Meteorology both masks and magnifies the aerosol-cloud radiative effect

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LES ARM Symbiotic Simulation and Observation (LASSO)

- Complement mega-site observations with routine large eddy simulation (LES)

- Support community study of atmospheric processes and evaluation of parameterizations (Gustafson, Vogelmann et al.)

- We have used LASSO and additional observations to study aerosol-cloud-radiation variability
What are the radiative consequences of aerosol co-variability with cloud?

• Understanding the shortwave radiative effect of shallow clouds over land is important for climate change science and solar power

• **Aerosol perturbations** can cause variation in cloud drop number, changing the brightness of clouds (Twomey effect)

• **Meteorology** also changes cloud brightness

• Here we look at co-variability between meteorological drivers of cloud albedo

Many bright clouds? Few, dim clouds?

Poster #32 Wednesday 5:00 – 6:30 p.m.
We added **Aerosol Variability** from observations to LASSO

- LES input :: 1-minute (1-hour smoothed) SGP near-surface observations
  - NOAA-AOS / CCN and CN-counter
    Betsy Andrews (NOAA / CIRES)

- Mixing and aerosol activation is simulated
  - System for Atmospheric Modeling (SAM-LES)
    \( \Delta z = 30 \text{m}, \Delta x = 100 \text{m}, D \approx (24 \text{ km})^3 \)
    Microphysics: 2-moment
    Radiation: RRTMG

- Number of cloud droplets \( N \) is thus a simulated quantity, constrained by observations
Does aerosol and "meteorological" co-variation mask or magnify the radiative effect of cloud droplet number perturbations?
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)

$$rCRE = f \cdot A$$
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\[ r\text{CRE} = f \cdot A, \quad A \approx A(L, N) \]

- \( A \) = Cloud Albedo
- \( L \) = Liquid Water Path
- \( N \) = Number of Cloud droplets
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- **A** = Cloud Albedo
- **L** = Liquid Water Path
- **N** = Number of Cloud droplets
\[ rC{\text{CRE}} = f \cdot A, \quad A \simeq A(L, N) \]

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

\[ r\text{CRE} = f \cdot A \quad , \quad A(L, N) \]

Budget analysis:
How does rCRE change as cloud drop number \( N \) changes?
rCRE Budget

\[ rCRE = f \cdot A \quad , \quad A(L, N) \]

Budget analysis:
How does rCRE change as cloud drop number \( N \) changes?

\[ \ln(rCRE) = \ln f + \ln A \]

\[ \frac{d \ln rCRE}{d \ln N} = \]
rCRE Budget

\[ rCRE = f \cdot A, \quad A(L, N) \]

Change in rCRE with change in \( N \) = Radiative effect of drop Number variation (Twomey Effect) + Radiative effect of LWP variation + Radiative effect of cloud fraction variation

\[
\frac{d \ln rCRE}{d \ln N} = \left( \frac{\partial \ln A}{\partial \ln N} \right) + \left( \frac{\partial \ln A}{\partial \ln L} \right) \frac{d \ln L}{d \ln N} + \frac{d \ln f}{d \ln N}
\]
rCRE Budget

\[ r\text{CRE} = f \cdot A \cdot A(L, N) \]

Temporal Numerical Differentiation
(Numerical Recipes, 2007)

Timescale of variation
\( \sim 1 \) hour

\[
\frac{d \ln r\text{CRE}}{d \ln N}(t) = \frac{\partial \ln A}{\partial \ln N}(t) + \frac{\partial \ln A}{\partial \ln L} \frac{d \ln L}{d \ln N}(t) + \frac{d \ln f}{d \ln N}(t)
\]
rCRE Budget

Change in rCRE with change in $N$ = Radiative effect of drop Number variation (Twomey Effect) + ... 

\[
\frac{d \ln rCRE}{d \ln N}(t) = \frac{\partial \ln \mathcal{A}}{\partial \ln N}(t) + \frac{\partial \ln \mathcal{A}}{\partial \ln L} \frac{d \ln L}{d \ln N}(t) + \frac{d \ln f}{d \ln N}(t)
\]

Bar = Mean
Whisker +/- 1.5 Std. Dev.
rCRE Budget

1. The radiative effect of an $N$ perturbation is magnified by concurrent changes in cloud fraction $f$.

2. The concurrent $L$ response is sometimes positive, sometimes negative - magnifying or masking $N$.

\[
\frac{d \ln \text{rCRE}}{d \ln N}(t) = \frac{\partial \ln A}{\partial \ln N}(t) + \frac{\partial \ln A}{\partial \ln L} \frac{d \ln L}{d \ln N}(t) + \frac{d \ln f}{d \ln N}(t)
\]
Mutual Information:

We use an independent analysis called Mutual information ($\text{MI}$) to quantify how much rCRE variability is explained by different variables (Shannon 1949)

\[
\text{MI}(y, x) = \sum_{X} \sum_{Y} p(x, y) \log \frac{p(x, y)}{p(x) \cdot p(y)}
\]

