High Penetration Solar Forum

March 2011

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Solar Variability, Forecasting, and Modeling Tools

Jan Kleissl, Byron Washom*,
Chi Chow, Peter Cottle Matt Lave, Jennifer Luoma, Patrick Mathiesen,
Anders Nottrott, Bryan Urquhart, Johnny Zheng
Mechanical & Environmental Engineering, http://solar.ucsd.edu
*Director, Strategic Energy Initiatives, UC San Diego
Kevin Meagher, Silviu Darie (Power Analytics)

CSI Solar RD&D Program
www.calsolarresearch.ca.gov

Itron CSI RD&D Program Manager

GO solar CALIFORNIA

Focus Areas

- Solar Resources for California
- Solar irradiance variability
  - How likely are extreme ramps?
  - Does geographic dispersion help?
  - Case study at UC San Diego
- Irradiance input for power flow models: EDSA Designbase (Kevin Meagher)
- Solar Forecasting
  - Sky Imagery

Key Deliverables

CPUC-CSI

- More accurate CA solar resource map at high spatial and temporal resolution with online calculator
- Solar forecast model

DOE

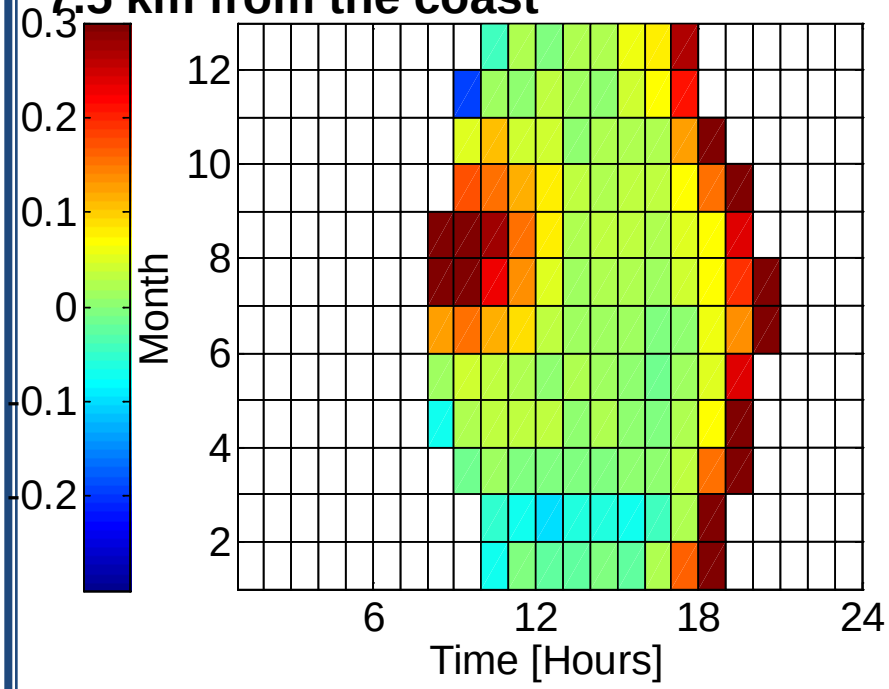
- Open source simulation application for power system designers for distribution feeder design
- Characterization of PV variability
- Cloud tracking and forecast model
- Utility command / control interface

NSRDB Overpredicts GHI near Coast

MBE between SUNY model and CIMIS GHI measurements

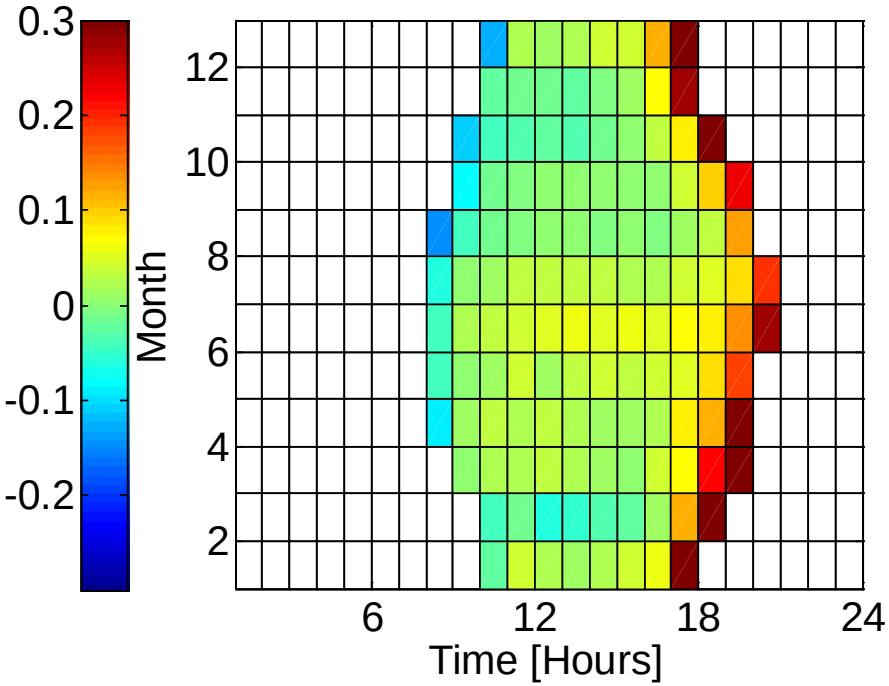
CIMIS #111 – Green Valley, Santa Cruz Co.

7.5 km from the coast



CIMIS #008 – Gerber, Tehama Co.

93.0 km from the coast



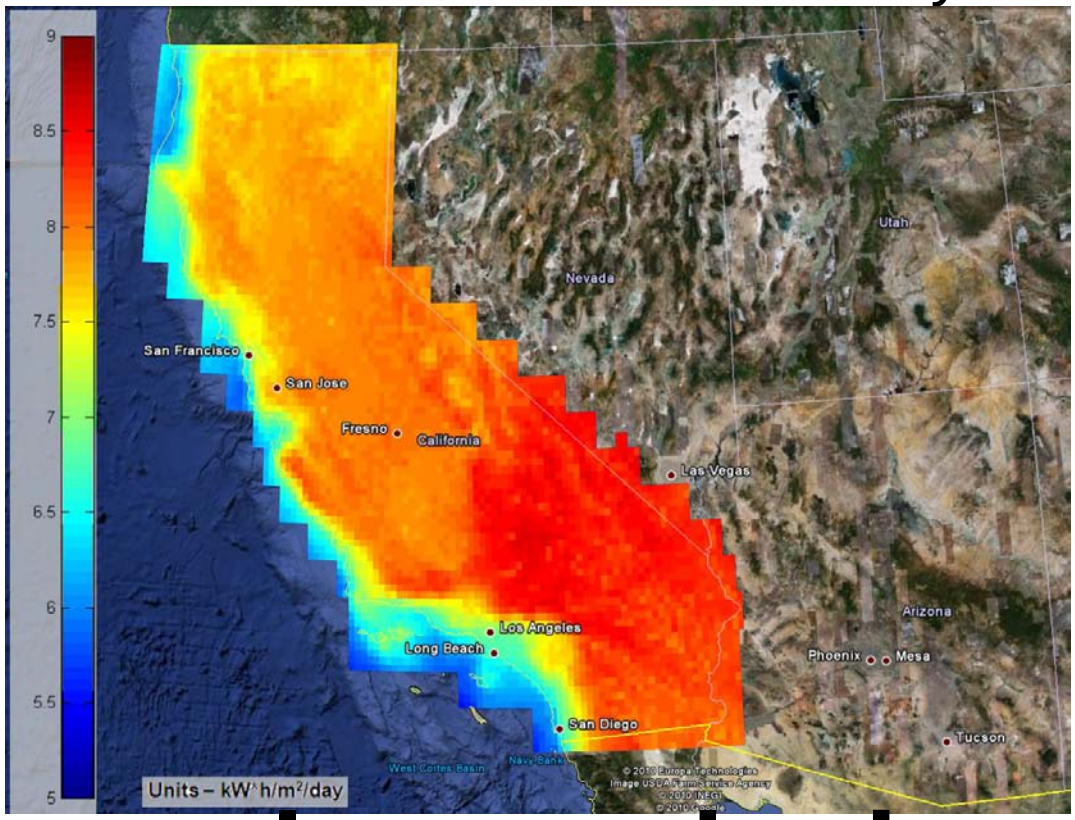
(SUNY – CIMIS) / CIMIS

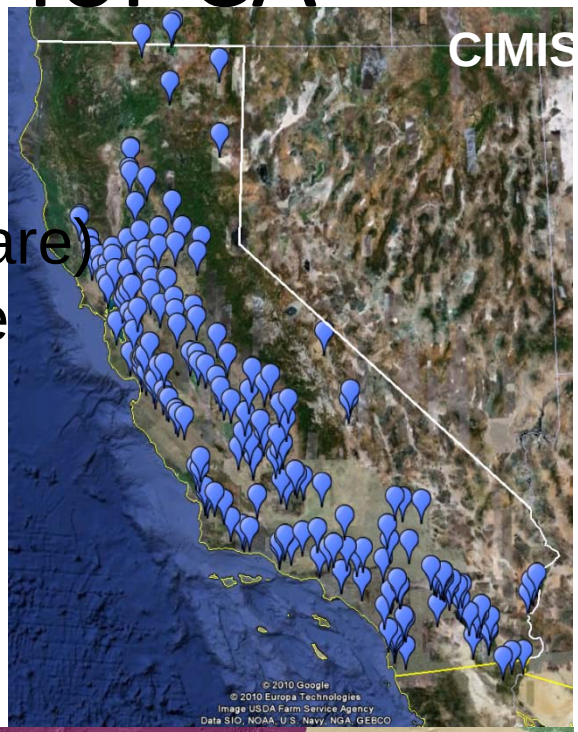
Units →[%·10^{-2}]

