SunSolve

Addressing radiative loss in the thermal analysis of PV systems

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PV LIGHTHOUSE

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Motivation

- Solar cells commonly have power temperature coefficients of -0.3%/°C:

  ~3°C of uncertainty in T_{cell} → ~1% uncertainty in P_{DC}

- The Faiman model assumes all heat loss is proportional to the temperature difference from module to ambient:

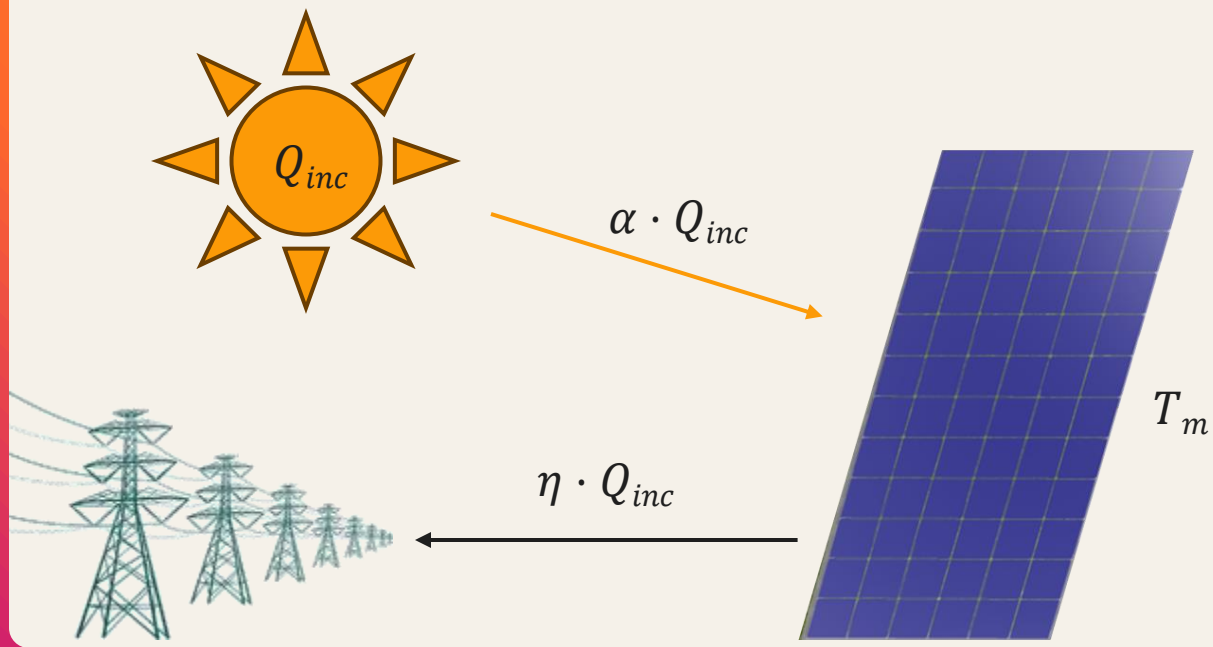
$$\propto T_{mod} - T_{amb}$$

- Radiative heat loss follows the Stefan-Boltzmann law from module to sky:

$$\propto T_{mod}^4 - T_{sky}^4$$

- What error in yield arises from using T_{amb} instead of T_{sky} for radiative loss?

The Faiman model

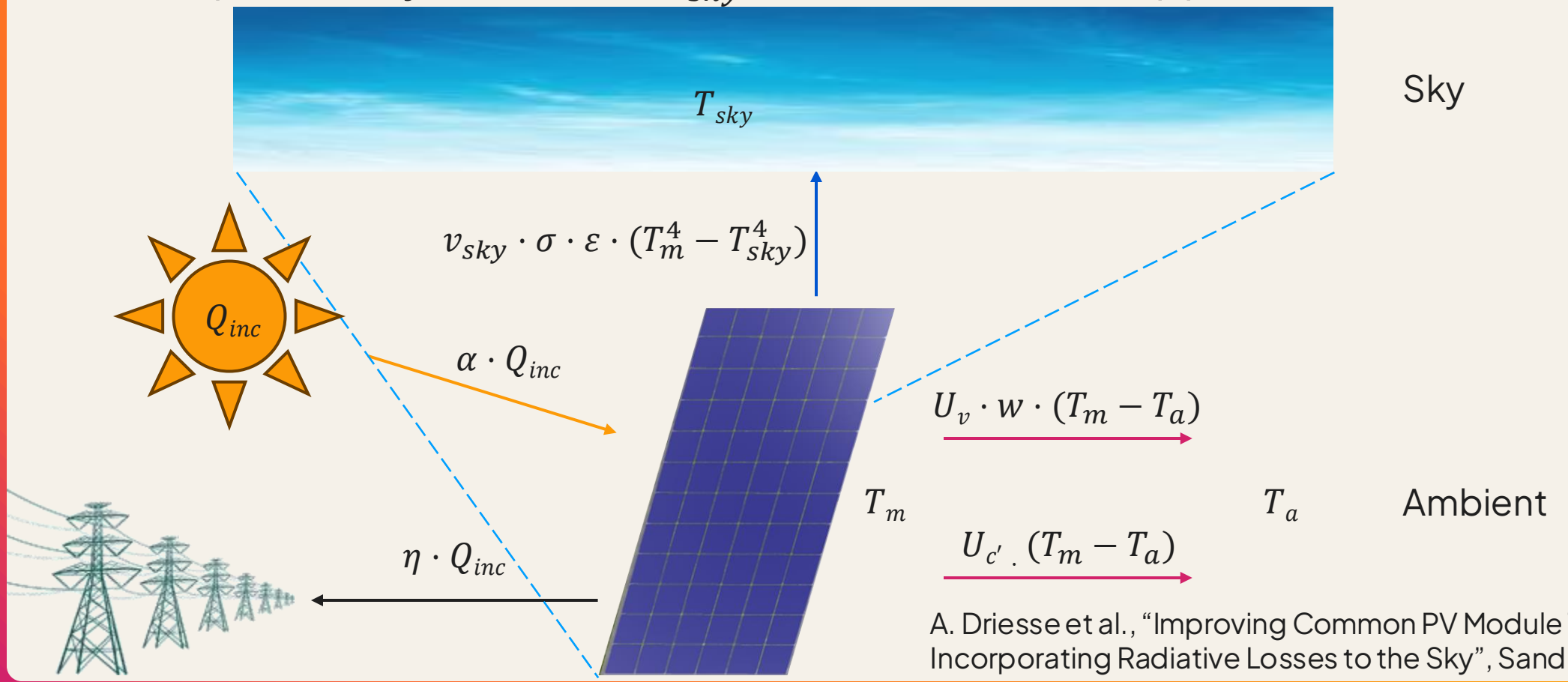


Forced convection
Proportional to wind speed, w

Everything else

The Faiman model with radiative heat loss

- Radiative loss can be calculated separately to the U_c term.
- It requires a 'sky view factor' v_{sky}. (We take the same approach as Driesse 2022.)

