Surface Solar Irradiance in Complex Cloud-Aerosol Environments

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Motivation & Aim

- Ubiquitous shallow cumulus clouds exhibit detailed 3D structure causing complex variability in surface solar irradiance (SSI) relevant for renewable energy and other applications.
- We aim to understand and predict the SSI variability by examining its relationship with the cloud-aerosol environment.

Cloud-Aerosol-Radiation Simulation

- Large eddy simulation (LES) - with a horizontal grid spacing of 100 x 100 m and domain size of 24 km - is run for more than 40 separate days spanning the summers of 2015-2018 that each develop shallow cumuli at the Southern Great Plains (SGP) Atmospheric Observatory in Oklahoma[1,2,3] (e.g., Fig. 1).

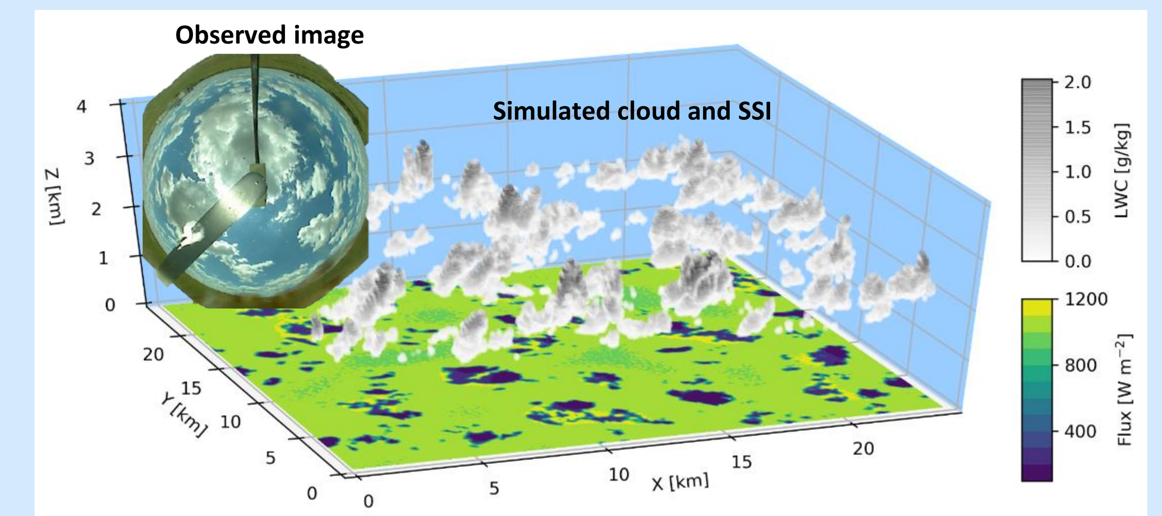

Fig. 1. Simulation of shallow cumulus clouds and associated SSI at 14:30 on 27 June 2015 at the SGP site in Oklahoma. An observed total sky image valid at the same location at time is provided for reference in the upper left.

- For simulated days in 2018[3], an observationally-constrained aerosol variability is implemented and the resulting 3D cloud and aerosol fields are ingested into 3D radiative transfer.

3D Radiative Effects Control Surface Solar Irradiance

- The observed shape of the SSI probability density function (PDF) beneath shallow cumulus clouds is only reproduced with 3D radiative transfer[1,2] (e.g., Fig. 2).