**MI** tells us:
Which variable $x$ is best at explaining $y$?

**CMI** tells us:
Which pair $(x,z)$ is best at explaining $y$?

\[
\text{CMI}(y, x|z) = \sum_{X} \sum_{Y} \sum_{Z} p(x, y, z) \log \frac{p(z) \cdot p(x, y, z)}{p(x, z) \cdot p(y, z)}
\]
Mutual Information:

\[
\text{MI} :: \text{rCRE} \leftrightarrow f_c = 65\%
\]

\[
\text{MI}(x, y) = \sum p(x, y) \log \frac{p(x, y)}{p(x) \cdot p(y)}
\]
Mutual Information:

\[ \text{MI} :: \text{rCRE} \leftrightarrow f_c = 65\% \]

\[ \text{MI} :: \text{rCRE} \leftrightarrow L_c = 34\% \]

\[ \text{MI}(x, y) = \sum p(x, y) \log \frac{p(x, y)}{p(x) \cdot p(y)} \]
Mutual Information:

\[ MI :: rCRE \leftrightarrow f_c = 65\% \]

\[ MI :: rCRE \leftrightarrow L_c = 34\% \]

\[ MI :: rCRE \leftrightarrow N_c = 18\% \]

\[ MI(x, y) = \sum p(x, y) \log \frac{p(x, y)}{p(x) \cdot p(y)} \]
Mutual Information:

\[
\text{MI} :: \text{rCRE} \leftrightarrow f_c = 65\%
\]

\[
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\]

\[
\text{MI} :: \text{rCRE} \leftrightarrow N_c = 18\%
\]

\[
\text{MI}(x, y) = \sum p(x, y) \log \frac{p(x, y)}{p(x) \cdot p(y)}
\]

\[
\text{CMI}(y, x | z) = \sum_x \sum_y \sum_z p(x, y, z) \log \frac{p(z) \cdot p(x, y, z)}{p(x, z) \cdot p(y, z)}
\]

\[
\text{CMI (rCRE, } f | L) = 71\%
\]
### Mutual Information:

<table>
<thead>
<tr>
<th>MI :: rCRE ↔ $f_c$</th>
<th>$65%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MI :: rCRE ↔ $L_c$</td>
<td>$34%$</td>
</tr>
<tr>
<td>CMI (rCRE, $f$</td>
<td>$L$)</td>
</tr>
<tr>
<td>CMI (rCRE, $L$</td>
<td>$N$)</td>
</tr>
<tr>
<td>MI :: rCRE ↔ $N_c$</td>
<td>$18%$</td>
</tr>
</tbody>
</table>

\[
\text{MI}(x, y) = \sum p(x, y) \log \frac{p(x, y)}{p(x) \cdot p(y)}
\]

\[
\text{CMI}(y, x|z) = \sum_x \sum_y \sum_z p(x, y, z) \log \frac{p(z) \cdot p(x, y, z)}{p(x, z) \cdot p(y, z)}
\]
Mutual Information:

\[
\text{MI} :: r\text{CRE} \leftrightarrow f_c = 65\%
\]

\[
\text{MI} :: r\text{CRE} \leftrightarrow L_c = 34\%
\]

\[
\text{MI} :: r\text{CRE} \leftrightarrow N_c = 18\%
\]

\[
\text{CMI} (r\text{CRE}, f | L) = 71\%
\]

\[
\text{CMI} (r\text{CRE}, L | N) = 65\%
\]

\[
\text{CMI} (r\text{CRE}, f | N) = 80\%
\]
Explanation?

**rCRE Budget**

The role of $N$ is small compared to $f$ and $L$

**Mutual Information:**

The role of $N$ is larger than the role of $L$

\[
\text{CMI (rCRE, } f | N) = 80\%
\]
Co-variability between terms

rCRE Budget

The role of $N$ is small compared to $f$ and $L$

Mutual Information:

The role of $N$ is larger than the role of $L$

$$\text{CMI (rCRE, } f\mid N) = 80\%$$

$$\frac{d \ln \text{rCRE}}{d \ln N} = \frac{\partial \ln A}{\partial \ln N} + \frac{\partial \ln A}{\partial \ln L} \frac{d \ln L}{d \ln N} + \frac{d \ln f}{d \ln N}$$
\[
\frac{\ln r \text{CRE}}{\ln N}(t) = \frac{\partial \ln A}{\partial \ln N}(t) + \frac{\partial \ln A}{\partial \ln L} \frac{\ln L}{\ln N}(t) + \frac{\ln f}{\ln N}(t)
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\]
Summary:

**Magnifying** the radiative effect

(Most common case)
A given $N$ perturbation is able to increase the albedo a relatively **large** amount. The $L$ response is **positive**.
Summary:

**Magnifying** the radiative effect

(Most common case)
A given \( N \) perturbation is able to increase the albedo a relatively **large** amount. The \( L \) response is **positive**.

**Masking** the radiative effect

(Less common)
They same size of \( N \) perturbation is only able to increase the albedo a **small amount**. The \( L \) response is **zero/negative**.

\[
\frac{d \ln r \text{CRE}}{d \ln N} = \frac{\partial \ln A}{\partial \ln N} + \frac{\partial \ln A}{\partial \ln L} \frac{d \ln L}{d \ln N} + \frac{d \ln f}{d \ln N}
\]

CMI (rCRE, \( f \)) \( \mid N = 80\% \)
Conclusions:

1. Detailed cloud simulations constrained by observations allow us to study the natural variation of aerosol-cloud-radiation interactions.

2. Mutual information analysis shows $f$ and $N$ variation explains 80% of the rCRE, while $L$ and $N$ variation explains 65%.

3. The radiative effects of $N$ perturbations are magnified more often than masked by $L$ and $f$ responses.

A figure looking like this does imply aerosol effect is small... meteorological co-variability matters!