Improvements in Wind Power Estimates from Numerical Weather Models using Rotor Equivalent Wind Speed and the Full Power Equation

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Photo: Chuck Coker via Flickr

Motivation and Purpose

- Wind energy is becoming more important over large geographic areas.
- Numerical Weather Models can be used to produce wind power estimates.
- Incorporating more information into the processing of NWPM outputs should increase the accuracy of the wind power estimates
- Rotor Equivalent Wind Speed (REWS) provides a simplistic way to incorporate shear over the rotor swept area.
- The “full” power equation provides a novel technique to account for changes in wind speed over time (between the model output periods).
- A suitability metric that incorporates variability is investigated.

Weather Data Inputs

- The Rapid Update Cycle (RUC) Assimilation Model is leverage for every hour of the years of 2006, 2007, and 2008. It is 13 km resolution. We are currently extending this to include 2009 to 2014.

- The Assimilation model is the "optimal estimate" of the state of the atmosphere when incorporating observations, a background state, and error covariance.

Forward Observational Operator

$$\min_{\mathbf{x}} J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + \frac{1}{2}[\mathbf{y}_0 - H(\mathbf{x})]^T \mathbf{R}^{-1}[\mathbf{y}_0 - H(\mathbf{x})]$$

Model variables

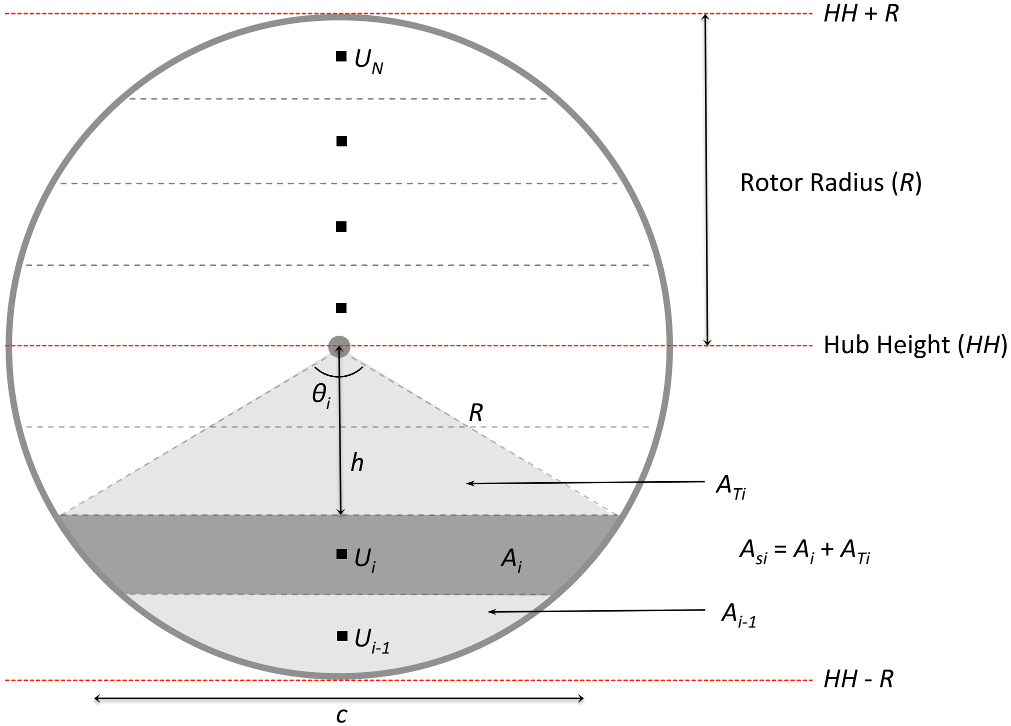
Background values of model variables

Background error covariance matrix

Observation error covariance matrix

Observation variables

Rotor Equivalent Wind Speed from NWPM



$$A_i = A_{Si} - A_{Ti} - \sum_{j=0}^{i-1} A_j, \quad i \geq 1$$

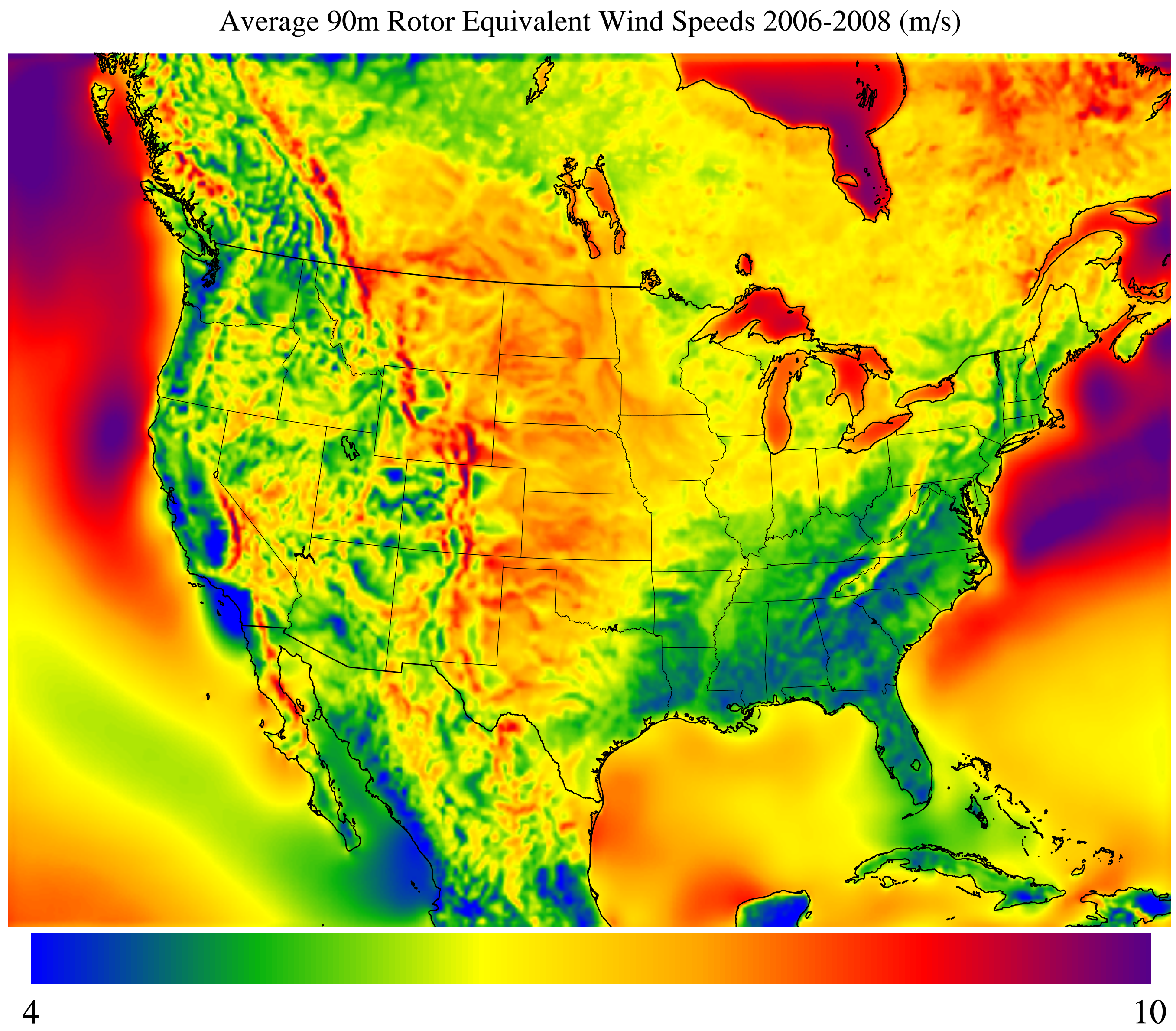
$$A_{Si} = \frac{\theta_i}{2\pi} \cdot \pi R^2 = \frac{\theta_i R^2}{2}$$

$$A_{Ti} = \frac{1}{2} \cdot c \cdot h = R \sin\left(\frac{\theta_i}{2}\right) R \cos\left(\frac{\theta_i}{2}\right) = \frac{R^2}{2} \sin\theta_i$$

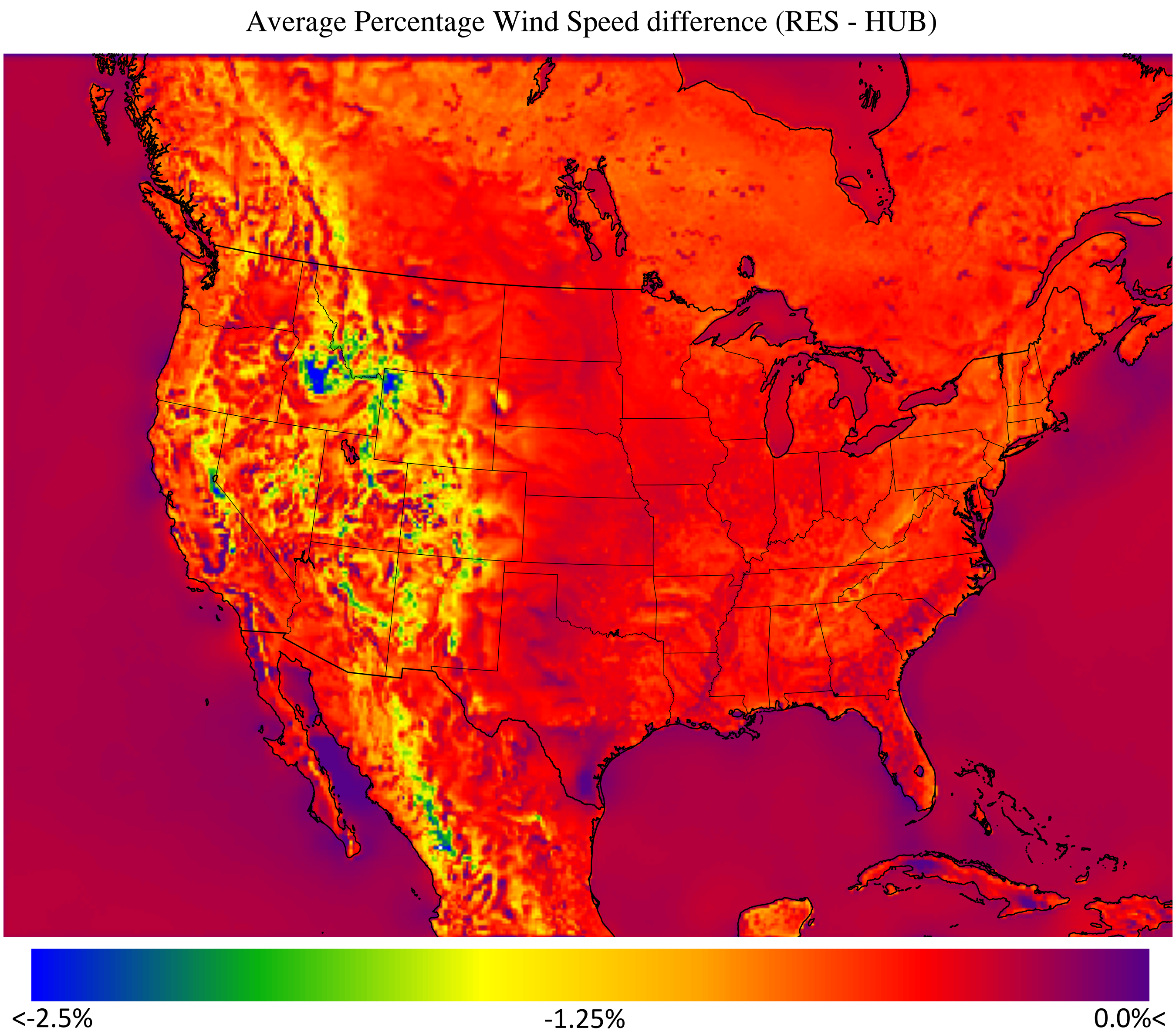
$$\boxed{\begin{gathered}\alpha_i = \frac{A_i}{A} = \frac{(\theta_i - \sin\theta_i)}{2\pi} - \frac{1}{A}\sum_{j=0}^{i-1} A_j, \quad i \geq 1 \\ U_R = \sum_{i=1}^{N} \alpha_i \cdot U_i\end{gathered}}$$

