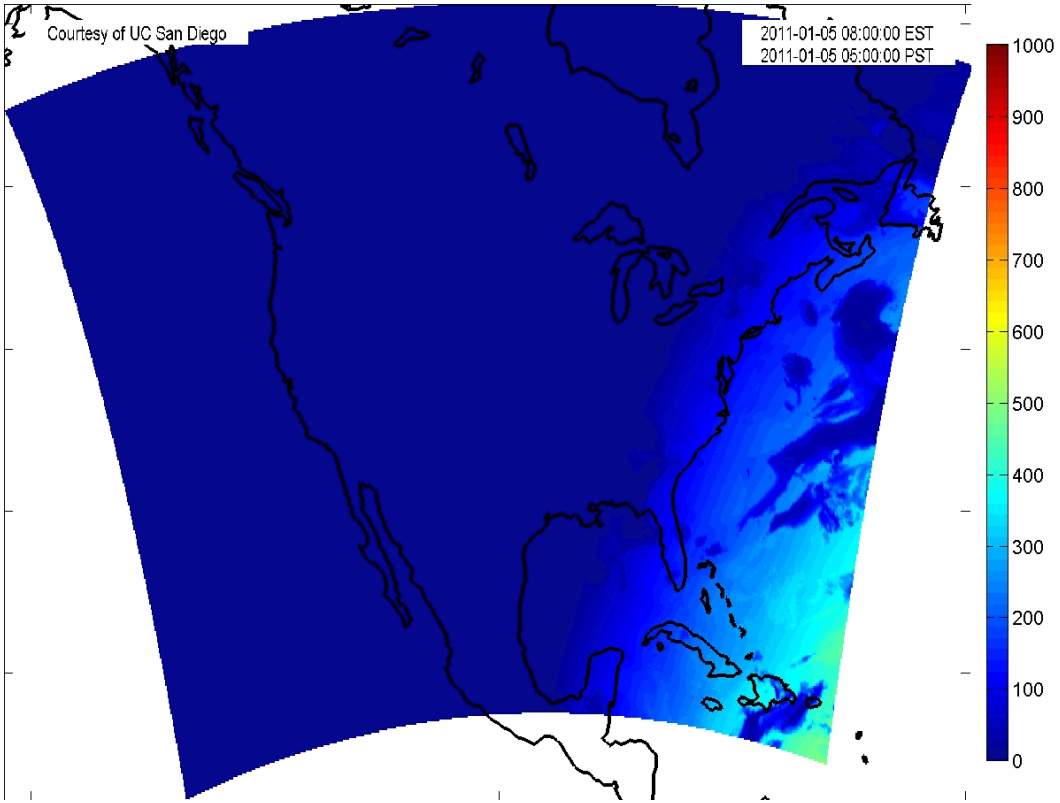


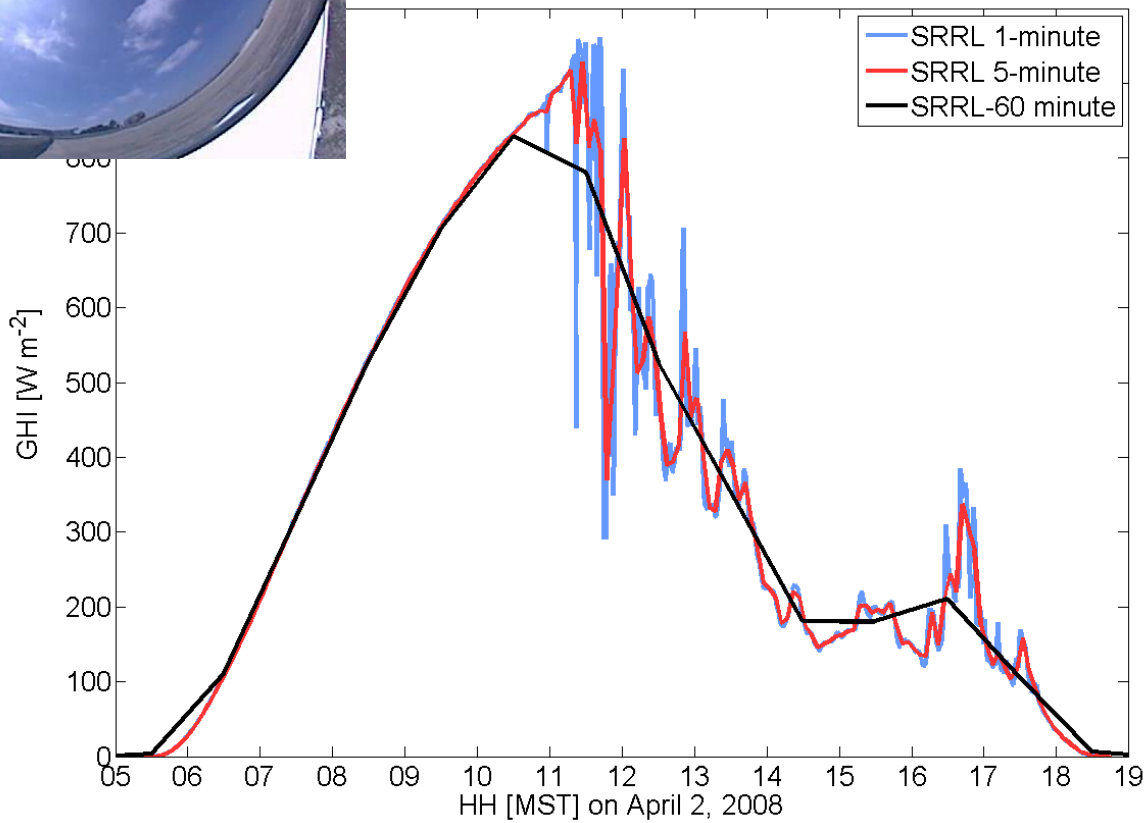
Solar Variability and Forecasting

Jan Kleissl, Chi Chow, Matt Lave, Patrick Mathiesen, Anders Nottrott, Bryan Urquhart

Mechanical & Environmental Engineering, UC San Diego

http://solar.ucsd.edu

Variability of GHI



Grid with 35% Renewables

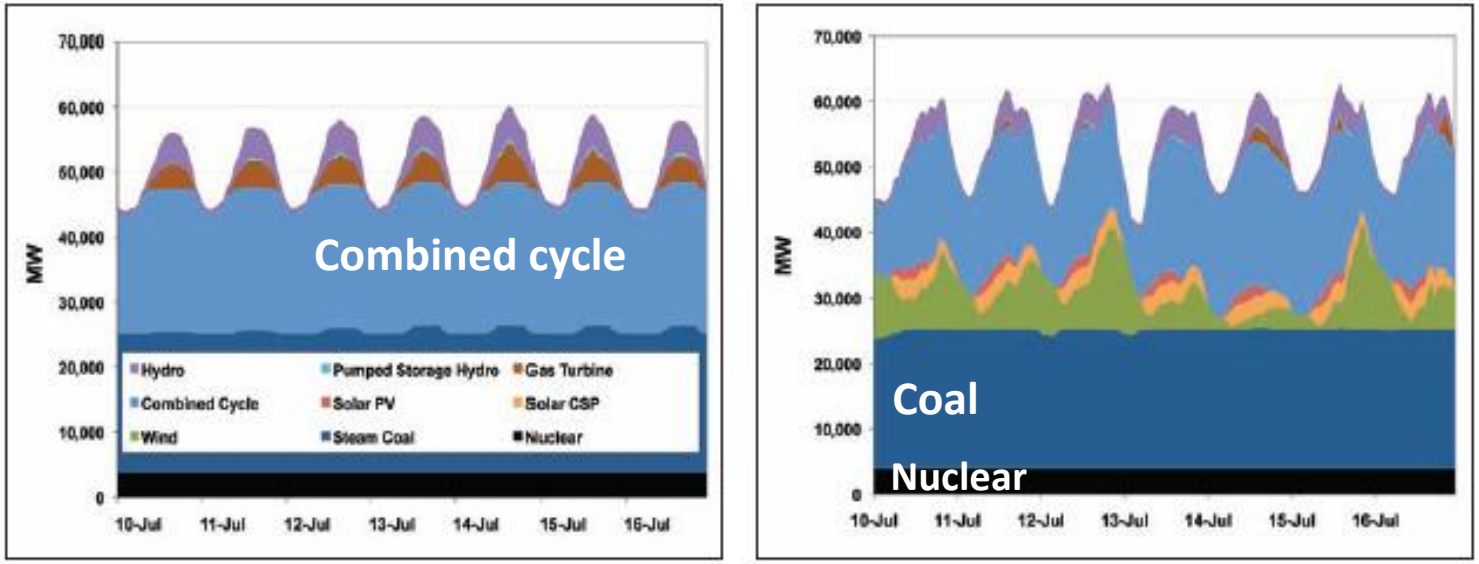


Figure 3 – 35% renewables have a minor impact on other generators during an easy week in July, 2006. WestConnect dispatch - no renewables (left) and 30% case (right)

