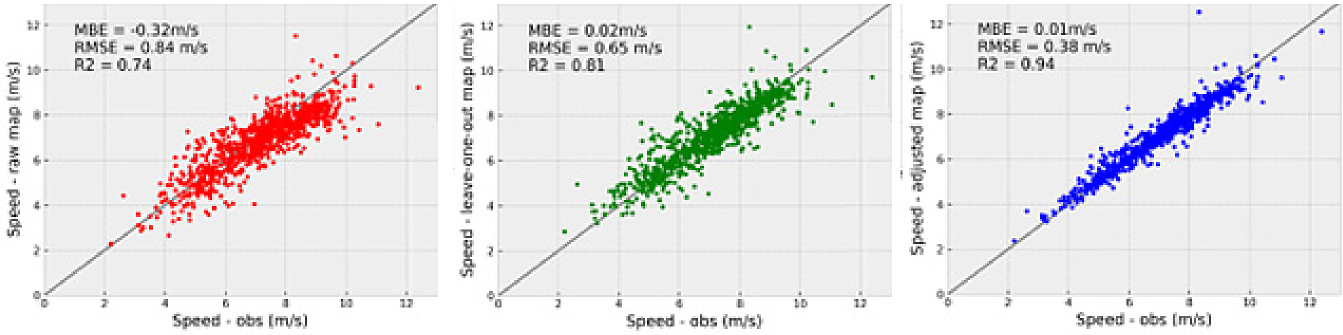

Figure 2.4: Scatterplots of 100 m a.g.l mean wind speeds at the 913 representative met stations. The X axis represents the observed mean wind speeds while the Y axis corresponds to the raw map (left panel), leave-one-out (center panel) and adjusted map (right panel).

3. Validation of northern american map

The primary goal of the validation is to provide an objective estimate of the map accuracy. The 2024 Northern American wind map was validated against 360 met stations in Canada and the U.S. using a different set of met stations than the ones used in the map adjustment. In other words, the observation datasets for the map adjustment and validation are independent. The 2024 Northern American wind map was also compared to UL Solutions' original wind map (AWST 2012) as well as the publicly available Global Wind Atlas (Davis et al. 2023).

For the validation, one met station per cluster is selected with the additional constraint that this met station has not been previously used in either the original map or the 2024 map to ensure a fair comparison between the maps. Note that the met station clusters are the same as defined in the previous section related to the map adjustment. After filtering the 913 clusters for met stations not previously used in the original and 2024 map adjustment, the validation sample consists of a total of 39 met stations in Canada and 321 in the U.S. The validation statistics by country are provided in Table 3.1. The 2024 Northern American wind speed map is performing better than UL Solutions' original map or the Global Wind Atlas map with regards to the mean bias error (MBE), the standard deviation (STDEV), the mean absolute error (MAE), the root mean square error (RMSE) and the coefficient of determination (R^2). It is worth pointing out that the mean bias of the 2024 map is very close to 0 m/s. In addition, UL Solutions' original map is performing well which is not a surprise to us given prior validation exercises. Our original map had a good spatial coverage of met stations at the time. The Global Wind Atlas map is not performing as well but it is doing a reasonable job in the absence of any met stations to adjust their map. In short, the Global Wind Atlas map for North America is effectively a raw (non-adjusted) wind speed map.

Country	Map	MBE (m/s)	STDEV (m/s)	RMSE (m/s)	R^2	Sample size
Canada	Global Wind Atlas	-0.07	0.67	0.66	0.14	39
	UL Solutions original map	-0.06	0.52	0.51	0.45	
	UL Solutions 2024 map	0.02	0.48	0.48	0.52	
USA	Global Wind Atlas	0.08	0.71	0.71	0.53	321
	UL Solutions original map	-0.09	0.53	0.54	0.74	
	UL Solutions 2024 map	0.01	0.44	0.44	0.81	

Table 3.1: Comparison of 2024 Northern American wind map against UL Solutions' original version and the Global Wind Atlas by country

The error statistics in Table 3.1 above do not convey much information about the spatial variations between the original and 2024 Northern American maps. The two maps deviate from one another substantially in some regions, mainly in complex terrain like the Rocky Mountains, while they remain somewhat similar in simple terrain like the U.S. Great Plains as shown in Figure 3.1.

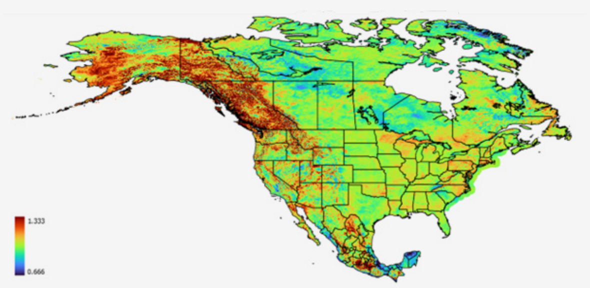

Figure 3.1: Wind speed ratio at 100 m a.g.l. between the 2024 and original map

Table 3.2 provides a closer look at the validation results by U.S. region. Table 3.3 and Table 3.4 show the validation results by U.S. state and Canadian province but only for the states (provinces) in the top 10 (top 3) for highest installed wind power capacity. All three maps exhibit error statistics that tend to be worst in regions where the orography and land cover are more complex such as the West and Northeast regions as opposed to the Midwest and South. By and large, UL Solutions' 2024 Northern American map performs better than the other two maps in each U.S. region although results are mixed in the Northeast where the differences are small between our original map and the 2024 map, except for the sign of the mean bias. It also happens to be the one region with the lowest sample size.