* We also perform the same technique to obtain the Rotor Equivalent Density

Rotor Equivalent Wind Speed from NWPM

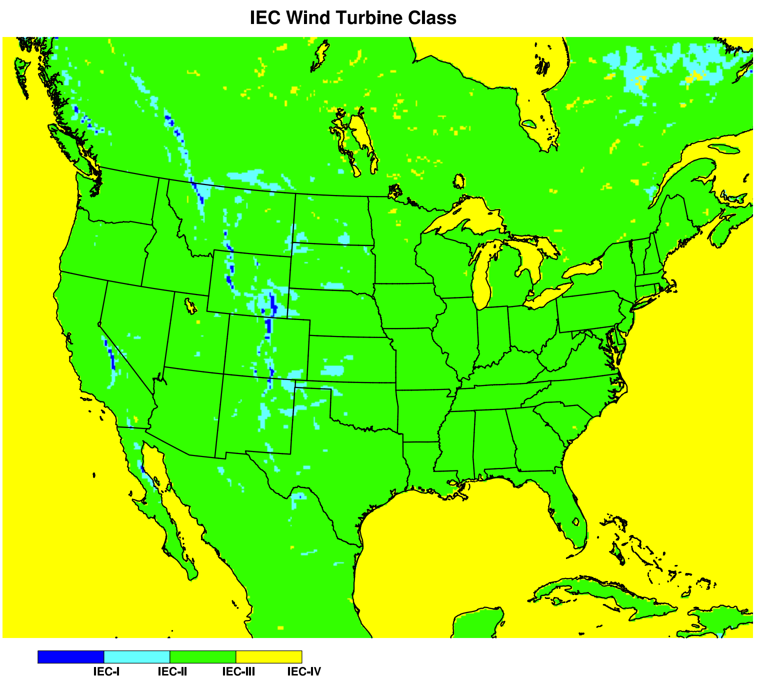


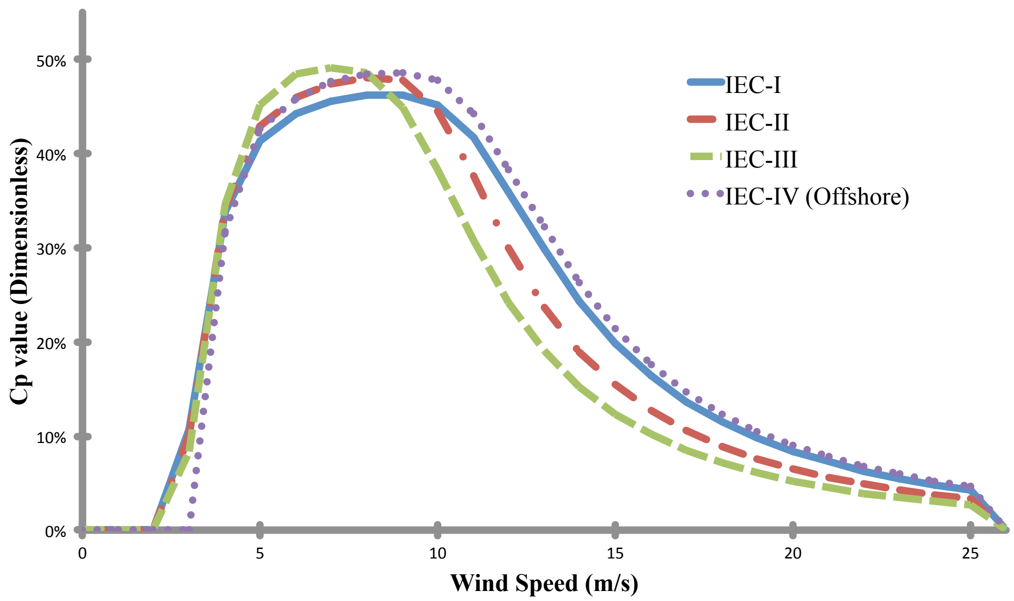
Rotor Equivalent Wind Speed from NWPM



Wind Power Estimates from REWS

	Turbine	Rated Power (MW)	Cut-In Speed (m/s)	Max Output Speed (m/s)	Cut-Out Speed (m/s)	Rotor Diameter (m)
IEC-I	Siemens 3.0 MW	3.0	3.0	14.0	25.0	101.0
	Gamesa G80	2.0	4.0	17.0	25.0	80.0
	Nordex N90HS	2.5	4.0	14.0	25.0	90.0
	Vestas V90	3.0	4.0	14.0	25.0	90.0
IEC-II	Vestas V112	3.0	3.0	13.0	25.0	112.0