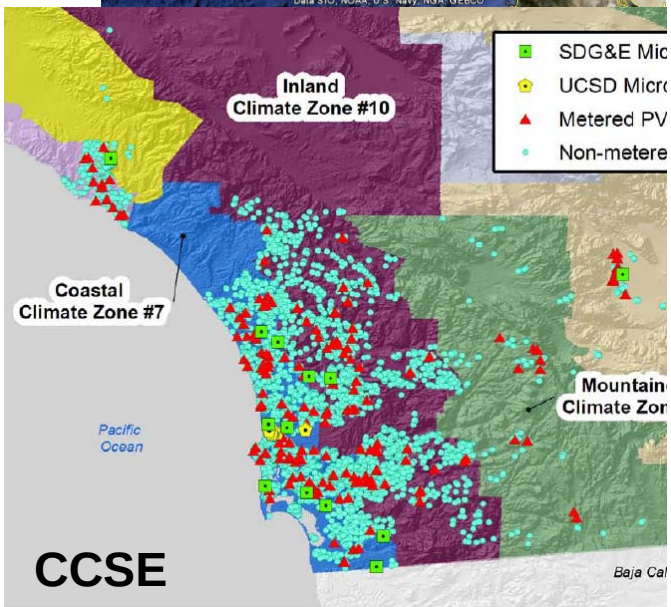
Nottrott & Kleissl (2010)

Corrected Solar Maps for CA

- Applied correction algorithm to generate a corrected GHI data set for California
- Visualized using Google Earth (free software)
- GIS tool facilitates accurate solar resource assessment and economic analysis



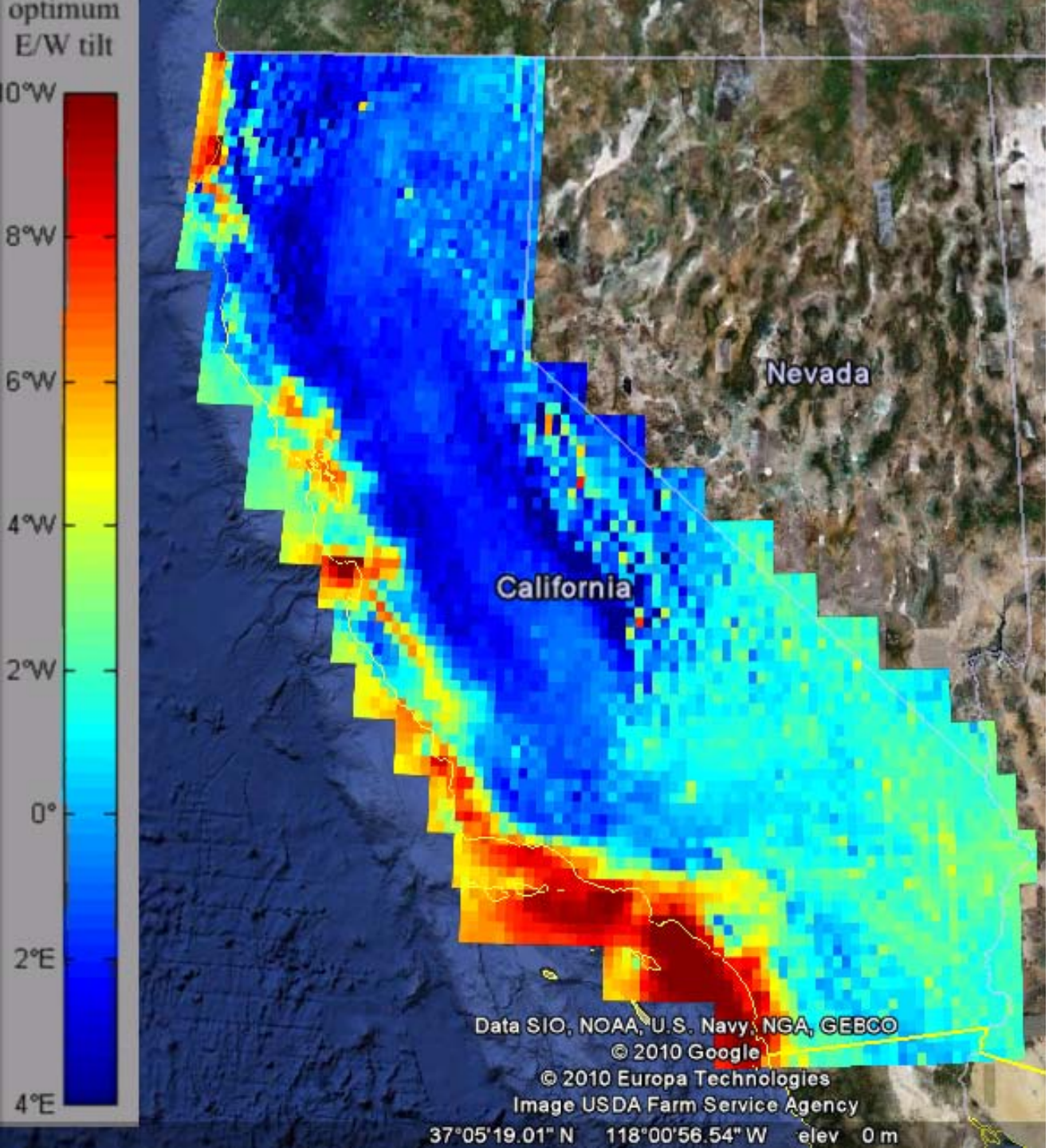




solar.ucsd.edu

Improve NSRDB

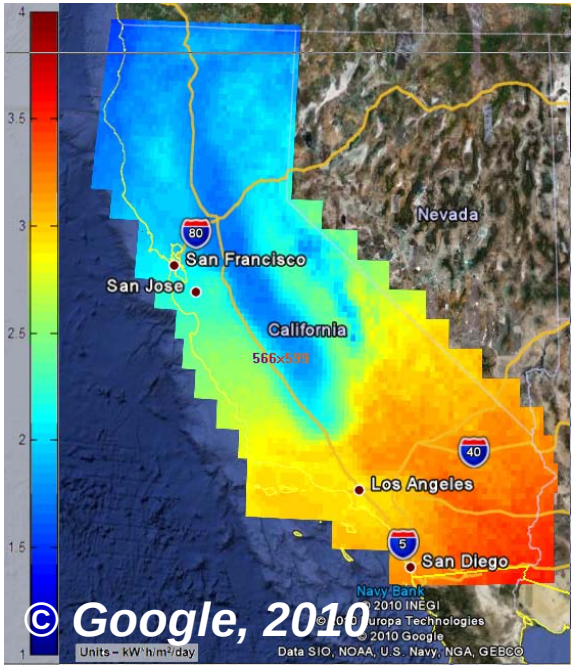
- Accuracy (similar to CIMIS analysis, now with 1000s of systems)
- Spatial scale: detect fine spatial gradients in areas of high PV penetration to get 5 km resolution
- Temporal scale:
  - 1 hour → 15 minutes using PV data
  - Given clearness index, develop probabilistic timeseries down to 5 minutes. Calibrate model using UCSD 1 second data
- Publish in Google Earth, other formats on demand
  - survey



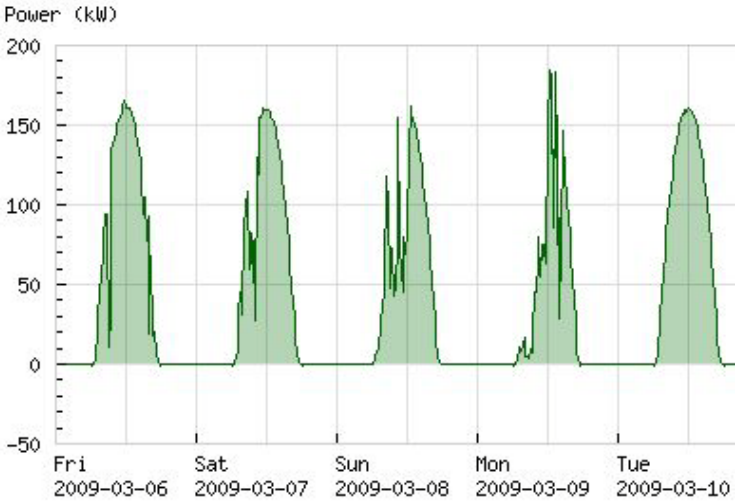
Optimum azimuth angles for PV

© Google, 2010

Working the Magic



15 minute PV AC output



azimuth, tilt, rated efficiency, shading, location

DJI

GHI, DNI

clearness index

PV temperature

tilt

azimuth

PV Variability

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

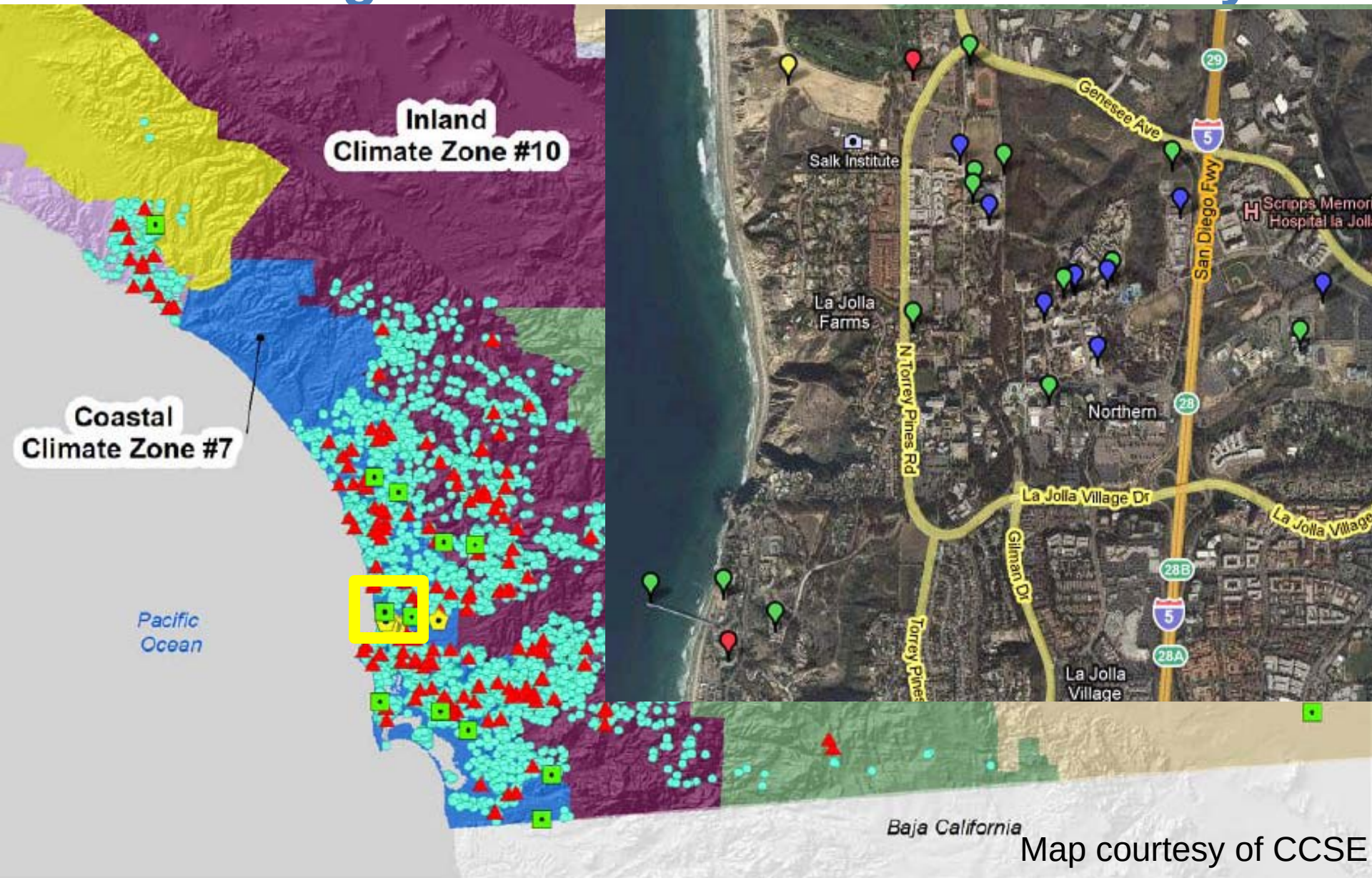
Why are solar costs lower?

