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**?

Many bright clouds?

Few, dim clouds?

- 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

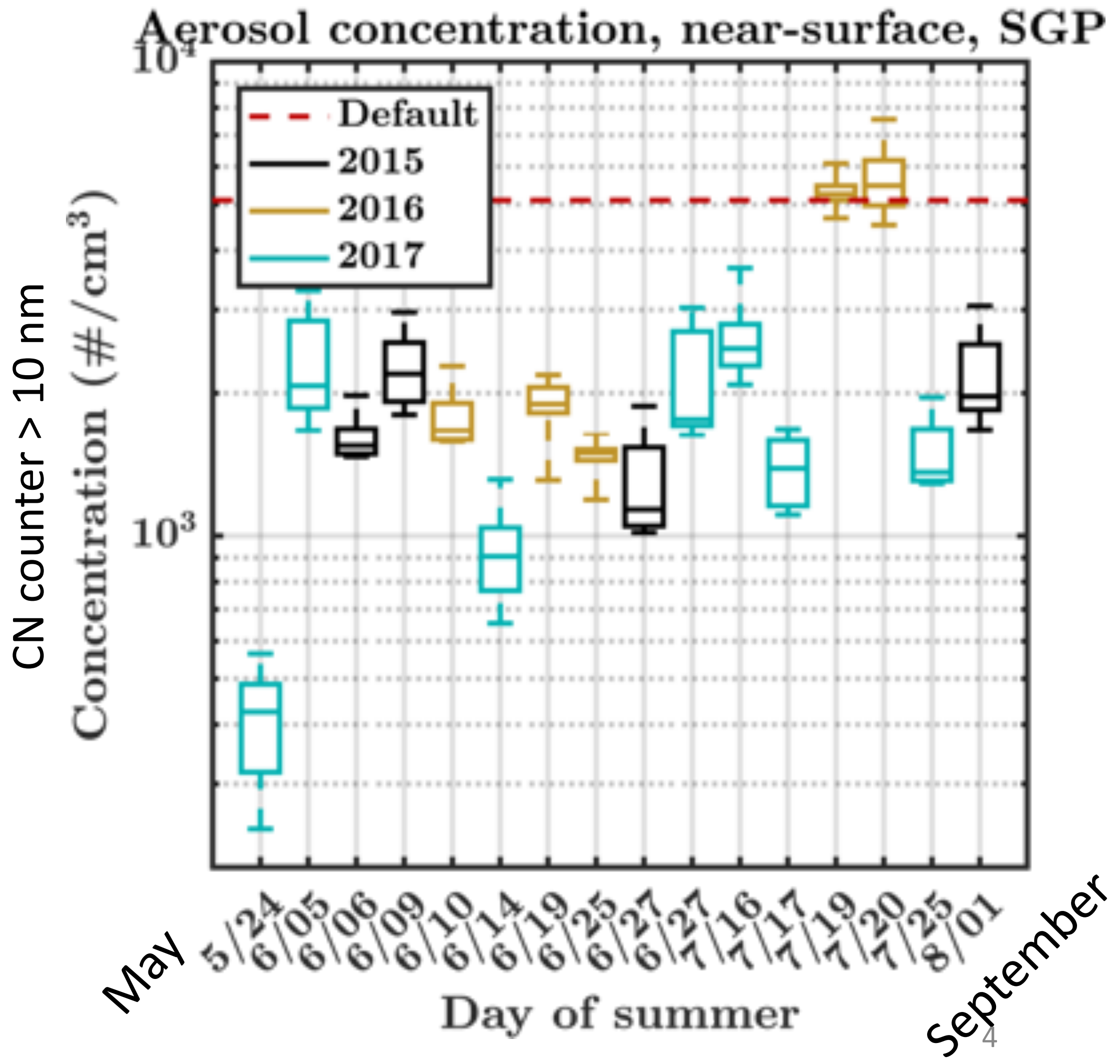
Poster #32 Wednesday 5:00 – 6:30 p.m.