	Siemens 2.3 MW	2.3	3.0	13.0	25.0	93.0
	GE1.6 82.5	1.6	4.0	12.0	25.0	82.5
	GE2.5xl	2.5	3.0	14.0	25.0	100.0
IEC-III	Vestas V100	1.8	3.0	12.0	20.0	100.0
	GE1.6-100	1.6	3.0	12.0	25.0	100.0
	Repower 3.2M	3.2	3.0	12.0	22.0	114.0
IEC-IV	Siemens 3.6 MW	3.6	4.0	14.0	25.0	107.0
	GE4.1MW	2.3	4.0	14.0	25.0	113.0
	Repower 6M	6.15	3.5	14.0	30.0	126.0



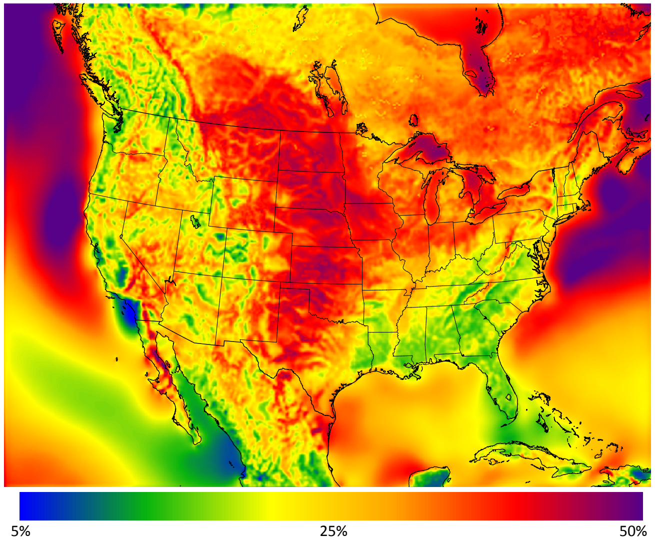


$$C_p = P_t / P_w$$

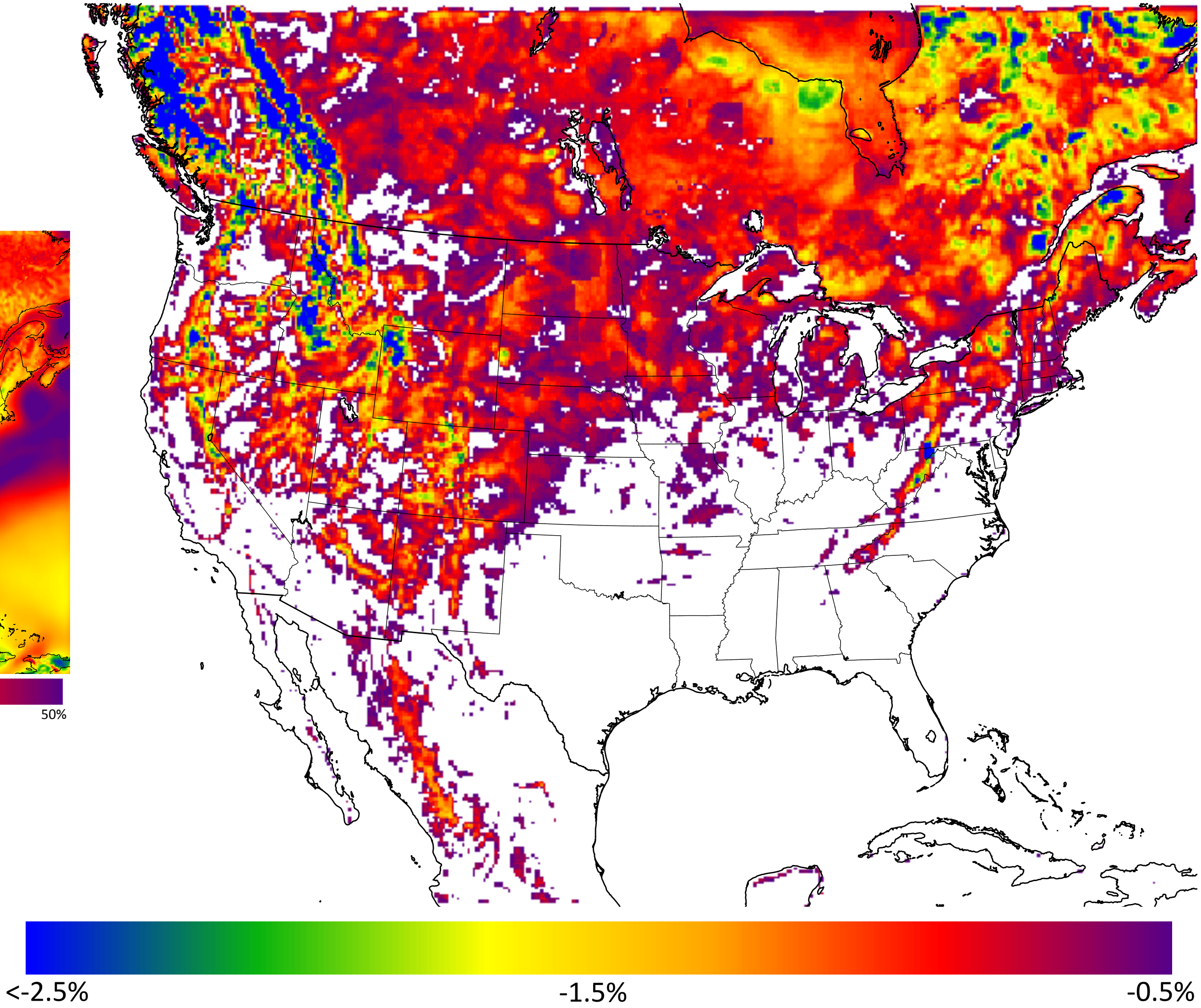
$$P_t = \frac{1}{2} C_p \rho A U^3$$

Wind Power Estimates from REWS

Average RES Capacity Factors 2006-2008 (%)