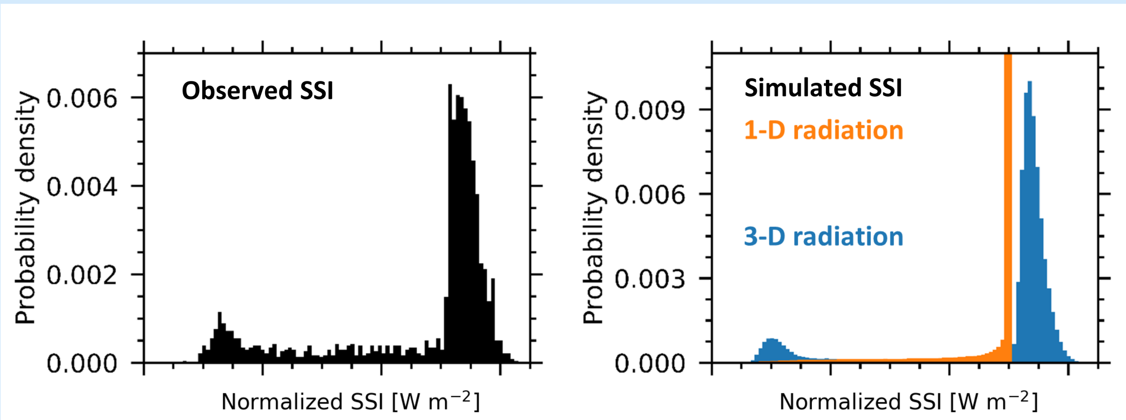

Fig. 2. Observations (left) and simulations (right) of shallow cumulus clouds and associated SSI PDFs on the afternoon of 27 June 2015 at the SGP site in Oklahoma.

Conclusions

1. Surface solar irradiance variability beneath shallow cumulus clouds is complex but is predicted accurately with a handful of representative aerosol and cloud field properties via machine learning.
2. Aerosol exert an inordinately large influence on surface solar irradiance for shallow cumulus clouds.
3. Results have relevance for renewable energy assessments and several other applications.

Aerosol Perturbs Surface Solar Irradiance when Co-Existing with Shallow Cumulus Clouds

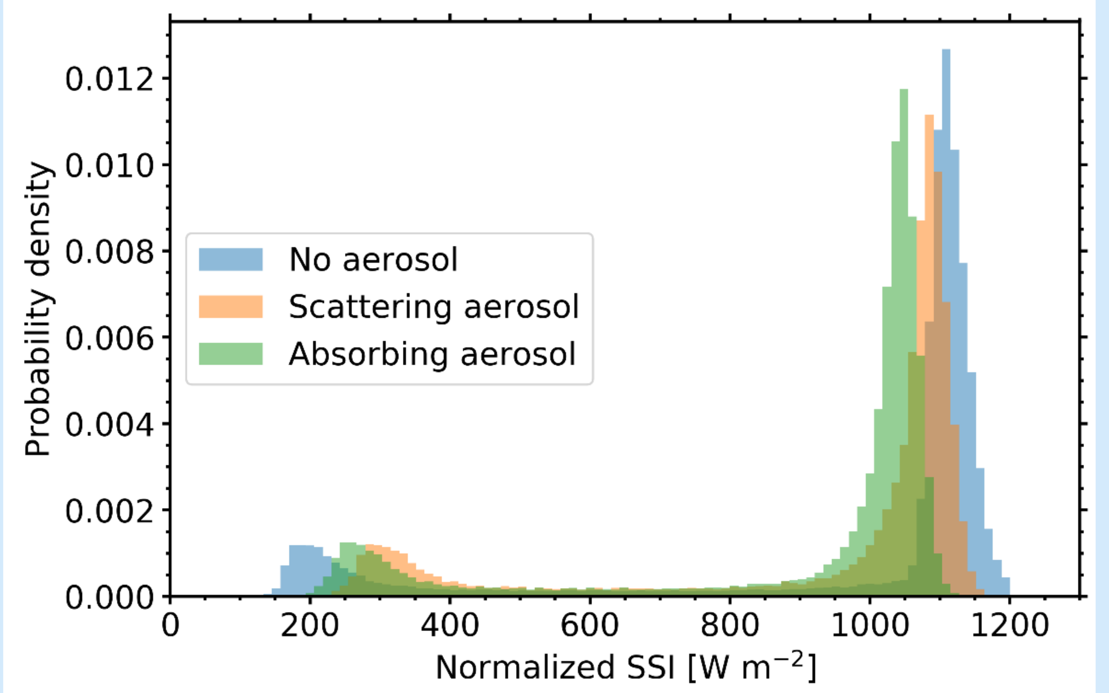

Fig. 3. Simulated SSI PDF at 14:30 on 22 May 2018 without aerosol (blue) and with aerosol that is non-absorbing (orange) and partially absorbing (green).

- Aerosol embedded in shallow cumulus cloud fields significantly perturbs the SSI PDF[3] (e.g., Fig. 3).

- The shape of the SSI PDF is quantified by fitting distributions[2,3].
  - Small SSI mode, normal: $f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$.
  - Large SSI mode, lognormal: $f(x) = \frac{1}{(x-\theta)s\sqrt{2\pi}} \exp\left(-\frac{\ln^2\left(\frac{x-\theta}{m}\right)}{2s^2}\right)$.
- Seek relationships between 9 aerosol and cloud field properties, and 7 SSI PDF fit parameters[3] (Table 1).