easy week:
-Large load
- small renewables

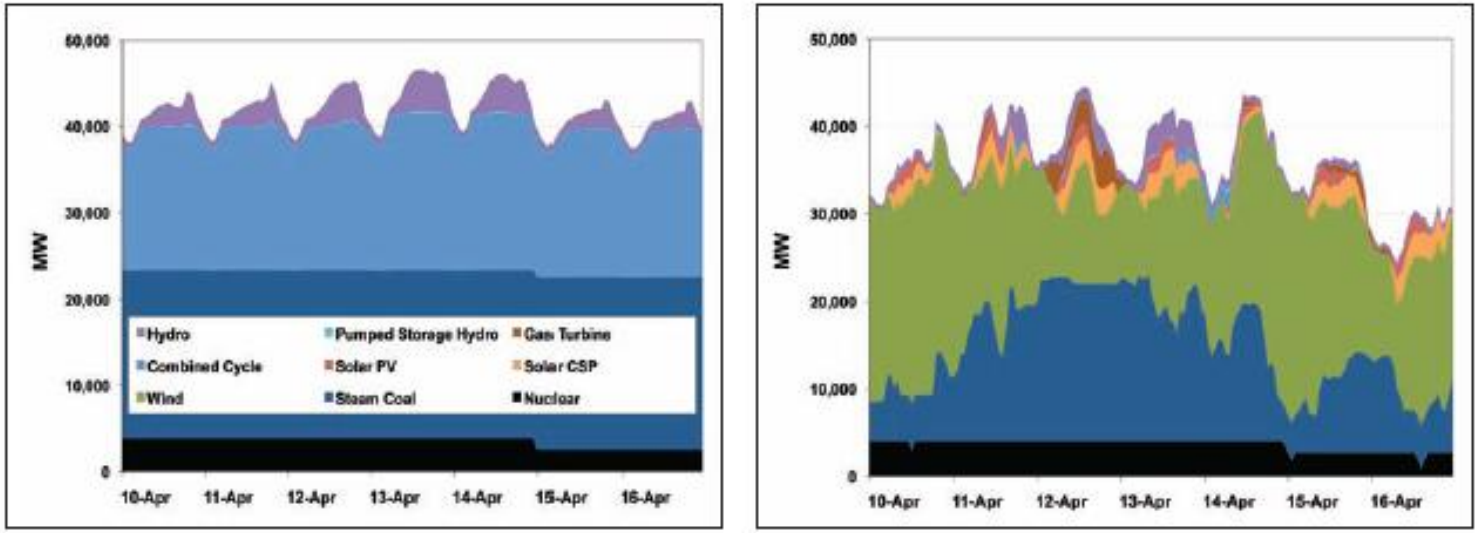


Figure 4 – 35% renewables have a significant impact on other generation during the hardest week of the three years (mid-April 2006). WestConnect dispatch - no renewables (left) and 30% case (right)

hard week:
- small load
- large renewables

Why does variability matter?

Integration Costs of Solar Dramatically Impacted By Geographic Diversity, and May Be Less than for Comparably Sited Wind

Time Scale	Increased Reserve Costs ($/MWh)				
	Reserves Constant Throughout Year				Reserves Change with Position of Sun
	Solar			Wind	Solar
	1 Site	5 Sites	25 Site Grid		
1-min Deltas (Regulation)	$14.7	$5.0	$1.6	$1.1	$0.2
5-min Deltas (Load Following)	$7.0	$2.1	$0.7	$0.2	$0.1
60-min Deltas (Reserve Margin for Hour-ahead Forecast Error)	$5.2	$2.2	$1.3	$0.8	$0.2
Total Cost	**$26.9**	**$9.3**	**$3.5**	**$2.1**	**$0.5**

Example costs based on 10% penetration of solar or wind on capacity basis

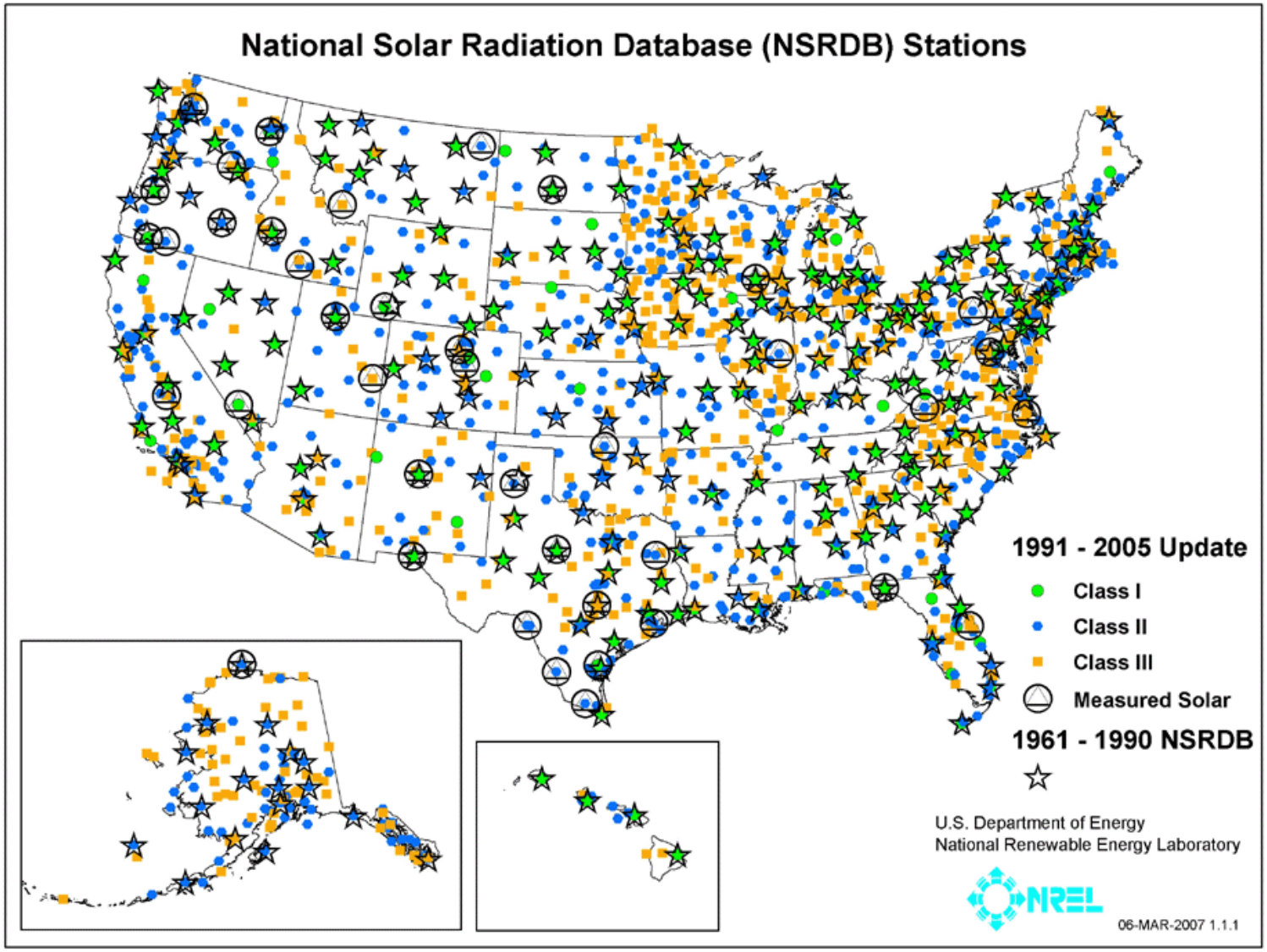
Why are solar costs lower?

