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Dependence on Geographic Location of Air Mass Modifiers For Photovoltaic Module Performance Models

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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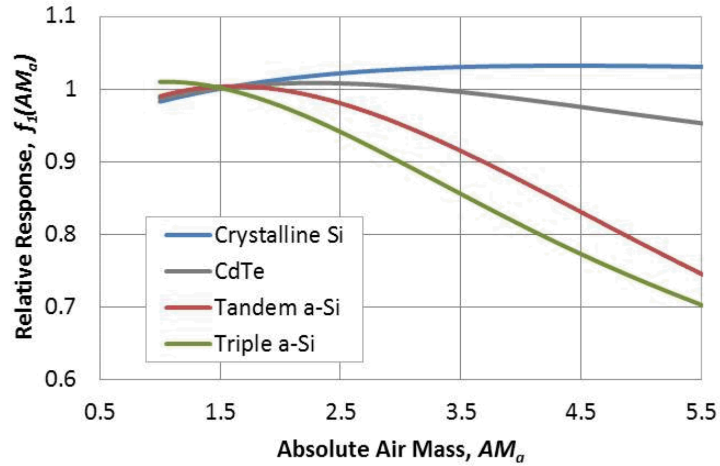
Overview

- Variations in the solar spectrum can cause changes in a module's short circuit current
- This effect is frequently represented by multiplying I_{SC} by an empirical polynomial in absolute air mass
  - $f_1(AM_a)$ in SAPM[1], $M(AM)$ in CEC model[2]

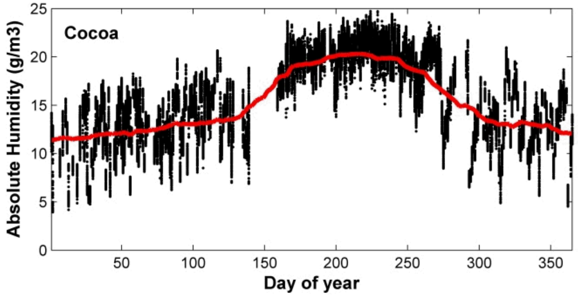


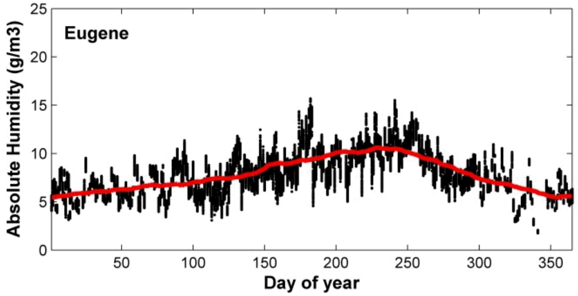
- Goal: Estimate $f_1(AM_a)$ and I_{sc0} using data from IV curves using several module technologies operating at different climatic conditions to track dependence on location and time of year

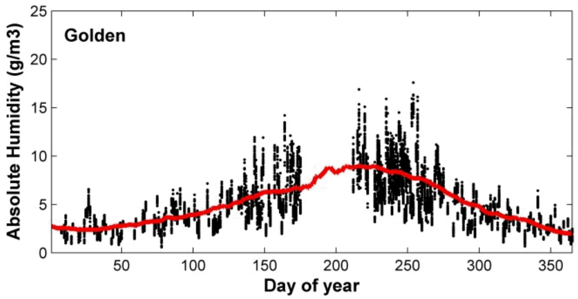
[1] King et al, "Photovoltaic Array Performance Model," Sandia National Laboratories, Albuquerque, NM SAND2004-3535, 2004.
[2] W. De Soto et al, "Improvement and Validation of a model for photovoltaic array performance", *Solar Energy* 80 (2006), pp 78-88

mPERT Data

- NREL mobile Performance and Energy Rating Testbed [1]
- Locations
  - Cocoa, Florida: subtropical
  - Eugene, Oregon: marine west coast
  - Golden, Colorado: semi-arid
- Technologies
  - Single crystalline silicon
  - Multi crystalline silicon
  - Cadmium telluride
  - Copper indium gallium selenide
  - Amorphous silicon
- Modules on fixed tilt racking







[1] Marion et al., "User's Manual for Data for Validating Models for PV Module Performance," National Renewable Energy Laboratory NREL/TP-5200-61610, 2014.