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

Reserves are held at the same level all year for wind

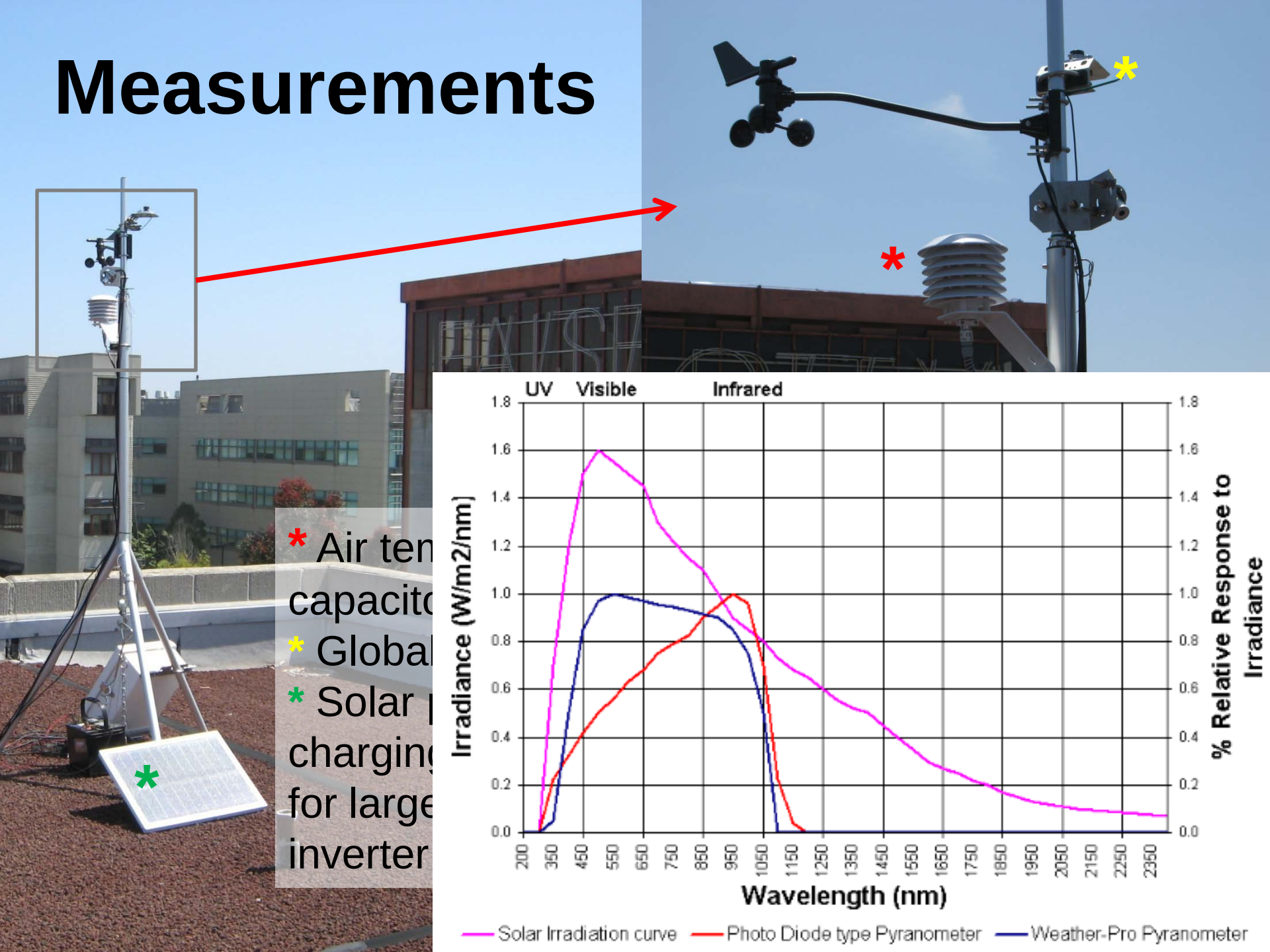
Source: Andrew Mills, Lawrence Berkeley National Lab

