Cloud Advection and Spatial Variability of Solar Irradiance

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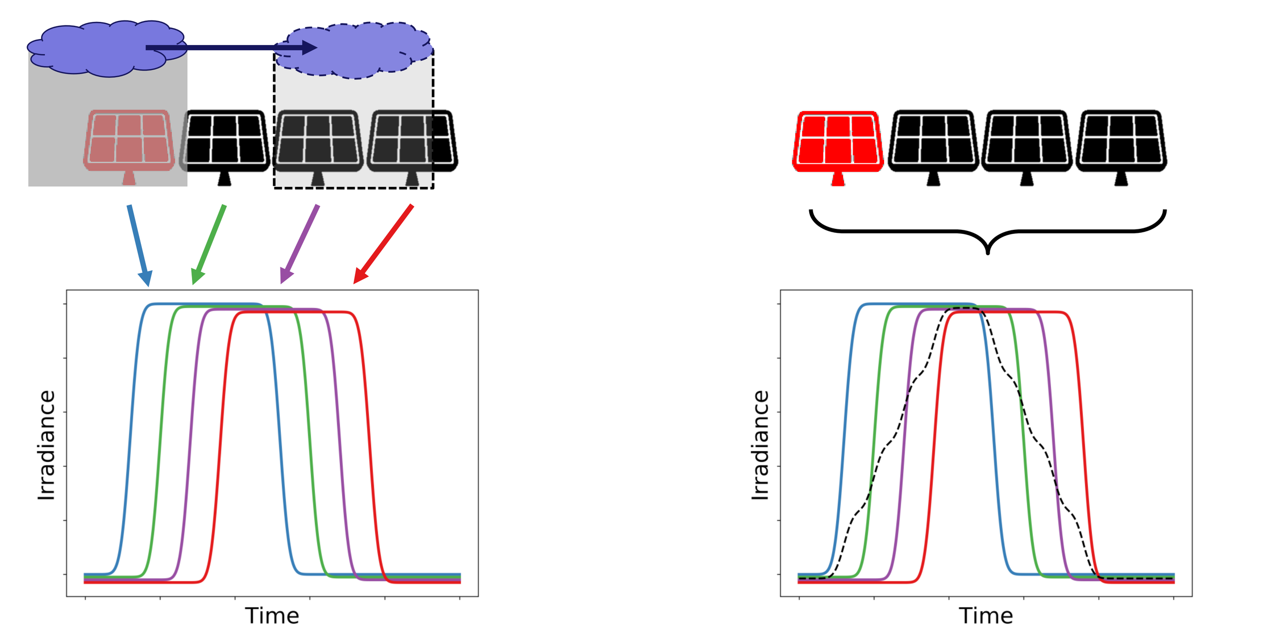
Distributed plants smooth out an irradiance time series

Grid operators need to anticipate variability in PV generation. Spatially distributed generation smooths a single-point's irradiance time series, reducing variability. Previous studies have modeled spatial aggregation effects due to cloud advection [1] and have used the frequency domain [2,3], but none have combined the two.



Clouds advect over a distributed array, causing a delayed, but correlated response.

Aggregating the irradiance smooths the time series and reduces ramp rates.

The plant transfer function represents variability reduction

With cloud advection, a 1-D plant's output is the convolution of a single reference point's irradiance time series with the plant's spatial distribution. This means that the actual transfer function is equal to the Fourier Transform of the plant's distribution. The transfer function is essentially a low-pass filter with time delay equivalent to advection from the reference site to the center of the plant. We call this the Cloud Advection Model (CAM).

$$g(x,t) = g_{ref}\left(t - \frac{x}{V_c}\right)$$

Irradiance signal at any point x is the reference signal delayed by cloud advection.

