Meteorology both masks and magnifies the aerosol-cloud radiative effect

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Motivation & Aim

- The influence of aerosol on shallow continental cumulus clouds is poorly understood.
- Here we leverage LASSO simulations at SGP to study:
  - The extent to which aerosol effects on cloud brightness are either masked or magnified by co-varying meteorology.
  - The ability of LASSO simulations to represent observed surface irradiance.
  - A modelled hysteresis in cloud radiative effect

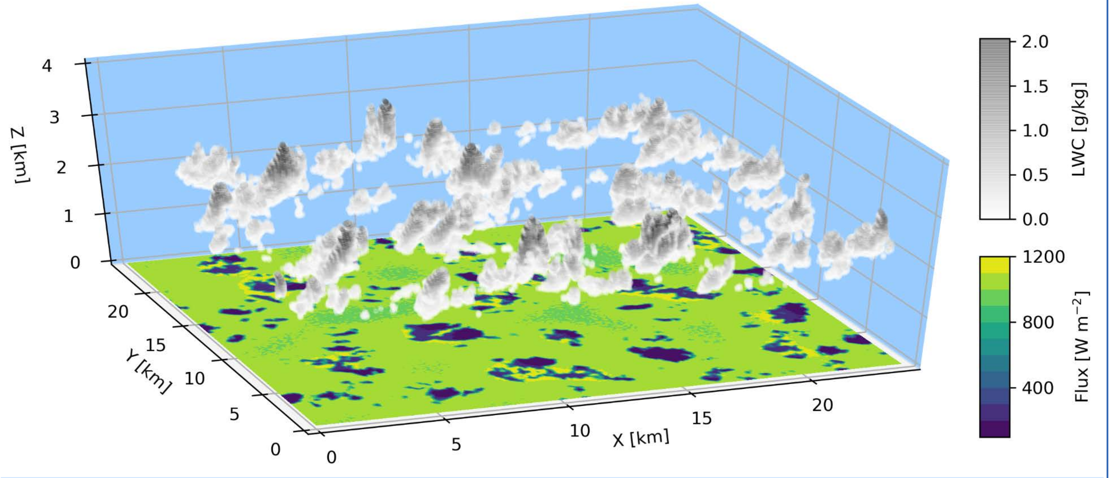
LASSO Data

- The LASSO project (LES ARM symbiotic simulation and observation workflow) brings together shallow cumulus observations at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) atmospheric observatory with high resolution simulations.

(left) Shallow cumulus clouds above the ARM SGP atmospheric observatory in Lamont, Oklahoma.

"A research laboratory more than 100 km wide, without walls or a roof" – just the right size for a cloud field

- Large Eddy Simulation (LES) - with domain size ~24 km, horizontal resolution ~100 m and vertical resolution ~30 m - provide a wider dynamical context for the observations, and help to bridge the gap to weather prediction scales.



(above) System for Atmospheric Modelling (SAM) LES of shallow cumulus cloud liquid water content and surface solar irradiance at SGP, June 27th, 2015.

- **We have re-simulated all 2015 – 2017 LASSO cases using observed aerosol inputs**
- **Here we analyze 16 days of simulations constrained by observations of fair-weather surface-forced shallow cumulus**

Aerosol-Meteorological Co-variability and its Effect on Surface Radiation

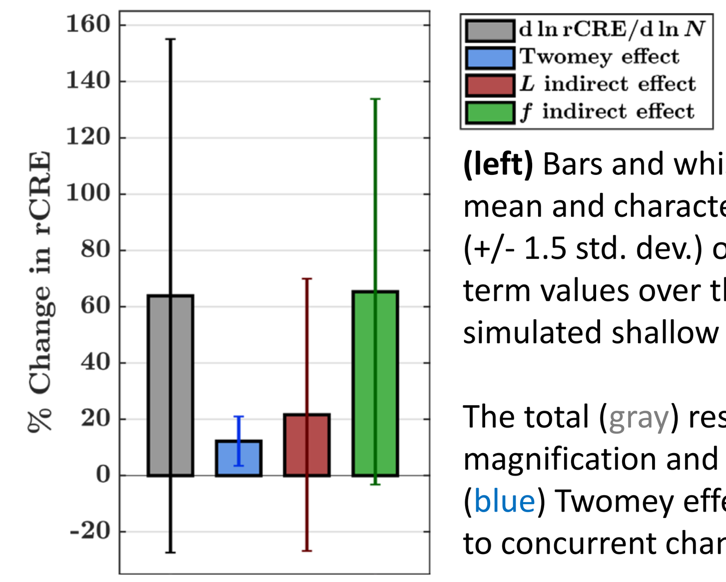
$$\mathrm{rCRE} \simeq f \cdot \mathcal{A}, \qquad \mathcal{A} \simeq \mathcal{A}(L, N)$$