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

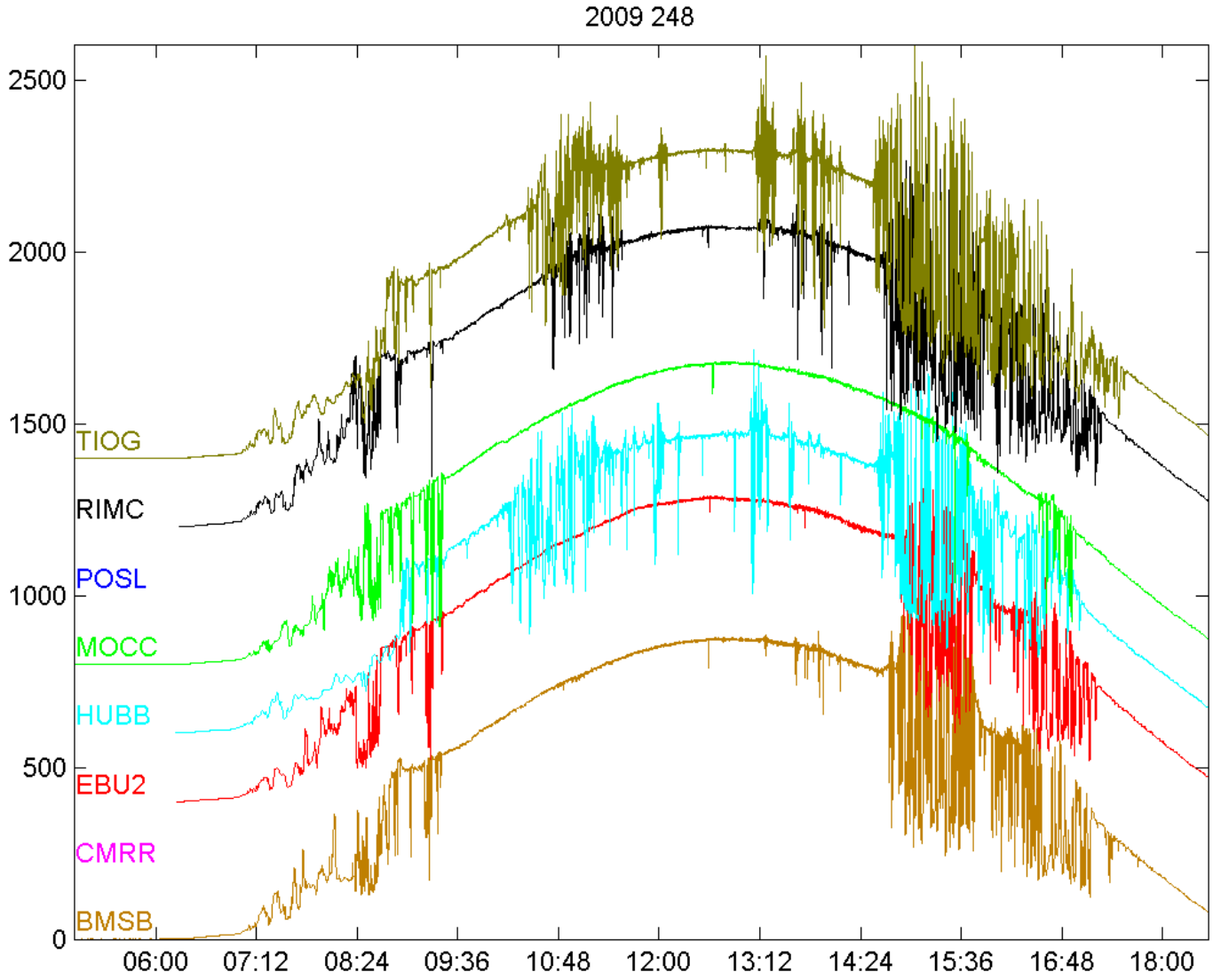


Map courtesy of CCSE

Measurements

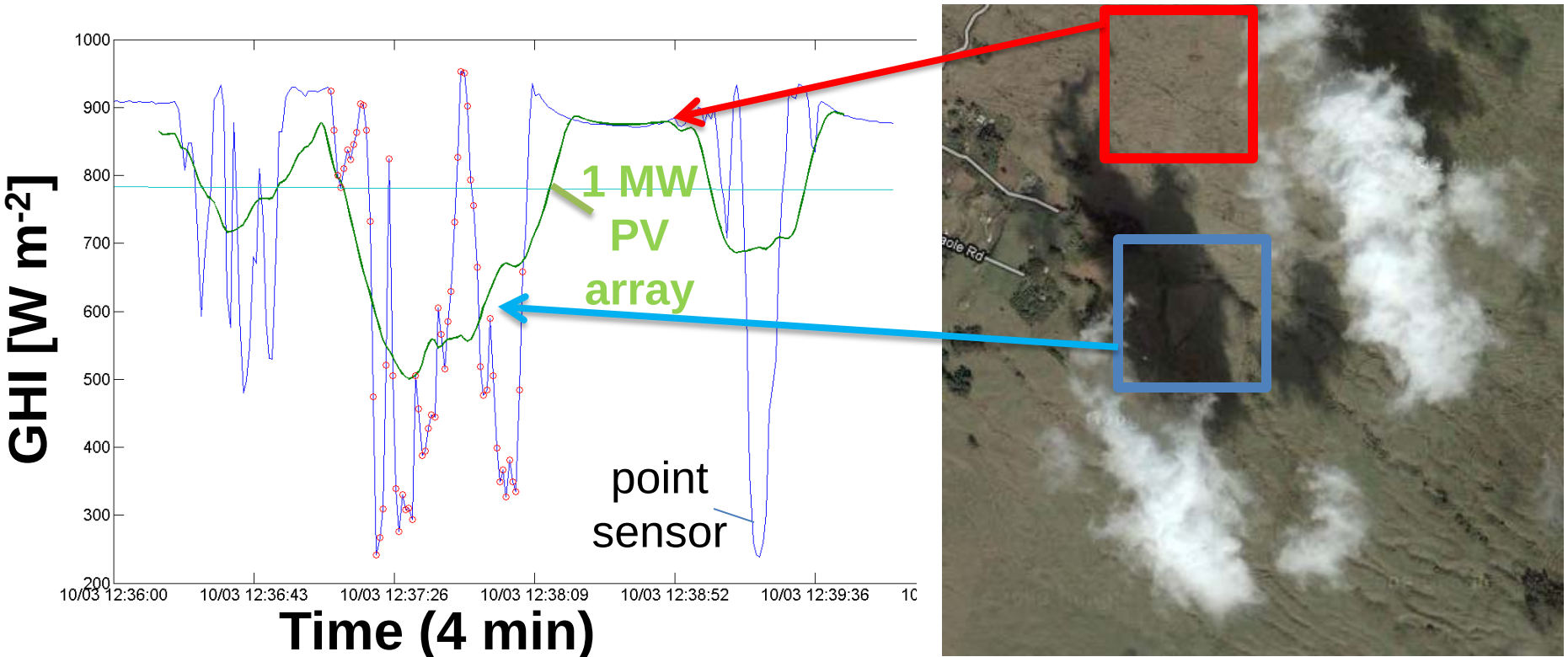


1 sec data – partly cloudy day



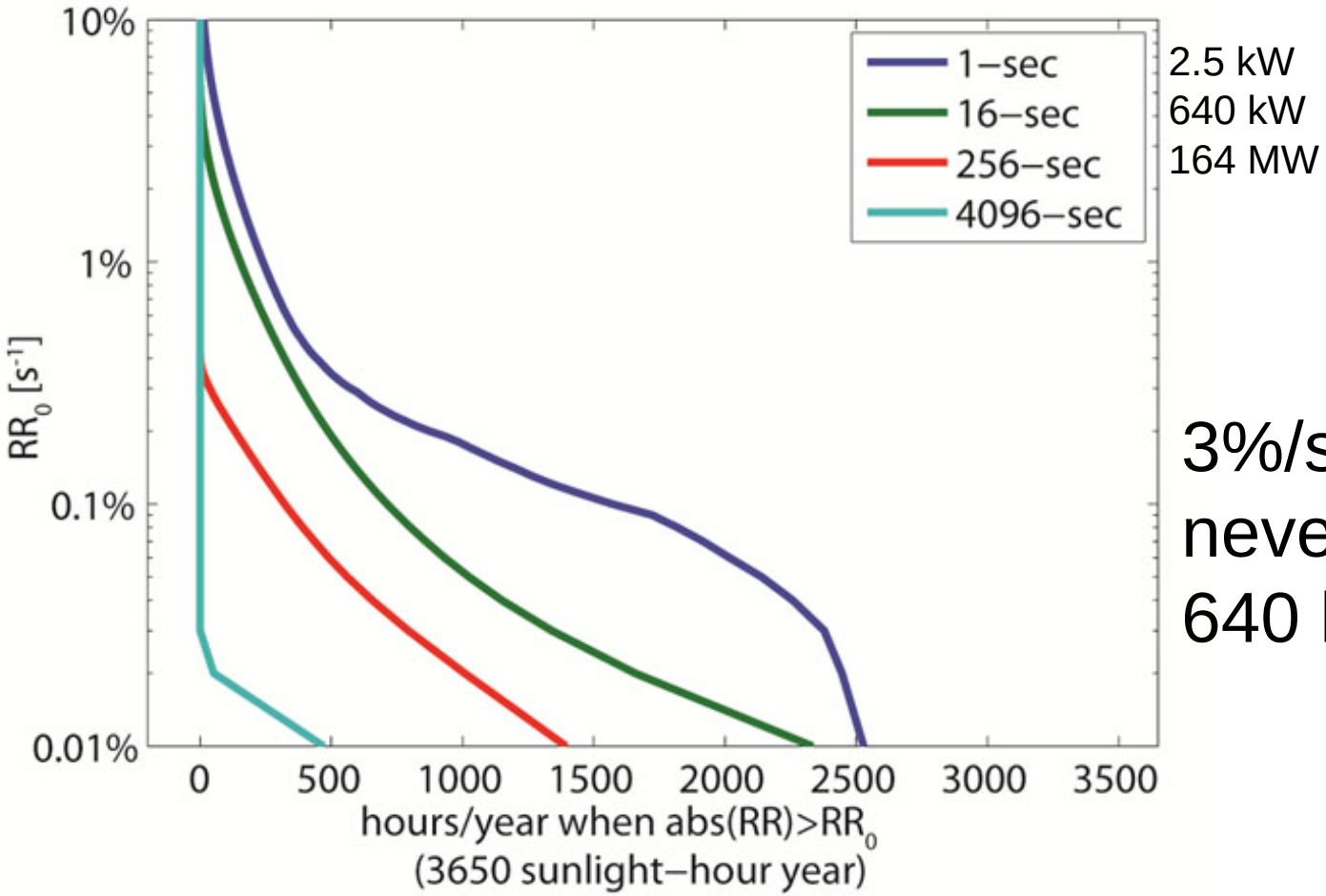
Spatial Averaging Effect of PV Array

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



Effect of PV Array Size on Ramp Rates

Simulating different size PV plants through moving averages:
640 kW: t = 16 sec moving average
(plant at efficiency of 0.1, cloud speed of U = 5 m s^{-1})



3%/sec change never occurs for 640 kW plant

Ramp Rates of Individual Solar Power Plants

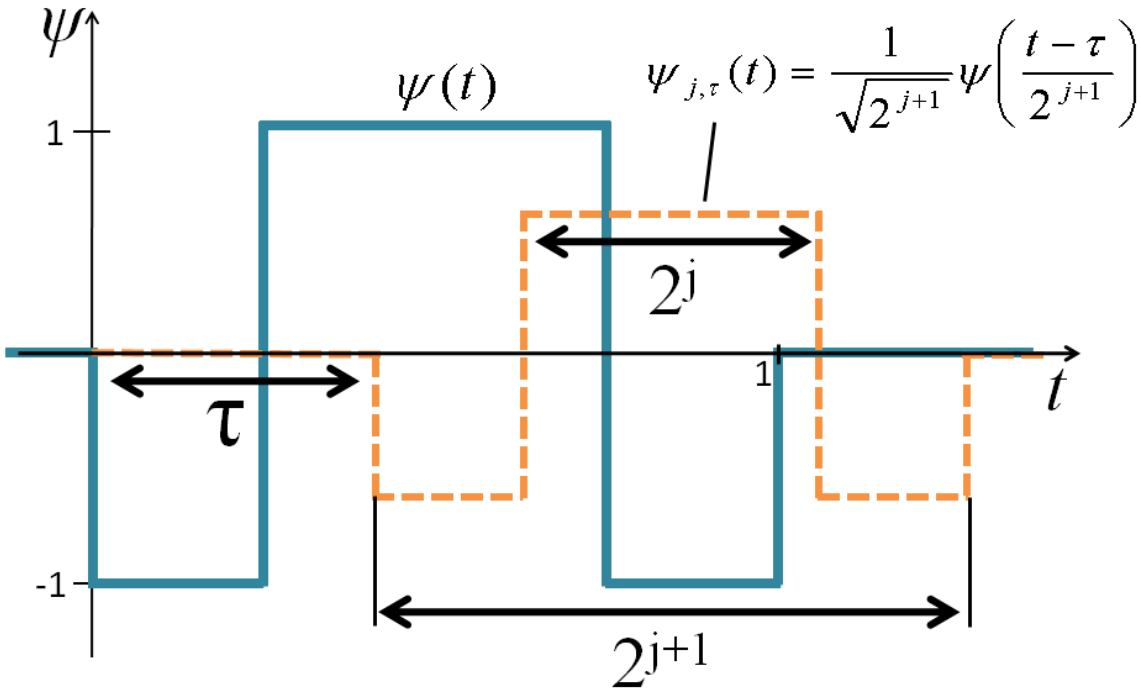
- Misperception of actual ramp rate magnitudes need to be corrected