Reserves can be held in proportion to clear-sky insolation for solar

Reserves are held at the same level all year for wind

Source: Andrew Mills, Lawrence Berkeley National Lab

The plight of Solar Data

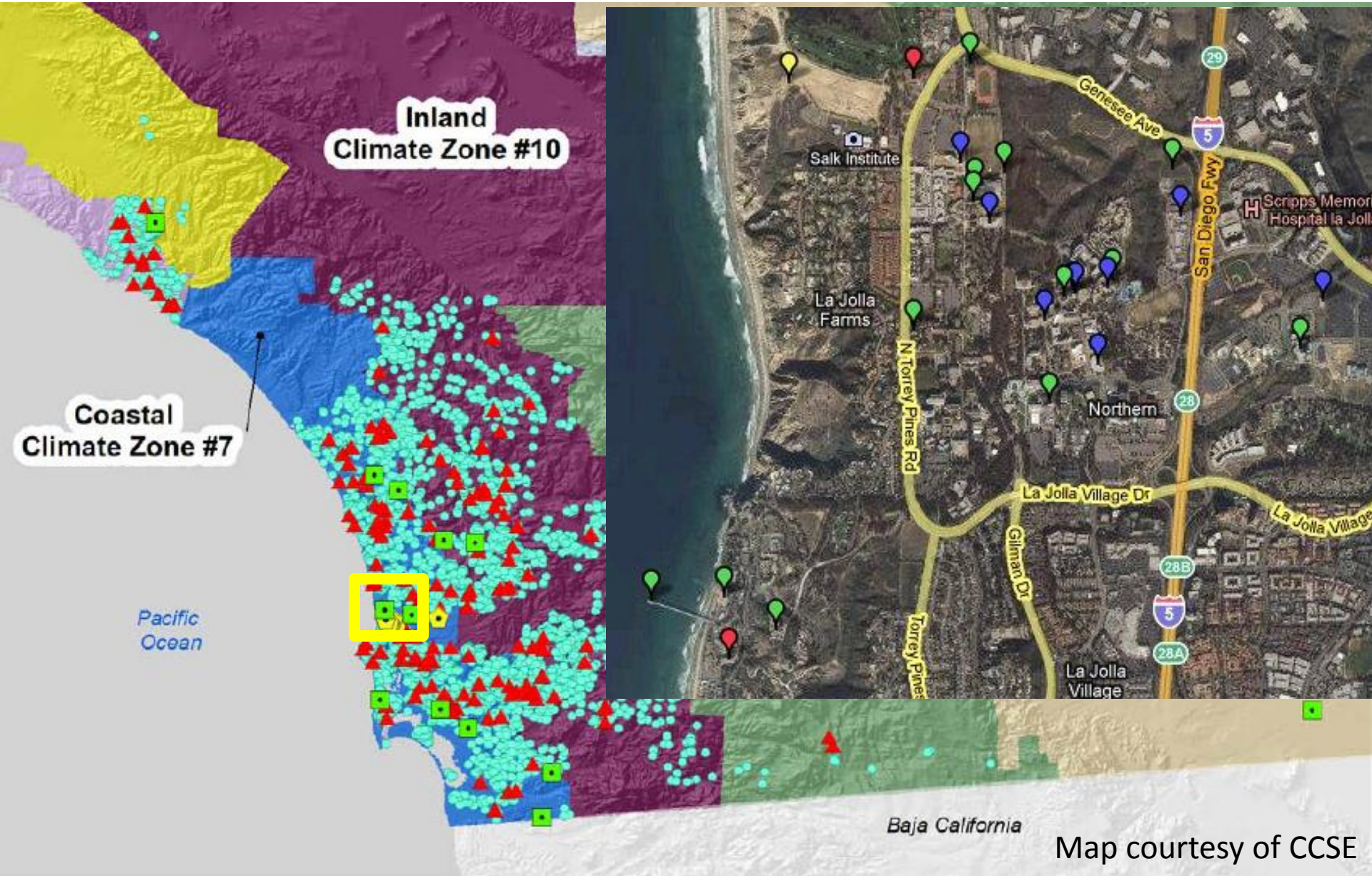


Variability of Solar Irradiance

- Variability of Irradiance
- Variability of spatially averaged irradiance
-Variability of PV power plant

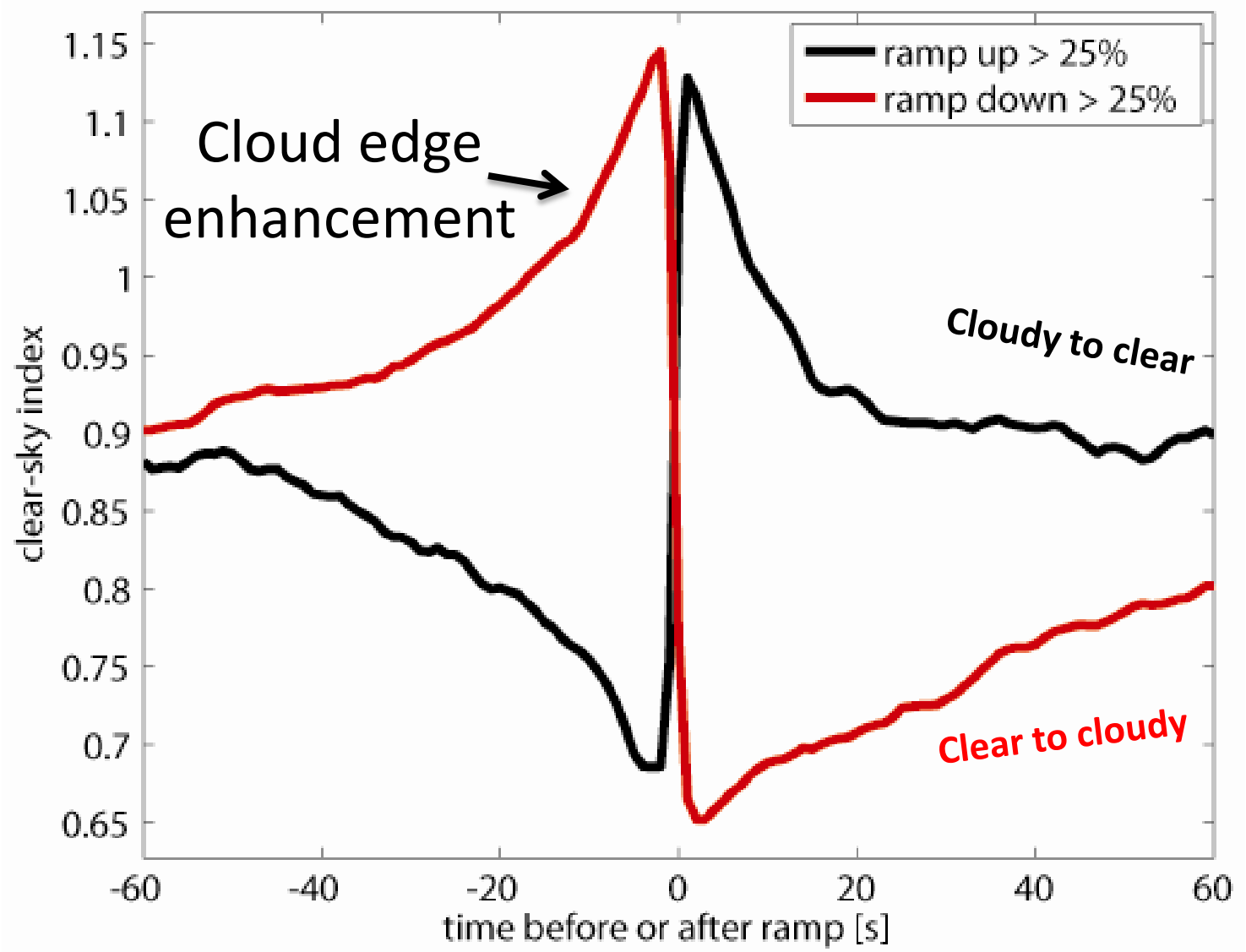
Further Reading: Stein J., 4th International DER Conference, http://www.4thintegrationconference.com/downloads/Session%205-5_Sandia%20National%20Labs_Stein.pdf; Mills, A. et al. LBNL-2855E