Table 1. Machine learning inputs (range of values in square brackets) and outputs.

Aerosol and cloud field properties (inputs)	SSI PDF fit parameters (outputs)
Mean cloud fraction: $\overline{f_C}$ [5.2–34.0 %]	Normal location parameter: μ
Dispersion in cloud liquid water path: **D(LWP)** [1.0–2.3]	Normal shape parameter: σ
Mean in-cloud drop number concentration: $\overline{N_C}$ [312–1540 cm^{-1}]	Weight of small SSI mode: w_1
Mean projected cloud area: $\overline{A_C}$ [0.15–1.56 km^2]	Lognormal location parameter: θ
Mean distance to nearest cloud: $\overline{D_{C-NN}}$ [0.80–1.23 km]	Lognormal shape parameter: **s**
Cosine of solar zenith angle: **cos(SZA)** [0.77–0.97]	Lognormal scale parameter: **m**
Minimum aerosol optical depth at 500 nm: AOD_{min} [0.06–0.91]	Weight of large SSI mode: w_2
Mean aerosol single scattering albedo at 500 nm: $\overline{\omega_a}$ [0.75–1.00]	
Mean aerosol asymmetry parameter at 500 nm: $\overline{g_a}$ [0.50–0.66]	

Machine Learning Predicts Surface Solar Irradiance Accurately

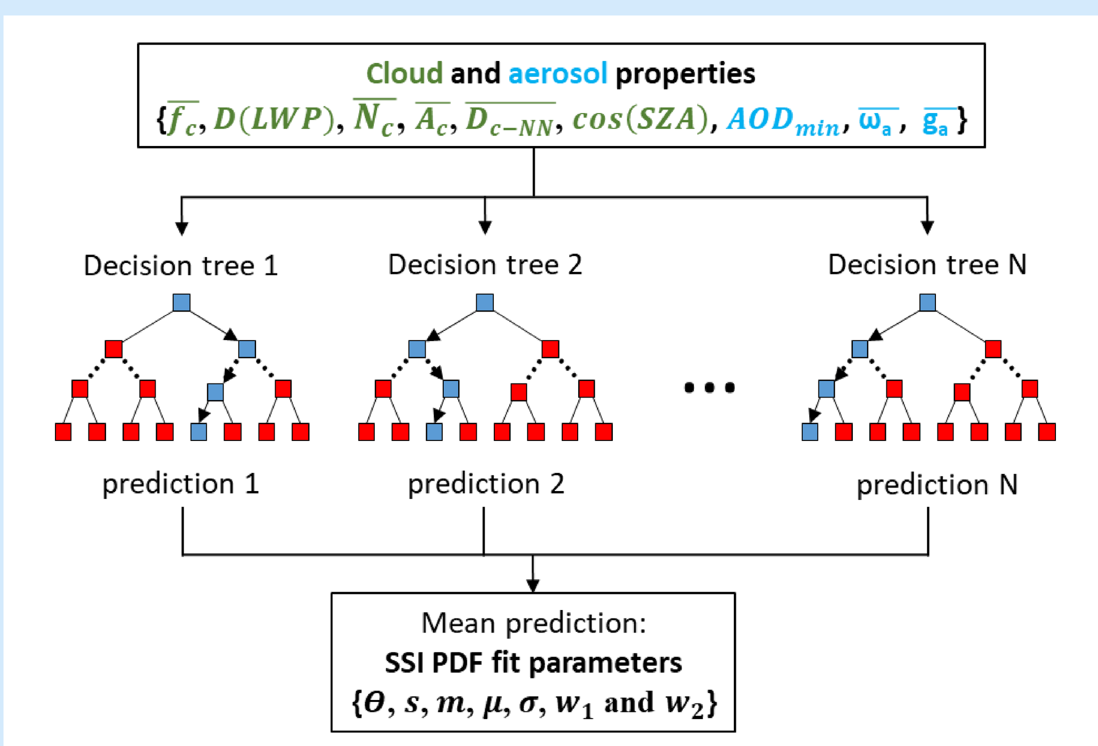

Fig. 4. Schematic of Random Forest as employed in this study.

- A random forest[2,3] is used to predict the SSI PDF (Fig. 4).

- Predictions capture variations in the shape and size of both modes[3] (Fig. 5). Note that 1D radiative transfer does not capture even the bimodal shape, let alone the detailed variations.