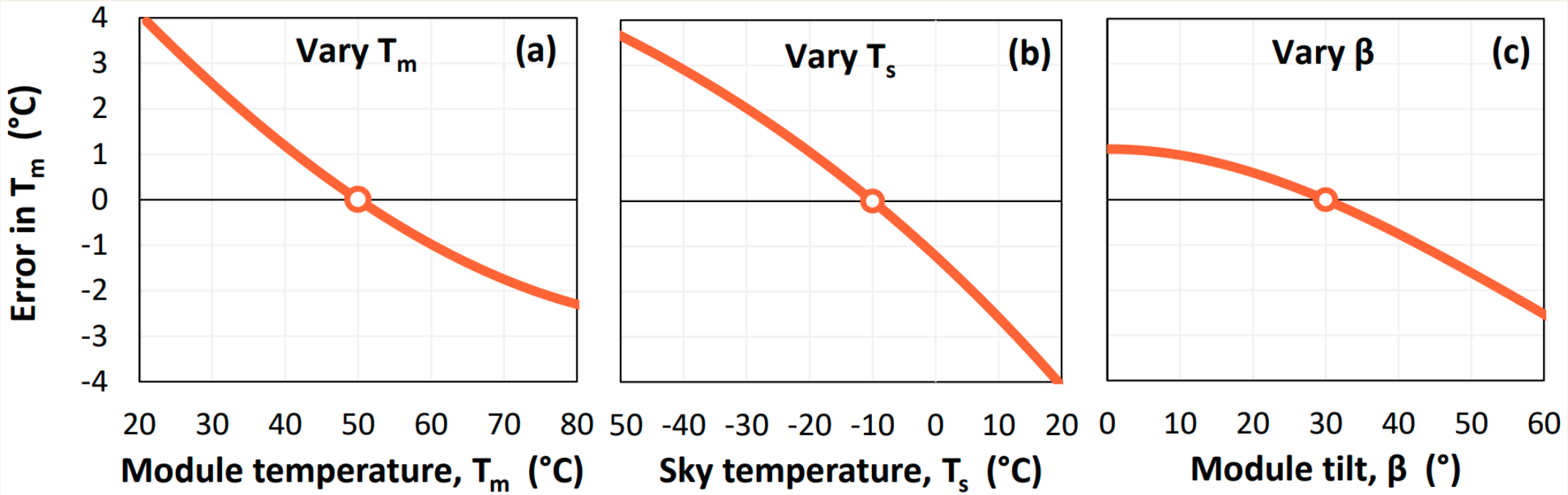


A. Driesse et al., "Improving Common PV Module Temperature Models by Incorporating Radiative Losses to the Sky", Sandia, 2022.

Error in module temperature

Error in T_m when radiative loss to the sky is treated as $U_{c,s} \cdot (T_m - T_a)$ (1)

instead of $v_{sky} \cdot \sigma \cdot \varepsilon \cdot (T_m^4 - T_s^4)$ (2)



Where $U_{c,s}$ is calibrated such that (1) is correct at T_m = 50, T_s = -10, β = 30

Downwelling Longwave Radiation (DLR)

- Effective sky temperature T_{sky} is inferred from satellite measurements of solar 'downwelling' radiation at long wavelengths (DLR).
- We retrieve hourly DLR data from the ERA5-Land database, to model T_{sky}.

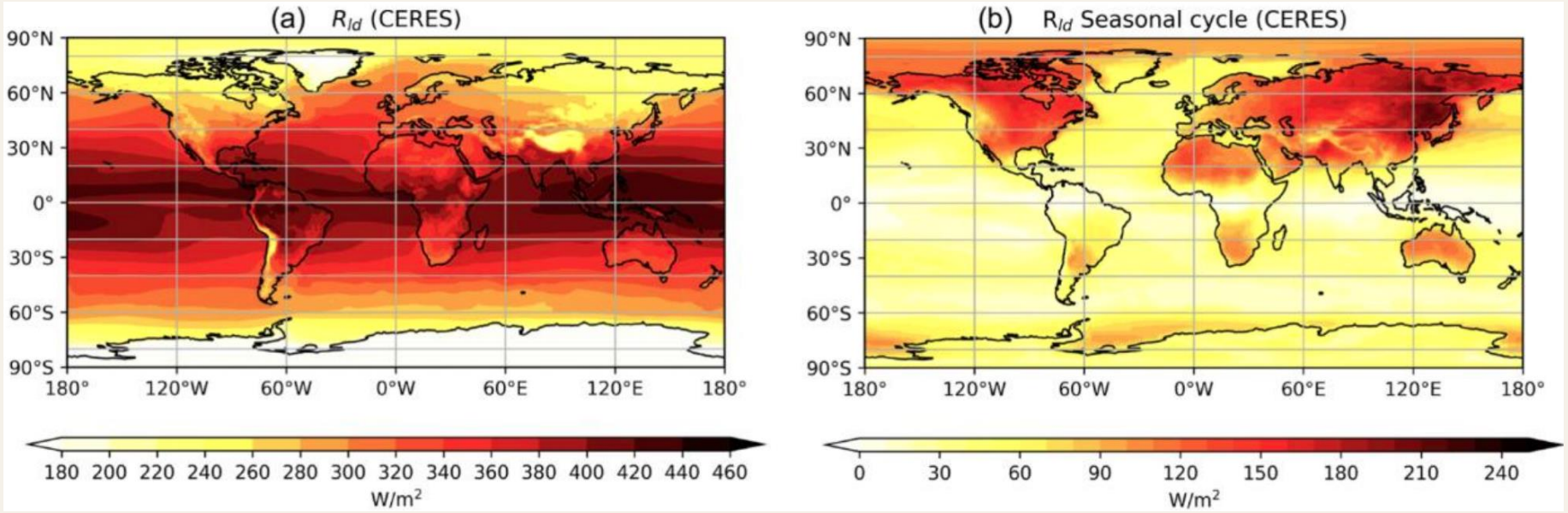
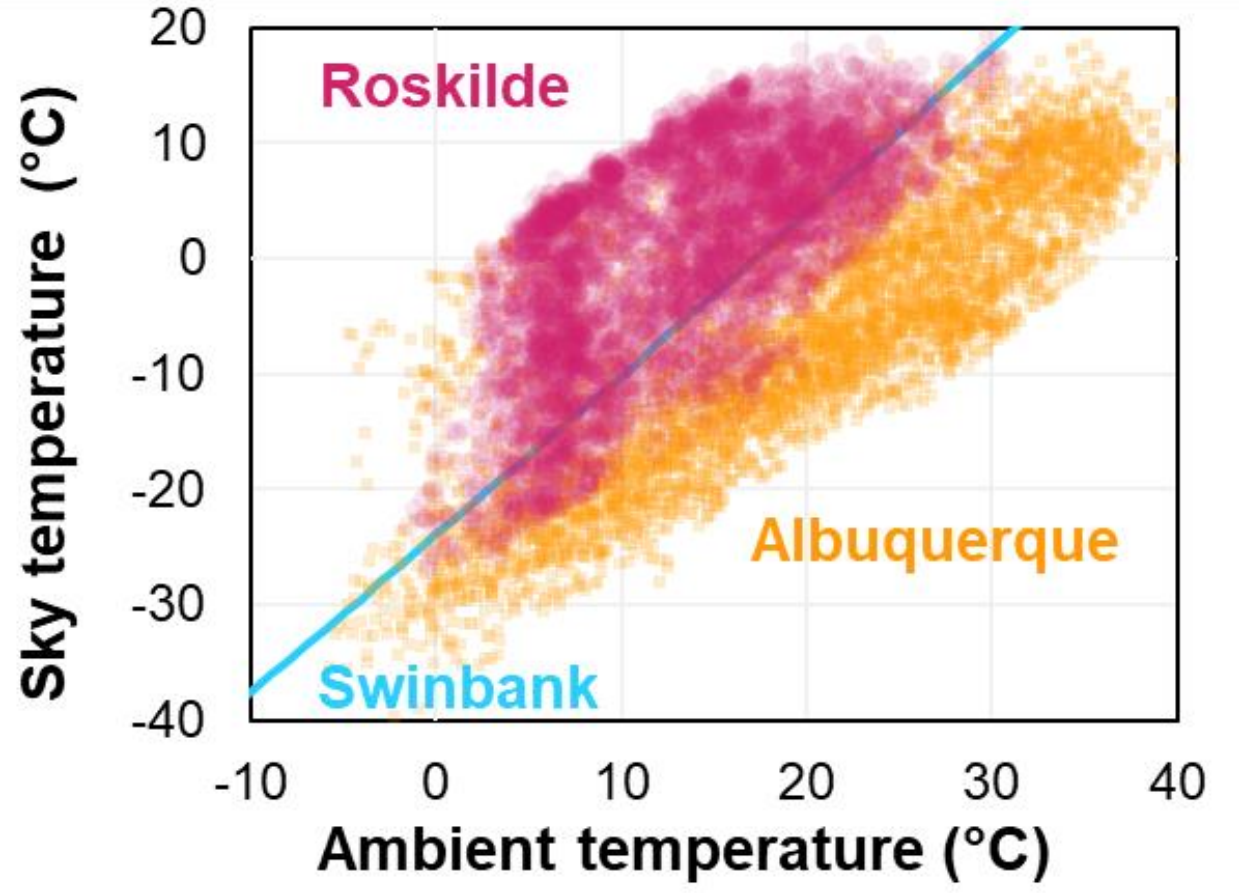
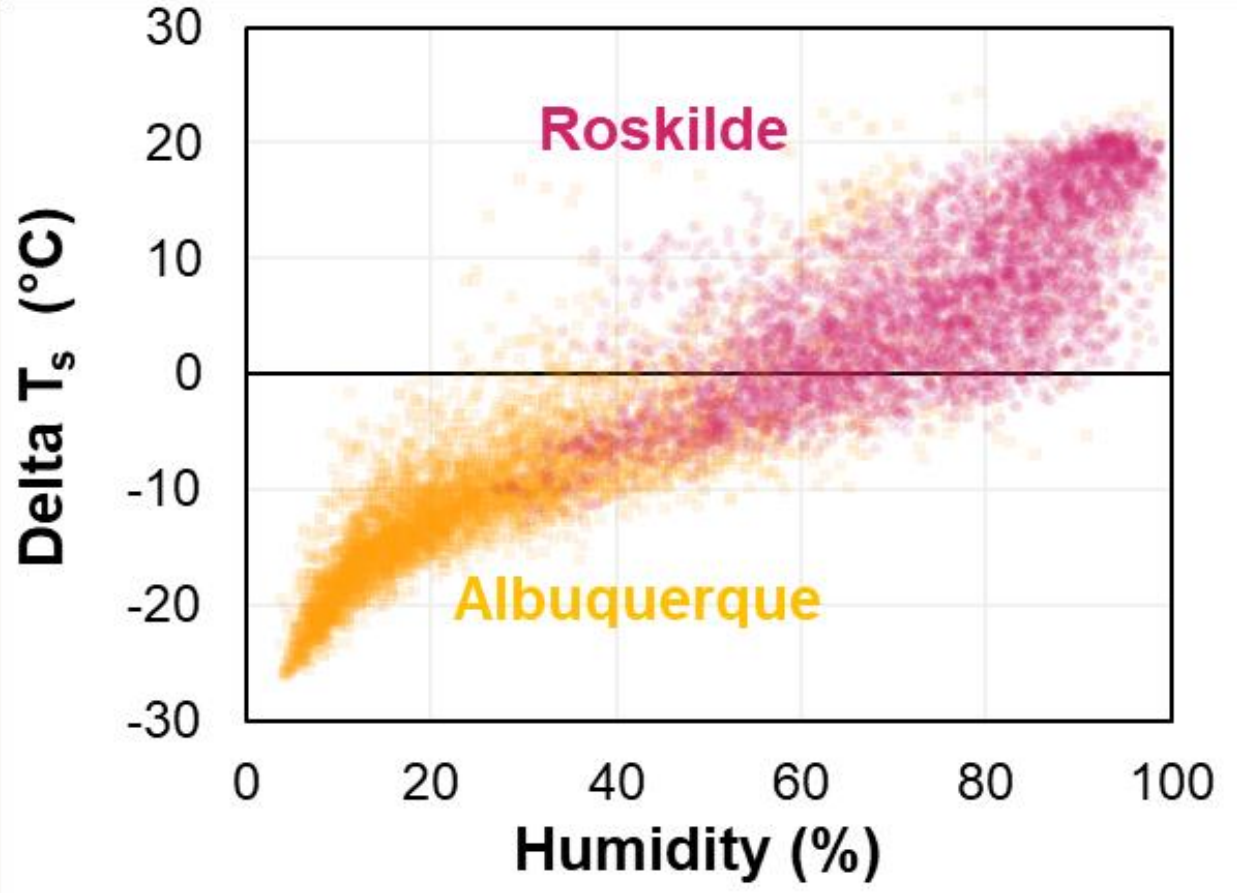