Methods

- I_{sc0} and $f_1(AM_a)$ are estimated from the I_{sc} equation in SAPM [1]

$$I_{SC} = I_{SC0} f_1\left(AM_a\right)\frac{E_b f_2\left(AOI\right)+f_d E_{diff}}{E_0}\left(1+\alpha_{SC}\left(T_C - T_0\right)\right)$$

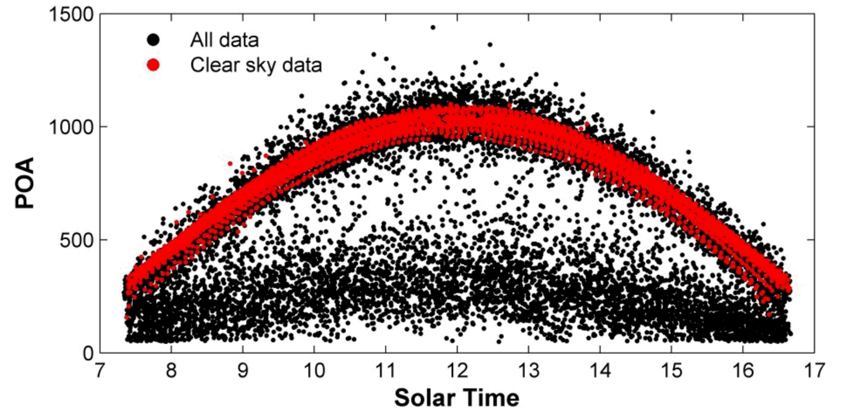
  - I_{sc} is extracted from IV curves
  - E_b and E_{diff} are estimated from G_{POA} under <u>clear sky conditions</u>
  - $f_2(AOI)$ is defined using a model from Martin and Ruiz [2]
  - f_d is set to 1
  - T_c is computed from module back-surface temperature
  - α_{SC}, T_0, *and* E_0 are taken from datasheet specifications

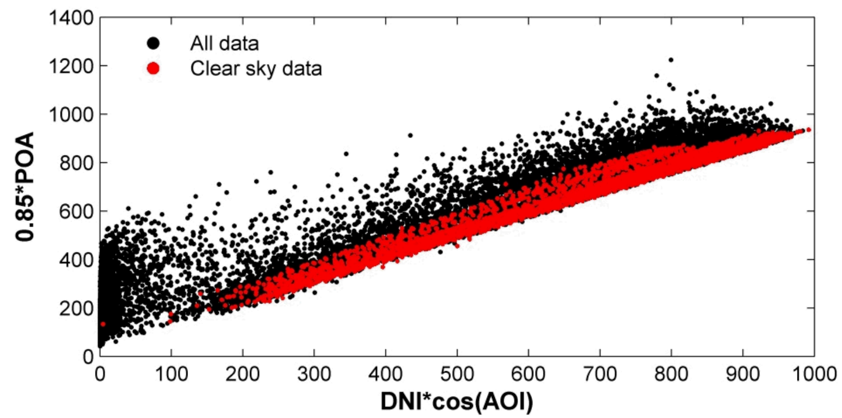
- By convention, $f_1(1.5) = 1$
- $f_1(AM_a)$ is typically fit using a 4th order polynomial

[1] King et al, "Photovoltaic Array Performance Model," Sandia National Laboratories, Albuquerque, NM SAND2004-3535, 2004.
[2] Martin, Ruiz, "A New Model for PV Modules Angular Losses Under Field Conditions", *International Journal of Solar Energy*, 22(1), 19-31, 2002

Methods

- Clear sky filter
  - Compare G_{POA} to a clear sky model
    - Threshold (< 150 W/m2)
    - Rate of change (< 2.5)
    - 90% of the day
  - Number of clear sky days
    - Cocoa: 28
    - Eugene: 54
    - Golden: 26