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)
      Δz = 30m, Δx = 100m, D ≈ (24 km)^3
      Microphysics: 2-moment
      Radiation: RRTMG

- Number of cloud droplets ***N*** is thus a simulated quantity, constrained by observations



Surface **aerosol** concentration tendency

Re-analysis **meteorological** forcing

LASSO+N_A

16 re-simulations

Does aerosol and "meteorological" co-variation **mask** or **magnify** the radiative effect of cloud droplet number perturbations?

$$\mathrm{rCRE} = f \cdot \mathcal{A} \ ,$$

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)

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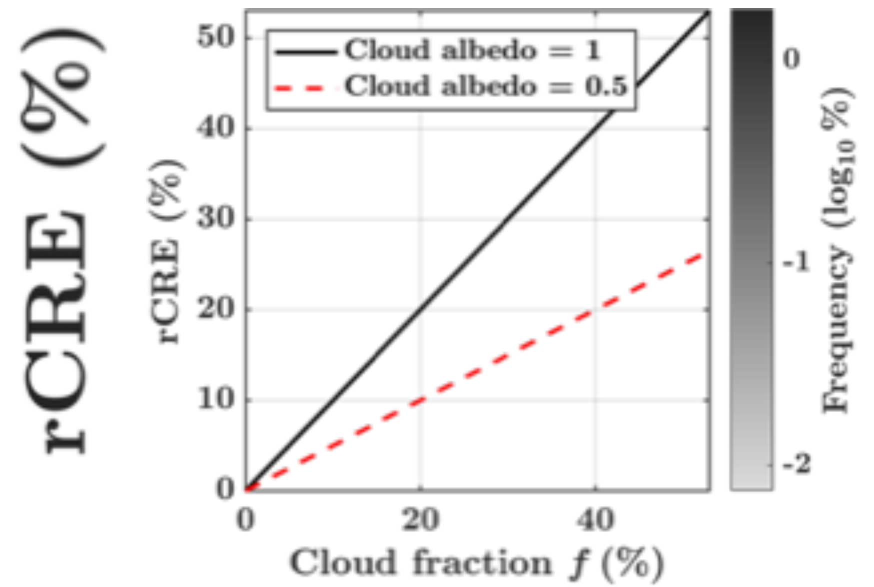
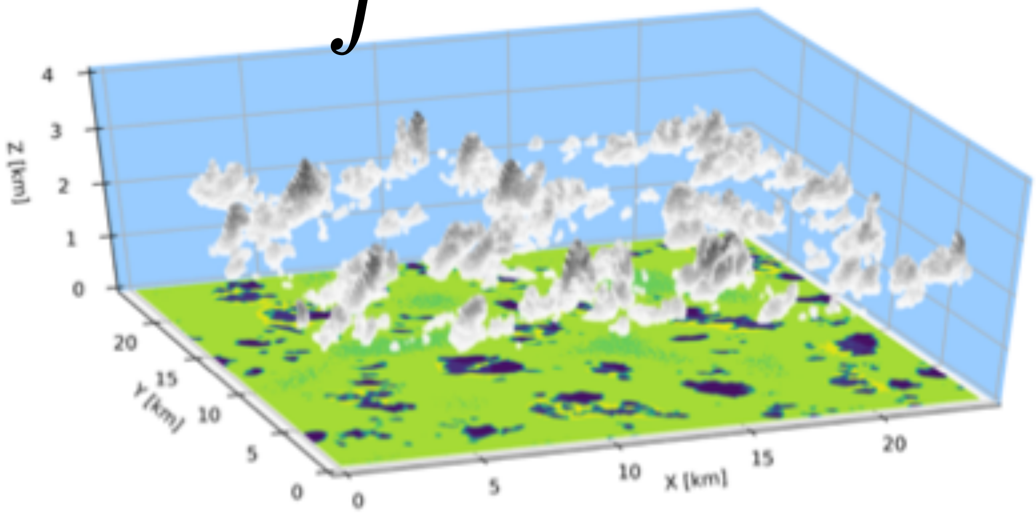