Image from Y. Tian et al., "Understanding variations in downwelling longwave radiation using Brutsaert's equation", Earth System Dynamics, vol. 14, pp. 1363–1374, 2023.

T_{sky} changes with location and conditions





[1] W.C. Swinbank, “Long wave radiation from clear skies”, Quarterly Journal of the Royal Meteorological Society, vol. 89, pp. 339, 1963.

Experimental sites

Test facility	Location	System configuration	Module	Refs	Months
FTC Solar	Denver, USA	Single-axis tracker	Bifi PERC	[2]	1.5
Sandia	Albuquerque, USA	Fixed-tilt, 35°	Mono-PERC	[3]	12
Sandia	Albuquerque, USA	Fixed-tilt, 35°	Mono-HIT	[3]	12
5B	Bungendore, Aus	E/W (“Maverick”), 10°	Mono-PERC	[4]	3
DTU	Roskilde, Denmark	Single-axis tracker	Mono-PERC	[3*,5]	12

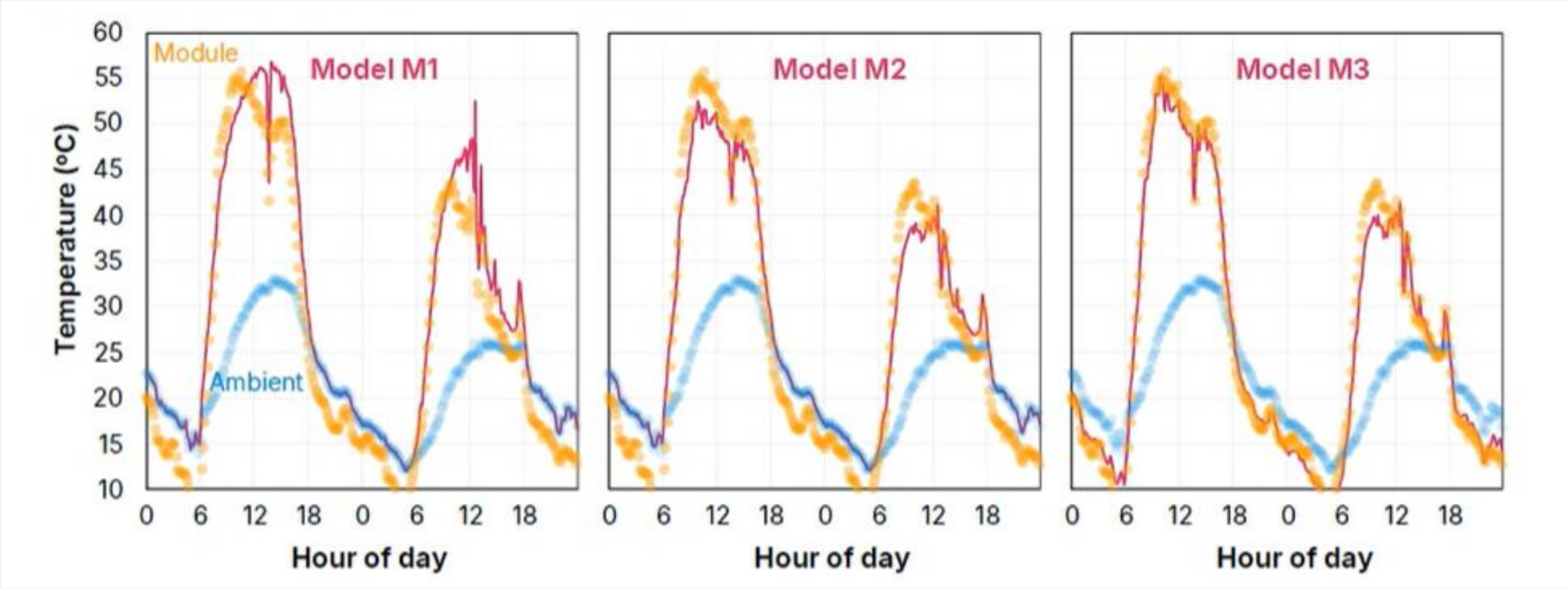
[2] K.R. McIntosh *et al.*, “The influence of wind and module tilt on the operating temperature of single-axis trackers”, *49th IEEE Photovoltaic Specialists Research Conference*, 2022.
[3] M. Theristis, N. Riedel Lyngskær, et al., “Blind photovoltaic modeling intercomparison: A multidimensional data analysis and lessons learned”, Progress in Photovoltaics, vol. 31, no. 11, pp. 1144–1157, 2023.
[4] P. Hamer et al., “Improved thermal modelling of the 5B MAVERICK system: impact of sky temperature”, Asia-Pacific Solar Research Conf., 2023.
[5] N. Riedel Lyngskær, et al., "Validation of Bifacial Photovoltaic Simulation Software against Monitoring Data from Large Scale Single Axis Trackers and Fixed Tilt Systems in Denmark", Applied Sciences, vol. 1, 8487, 2020.
[*] With revised Tm data.