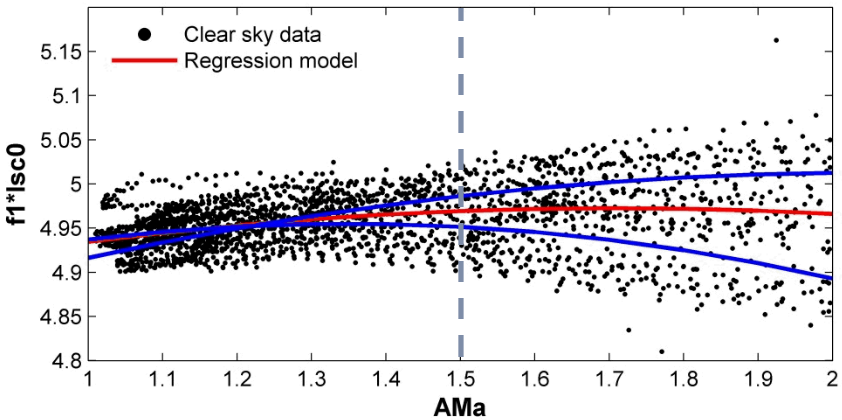


- Define E_b and E_{diff}
  - $E_b = 0.85*G_{POA}$
  - $E_{diff} = 0.15*G_{POA}$

Estimated I_{sc0}

- 2^{nd} order polynomial fit to clear sky data where $1 < AM_a < 2$
- I_{sc0} normalizes f_1 at $AM_a = 1.5$
- Systematic higher values at Cocoa
- Little change throughout the year

Single c-Si, Cocoa



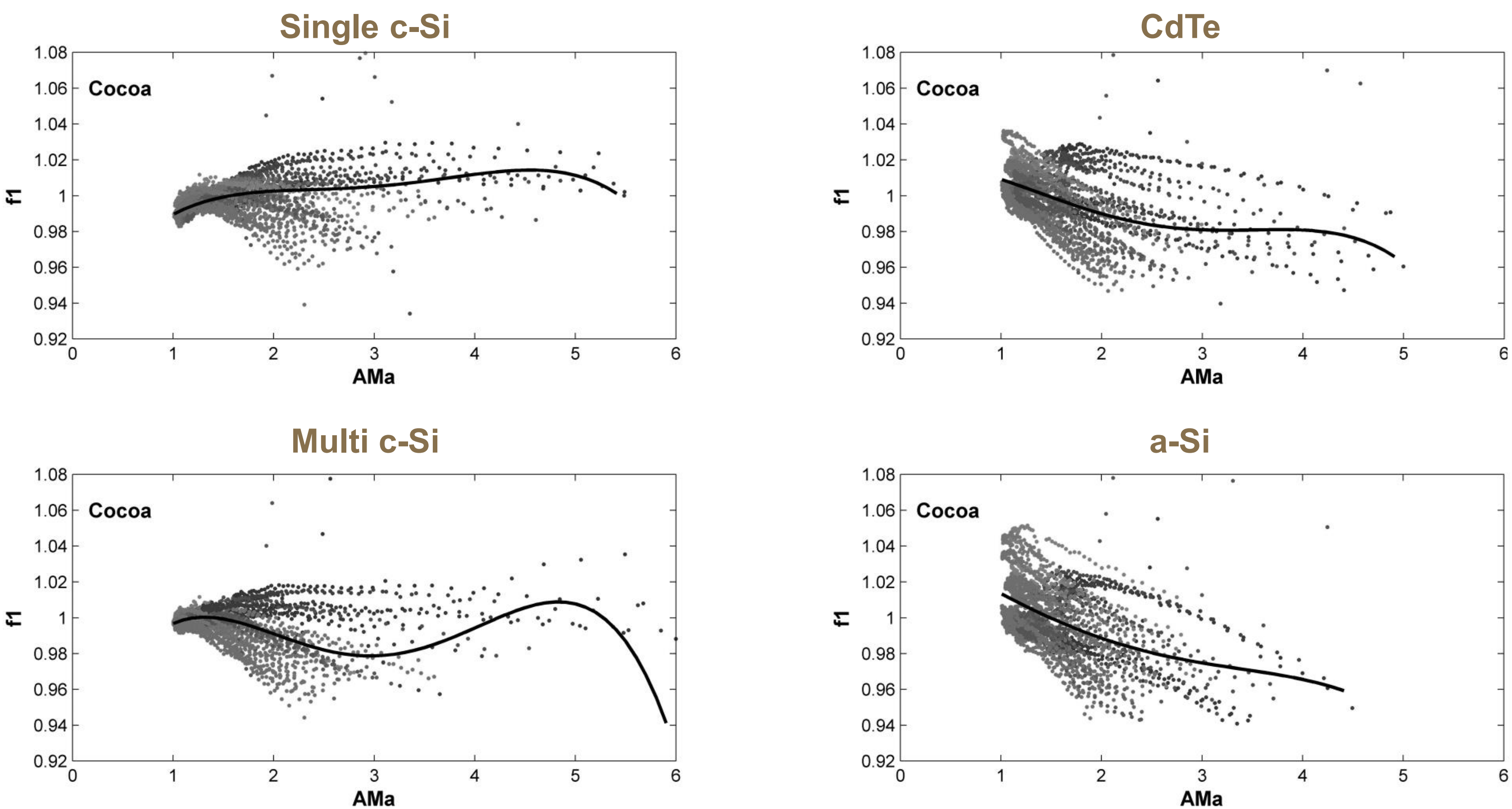
$I_{sc0} = 4.97$
Winter only: $I_{sc0} = 4.99$ (+0.4%)
Summer only: $I_{sc0} = 4.95$ (-0.4%)

