Modeling Solar Irradiance and Solar PV Power Output to Create a Resource Assessment using Linear Multiple Multivariate Regression

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Photo: Joel Courcy Browne

Motivation and Purpose

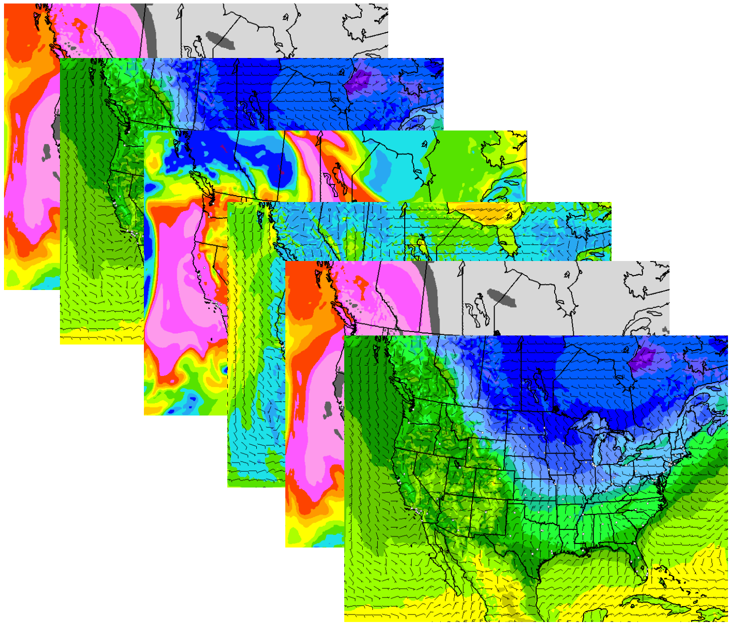
- The create total, direct (normal and horizontal), and diffuse irradiance estimates on RUC model grid. From the irradiance estimates produce solar PV power estimates.

- Leverage satellite, model hydrometeors, and high quality surface measurements to train the technique. Compute top of atmosphere irradiance to bound the regression from above.

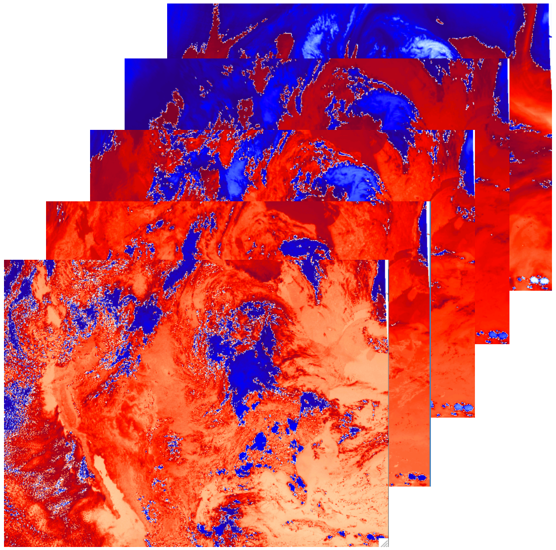
- Apply the technique over the CONUS domain to create an hourly data set of irradiance resource assessment (2006-2008). Working to extend this to 2014.

- Validate the methodology with observations.

Data Inputs



6 NWP Hydrometeors (Rapid Update Cycle)



5 Satellite Channels (where available)

Calculated Zenith Angle

$$\cos(sza) = \sin(lat) \cdot \sin(dec) + \cos(lat) \cdot \cos(dec) \cdot \cos(ha)$$

$$dec = \epsilon \cdot \sin[\delta + \frac{\pi}{180} \cdot (279.93 + 1.915 \cdot \sin(\delta) - 0.0795 \cdot \cos(\delta) + 0.02 \cdot \sin(2\delta) - 0.00162 \cdot \cos(2\delta))]$$

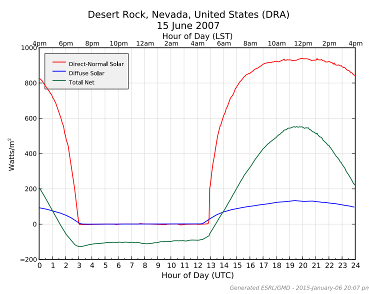
$$ha = \pi \cdot \left(1 - \frac{hr}{12}\right) - lon$$