Modelling vs measurement, SAT at Denver

Model 1
Faiman, standard inputs
Uc = 29, Uv = 0

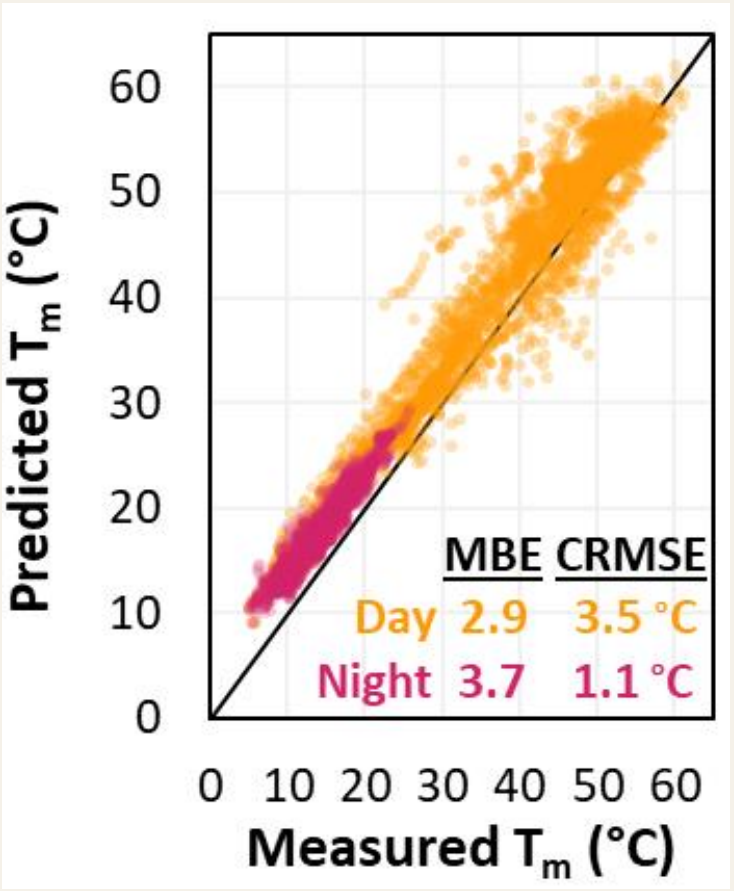
Model 2
Faiman, calibrated inputs & transient effects