f



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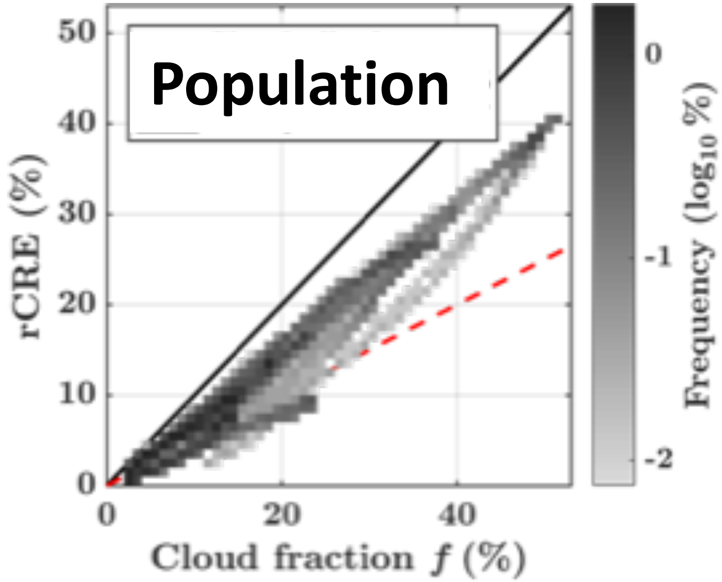
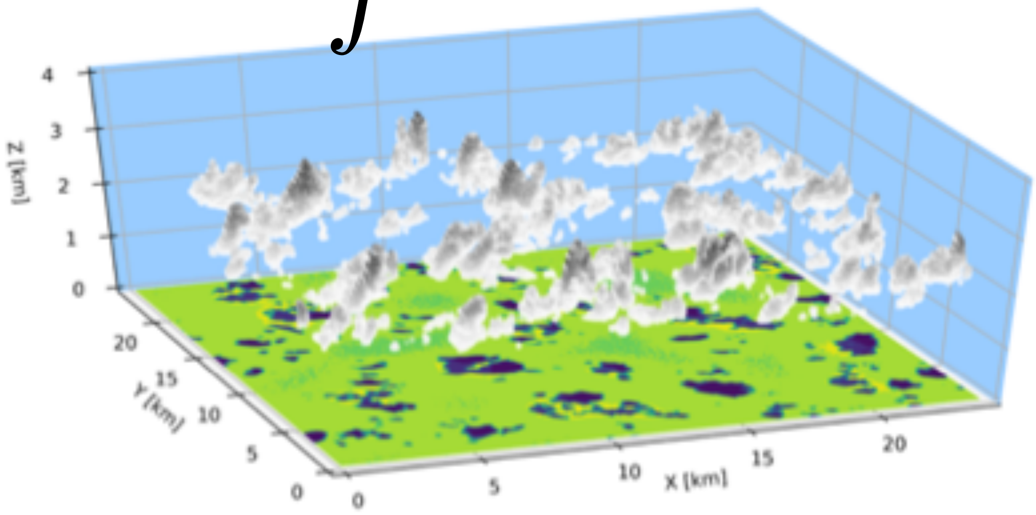
$$\mathrm{rCRE} = f \cdot \mathcal{A} \;, \quad \mathcal{A} \simeq \mathcal{A}(L, N)$$

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

rCRE (%)