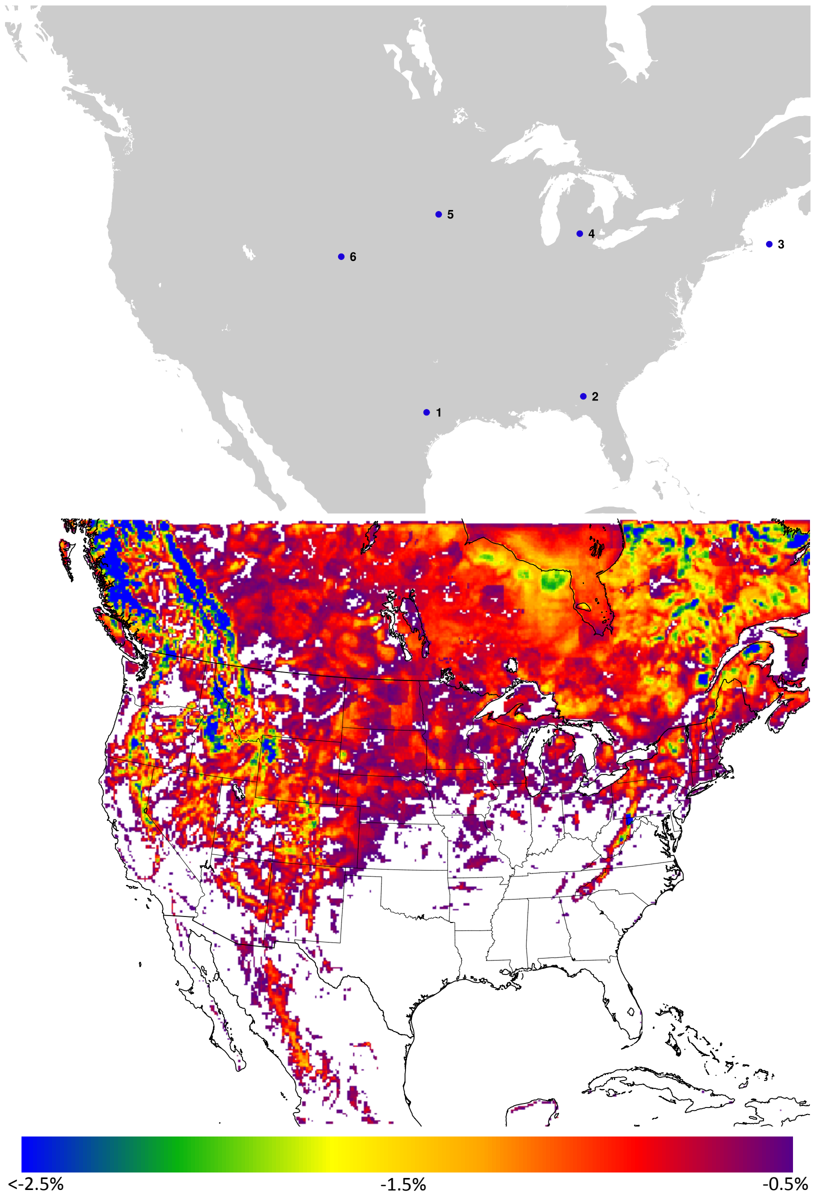


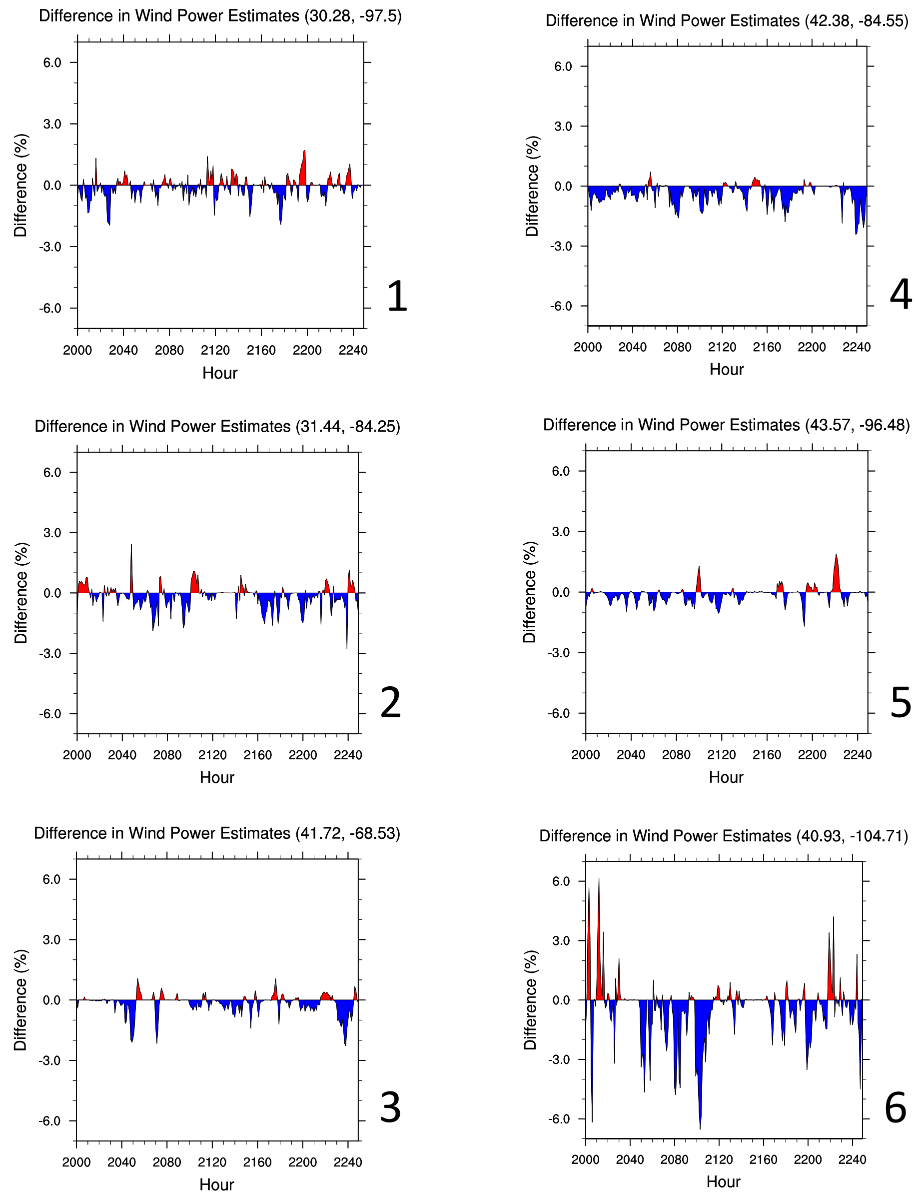
Average Capacity Factor Difference (RES - HUB)



Wind Power Estimates from REWS

Locations of the six sites analyzed





“Full” Power Equation

$$P_w(U(t)) = \frac{d[E_w(U(t))]}{dt} = \frac{d}{dt}\left[\frac{1}{2}\cdot m(t)\cdot U^2(t)\right]$$