Model 3
Faiman, calibrated inputs, transient effects & radiative eq

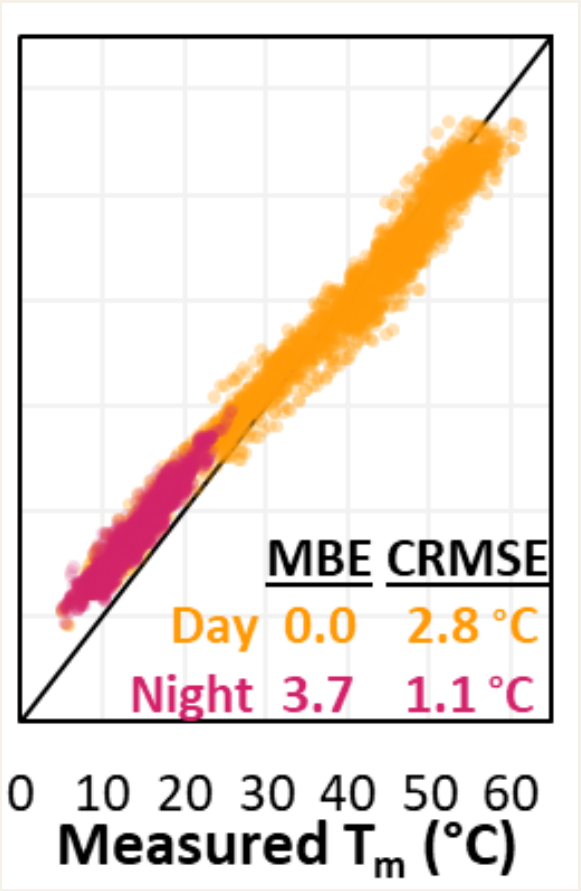


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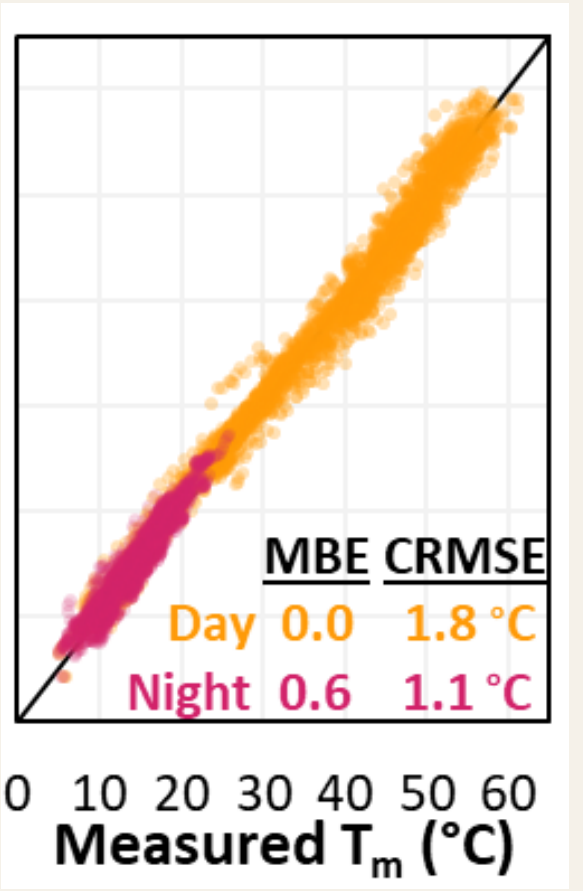
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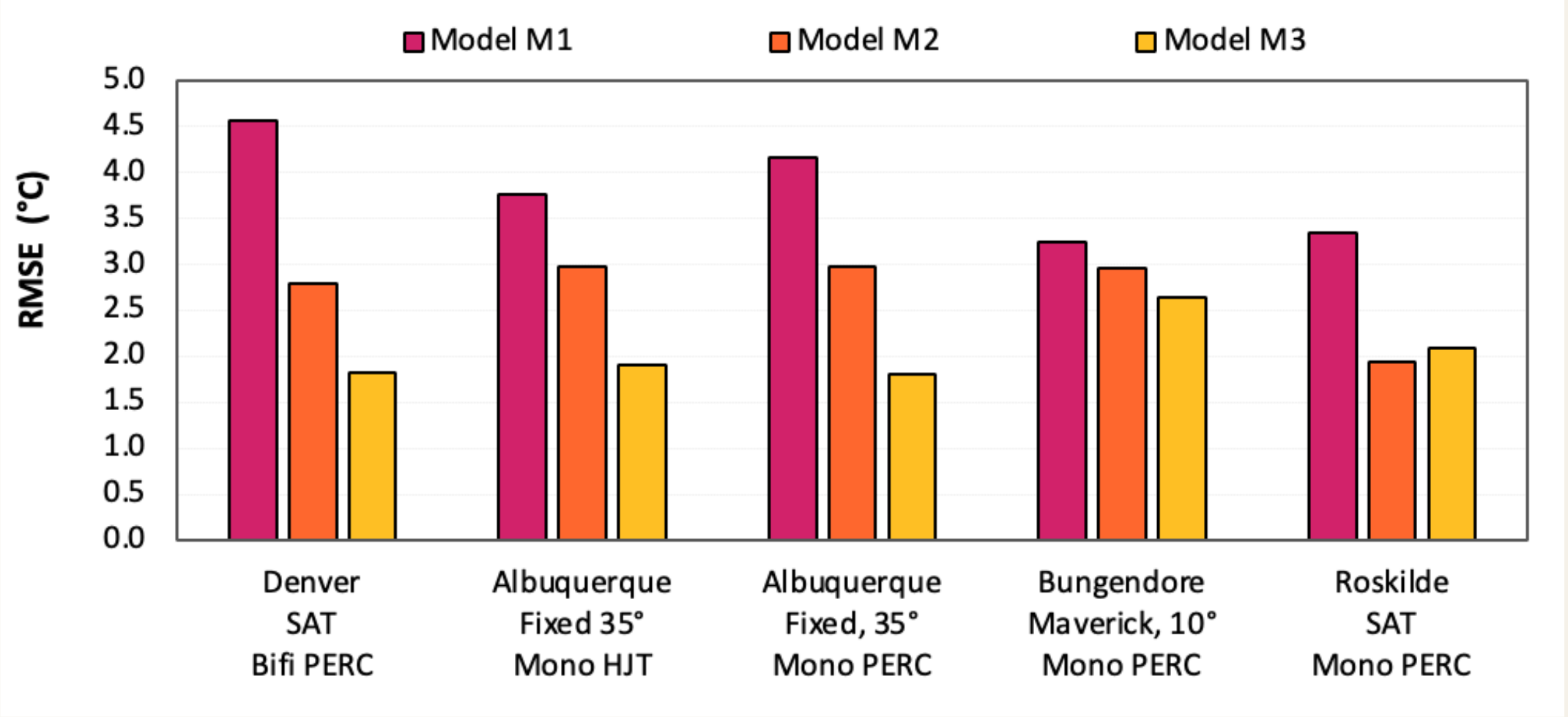
Model 2
Faiman, calibrated inputs & transient effects



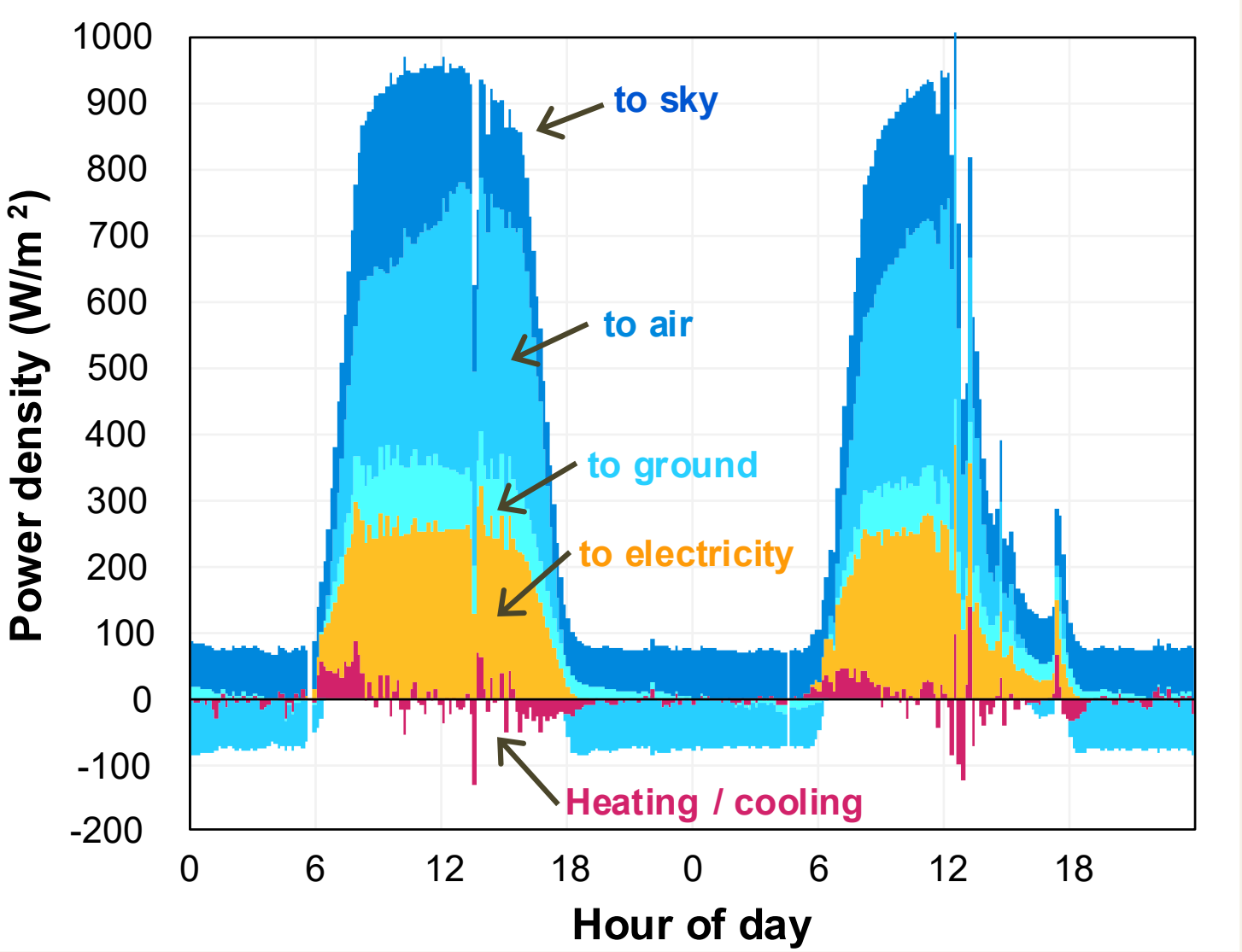
Model 3
Faiman, calibrated inputs, transient effects & radiative eq