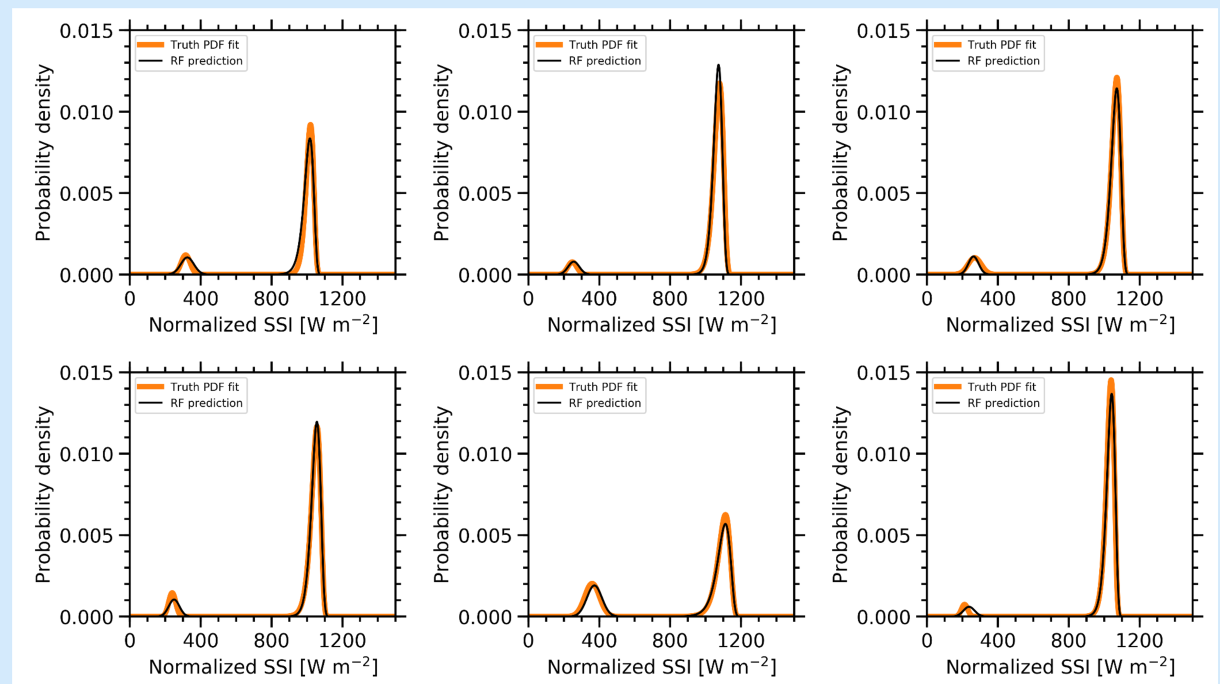

Fig. 5. Six random predictions of SSI PDFs on independent test data.

Importance Metrics Reveal Radiative Processes

- Aerosol extinction of the direct beam darkens clear-sky SSI, and aerosol scattering brightens cloud shadows (Fig. 6).