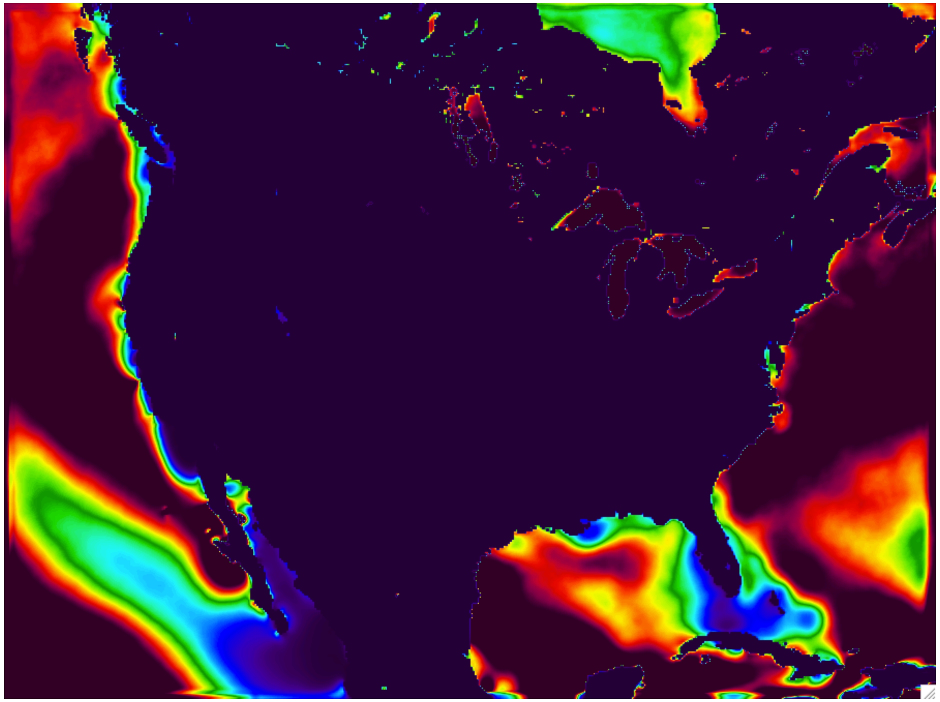
$$P_w(\rho(t), U(t)) = \frac{d}{dt}\left[\frac{1}{2}\cdot A\cdot \rho(t)\cdot L(t)\cdot U^2(t)\right]$$

$$\boxed{P_w(\rho, U) = \frac{\rho A U^3}{2}\left[1 + \left(\frac{\int U\ dt}{U}\right)\left(\frac{1}{\rho}\frac{d\rho}{dt} + \frac{2}{U}\frac{dU}{dt}\right)\right]}$$