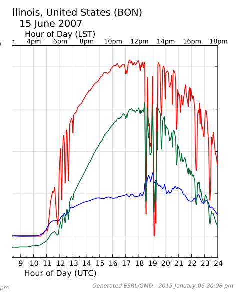
Calculated top of atmosphere Irradiance

$$DNI_0 = I_0 \cdot \left(\frac{R_{av}}{R}\right)^2$$

$$\left(\frac{R_{av}}{R}\right)^2 \approx 1.000110 + 0.034221 \cdot \cos(\delta) + 0.001280 \cdot \sin(\delta) + 0.000719 \cdot \cos(2\delta) + 0.000077 \cdot \sin(2\delta)$$

Ground-based Observations (SURFRAD and ISIS)





Linear Multivariate Multiple Regression

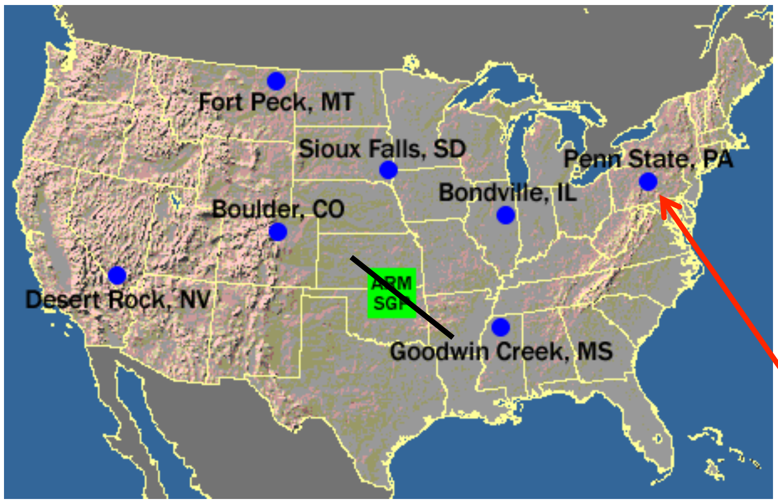
$$Y_{n\times p} = Z_{n\times(r+1)}\beta_{(r+1)\times p} + \epsilon_{n\times p},$$

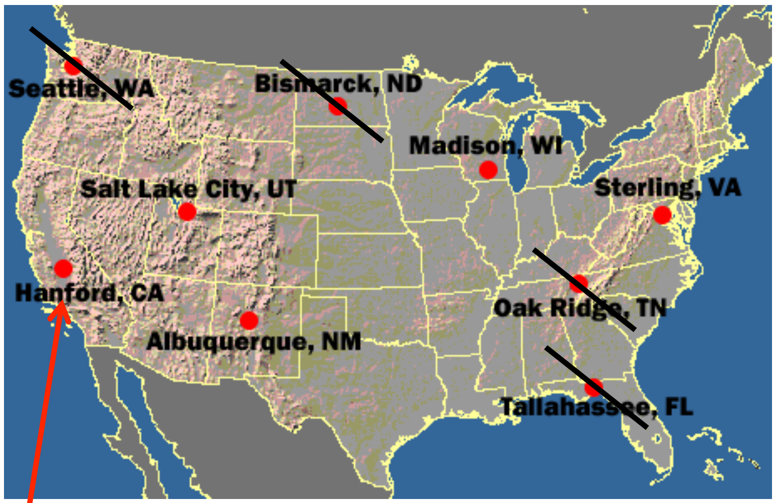
$$E(\epsilon_{(i)}) = 0, \quad \text{Cov}(\epsilon_{(i)}, \epsilon_{(k)}) = \sigma_{ik} I, \quad i, k = 1, 2, ..., p.$$

- We have p(=3) irradiance fields to calculate and n(=55258) observation of each field. The observations are taken from 10 sites (6 SURFRAD and 4 ISIS)
- The regressors (β) are the satellite data (3 infrared channels, a visible channel, and a water vapor channel), the RUC Assimilation Model values for water within the column (snow, ice, etc…), the temperature from the model, the calculated top of atmosphere irradiance, and the zenith angle.
- The measurements are taken from 2006 – 2008, and averaged over the top of the hour (for 12 minutes) and matched up with the model data.
- The data is quality controlled, and all night-time measurements were removed.

Linear Multivariate Multiple Regression

- Method relies on high quality ground measurements to train the regression procedure. We also use University of Oregon solar measurement sites for verification.





Initial Validation Sites

$$\boxed{\hat{\beta}_{(i)} = (Z'Z)^{-1}Z'\mathbf{Y}_{(i)}}$$

Can use numerous mathematical techniques to compute the coefficients. We do not go into that here… (I used SVD).

Regression Statistics

- The regression had differing success with total, direct, and diffuse.
- We trained on 10 individual sites and computed the accuracy of the regression at those sites.
- We use one SURFRAD and one ISIS site for initial verification.