Estimated I_{sc0} along with datasheet values

	Cocoa	Eugene	Golden
Single c-Si	4.97 (5.13)	4.87 (5.13)	4.89 (5.08)
Multi c-Si 1	4.92 (5.01)	4.80 (5.01)	4.85 (5.00)
Multi c-Si 2	2.66 (2.73)	2.62 (2.73)	2.64 (2.70)
Multi c-Si 3	2.67 (2.73)	2.60 (2.73)	2.64 (2.69)
CdTe	1.16 (1.17)	1.13 (1.17)	1.12 (1.18)
CIGS 1	6.27 (6.32)	6.03 (6.32)	5.90 (5.83)
CIGS 2	2.46 (2.49)	2.41 (2.49)	2.42 (2.52)
a-Si 1	5.35 (5.46)	5.21 (5.46)	5.34 (5.49)
a-Si 2	1.09 (1.12)	1.04 (1.12)	1.10 (1.20)
a-Si 3	4.61 (4.62)	4.51 (4.62)	4.36 (4.62)

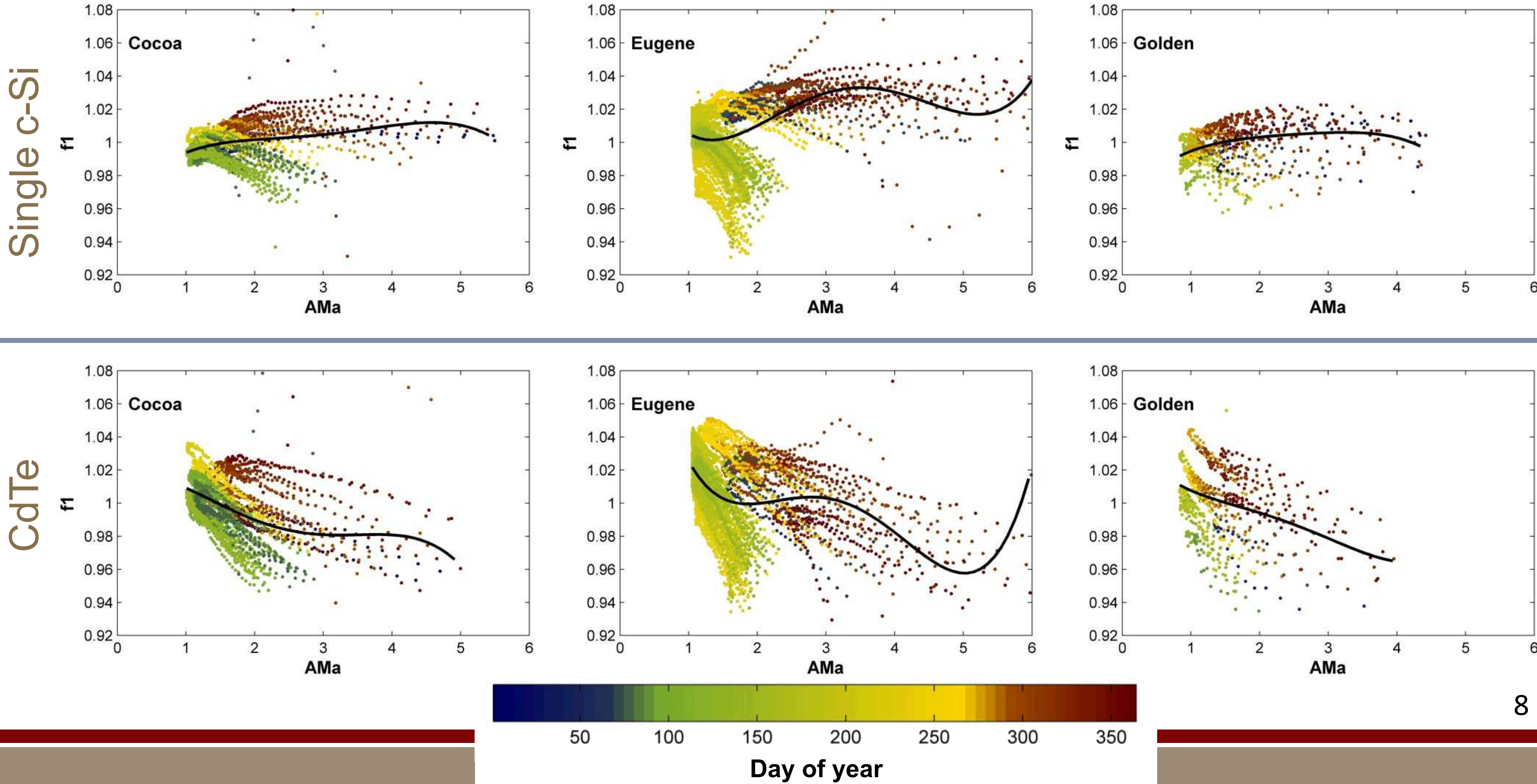
Estimated f_1

- 4^{th} order polynomial fit to clear sky data
- Up to 4-6% error in polynomial fit



Estimated f_1

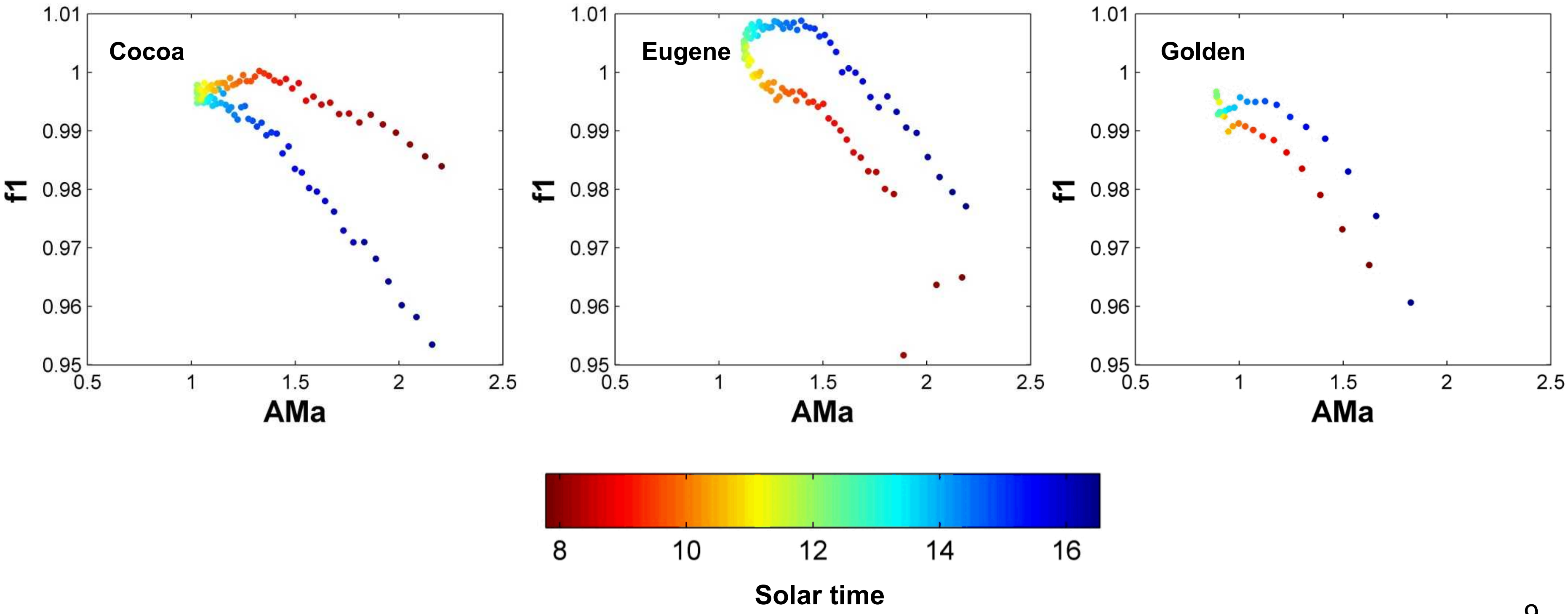
- Seasonal fluctuation in f_1
- For a given technology, fluctuations are similar across the three locations