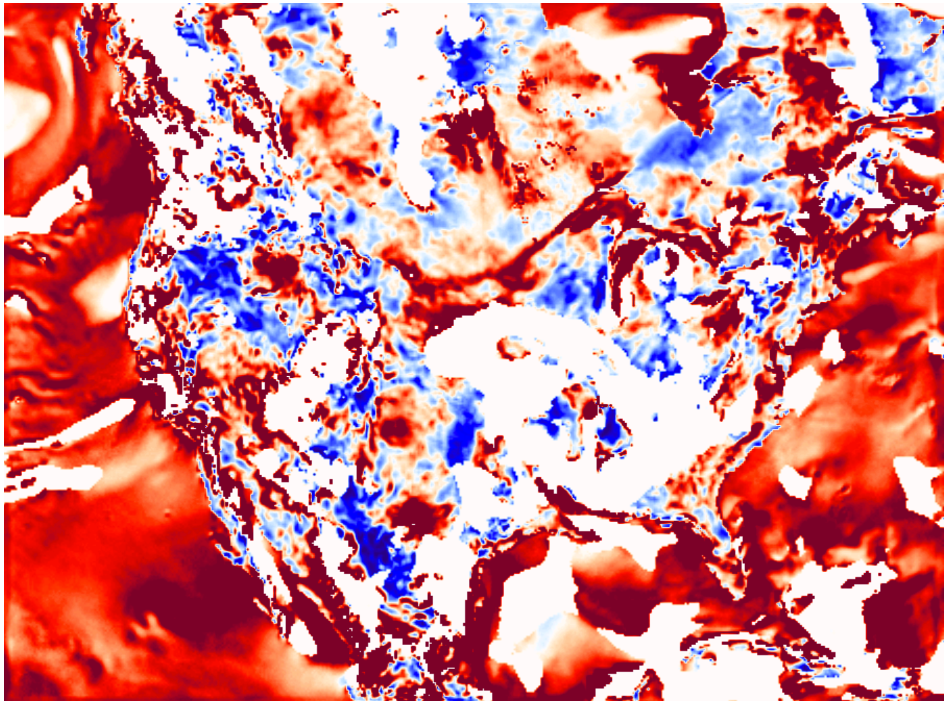
- Correction terms are related to ramp events and turbulence
- As integration period decreases so does the magnitude of the correction terms
- Constant speed and density results in the standard power equation
- Simple way to adjust NWPM outputs to incorporate more information

“Full” Power Equation

- The “full” power equation does not significantly alter the hourly average values over the whole study period.
- Shows significant differences over individual hourly time steps.
- Validation is required to confirm the usefulness of the “full” power equation
- It will be incorporated into the Wind Farm Parameterization and work for this has already begun.

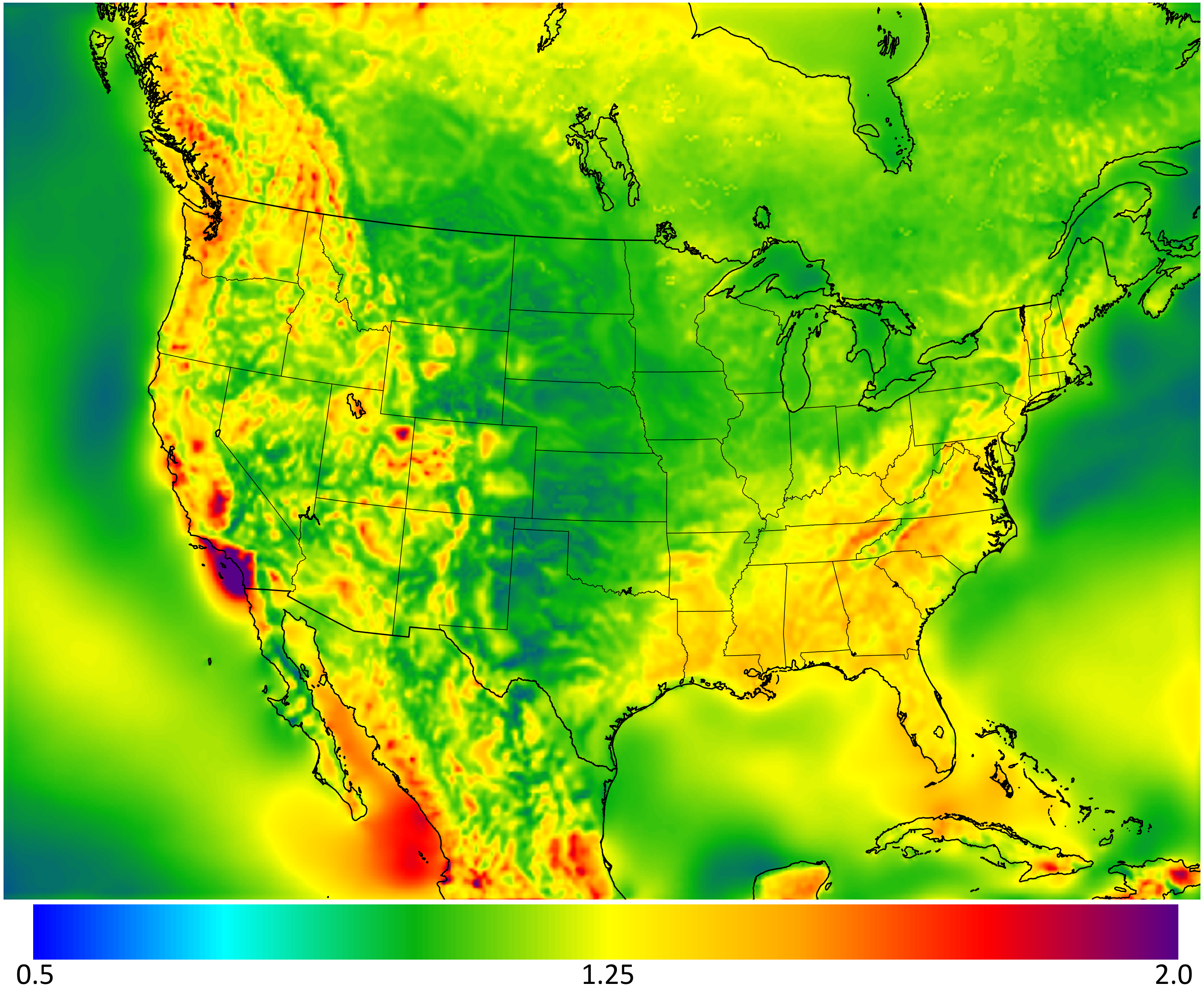


Yearly average difference; entire color range is 2% to 5%. Black denotes negligible difference.