US Region	Map	MBE (m/s)	STDEV (m/s)	RMSE (m/s)	R^2	Sample size
West	Global Wind Atlas	0.10	0.84	0.84	0.55	78
	UL Solutions original map	0.00	0.81	0.80	0.62	
	UL Solutions 2024 map	0.06	0.64	0.63	0.72	
Midwest	Global Wind Atlas	0.06	0.58	0.58	0.59	107
	UL Solutions original map	-0.08	0.31	0.32	0.88	
	UL Solutions 2024 map	-0.02	0.25	0.25	0.92	
South	Global Wind Atlas	-0.04	0.69	0.69	0.48	101
	UL Solutions original map	-0.16	0.43	0.46	0.79	
	UL Solutions 2024 map	-0.06	0.36	0.37	0.85	
Northeast	Global Wind Atlas	0.49	0.72	0.85	0.49	35
	UL Solutions original map	-0.16	0.49	0.51	0.76	
	UL Solutions 2024 map	0.17	0.52	0.54	0.74	

Table 3.2: Same as Table 3.1 but by US region

US State	Map	MBE (m/s)	STDEV (m/s)	RMSE (m/s)	R^2	Sample size
Texas	Global Wind Atlas	-0.24	0.59	0.64	0.50	65
	UL Solutions original map	-0.08	0.45	0.45	0.67	
	UL Solutions 2024 map	-0.09	0.41	0.41	0.74	
Iowa	Global Wind Atlas	-0.17	0.21	0.26	0.79	12
	UL Solutions original map	-0.05	0.18	0.18	0.77	
	UL Solutions 2024 map	-0.09	0.14	0.16	0.86	
California	Global Wind Atlas	0.82	0.86	1.16	0.59	10
	UL Solutions original map	0.29	1.01	1.00	0.37	
	UL Solutions 2024 map	0.58	0.80	0.95	0.55	
Oklahoma	Global Wind Atlas	0.09	0.65	0.65	0.23	26
	UL Solutions original map	-0.37	0.26	0.45	0.86	
	UL Solutions 2024 map	-0.05	0.26	0.26	0.86	
Illinois	Global Wind Atlas	-0.15	0.31	0.33	0.01	12
	UL Solutions original map	-0.27	0.35	0.43	0.12	
	UL Solutions 2024 map	-0.07	0.28	0.28	0.31	
Kansas	Global Wind Atlas	-0.24	0.68	0.70	0.00	18
	UL Solutions original map	-0.17	0.29	0.33	0.79	
	UL Solutions 2024 map	-0.13	0.24	0.27	0.85	
Colorado	Global Wind Atlas	-0.46	0.54	0.69	0.02	10
	UL Solutions original map	-0.34	0.47	0.56	0.37	
	UL Solutions 2024 map	-0.01	0.59	0.56	0.20	
Minnesota	Global Wind Atlas	0.18	0.46	0.47	0.03	9
	UL Solutions original map	0.12	0.31	0.32	0.67	
	UL Solutions 2024 map	0.16	0.34	0.36	0.42	
North Dakota	Global Wind Atlas	-0.40	0.22	0.45	0.81	13
	UL Solutions original map	-0.31	0.19	0.36	0.85	
	UL Solutions 2024 map	-0.15	0.14	0.20	0.90	
Nebraska	Global Wind Atlas	-0.26	0.34	0.41	0.25	9
	UL Solutions original map	-0.03	0.35	0.33	0.45	
	UL Solutions 2024 map	-0.06	0.10	0.11	0.92	

Table 3.3: Same as Table 3.1 but by US state, for top 10 states with most wind power capacity.

Canadian Province	Map	MBE (m/s)	STDEV (m/s)	RMSE (m/s)	R^2	Sample size
Quebec	Global Wind Atlas	-0.19	0.55	0.57	0.27	18
	UL Solutions original map	0.15	0.34	0.36	0.58	
	UL Solutions 2024 map	0.17	0.33	0.37	0.67	
Ontario	Global Wind Atlas	0.12	0.86	0.84	0.00	14
	UL Solutions original map	-0.19	0.53	0.55	0.18	
	UL Solutions 2024 map	-0.20	0.56	0.57	0.19	
Alberta	Global Wind Atlas	-0.41	0.53	0.59	0.44	3
	UL Solutions original map	-0.48	0.34	0.55	0.76	
	UL Solutions 2024 map	-0.20	0.45	0.42	0.61	

Table 3.4: Same as Table 3.1 but by Canadian province, for top 3 provinces with most wind power capacity.

4. Conclusion

UL Solutions generated a new Northern American mean wind speed map to replace the original version. The new wind map leverages the latest advancements in wind modeling technology and provides wind data at higher heights, up to 300 m. Notable differences can be found between the original and 2024 Northern American wind map, especially in complex terrain. An objective estimation of the map accuracy was conducted using a met mast dataset independent from the one used in the map adjustment process. The accuracy of the 2024 Northern American wind map was compared to UL Solutions' original wind map and the Global Wind Atlas map. Overall, the 2024 Northern American map performs better than the other two maps in terms of the standard error metrics, i.e. mean bias, RMSE and R^2. In all cases, UL Solutions recommends that the wind resource be measured onsite before committing funds to a wind energy project of a substantial size.

Attribution

GWA data was obtained from the Global Wind Atlas 3.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex and funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info/en/

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