For shortwave (solar) radiation, the relative Cloud Radiative Effect (**rCRE**) is approximately equal to the cloud fraction, ***f***, times the cloud albedo, ***A*** (Xie et al. 2014)

A = Cloud Albedo
L = Liquid Water Path
N = Number of Cloud droplets

What is the change in rCRE associated with perturbations in cloud drop number *N*?

$$\frac{d\ln \mathrm{rCRE}}{d\ln N} = \frac{\partial \ln \mathcal{A}}{\partial \ln N} + \frac{\partial \ln \mathcal{A}}{\partial \ln L}\frac{d\ln L}{d\ln N} + \frac{d\ln f}{d\ln N}$$



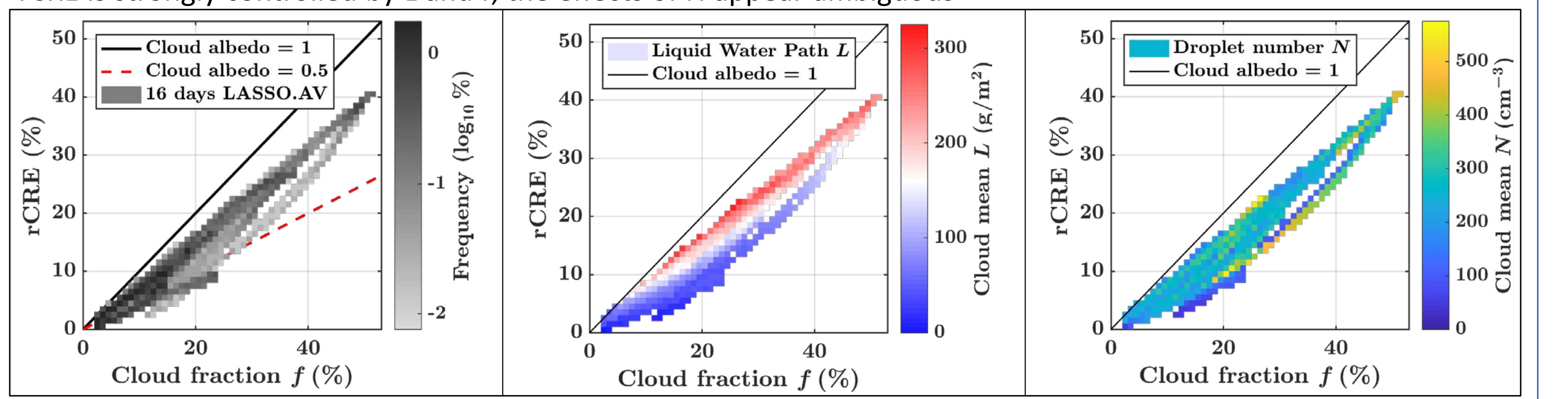
(left) Bars and whiskers show the mean and characteristic range (+/- 1.5 std. dev.) of the budget term values over the 16 simulated shallow cumulus days.

The total (gray) result shows magnification and masking of the (blue) Twomey effect values due to concurrent changes in *L* and *f*.

Key Result:
Assessment of relative contributions to rCRE:

1. Twomey effect is smaller but less variable than liquid water path *L* and cloud fraction *f* responses
2. Mutual information analysis shows *f* and *N* explain 80% of rCRE variability, while *L* and *N* explain 65%.
3. The radiative effect of an *N* perturbation is magnified by L much more often than it is masked by L

(Below) Simulation results in relative Cloud Radiative Effect (**rCRE**) vs cloud fraction (***f***) state space.
rCRE is strongly controlled by L and f; the effects of N appear ambiguous