PV Systems in San Diego County and UC San Diego: Testbed for Solar Variability



Map courtesy of CCSE

Average 1-sec **irradiance** ramp event look like?

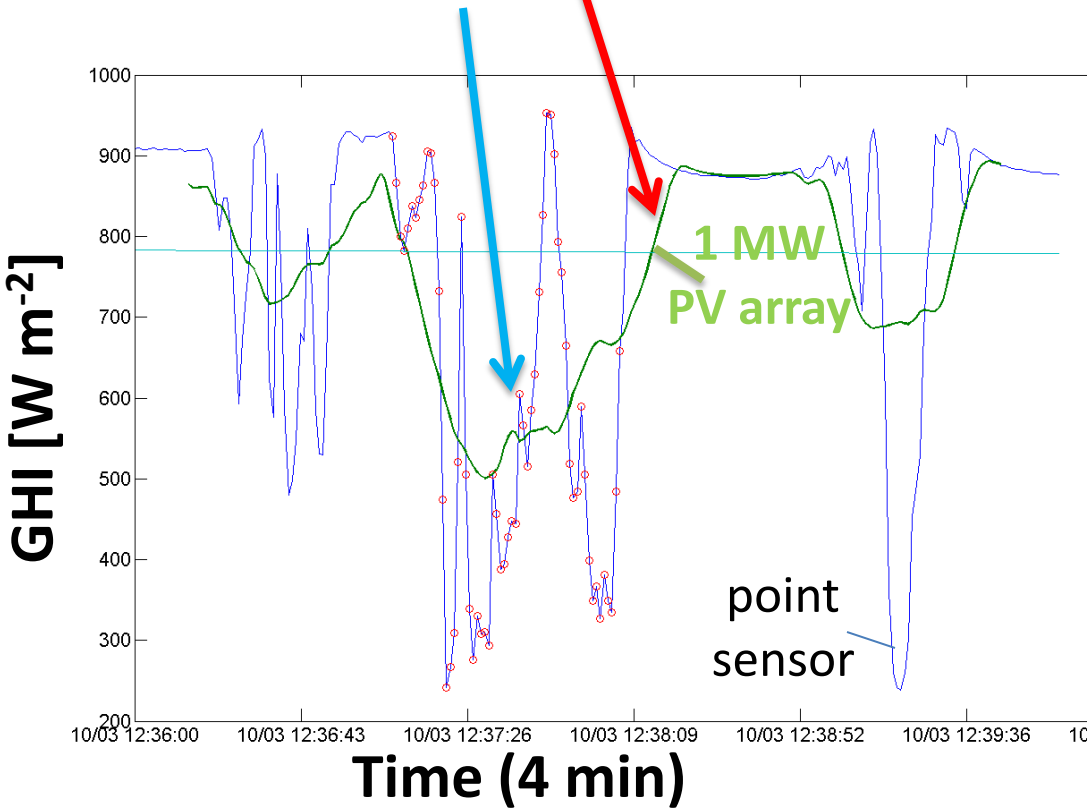


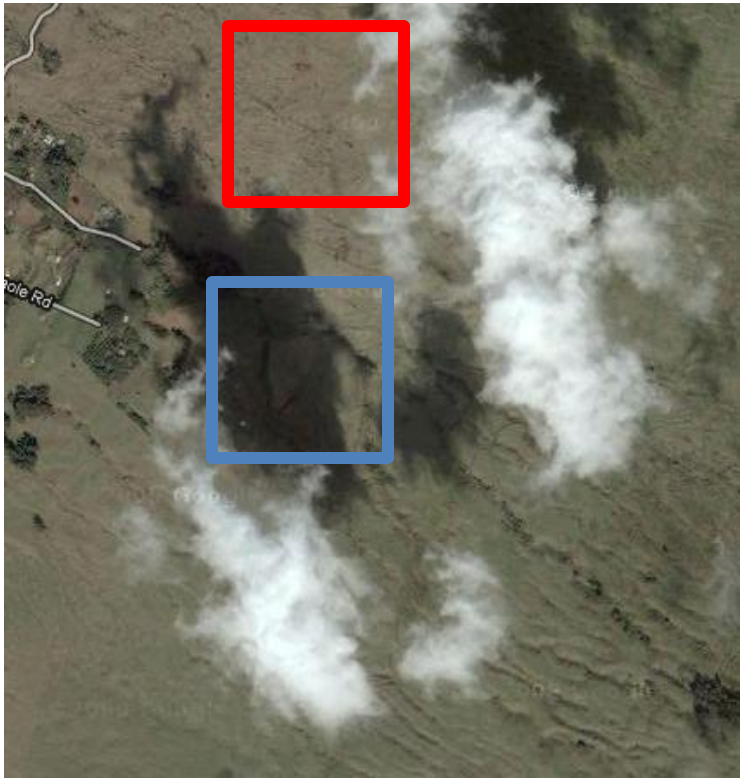
Spatial Averaging Effect of PV Array

- Irradiance measured by point sensor → spatial averaging occurs for PV array

PV size $A^{1/2}$ < shadow / clear size: decrease of ramp rate, but same amplitude