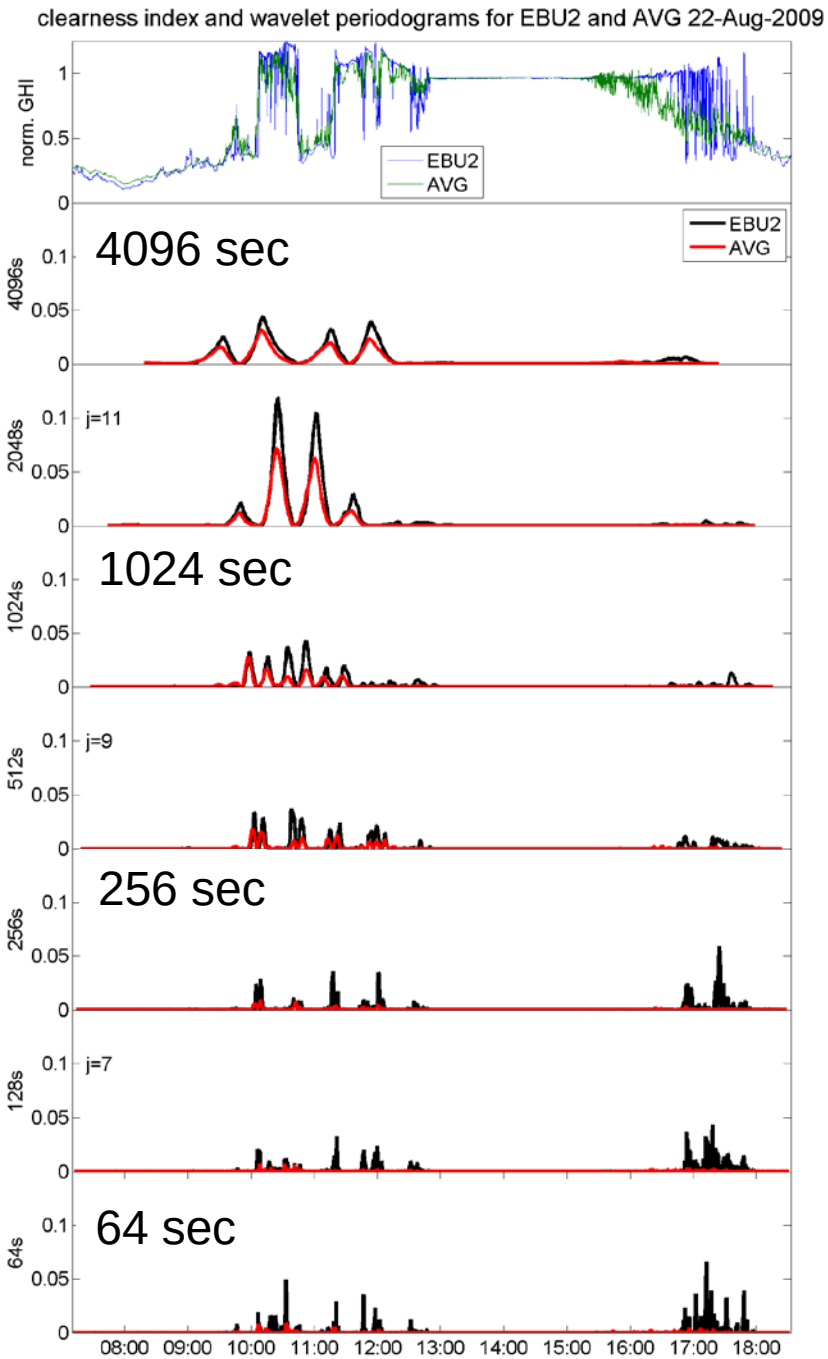
Moving average /	RR>1% s^{-1}		RR>5% s^{-1}	
Power plant	**Probability**	**#/day**	**Probability**	**#/day**
1-sec / 2.5 kW	0.0655	2,359	0.0135	486
4-sec / 40 kW	0.0590	2,125	0.0081	292
16-sec / 640 kW	0.4298	1,511	0.0004	15
64-sec / 10 MW	0.0103	370	0.0000	0
256-sec / 164 MW	0	0	0.0000	0

Geographic Smoothing

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

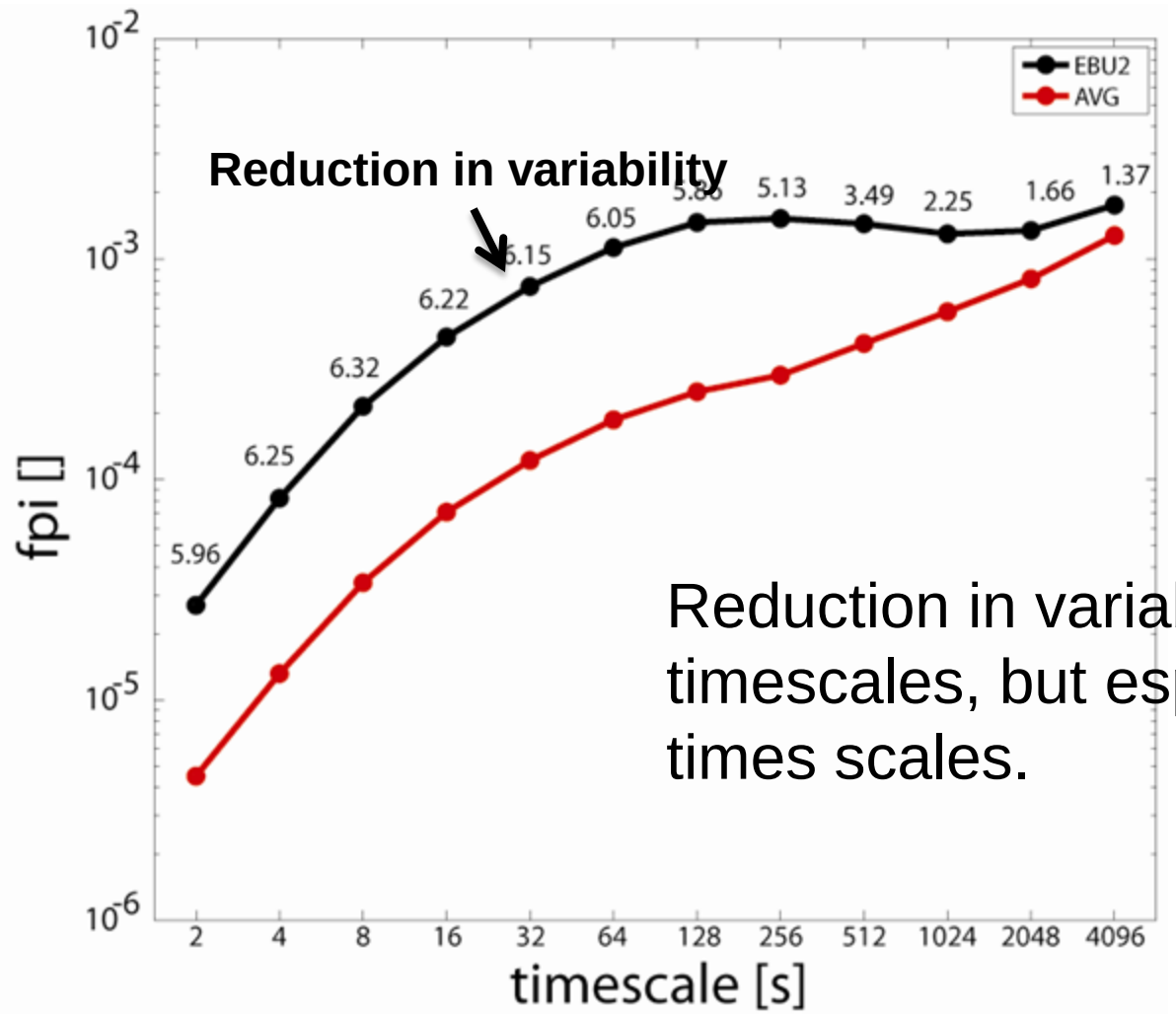
Wavelet decomposition for one site (EBU2) and the average of 6 sites.

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

1700-1800: Strong peaks of duration 256 sec (~4min) are detected at a single site, but much smaller peaks for the AVG of 6 sites.

→ Wavelets provide 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.

Conclusions Variability

- Unless PV systems are co-located or when examining long time scales (>= 1 hour):
  - PV system output uncorrelated
  - Standard deviation increase as $\sqrt{n}$, not n
- % Ramp rates decrease for large solar power plants
- Research needs: uniform framework and parameters for each climate zone

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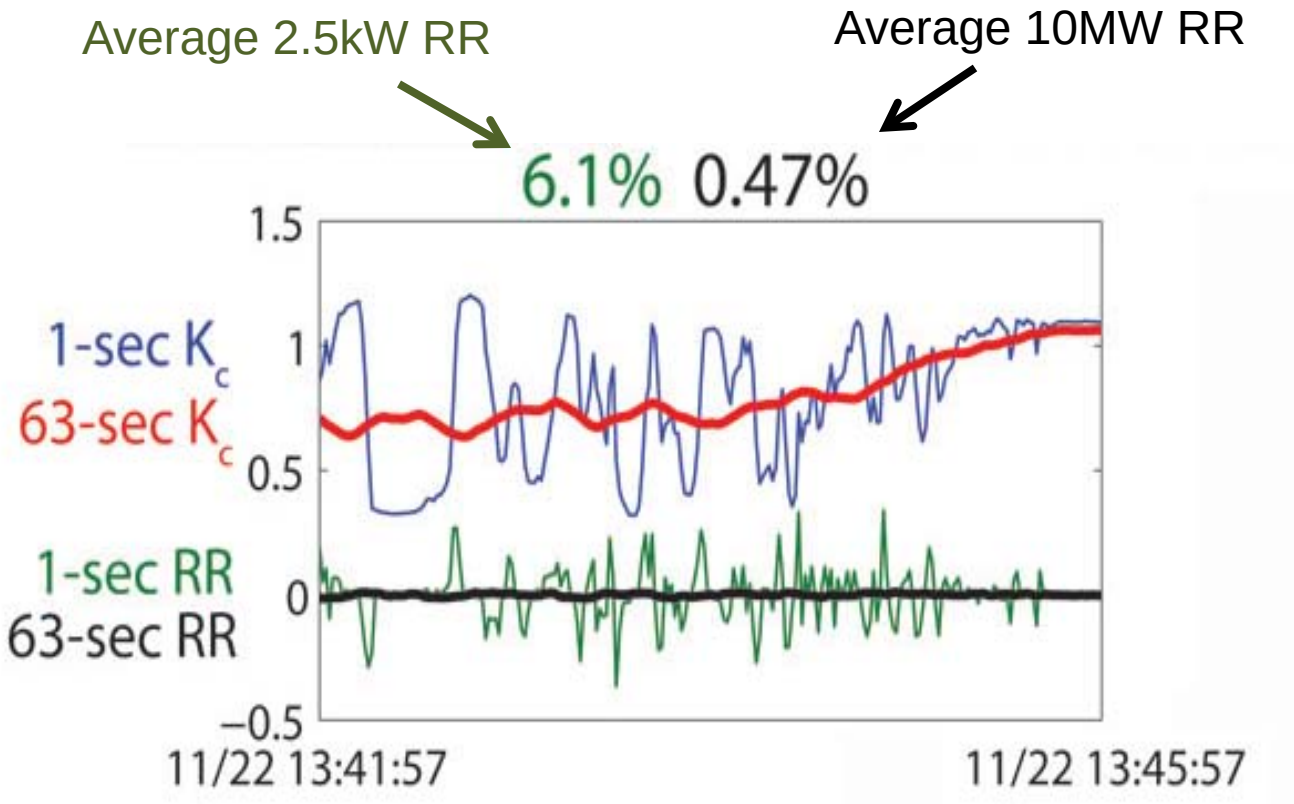
Irradiance Input for EDSA Designbase