MI (rCRE,*f*) = 65% | MI (rCRE,*L*) = 35% | MI (rCRE,*N*) = 18%

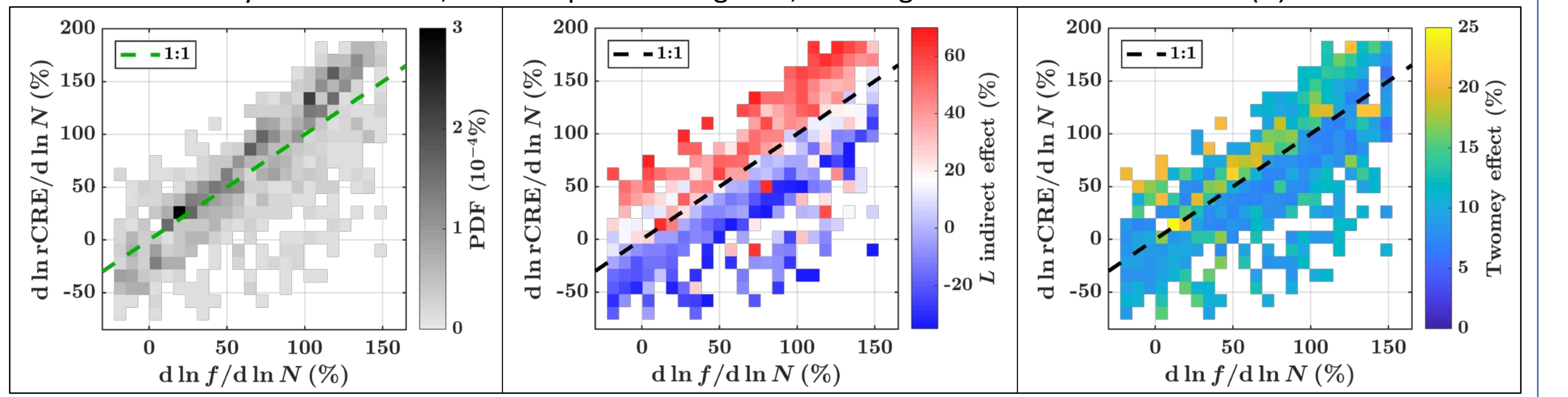
CMI (rCRE,*f*) | *L* = 71% | CMI (rCRE,*L*) | *N* = 65%

Mutual information (**MI**) measures how much rCRE variation is explained by ***1*** variable.

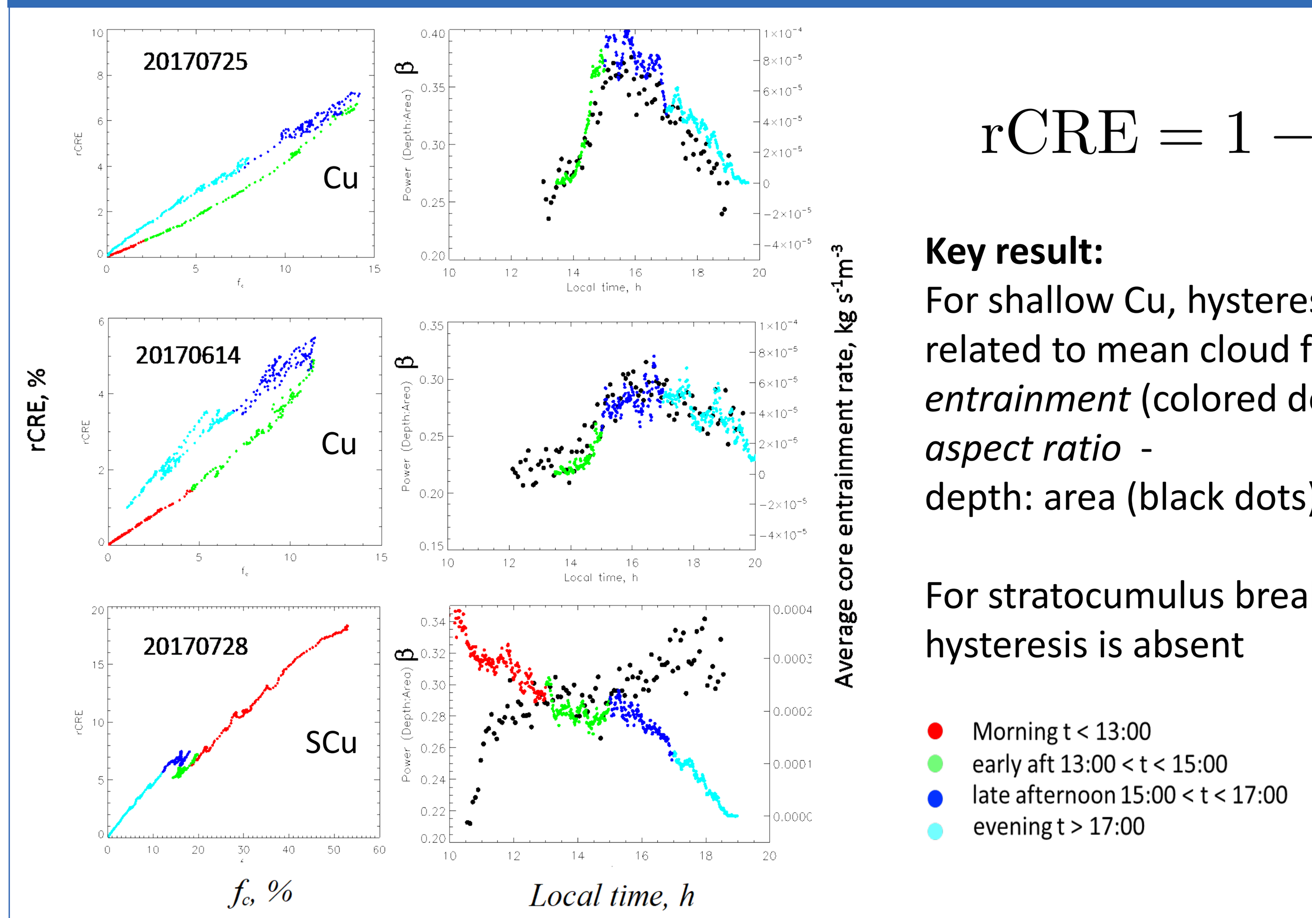
Conditional-MI (**CMI**) measures how much rCRE variation is explained by ***2*** variables.