PV size $A^{1/2}$ > shadow / clear size: decrease of ramp rate and amplitude

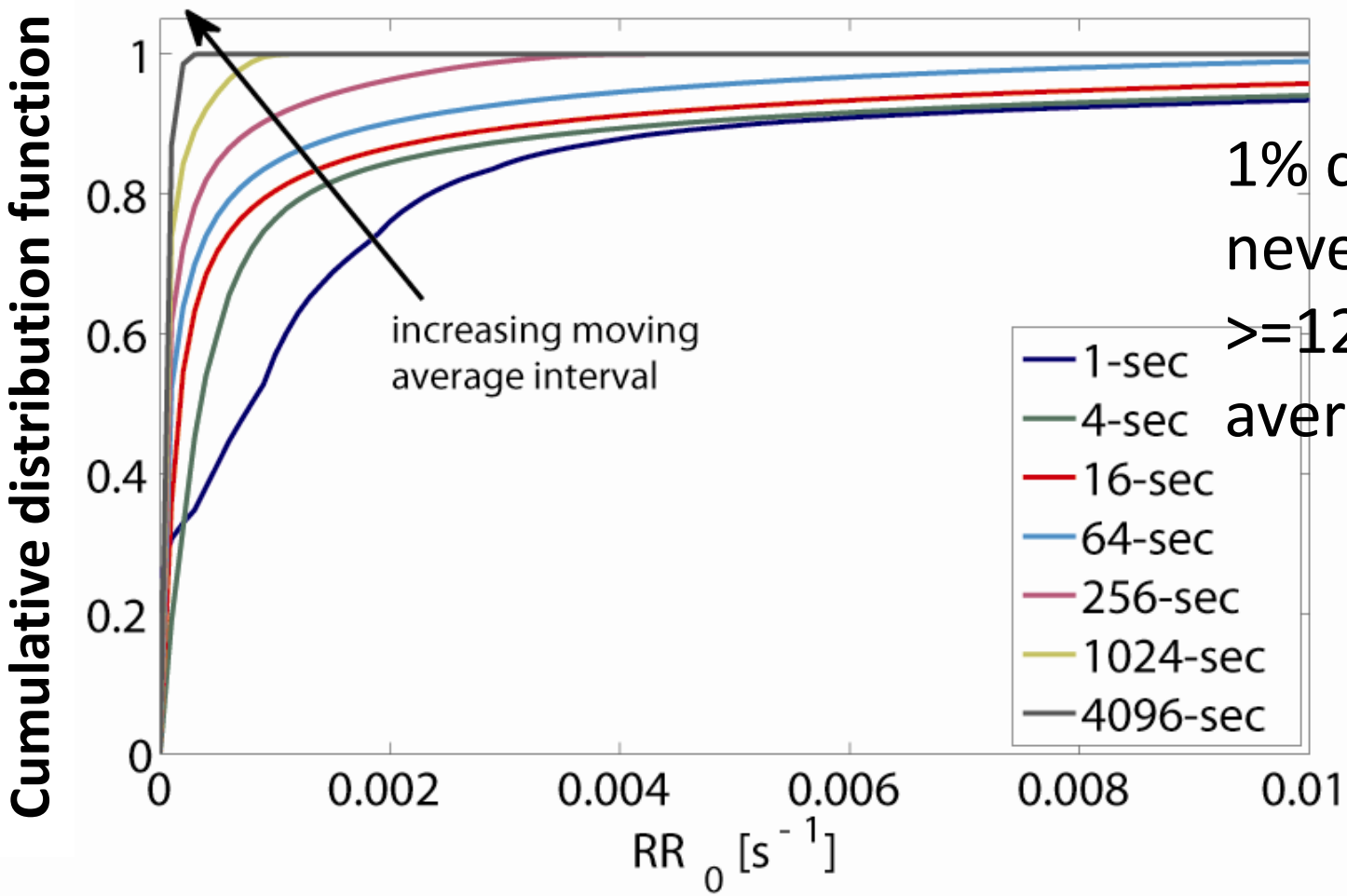




Effect of PV Array Size on Ramp Rates

Simulating different size PV plants through moving averages at timescale t. t ~ $A^{1/2}$ / Cloud speed U = $DC^{1/2}$ / ($\eta^{1/2}$ U), where DC: power rating in kW.

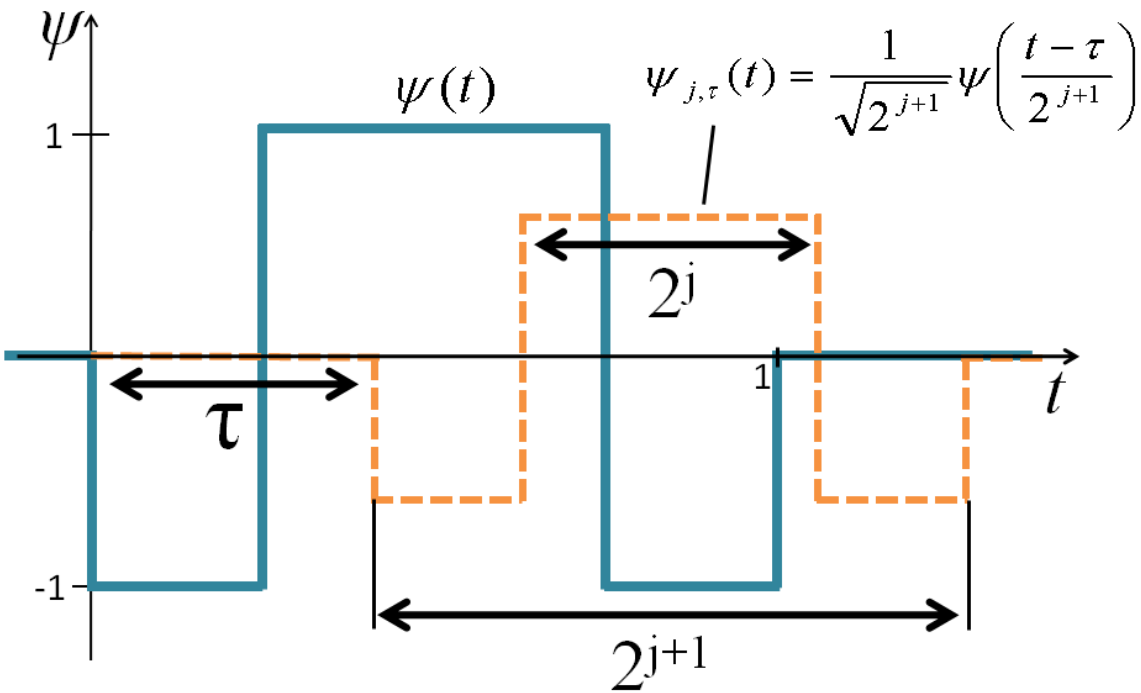
10 MW plant, at η = 0.1, U = 5 m s^{-1}: t = 63 sec

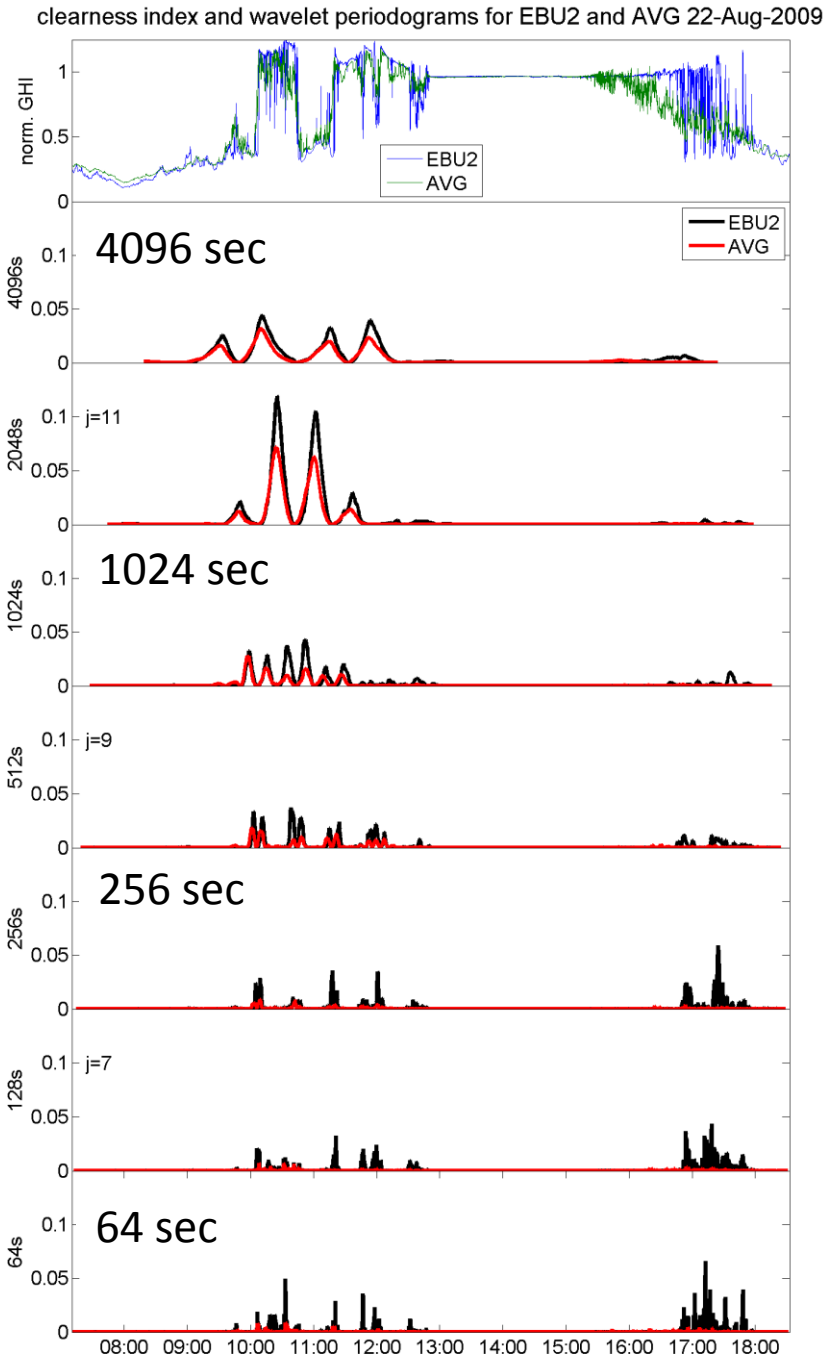


1% change per sec never occurs for >=128 sec moving average

Wavelets – A new tool to quantify variability

- Fit shape to clear sky index data
- Change duration and magnitude of increase to determine best fit