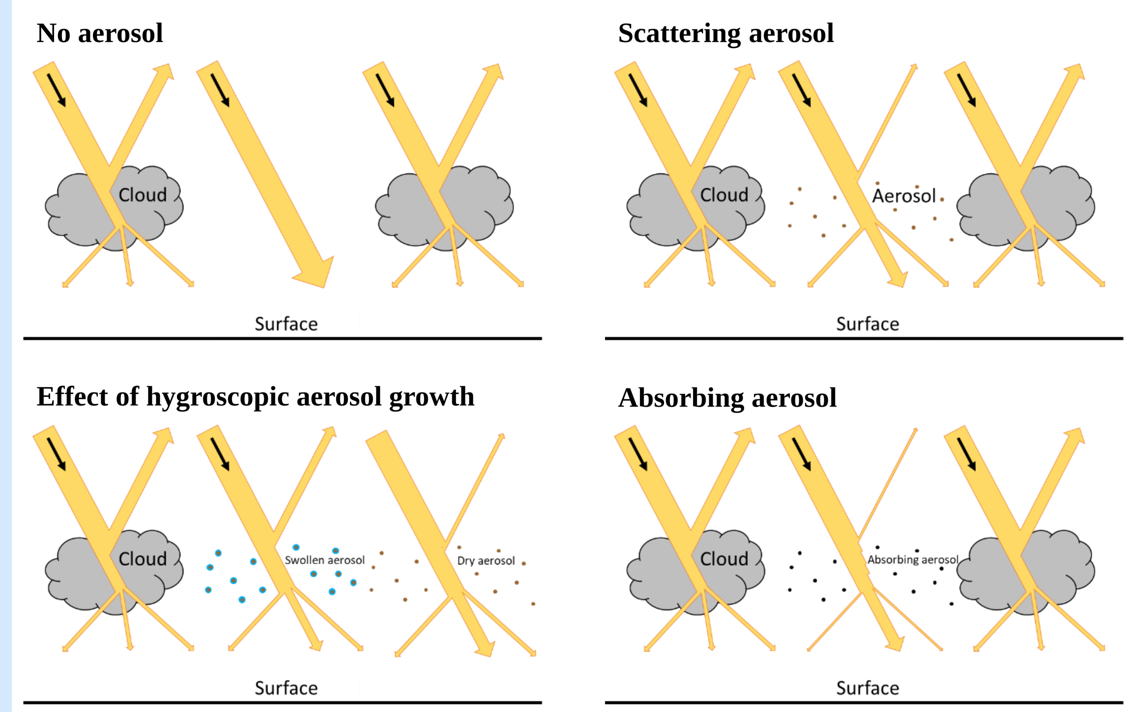

Fig. 6. Schematic of aerosol influence on SSI in the presence of shallow cumulus clouds.

- Machine learning importance metrics quantify the importance of aerosol between clouds for controlling the SSI (Table 2).

Table 2. Permutation importance of each input for each output separately. For each input, darker shading indicates relatively higher importance.

	μ	σ	w_1	θ	s	m	w_2
$\overline{f_C}$	9.5 ± 0.9	20.4 ± 1.6	41.1 ± 3.1	10.5 ± 0.8	10.8 ± 0.9	17.7 ± 1.5	28.6 ± 2.1
$D(LWP)$	0.3 ± 0.0	3.1 ± 0.2	1.3 ± 0.1	0.2 ± 0.0	2.0 ± 0.1	1.3 ± 0.1	1.4 ± 0.1
$\overline{N_C}$	0.6 ± 0.0	3.7 ± 0.2	2.3 ± 0.2	0.4 ± 0.0	3.1 ± 0.2	4.2 ± 0.3	6.0 ± 0.6
$\overline{A_C}$	0.7 ± 0.1	4.9 ± 0.3	8.4 ± 0.7	1.3 ± 0.1	3.4 ± 0.2	4.6 ± 0.4	5.6 ± 0.4
$\overline{D_{C-NN}}$	0.2 ± 0.0	2.6 ± 0.1	1.0 ± 0.1	0.2 ± 0.0	1.9 ± 0.1	1.7 ± 0.2	1.4 ± 0.2
$cos(SZA)$	1.0 ± 0.1	6.0 ± 0.5	2.9 ± 0.3	0.5 ± 0.0	4.2 ± 0.3	10.0 ± 1.0	4.7 ± 0.5
AOD_{min}	62.7 ± 4.4	37.9 ± 2.8	28.3 ± 2.2	58.8 ± 4.3	60.9 ± 3.5	37.7 ± 2.7	39.1 ± 2.6
$\overline{\omega_a}$	22.8 ± 2.1	14.8 ± 1.4	8.6 ± 1.2	23.5 ± 2.0	7.6 ± 0.7	14.1 ± 1.8	5.5 ± 0.4
$\overline{g_a}$	2.3 ± 0.1	6.6 ± 0.3	6.1 ± 0.5	4.6 ± 0.3	6.2 ± 0.4	8.7 ± 0.8	7.6 ± 0.5

- Within the shallow cumulus cloud regime, aerosol variations between clouds have a stronger influence on the SSI variability than variations in the cloud properties themselves.

References

1. Gristey et al., *JAS*, 2020: Surface solar irradiance in continental shallow cumulus fields: observations and large eddy simulation. https://doi.org/10.1175/JAS-D-19-0261.1
2. Gristey et al., *GRL*, 2020: On the relationship between shallow cumulus cloud field properties and surface solar irradiance. https://doi.org/10.1029/2020GL090152
3. Gristey et al., *under review*, 2022: Influence of aerosol embedded in shallow cumulus cloud fields on the surface solar irradiance.