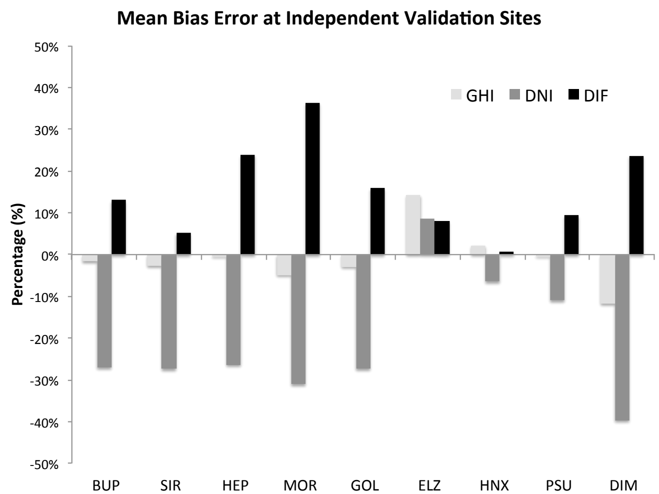
Irradiance		Mean (W/m^2)	MBE (%)	$\overline{R}^2$ (%)	RMSE (%)	CV (%)
GHI	A	442.00	-2.82	94.17	20.67	20.48
	B	442.00	-3.33	92.96	22.63	22.39
	C	442.00	-4.26	91.08	25.60	25.25
DNI	A	512.37	-12.41	77.75	41.82	39.94
	B	512.37	-15.33	71.80	47.92	45.40
	C	512.37	-22.16	54.29	57.46	53.01
DHI	A	148.66	-4.19	82.87	42.42	42.21
	B	148.66	-4.63	80.83	44.56	44.32
	C	148.66	-6.90	69.20	55.40	54.97

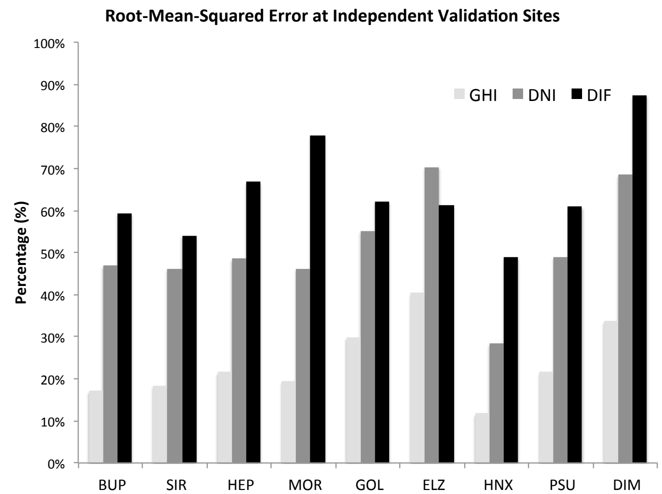
Composite metrics for training sites

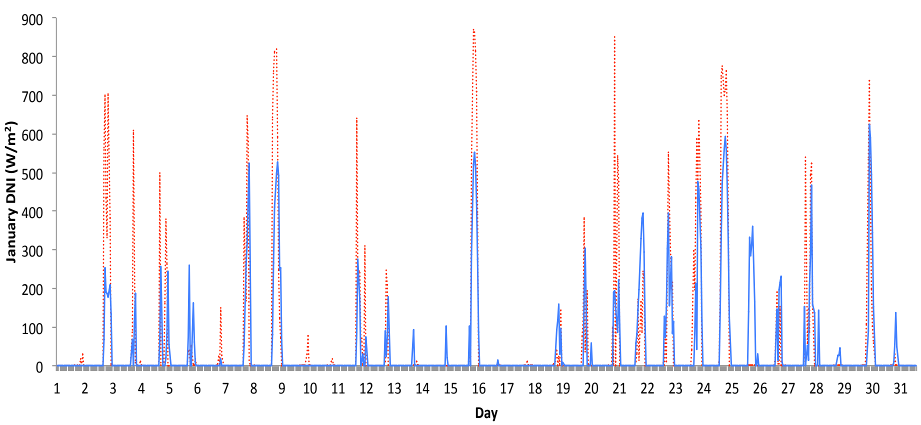
Irradiance		Mean (W/m^2)	MBE (%)	$\overline{R}^2$ (%)	RMSE (%)	CV (%)
GHI	A	458.13	2.41	89.37	19.57	19.42
	B	458.13	2.67	88.16	20.67	20.50
	C	458.13	1.08	83.91	24.03	24.01
DNI	A	468.03	2.35	65.91	39.51	39.44
	B	468.03	0.21	58.98	43.27	43.27
	C	468.03	-9.80	41.86	52.93	52.01
DHI	A	164.60	-9.26	66.26	40.33	39.25
	B	164.60	-10.32	63.43	42.08	40.80
	C	164.60	-10.60	48.26	49.92	48.78