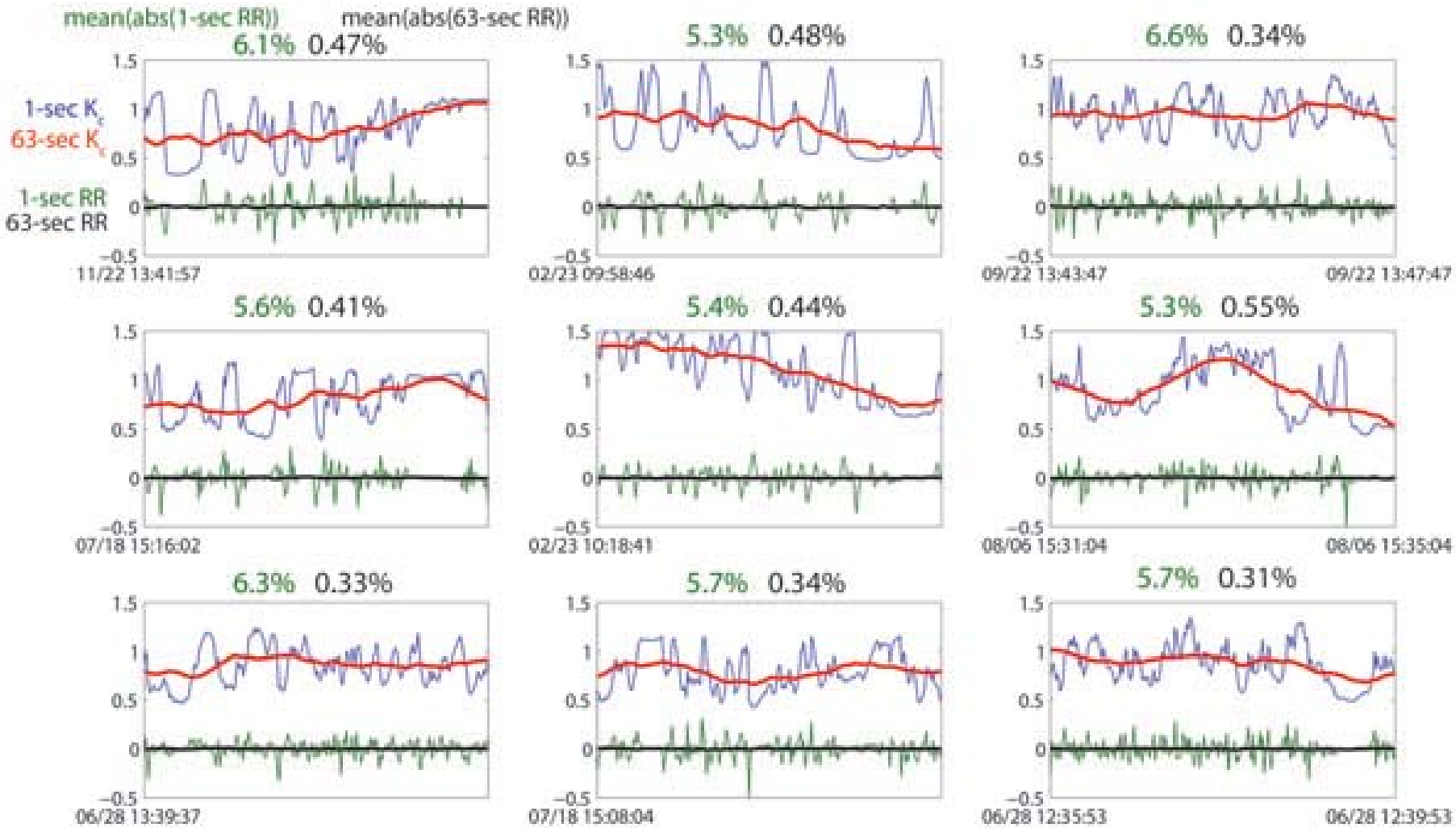
(And anybody else)

Sample Worst 4-min Period

1-sec K_c = clear-sky index, representative of home installation (2.5kW)
63-sec K_c = clear-sky index filtered by 63-sec moving average (10MW)
RR = change in PV output in1 second.



More Worst 4-min Examples



What kt(time) to use?

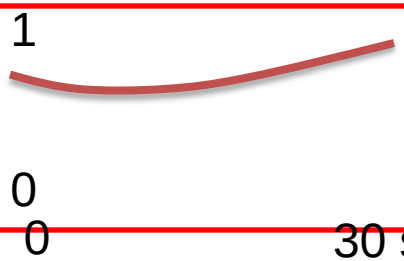
- Assume: transient power flow model
- Duration of event: 60 seconds
- Create 60 seconds GHI time series from
  - One ramp event based on cdf
  - One ramp event based on conditional average
  - Worst 60 seconds in 1 year timeseries
- Other factors:
  - Size of solar power plant (filters fluctuations), central or distributed
  - Goal of analysis (steady state power model, inverter frequency support, load following)

Flowchart for Transient Stability Model

Product
1 sec clearness index: *kt*

Input:
Table of 1 sec clearness index kt from t = 1 to 60 sec
Who: Raw data from UCSD

STEP 1

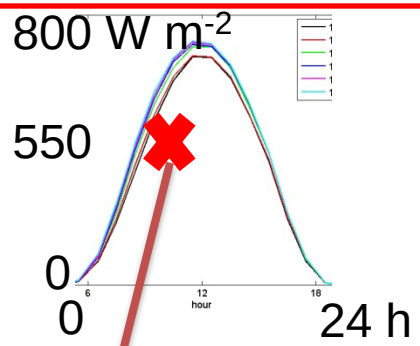


filter(*kt*): Filtered 1 sec *kt* for particular array

DC Power Rating [kW]

Equation: filter size [sec] = $A^{1/2}$ / U = $DC^{1/2}$ / ($\eta^{1/2}$ U); DC power rating [kW], atmospheric velocity U = 10 m/s and η = 15% PV efficiency.

STEP 2



GI_{SKC}: Clear sky global irradiance at panel tilt

User
OR
1107 W m^{-2}

STEP 3

GI: global irradiance input to EDSA model
$GI = GI_{SKC} * kt(\text{time})$

none

STEP 4

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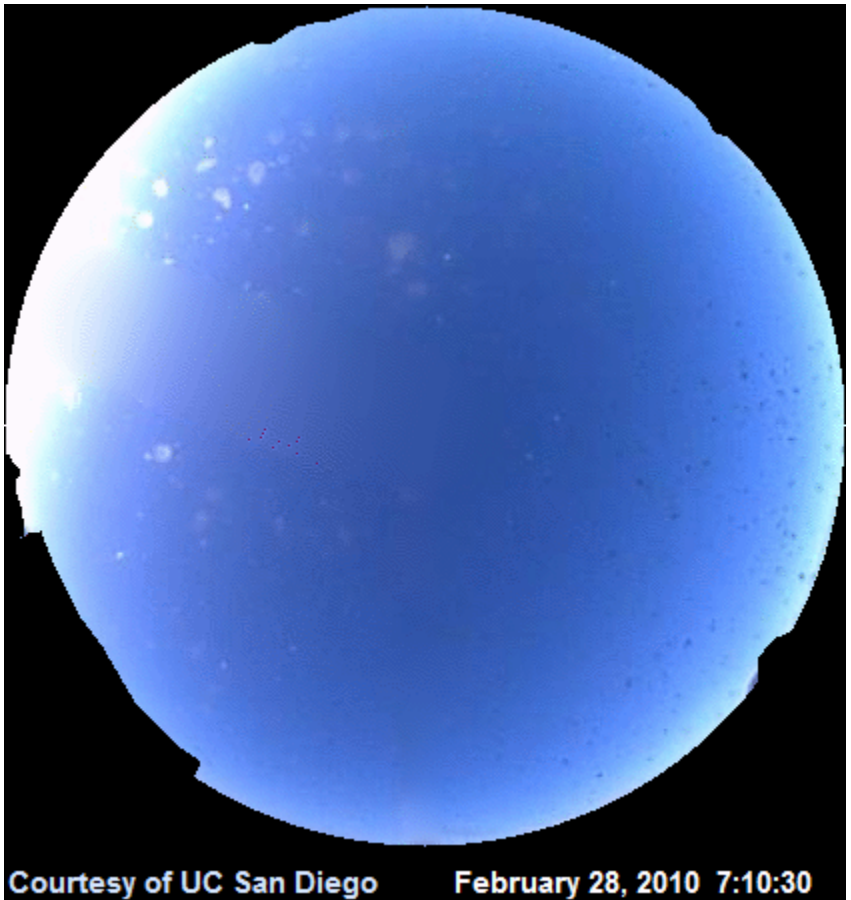
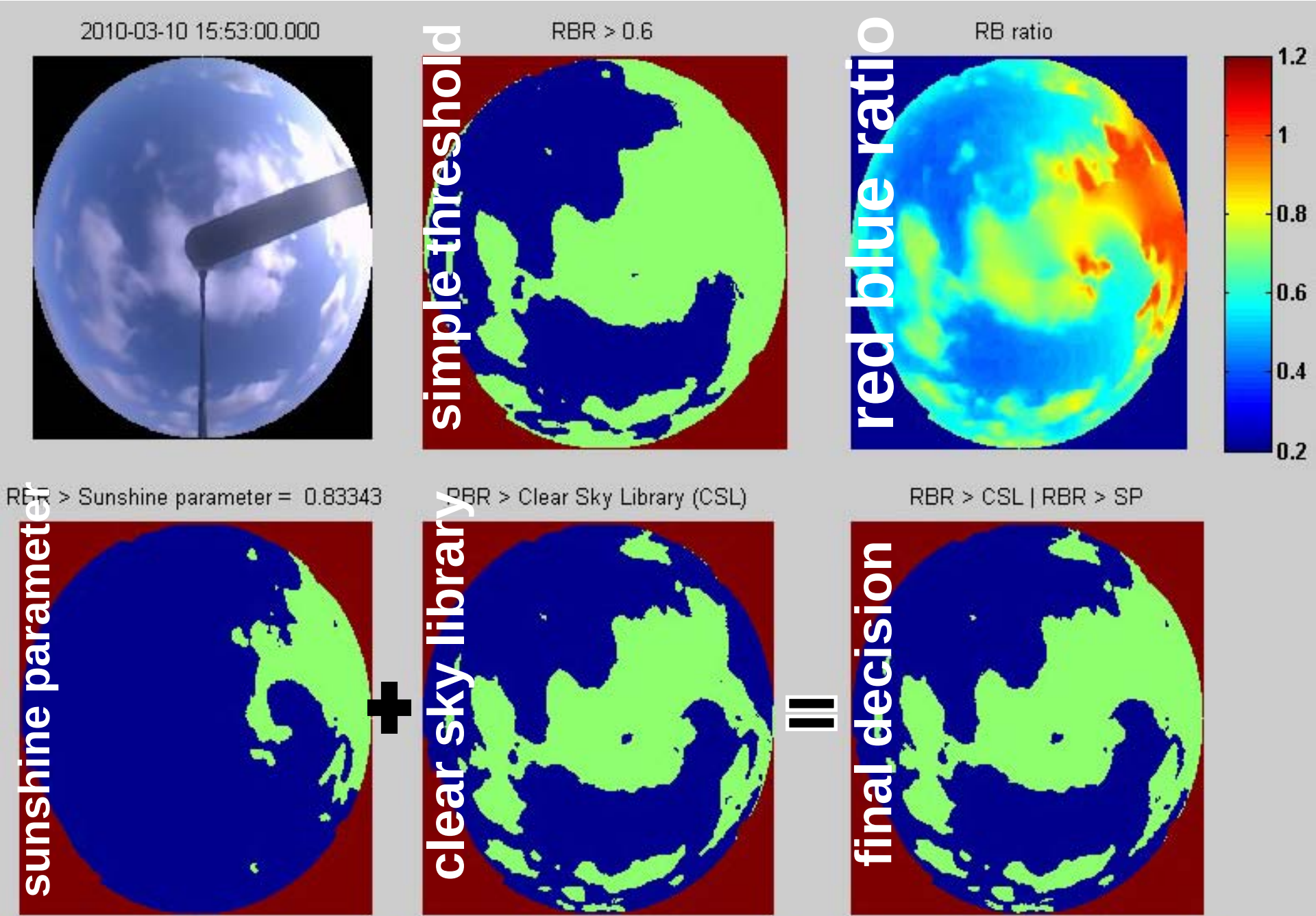
Solar Forecasting