CMI (rCRE,*f*) | *N* = 80%

(Below) The terms in the rCRE budget (bar chart):
When the Twomey effect is large, the L response is positive, magnifying the radiative effect of dln(*N*).
When the Twomey effect is small, the L response is negative, masking the radiative effect of dln(*N*).



Hysteresis in Relative Cloud Radiative Effect Vs. Cloud Fraction state space



$$\mathrm{rCRE} = 1 - \frac{F^{\downarrow}_{\mathrm{sw,all}}}{F^{\downarrow}_{\mathrm{sw,clr}}}$$

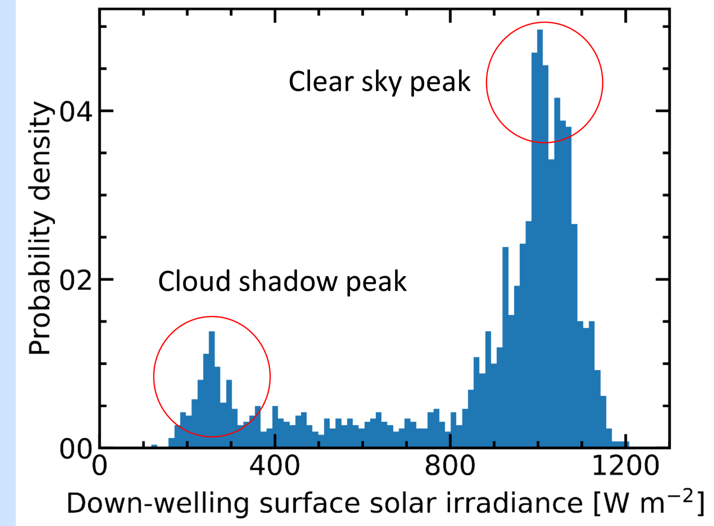
Key result:
For shallow Cu, hysteresis is often tightly related to mean cloud field core *entrainment* (colored dots) and *cloud aspect ratio* - depth: area (black dots)

For stratocumulus breaking into cumulus, hysteresis is absent

Summary

1. The cloud radiative effect of shallow cumulus at SGP is dominated by cloud fraction; aerosol effects on cloud brightness can be masked or magnified by concurrent changes in cloud liquid water path. Aerosol-meteorological co-variability matters!
2. Many shallow cumulus LASSO cases exhibit a hysteresis in the cloud radiative effect (rCRE) vs. cloud fraction (*f*) state space. This can be traced to temporal evolution in cloud entrainment as well as the cloud depth-to-area ratio
3. Modelled and observed downwelling surface shortwave radiation agree well only if 3D radiative effects are accounted for.