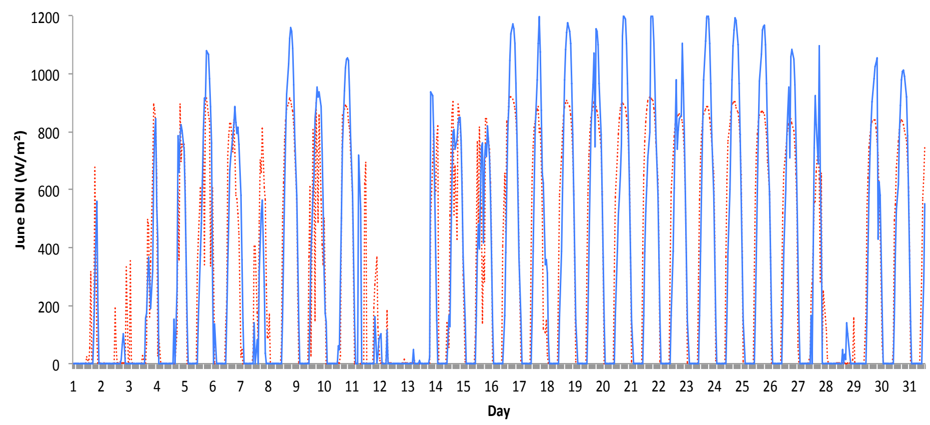
Composite metrics for initial verification sites