Estimated f_1

- Daily fluctuation in f_1
- Morning and afternoon values can differ by 3%

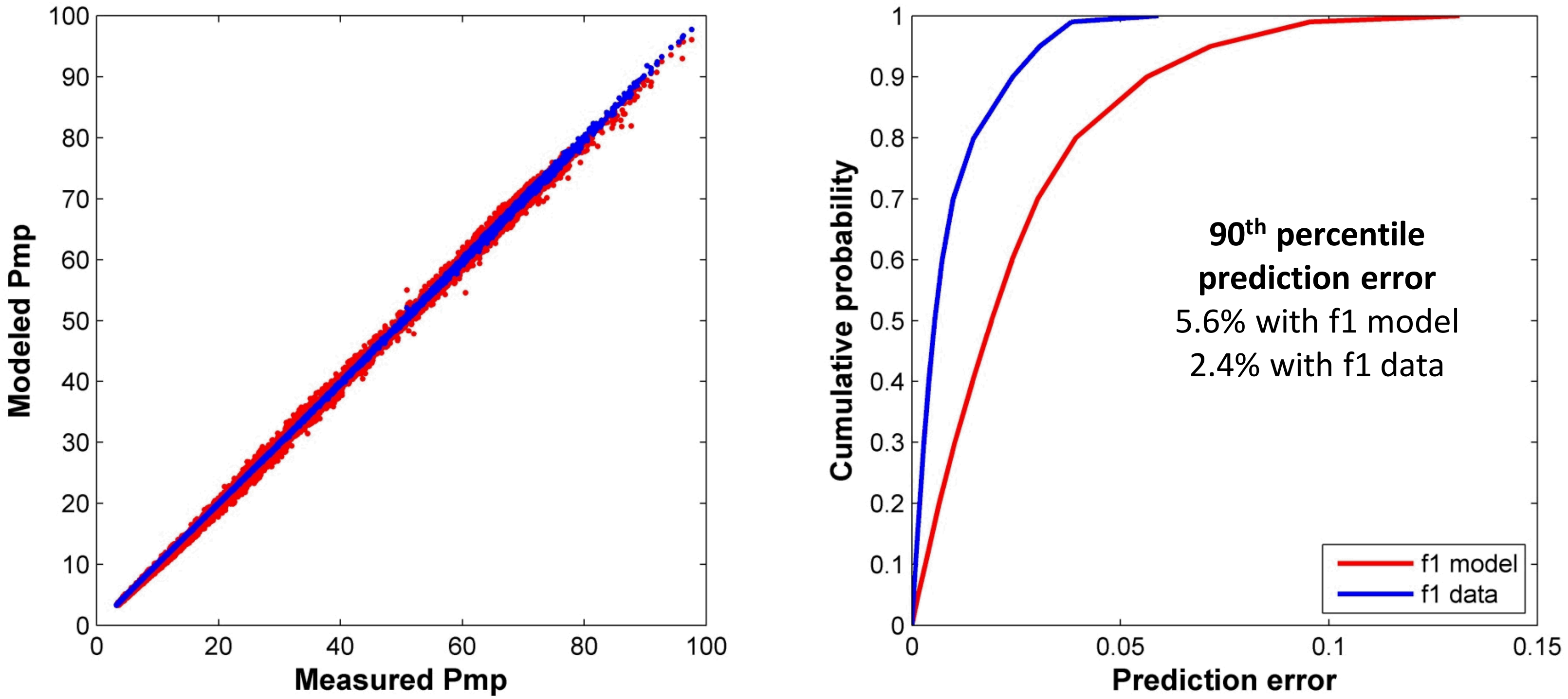
Amorphous silicon cell, single clear sky day in April



Impact on predicted power

- Parameter estimation for entire SAPM
- Predict power output, isolate error associated with the air mass modifier model, $f_1(AM_a)$

Multi-crystalline silicon cell, Eugene



Summary

- I_{sc0} shows systematic dependence on location; values are consistently higher at Cocoa.

- f_1 shows seasonal dependence with higher values in the winter. Given a specific technology, f_1 characteristics are similar at the three locations.

- A single polynomial in AM_a does not capture the range of variations in solar spectrum on I_{sc}.
  - Daily patterns, seasonal changes

- Performance model accuracy could be improved with alternative models for the air mass modifier.

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