Evaluating LES against Surface Radiation

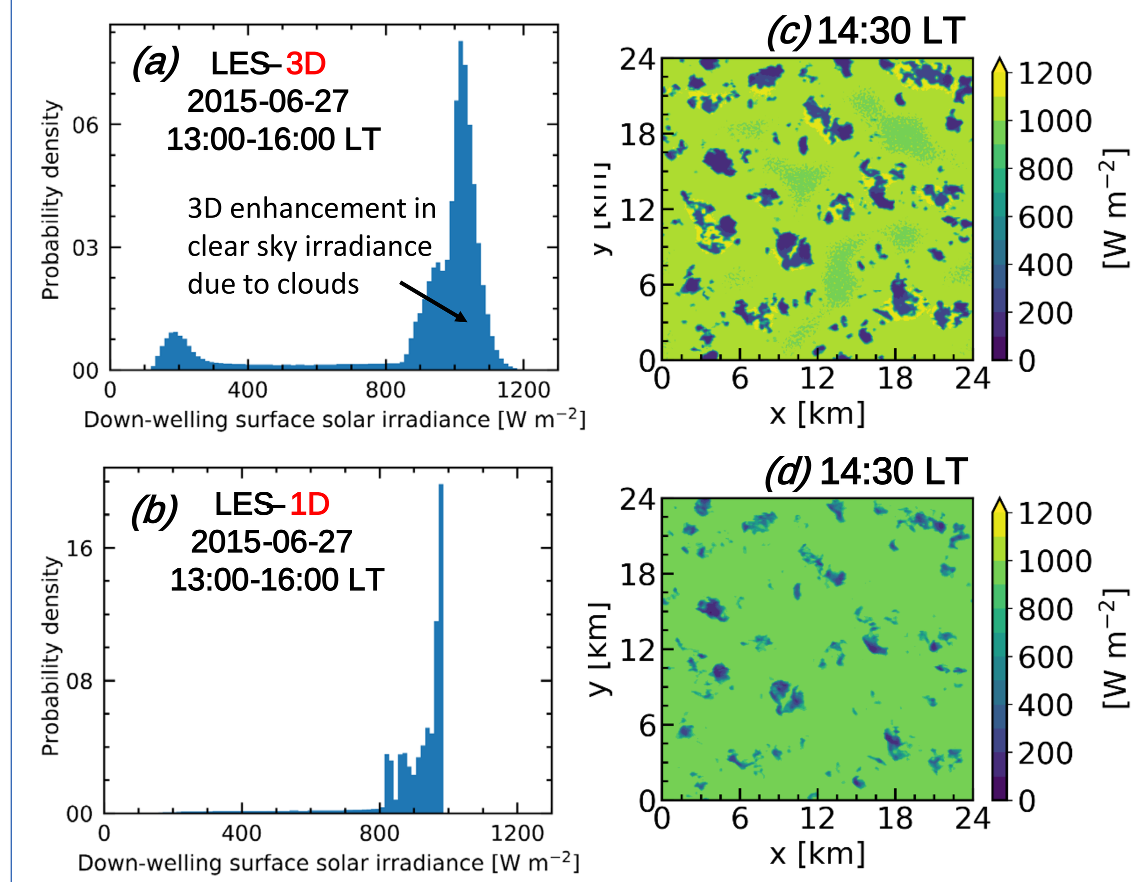


(left) PDF of observed down-welling surface solar irradiance, 1-min frequency Radiative Flux Analysis.

Data accumulated from 10 locations within 150 km of SGP, the afternoon of June 27th 2015.

Key Result:

The observed probability density function (PDF) of down-welling surface solar irradiance is bi-modal, and can only be reproduced in simulations when 3D radiative effects (i.e., horizontal photon transport) are included.



(above) (*a*) and (*b*): PDFs of simulated down-welling surface solar irradiance on the afternoon of June 27th 2015, the LES output was input to an offline radiative transfer model (Schmidt and Chen) with and without 3D effects, respectively. (*c*) and (*d*): Corresponding maps of the down-welling surface solar irradiance at 14:30 LST, near the time of peak cloud fraction.

Future work

- Extend analyses to all new (2018 →) LASSO cases
- Test current hypothesis on rCRE-*f* hysteresis and understand why it doesn't always appear
- Continue to quantify aerosol-meteorological co-variability and its influence on the aerosol-cloud radiative effect
- Examine the relationship between the bi-modal PDF of downwelling irradiance and properties of the cloud field (e.g., cloud fraction, size, spacing, optical thickness). Investigation of these relationships may enable a first order "retrieval" of such properties.

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