Modelling vs measurement, all sites



Extended simulation of SAT at Denver

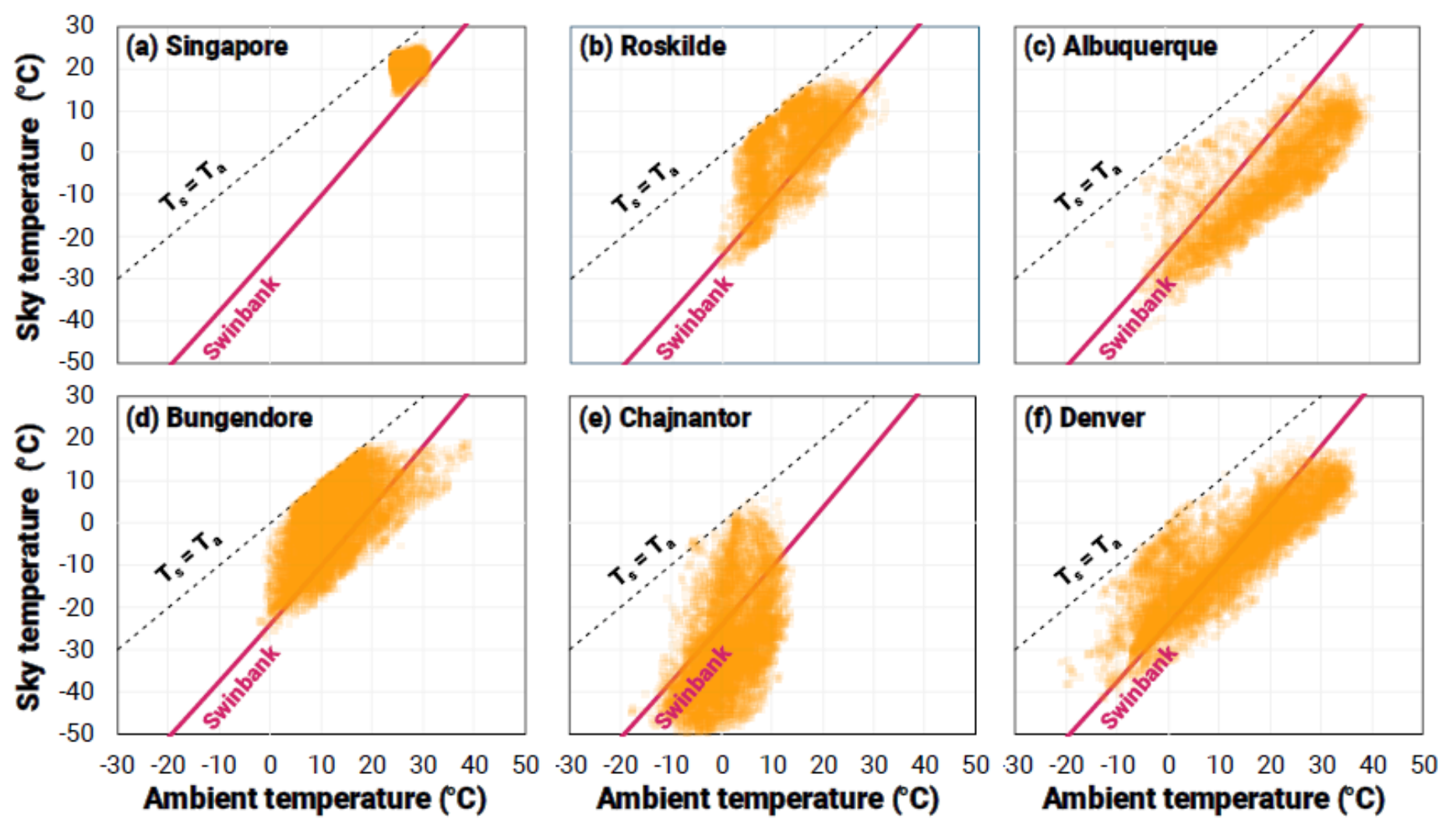


Simulation of six sites

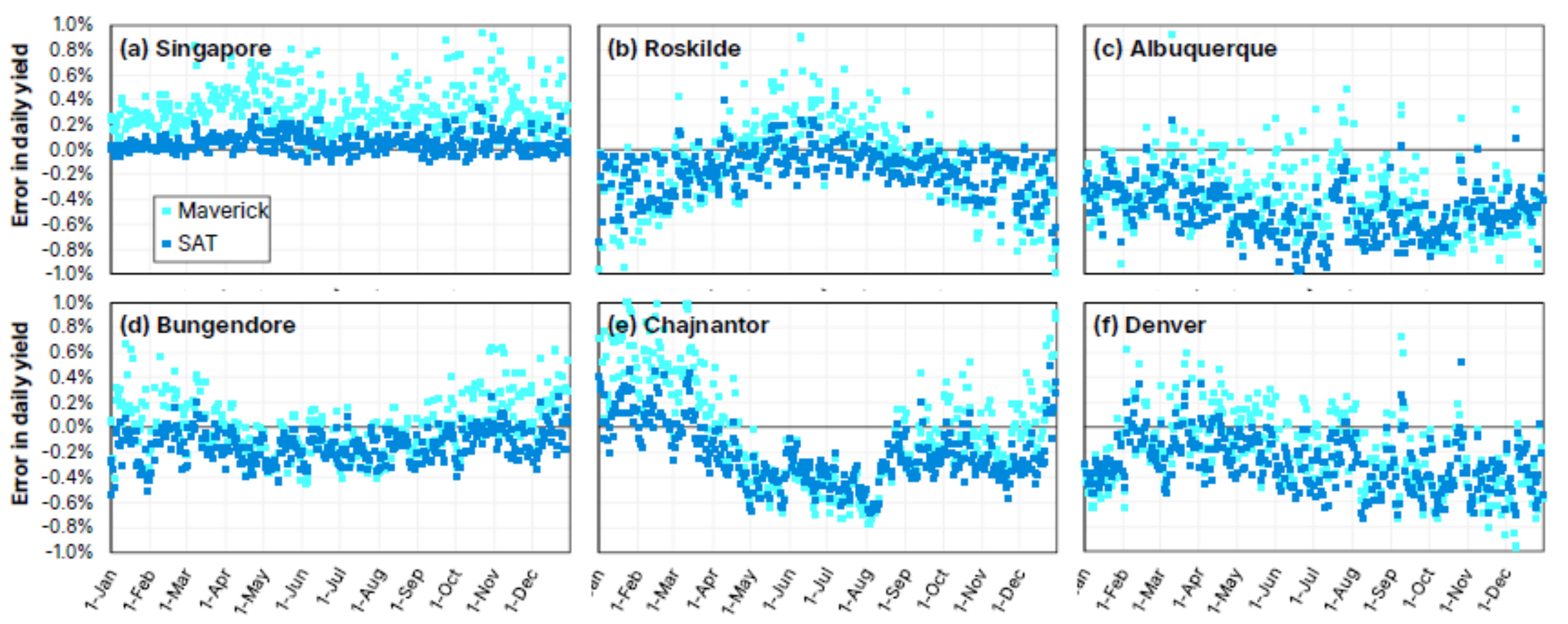
	Singapore	Roskilde	Albuquerque	Bungendore	Chajnantor	Denver
Köppen–Geiger class	Tropical rainforest	Oceanic	Cold semi-arid	Oceanic	Cold desert	Cold semi-arid
Average daytime weather						
T_a (°C)	27.5	13.1	19.8	14.9	3.5	15.3
T_{sky} (°C)	21.5	0.3	−6.6	1.2	−27.3	−5.7
WS (m/s)	4.3	2.2	2.3	4.6	5.1	4.0
RH (%)	74.8	73.3	28.1	–	35.6	40.5

Satellite data from [6] J. Muñoz Sabater, “ERA5 Land hourly data from 1950 to present.”, Copernicus Climate Change Service (C3S) Climate Data Store (CDS), 2019.