Wavelets to Detect and Measure Cloud Events

Wavelet decomposition using a "top-hat" wavelet for EBU2 and the average of 6 sites

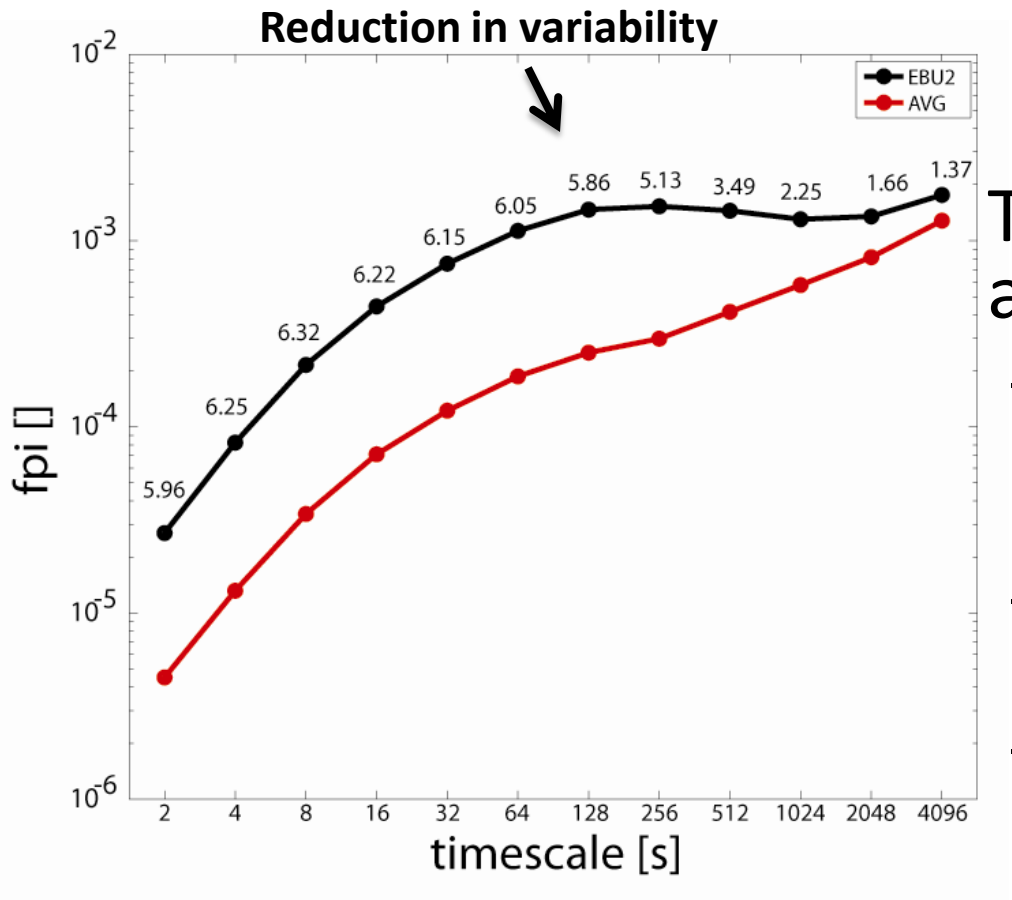
Strong peaks of duration 2048 sec (~34min) are detected at 1030 and 1100.

Strong peaks of duration 256 sec (~4min) are detected between 1700-1800 for EBU2.

Shorter durations has much smaller peaks for the AVG of 6 sites.

→ Identify time scale of variability

Reduction in Variability at 6 sites vs 1 site: Fluctuation Power Index



Reduction in variability over all timescales, but especially over shorter times scales.

Timescale of variability (t) allows estimating

- ramp rates: if [PV size / cloud speed] > t, reduction in amplitude of variability
- necessary storage capacity to smooth out ramps: P x t
- Effect of PV variability: voltage flicker (t small) vs load following (t large)

Other Solar Variability Research Needs

- Validated methods to estimate and predict single and aggregated PV plant output profiles for historical periods with minimal ground based measurements
  - Irradiance at a point to 2D irradiance
  - 2D irradiance to PV output (Kuszmaul et al., 2010)
- High time resolution (minute or less) → downscaling in time and space

Why?

- Link average solar forecasts to high frequency ramp rate forecasts estimates
- Provide inputs to grid integration studies that can help determine how large amounts of PV can be accommodated most cost-effectively