Regression Statistics

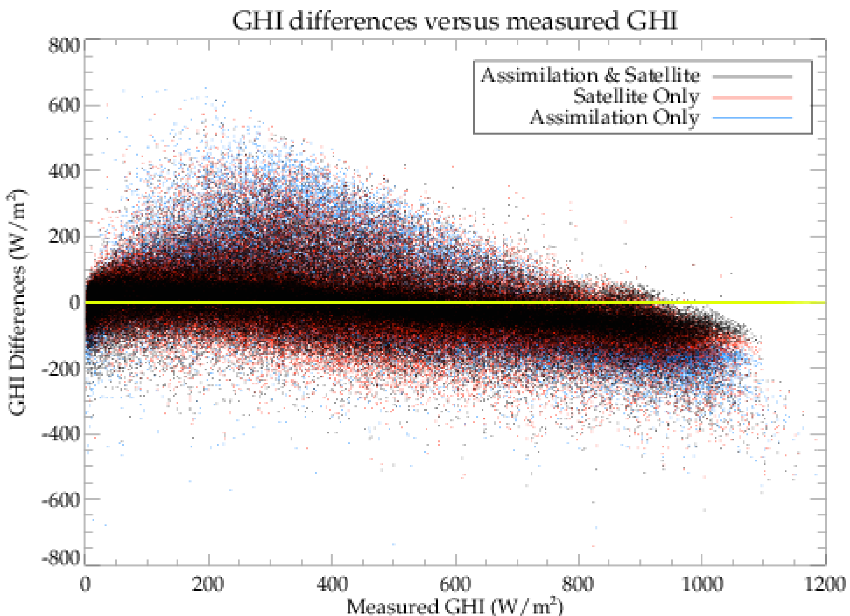


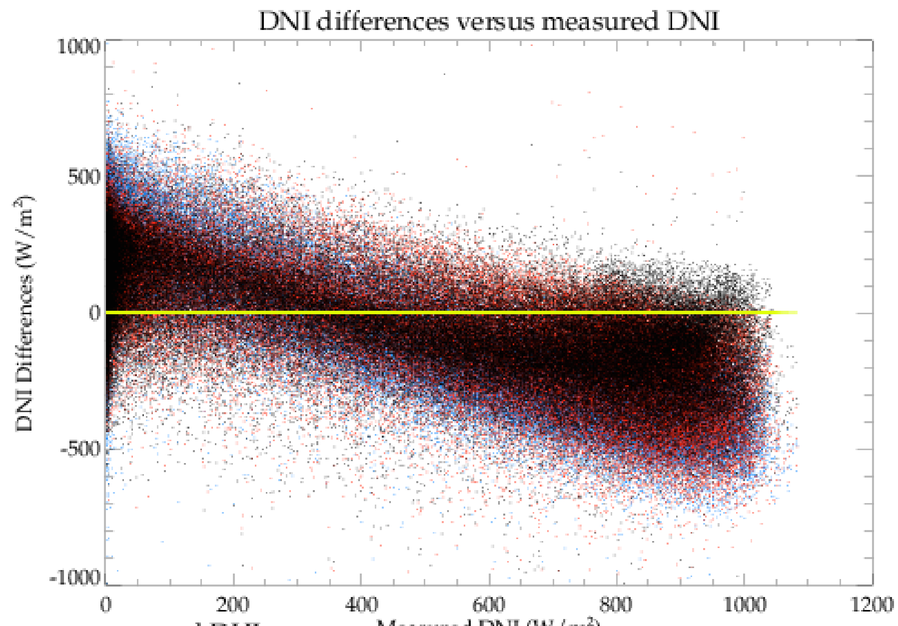


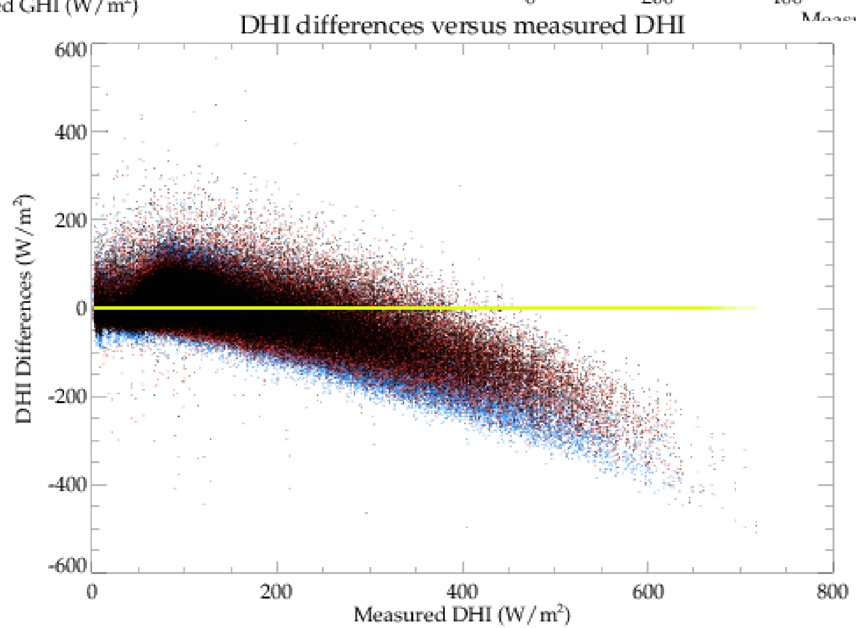




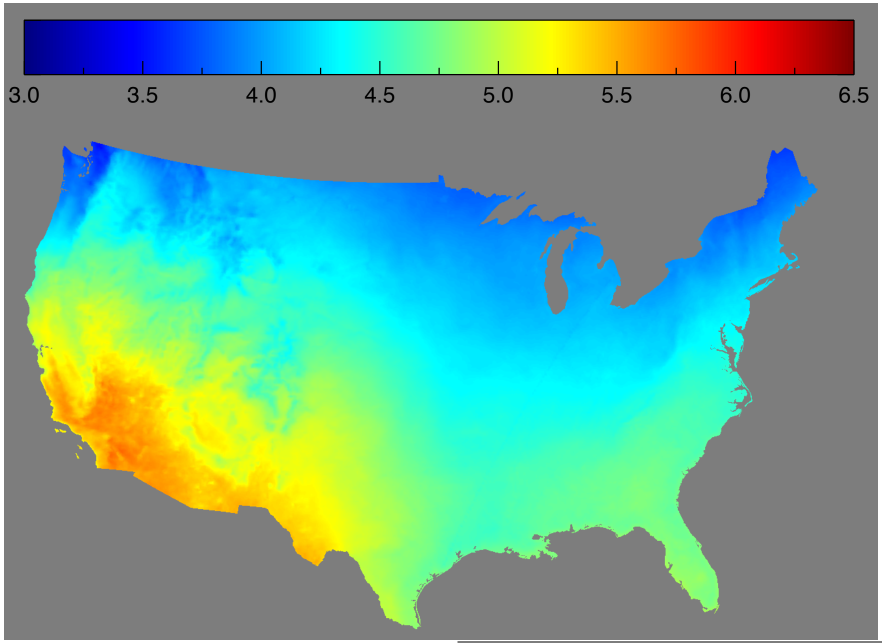
Regression Statistics



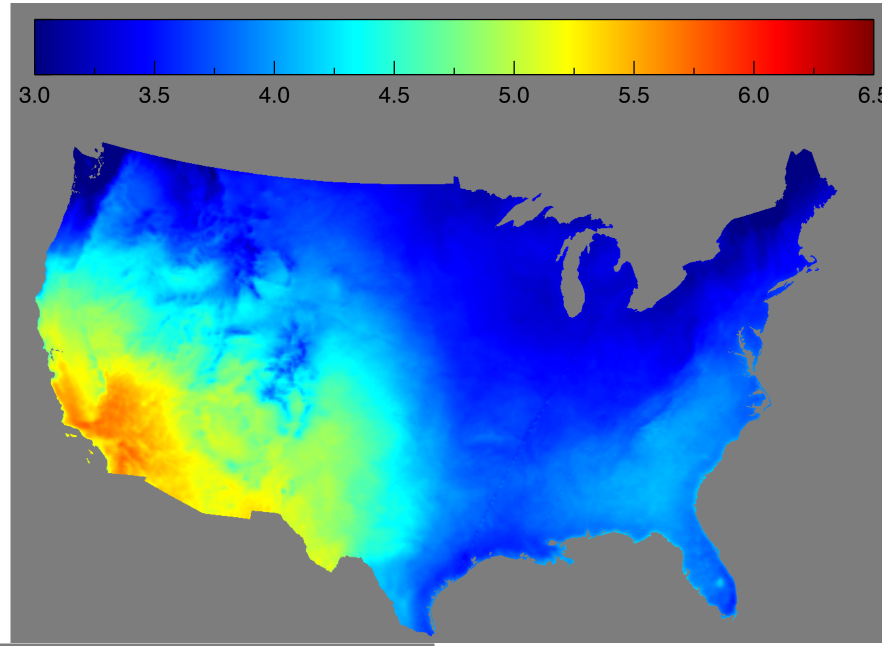




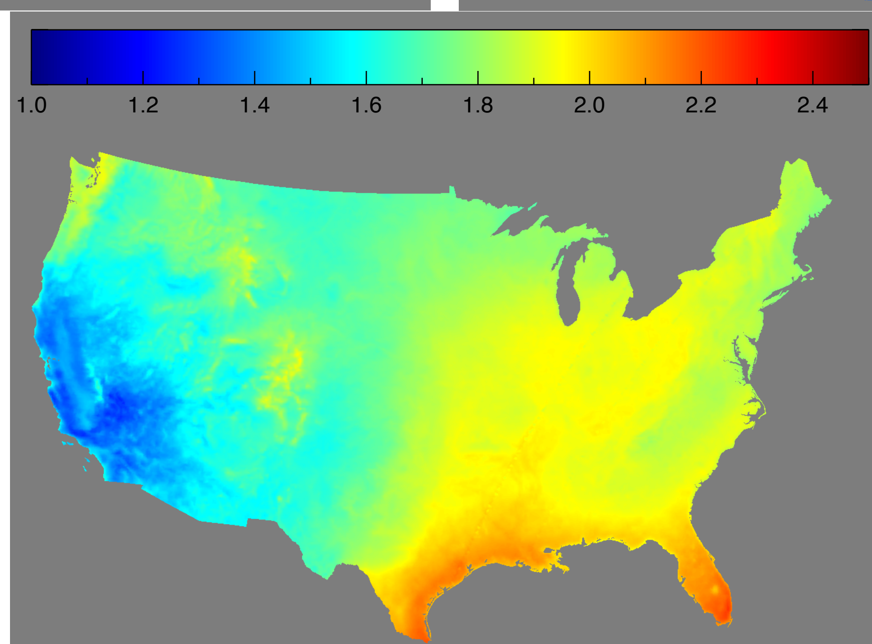
Regression Created Dataset



Average GHI kWh/m²/day

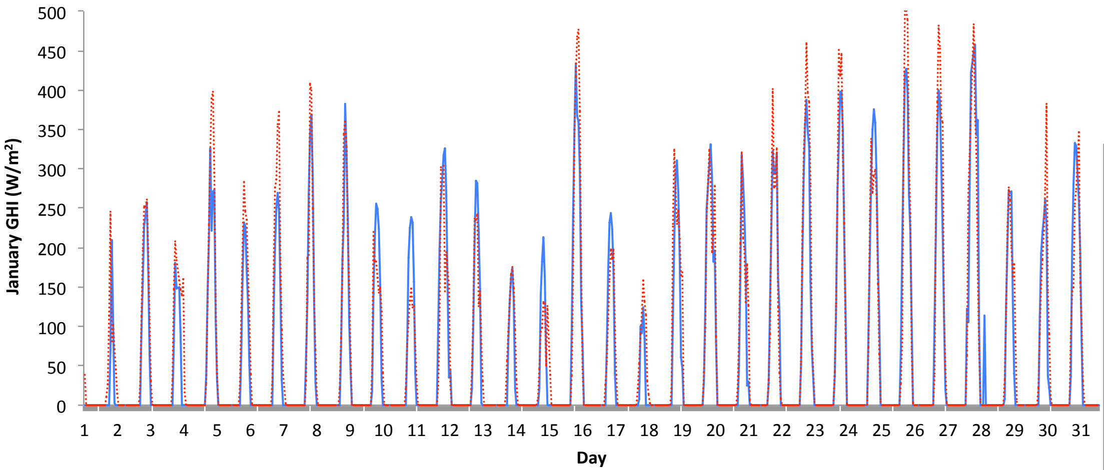


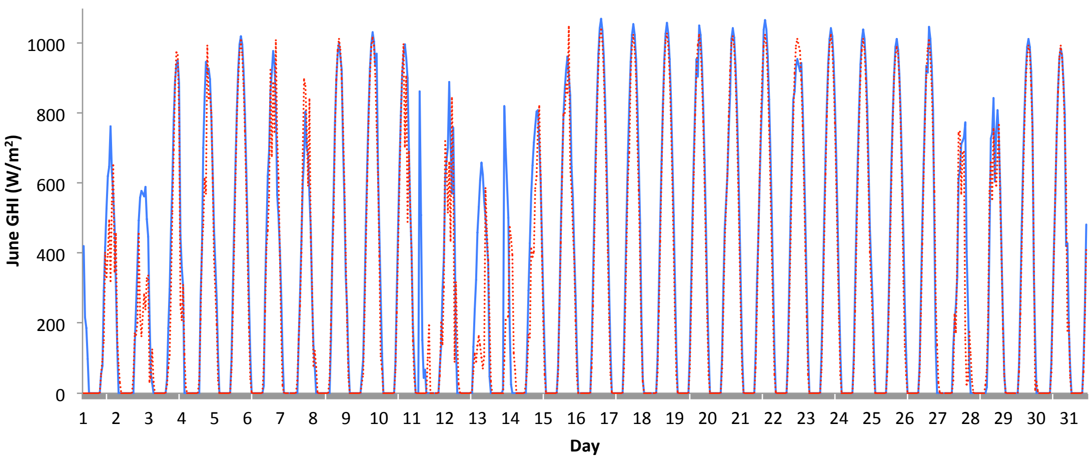