$$p(t) = \int d(\tau) \cdot g_{ref}(t-\tau)d\tau$$

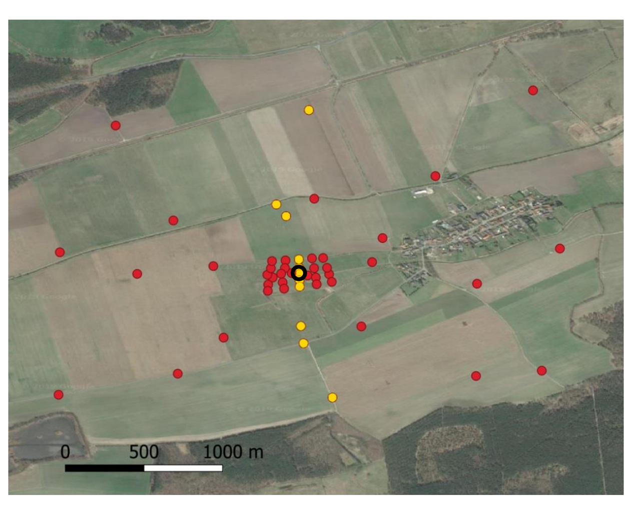
Plant irradiance p is obtained by convolution of plant distribution d with the delayed reference irradiance.

$$TF(f) = \frac{P(f)}{G_{ref}(f)} = \mathcal{F}(d)$$

The transfer function between the reference site and the plant is the Fourier Transform of the spatial distribution.

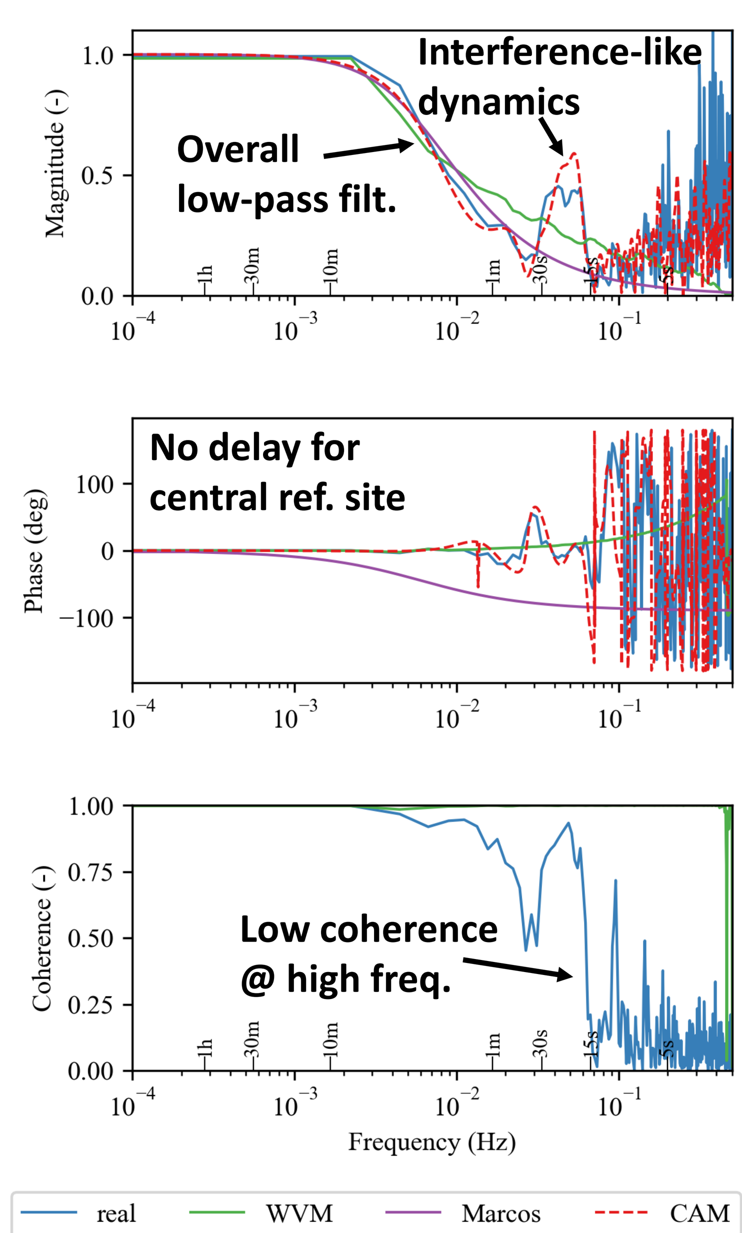
We can compute a transfer function from a spatial distribution

We considered a measurement site in Melpitz, Germany. There were 50 sites with 1 Hz sampling over the course of a month. We identified one-hour long segments where cloud advection was in a north-south direction, and looked at co-linear sites.