Kevin Meagher Presentation

Total Sky Imager: Cloud Detection



Final Cloud Detection

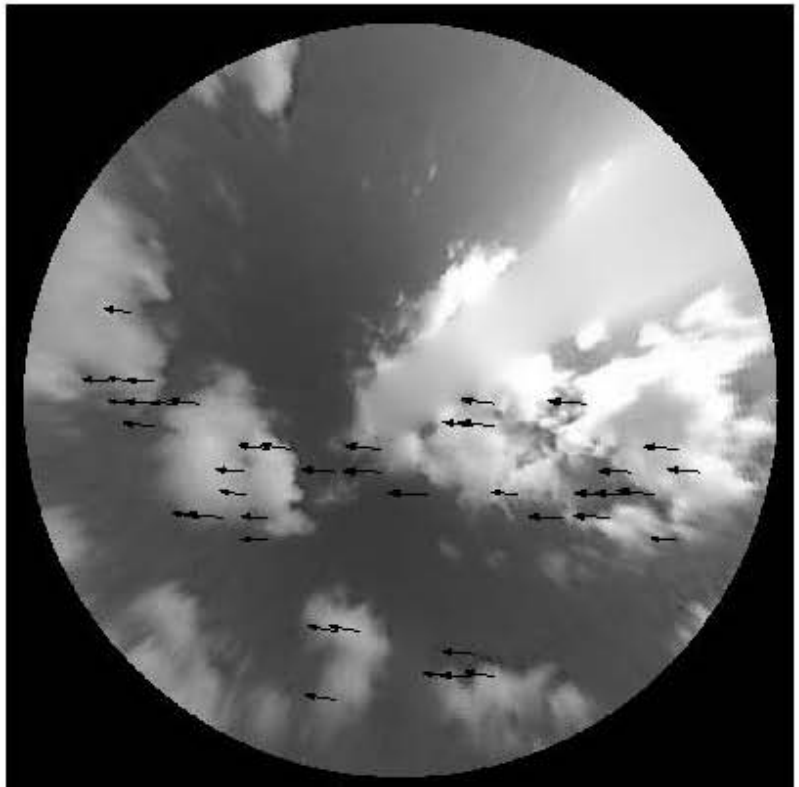


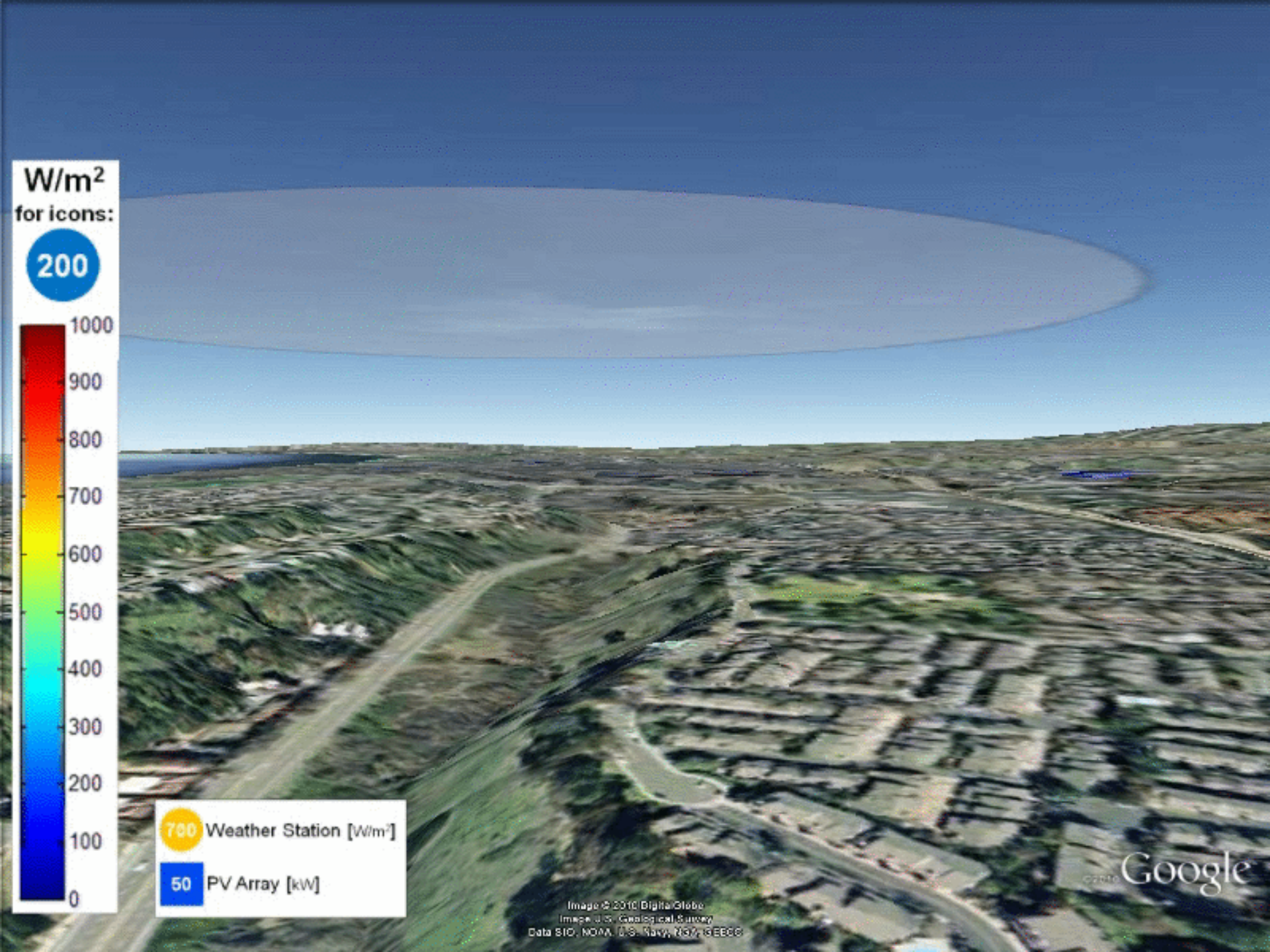
Cloud Motion Vectors

- 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




W/m2
for icons:
200
1000
900
800
700
600
500
400
300
200
100
0
700 Weather Station [W/m2]
50 PV Array [kW]
Image © 2010 DigitalGlobe
Image U.S. Geological Survey
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google