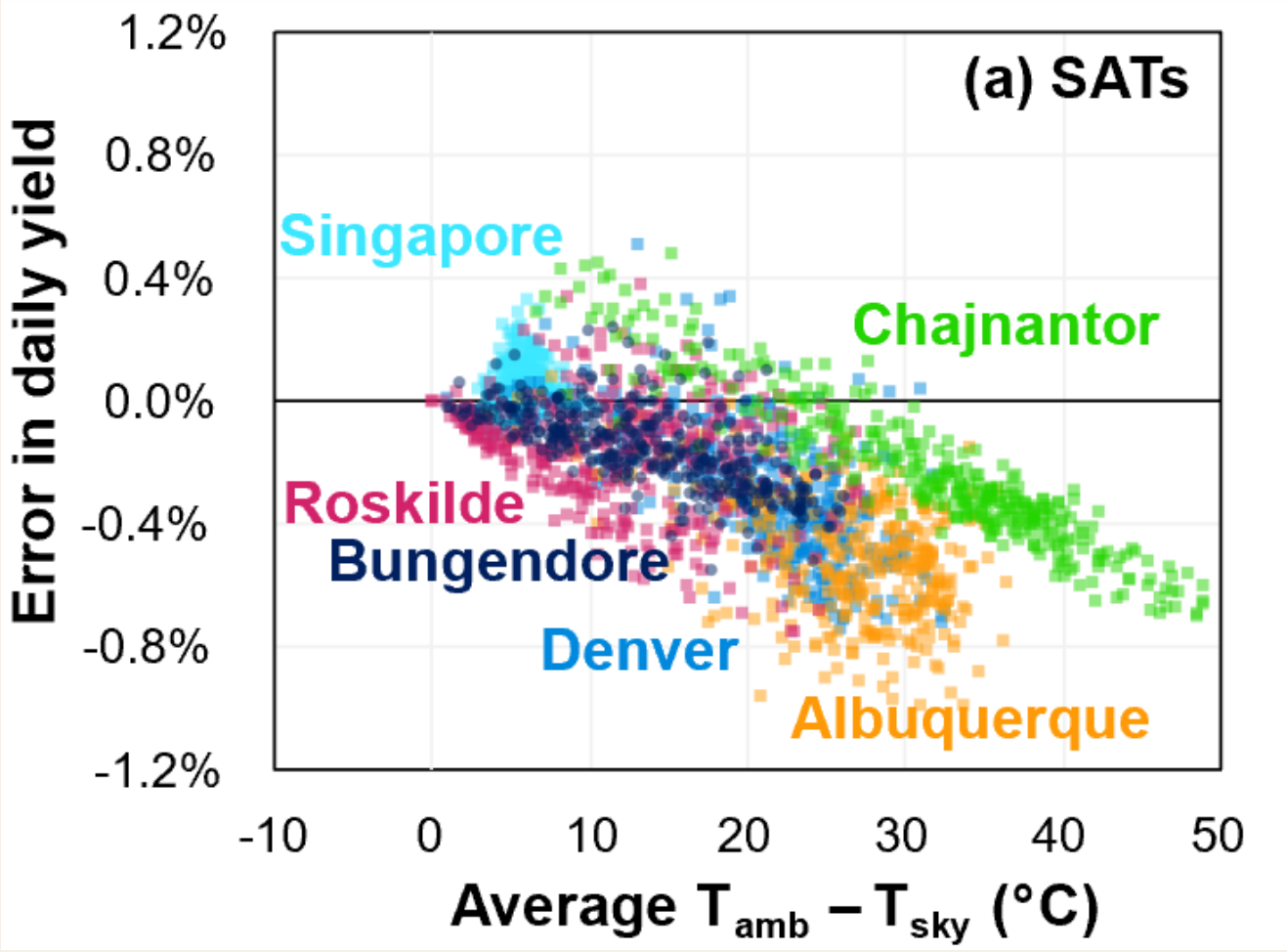
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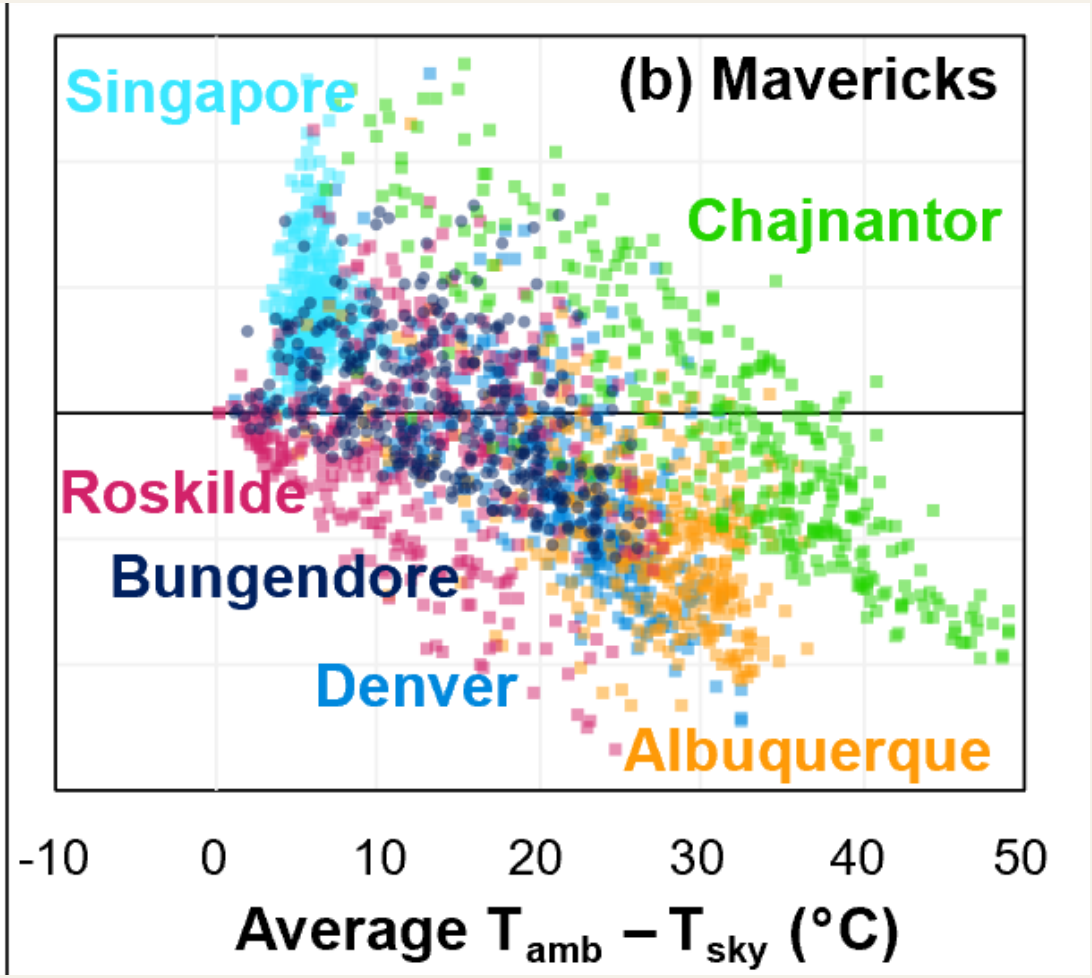


Error in daily yield (E_{Faiman}-$E_{Radiative}$)