Selected north-south aligned subset with central reference site

Real data was simulated by summing together site time series and calculating TF. Comparison was made between CAM, and two from literature. Interesting dynamics were observed at increased frequency that were only predicted by the CAM.



Transfer function magnitude, phase and coherence for Melpitz site, with cloud advection at 20 m/s.

Changing the plant shape changes the dynamics significantly

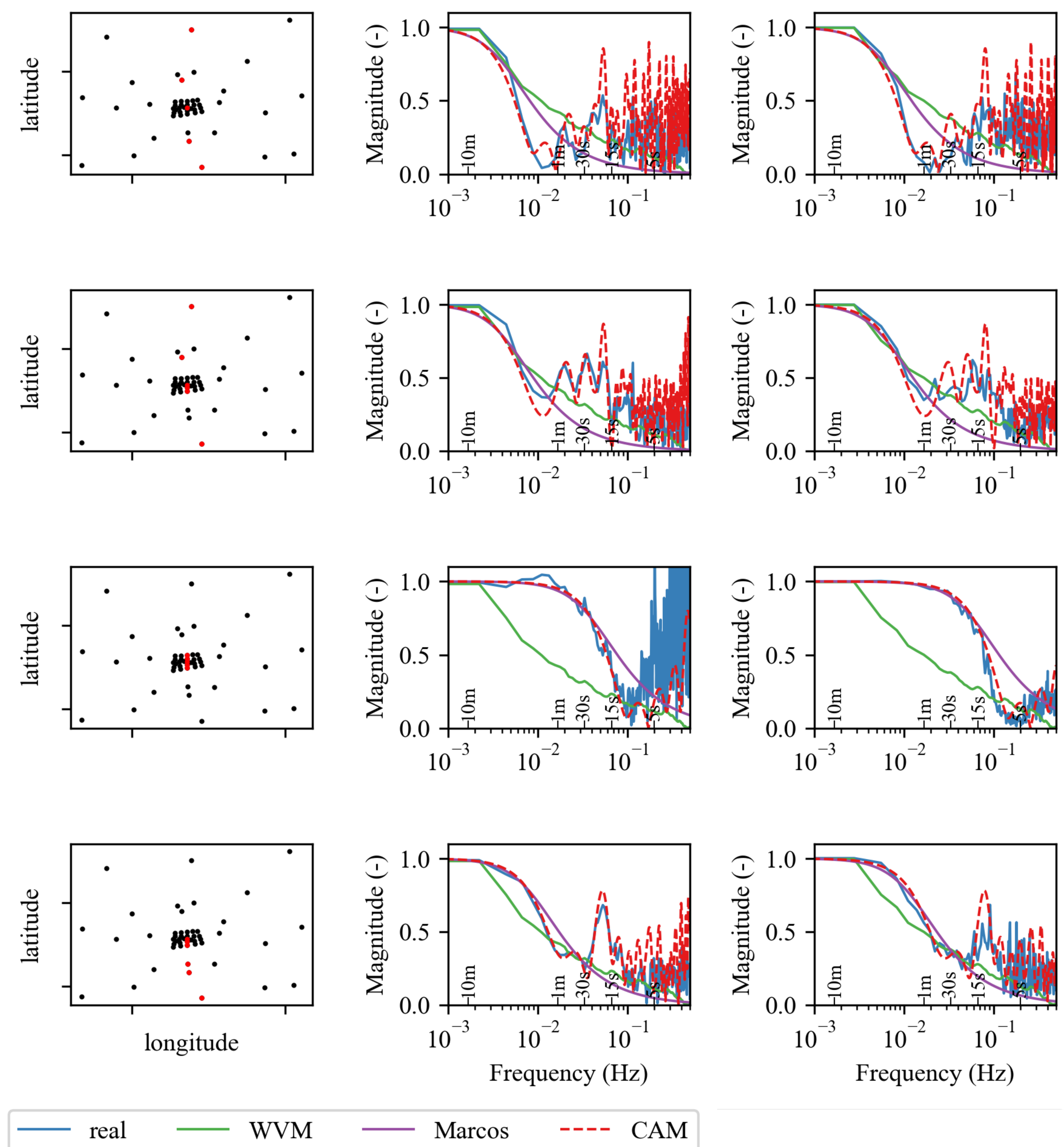
We compared different plants and different cloud speeds. The distribution changes the character of the transfer function for different plant layouts. The CAM tracks the major features in the transfer function, including changes to the cutoff frequency. In all cases, accuracy is better at low frequencies than high frequencies.