Average DNI kWh/m²/day



Average DHI kWh/m²/day

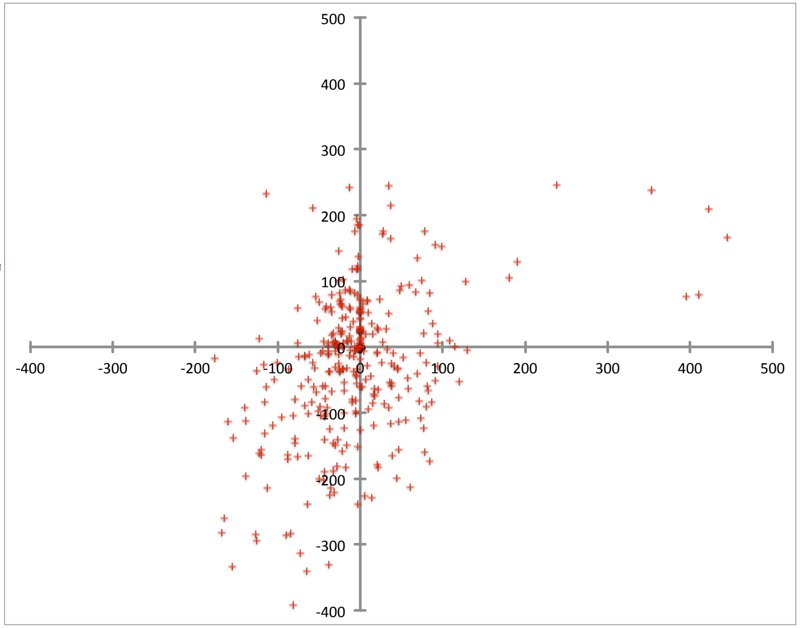
Regression Created Dataset





Burns, OR

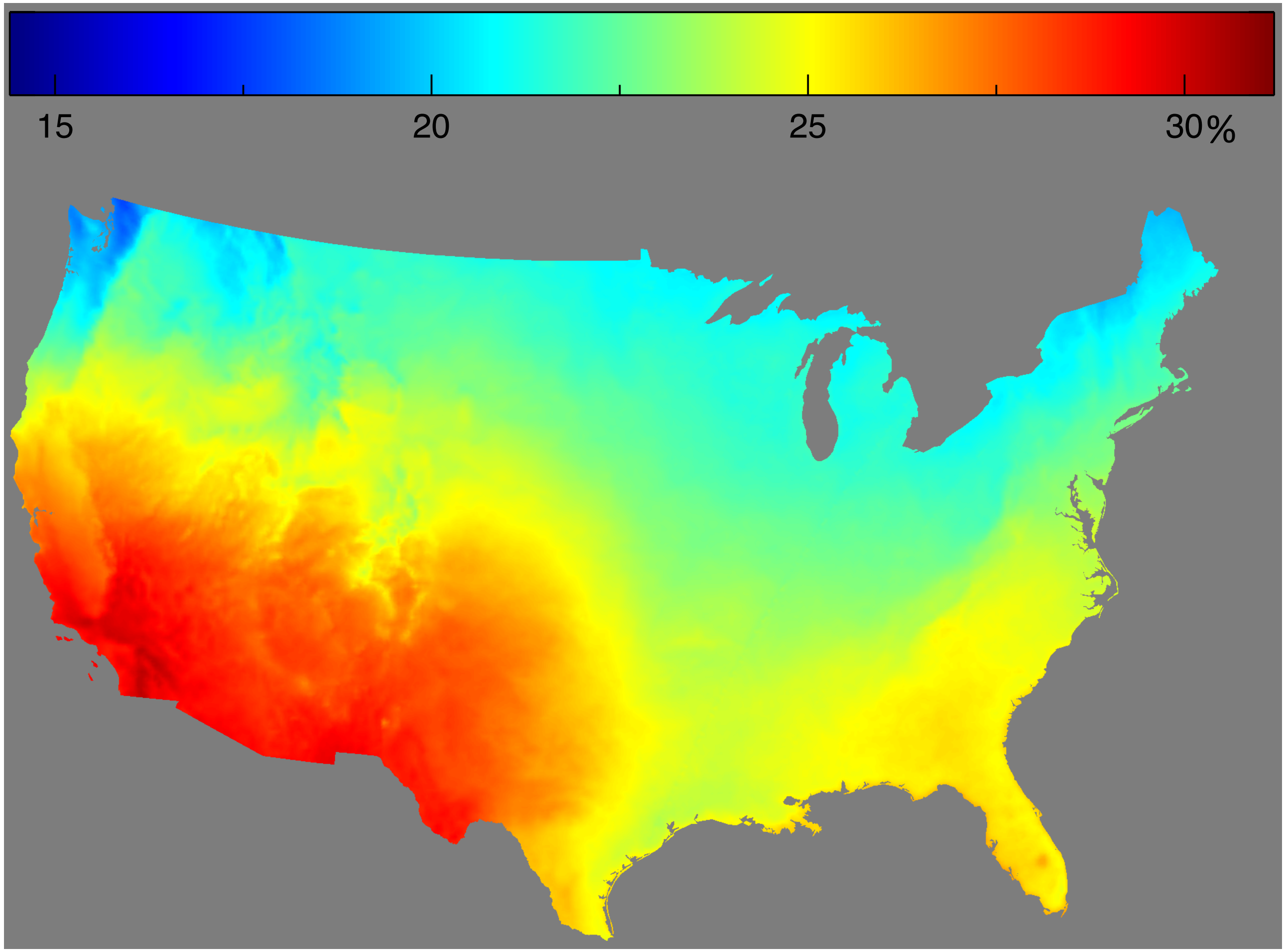
Solar Anywhere GHI Estimate Error (W/m²)



GHI Estimate Error (W/m²)

Irradiance to Solar Photovoltaic Power

- Take the output GHI, DNI and DHI and use them as inputs to a power modeling algorithm.
- In addition take temperature (at 2 m) and wind speed (at 10 m) from the RUC to help provide an estimate of the panel temperature.



Conclusions and Future Work

- The results are promising, even though an older, lower resolution model was utilized for the regression.

- The regression technique, once trained, is very computationally inexpensive to be used in real-time to improve GHI, DNI and DHI estimates.

- The solar irradiance estimates are comparable to other products available.

  ✓ We will extend the dataset to 2014 at 13 km and perform the same technique on 3 km HRRR.

  ✓ Will start to incorporate the GOES East/West composite satellite data.

  ✓ Calculating the line-of-sight model data rather than vertical column.

  ✓ Utilizing NREL's solar measurements and other sources of measurements to improve the accuracy of the regression.

  ✓ Extend the estimates to forecast hours

Questions?

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Photo: Chuck Coker via Flickr