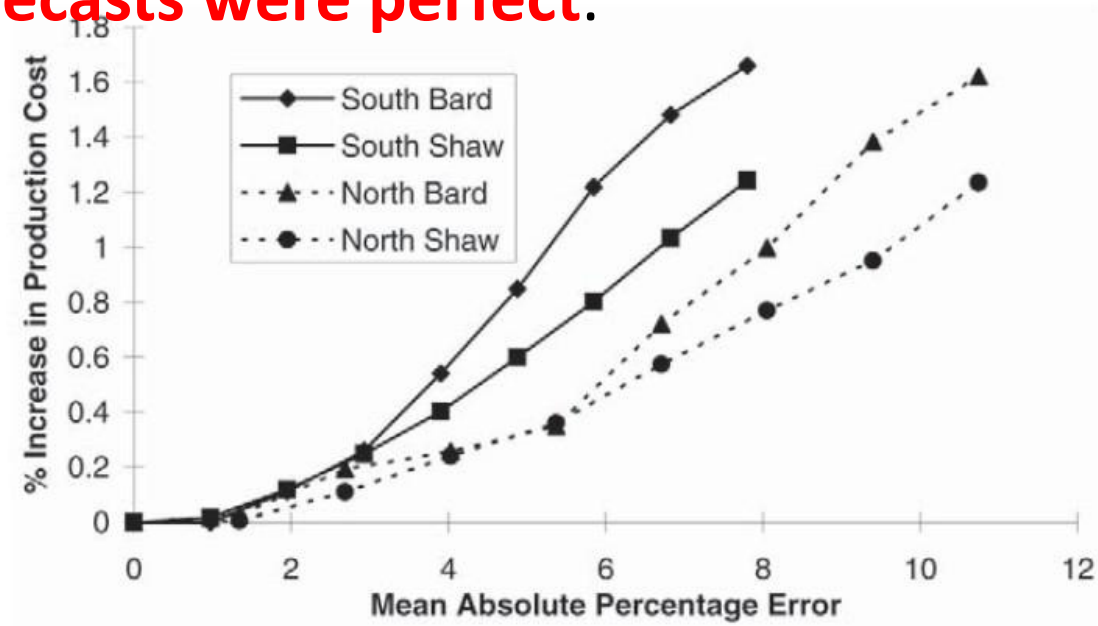
Stein, 2010

Solar Forecasting

Total Sky Imagery and Cloud Tracking

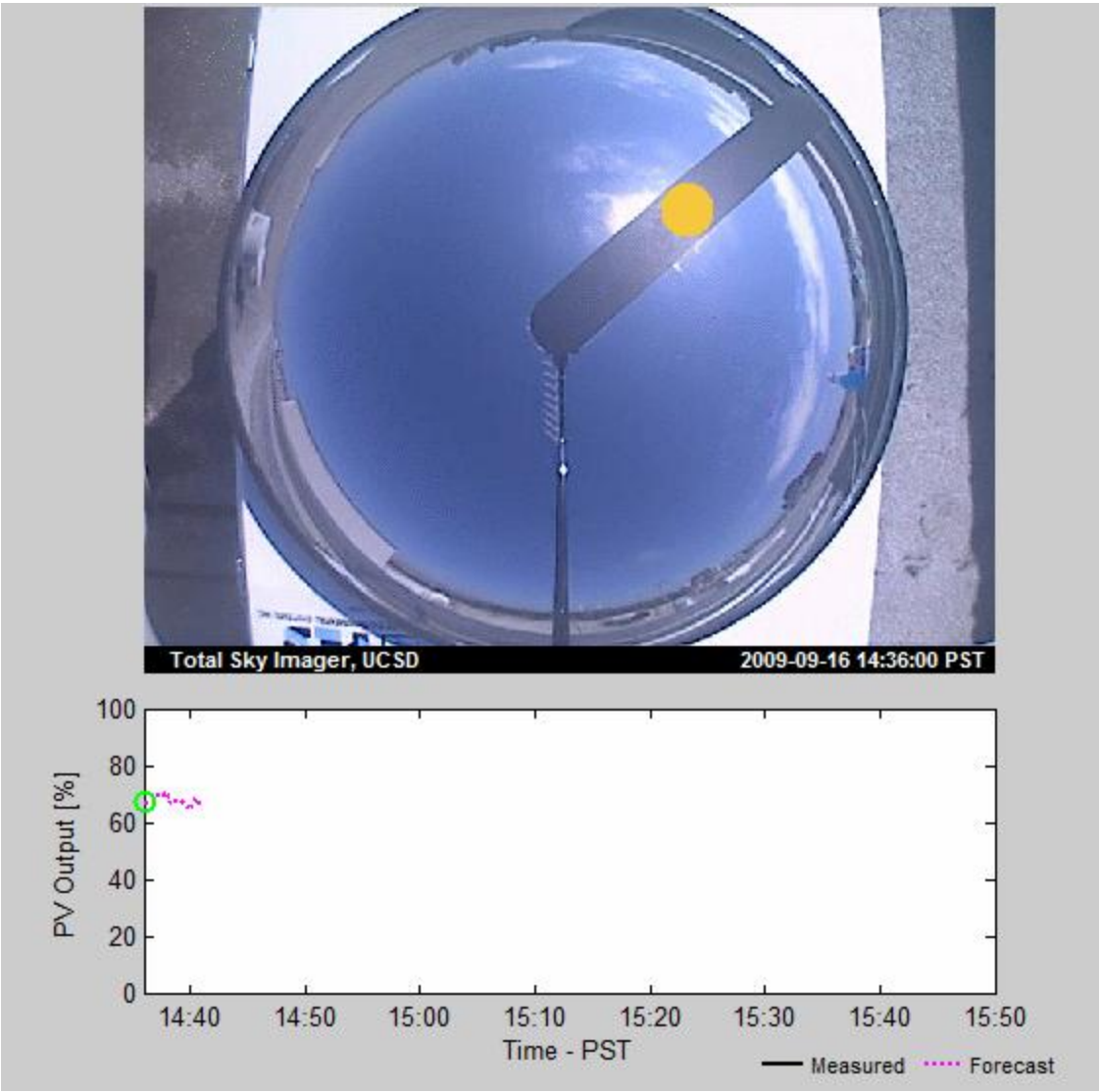
Solar Forecasting Benefits

Use of state-of-art wind and **solar forecasts reduces WECC operating costs by up to 14%, or $5 billion/yr**, as compared to not using wind or solar forecasts for day-ahead unit commitment ($12-20/MWh of wind and solar generation). WECC operating costs could be reduced by an **additional $500 million/yr in the 30% case if wind and solar forecasts were perfect**.