Each row represents a different subset of points within the plant.

Columns are two time windows: N-S advection, but different speeds: V_c = -20 & 30 m/s

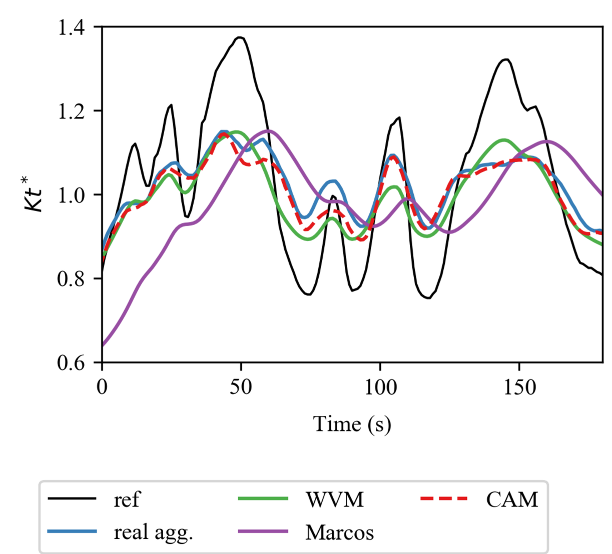
Smaller plants have a higher cutoff frequency than larger ones.

Higher wind speed makes the plant appear smaller, with higher cutoff frequency.

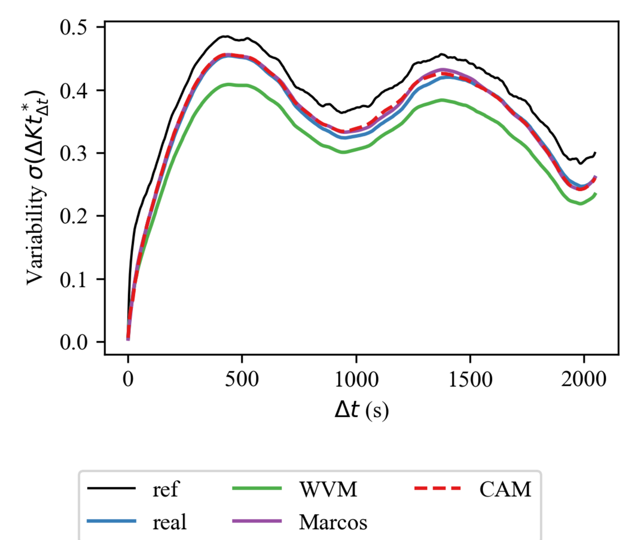


Modeling time series and variability is possible

The CAM provides reasonable model for smoothing of the time series, and reduction of the variability metric. Under advection-dominated conditions, representing the advection physics with a model of this type is necessary to capture some features of the plant output.



Example time series of clear-sky index for various models



Variability as measured by clear-sky index ramp rates

Conclusion: generalization still needed to move beyond 1-D

The CAM agreed with the plant transfer function in 1-D and for advection dominated cases, supporting the need for this physical approach. The model sees dynamics in the real transfer function that other models don't. We need to study ways to adapt this approach to deal with 2-D sites and for a broad range of cloud conditions.

Acknowledgments

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