Nowcast Statistics

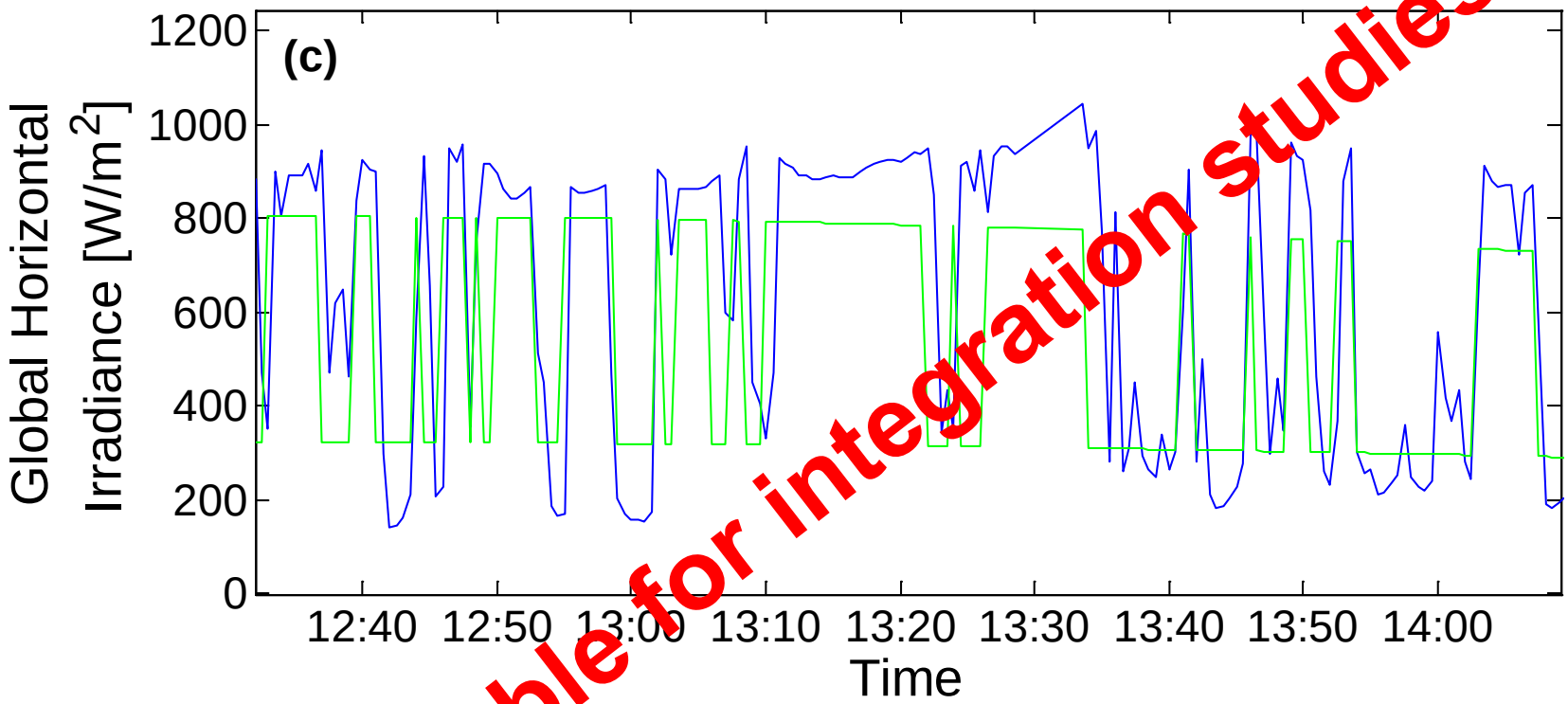
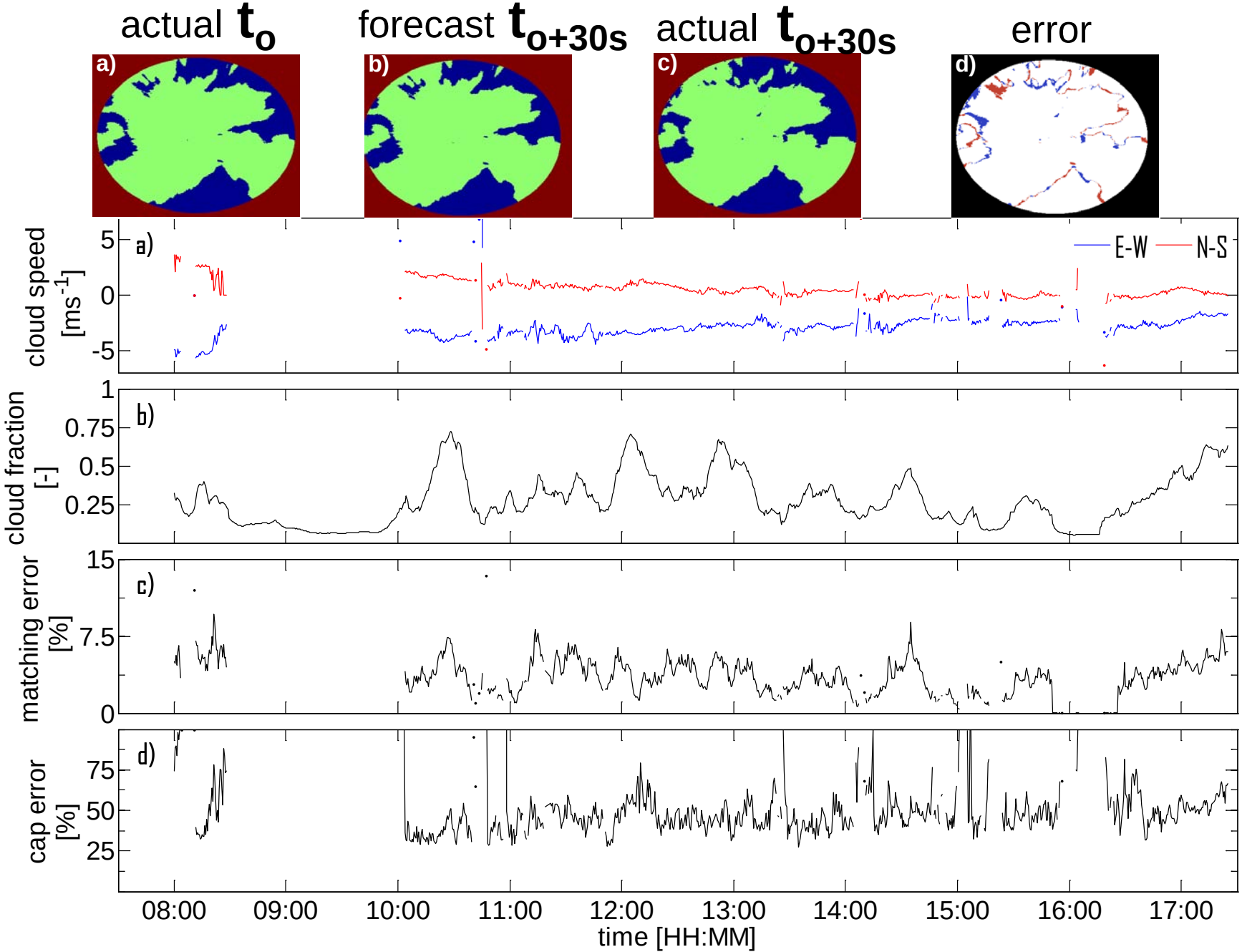


Table 5 Percentage co-occurrence of clear and cloudy conditions for measured/nowcast.

	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

Data available for integration studies

30 sec Forecast



1 to 5 minute forecast

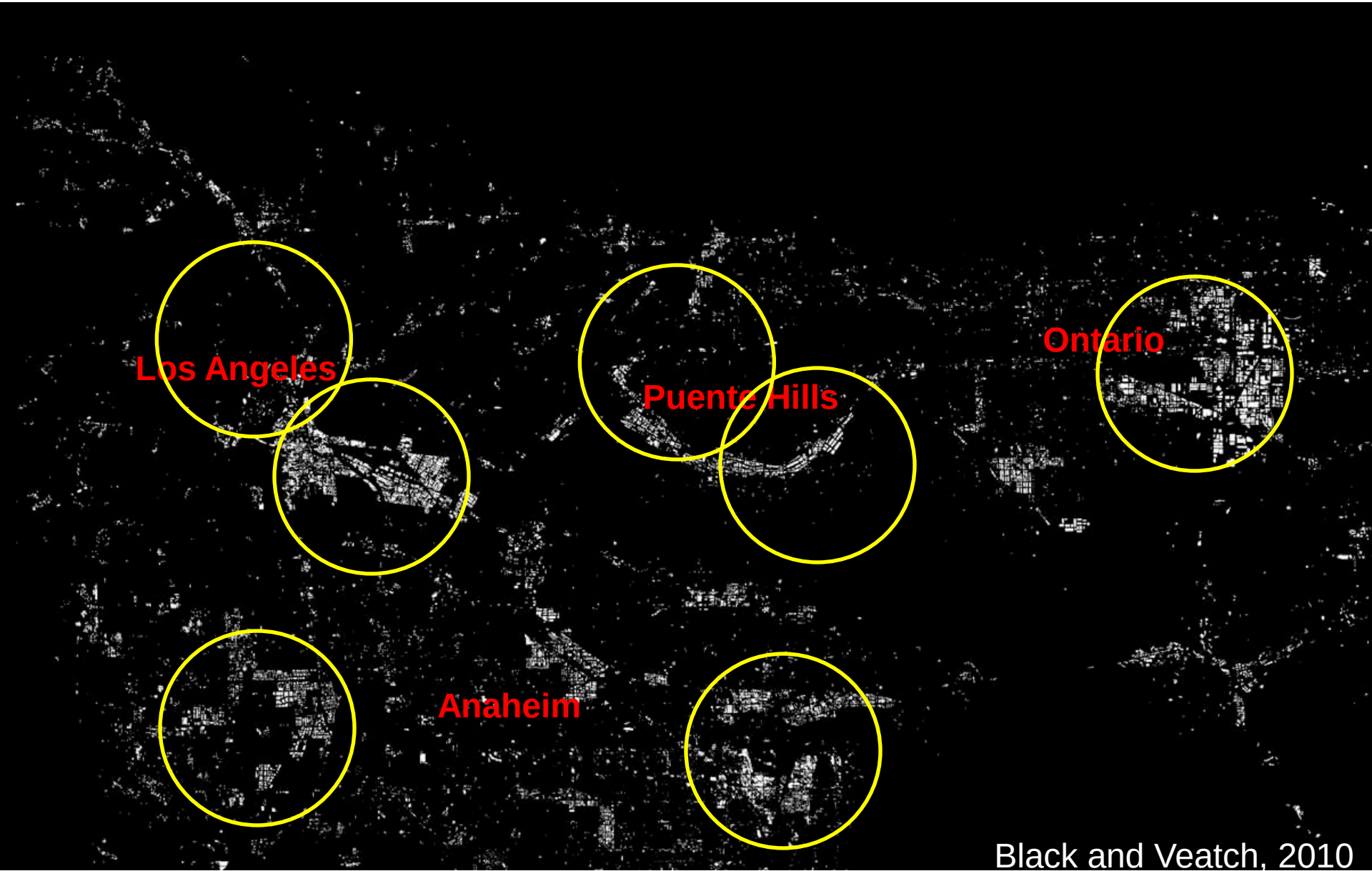
Mean total matching error and total cap error for 30-sec to 5-min ahead forecast. Since errors during overcast and clear conditions are zero, the errors in the table are biased high.

	30 sec	1 min	2 min	3 min	4 min	5 min	Time until advection out of scene [min]
	e_{cap} [%]						
Sept 14, 2009	45.0	51.5	63.9	70.0	76.5	123	4 - 27
Oct 4, 2009	47.2	49.8	55.6	61.5	66.6	70.3	8 - 18
Mar 4, 2010	54.6	55.3	59.3	63.4	67.7	71.8	9 - 24
Mar 10, 2010	48.8	53.9	62.3	68.8	75.1	78.0	9 - 15

Error increases with forecast horizon, but 25% better than persistence after 5 minutes.

After 10 to 25 minutes the scene is advected out of the field of view.

Los Angeles Warehouse Roof Market



Black and Veatch, 2010

Conclusions

- Total sky imager forecasting at UC San Diego and CAISO Henderson, NV 48 MW PV plant; SDG&E territory
- Deterministic sky imager forecast valuable up to 5-15 minutes
  - For longer time scales use probabilistic sky cover fraction
  - Hardware limitations
- Integration of solar forecasting products will further reduce forecast error