A single hour difference plot of “full” power equation vs. standard formula. Dark red is +25%, dark blue is -25%.

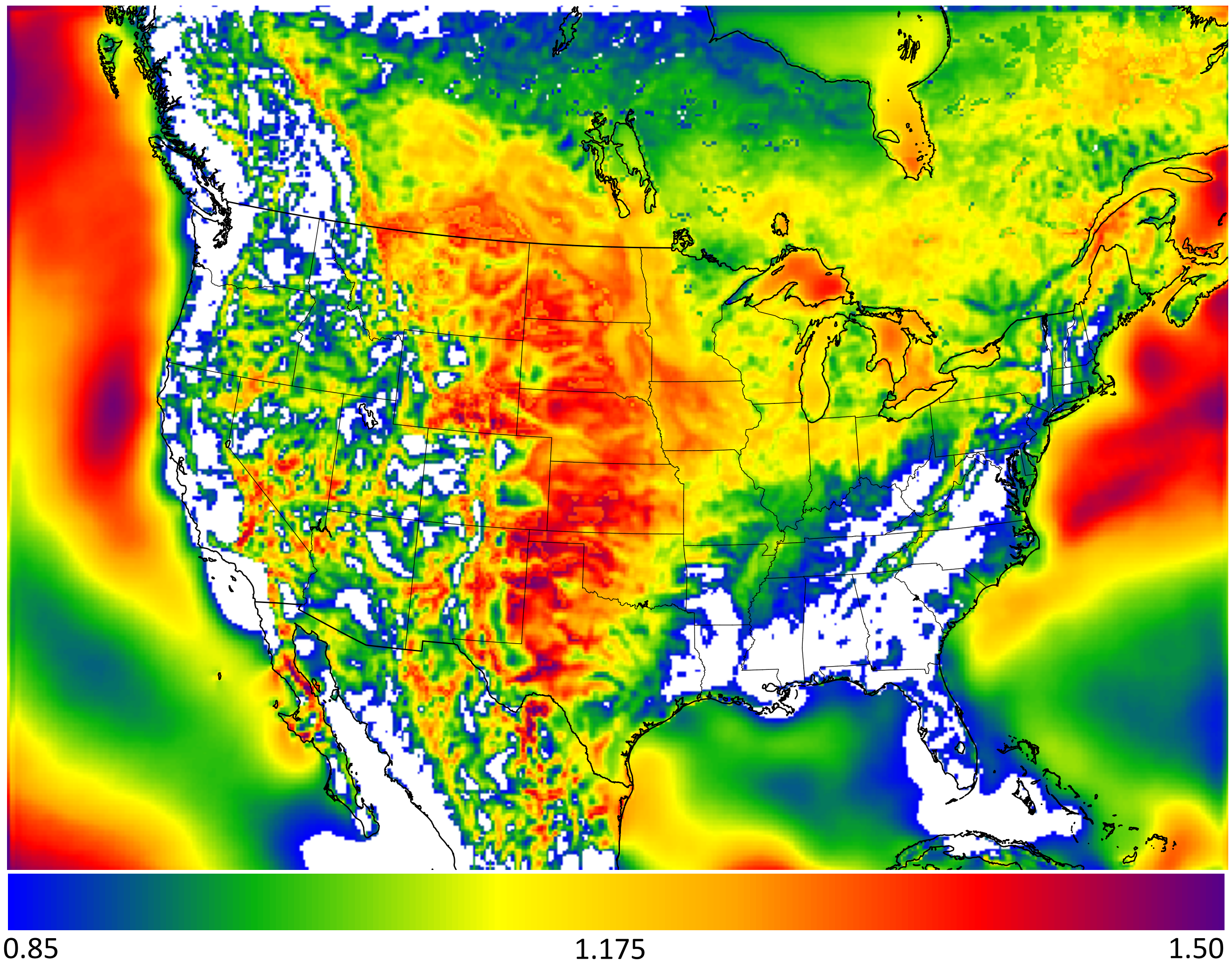
Coefficient of Variation



The coefficient of variation (CV) allows the direct comparison of the dispersion of distributions with different mean values.

Suitability Metric

$$S = \frac{CF}{CV} = \mu\frac{\mu}{\sigma} = \frac{\mu^2}{\sigma}$$



- Based on resource only
- All sites penalized in a homogenous way
- Incorporates seasonal variability
- Includes the diurnal cycle
- Simple to calculate
- Data is processed on hourly time steps
- Largest values indicate higher capacity factors with lower variability

Conclusions and Future Work

- Produced a demonstration of resource mapping using REWS and "full" power equation to include extra information that can be missing from NWPM derived products.

- Created a simplistic suitability metric that can be utilized to look at wind sites that include the variability of the resource along with the potential.

- The REWS and the "full" power equation alter the resource map due increased information being included. The main effects are at the individual time steps. It is not yet known if these alterations are consistent with observations. To do this we need power data within the study period.

  ✓ We are increasing the size of the data set from 2006-2008 to 2006-2014 at 13 km and 2010-2014 at 3 km.

  ✓ The "full" power equation is being coded into the WFP to see if there is any alteration in the power production at NWPM integration time periods.

  ✓ Turbulent intensity via Reynold's decomposition is to be incorporated in the resource mapping shortly.

Questions?

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