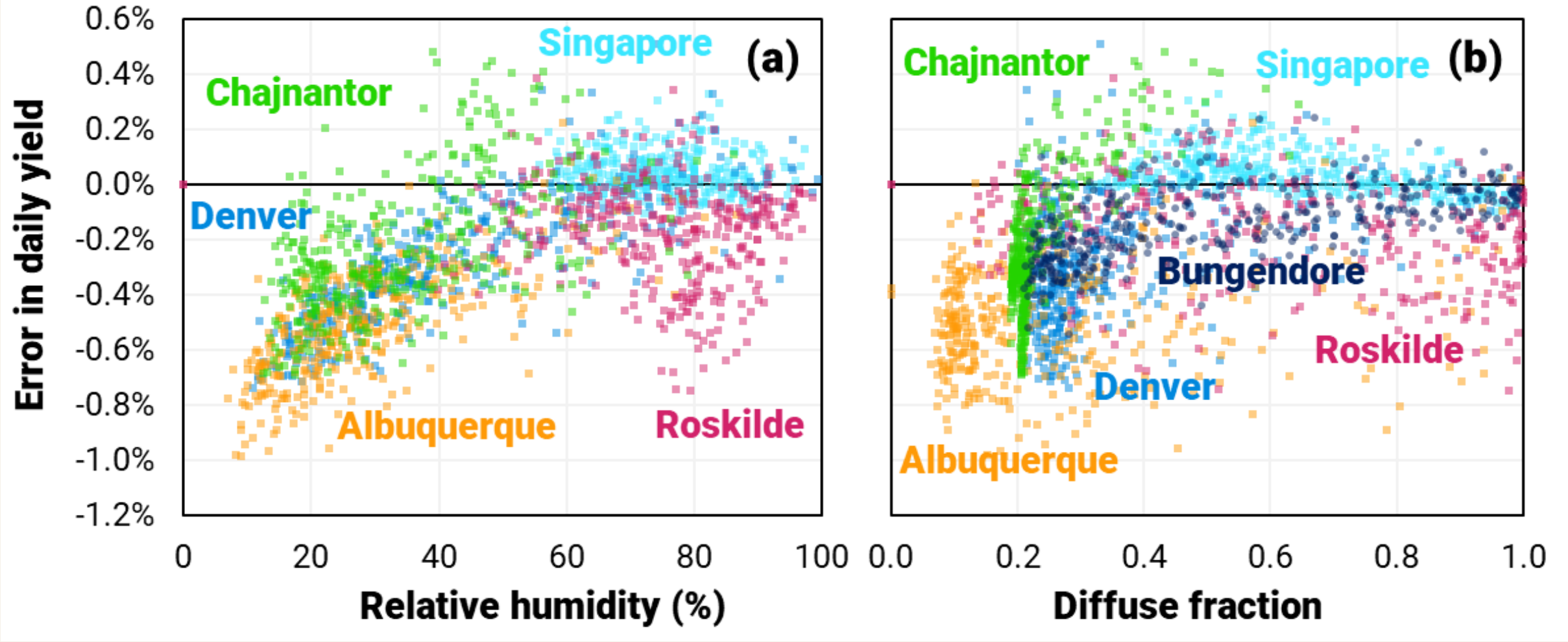
Error in daily yield (E_{Faiman} - $E_{Radiative}$)



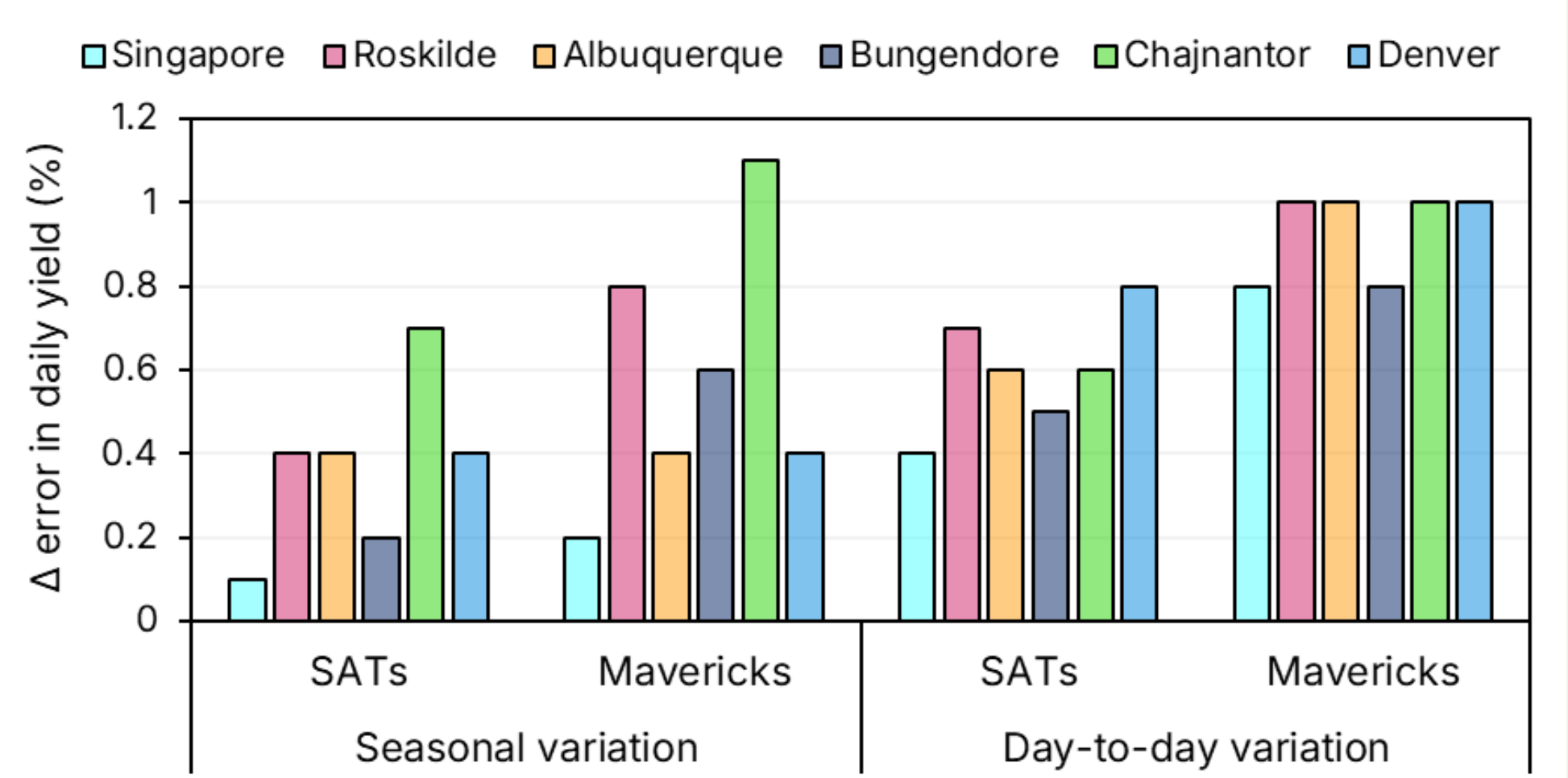


Error in daily yield (E_{Faiman} - $E_{Radiative}$)

SATs only



Error in daily yield



Conclusions

- Radiative loss accounts for 30–60 % of daytime heat loss.
- Simplified thermal models introduce up to ±0.5% uncertainty in the annual yield, and an additional ±0.5% into the daily yield.
- Using the standard approximation for radiative heat loss instead of the more realistic equation — introduces an error in the predicted module temperature of up to ±4 °C.
- Eq. 1 introduces error in the annual yield that varies from site to site by ~0.5%, and error in the daily yield that varies by ~1% throughout a year.
- It causes the yield to be more overestimated on humid days, and vice versa for dry days.

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PVPerformance MODELING COLLABORATIVE

DTU

FTC SOLAR

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