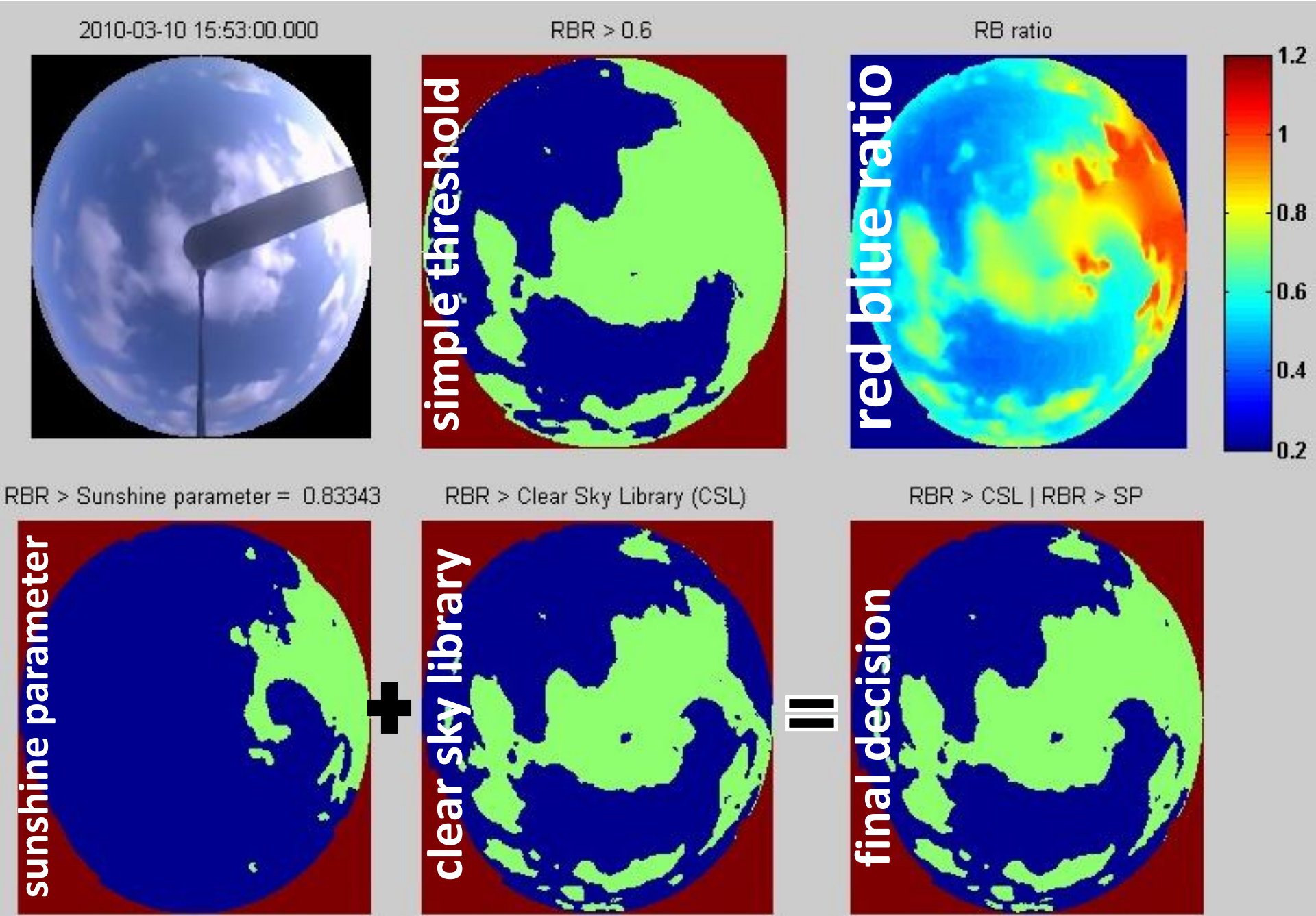


Source: Hobbs et al. (1999). © 1999 IEEE. Used with Permission

Total Sky Imager: Cloud Detection



Final Cloud Detection

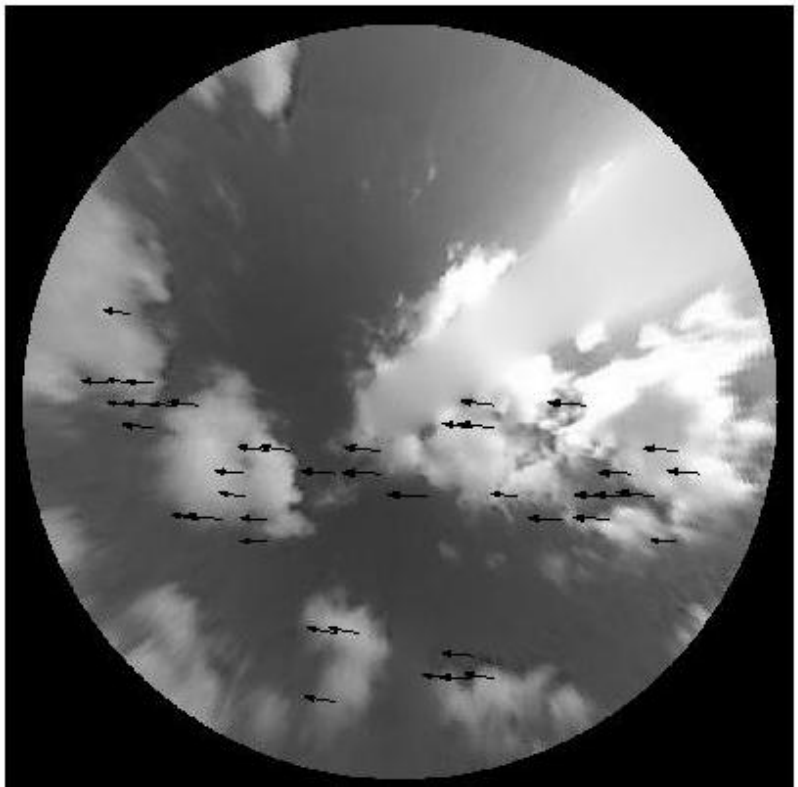


Cloud Motion Vectors

- Apply cross-correlation method to coordinate-transformed sky image.
- Retain only vectors for which high correlation is obtained
- Assume homogeneous cloud velocity

2009-10-04 16:26:30.000

U: -5.8532m/s V: 0.54762m/s



Forecast results

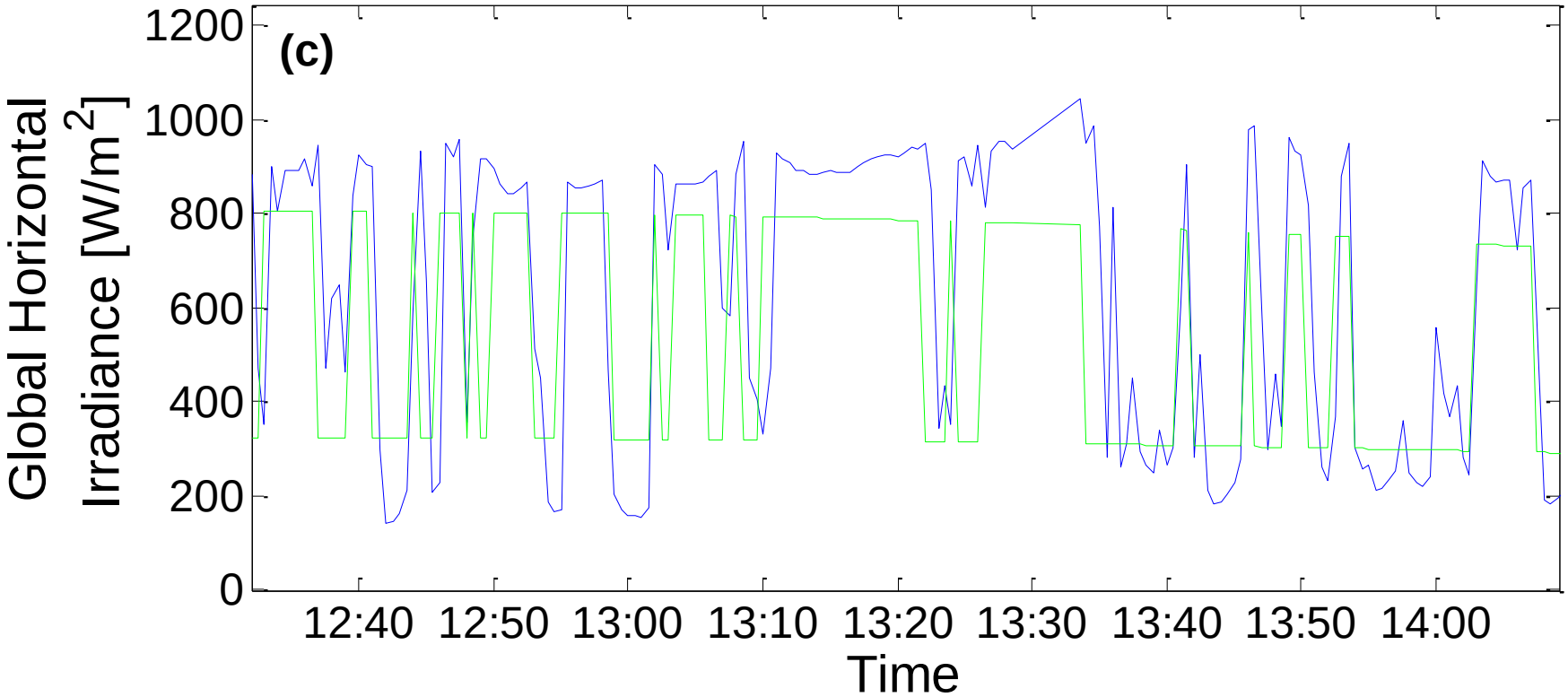


Table 5 Percentage co-occurrence of clear and cloudy conditions for measured/nowcast.

	CLR/CLR	CLR/CLD	CLD/CLR	CLD/CLD
September 14, 2009	56.1	20.6	8.1	15.2
October 4, 2009	55.2	9.9	3.2	31.7
March 4, 2010	59.2	18.3	7.8	14.6
March 10, 2010	54.2	12.8	4.2	28.9

Conclusions

- Solar variability analysis tools developed
  - Quantify variability for different array sizes and geographic layout
  - Quantify ramp rates
- Demonstrated sky imagery in testbed at UCSD
- Preparing for online sky imager forecast at UCSD and large PV plant

Lave M, **Kleissl J**, 'Solar Intermittency of Four Sites Across the State of Colorado', *Renewable Energy*, 35:2867-2873, 2010

Nottrott A, **Kleissl J**, Validation of the SUNY NSRDB global horizontal irradiance in California, *Solar Energy*, 84:1816–1827, 2010

Lave M, **Kleissl J**, Optimum fixed orientations and benefits of tracking for capturing solar radiation in the continental United States, *Renewable Energy*, 36:1145-1152, 2011

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Lave, M., **J. Kleissl**, High-frequency fluctuations in clear-sky index, submitted to *Solar Energy*, 2011

Mathiesen P, **Kleissl J**, Evaluation of numerical weather prediction for intra-day hourly solar irradiance forecasting in the CONUS, submitted to *Solar Energy*, 2011

Chow CW, Urquhart B, **Kleissl J**, Lave M, Shields J, Intra-hour forecasting with a total sky imager at the UC San Diego solar energy testbed, submitted to *Solar Energy*, 2011

Luoma JK, **Kleissl J**, Murray K, Optimal Inverter Sizing for Cloud Enhancement, submitted to *Solar Energy*, 2011