f



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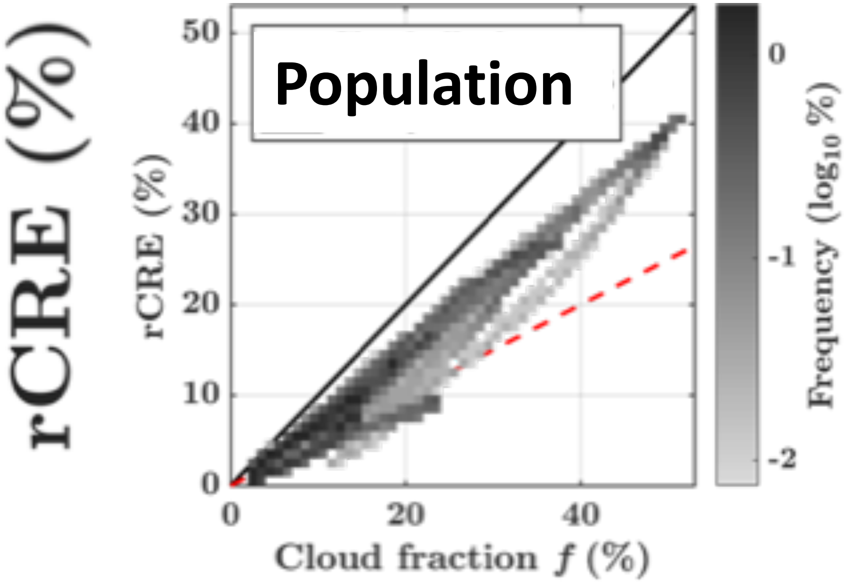
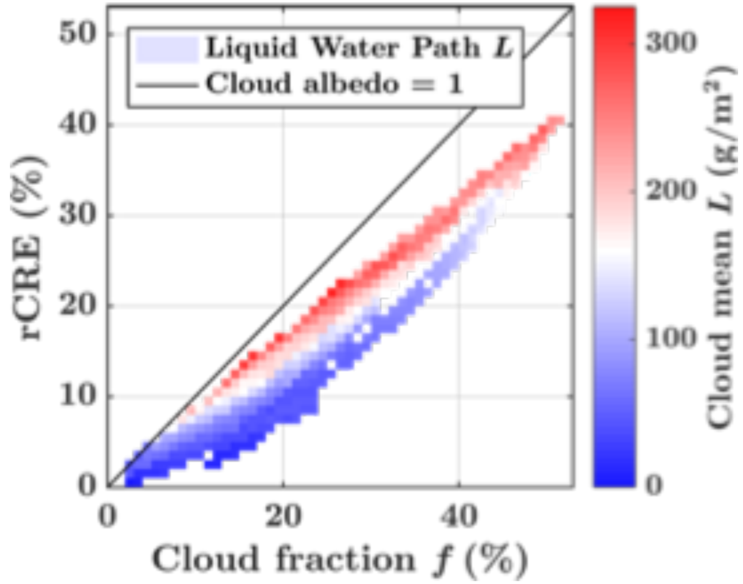
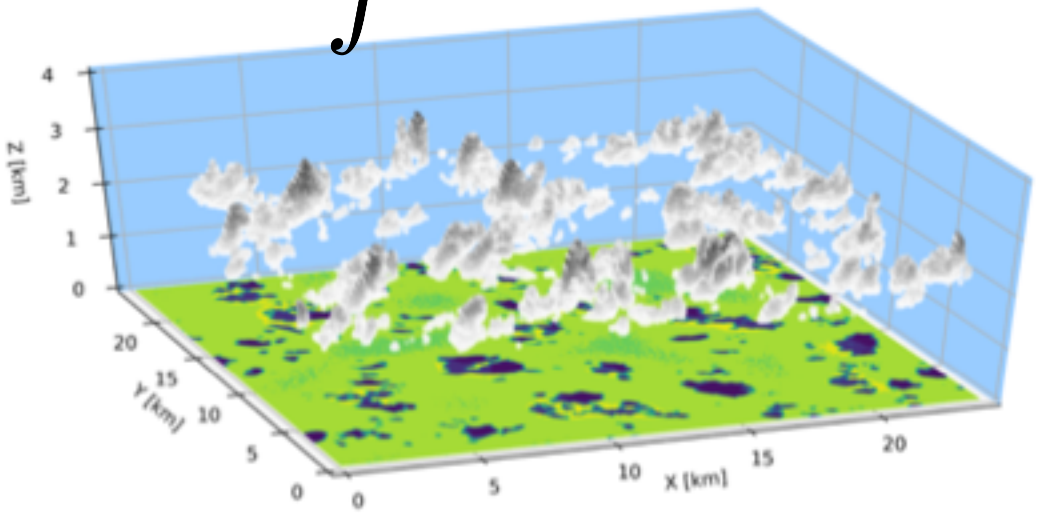




L

f



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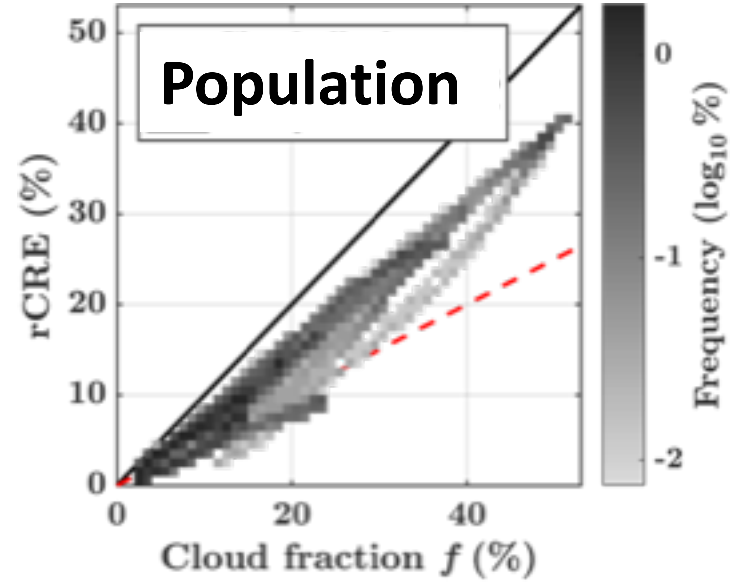
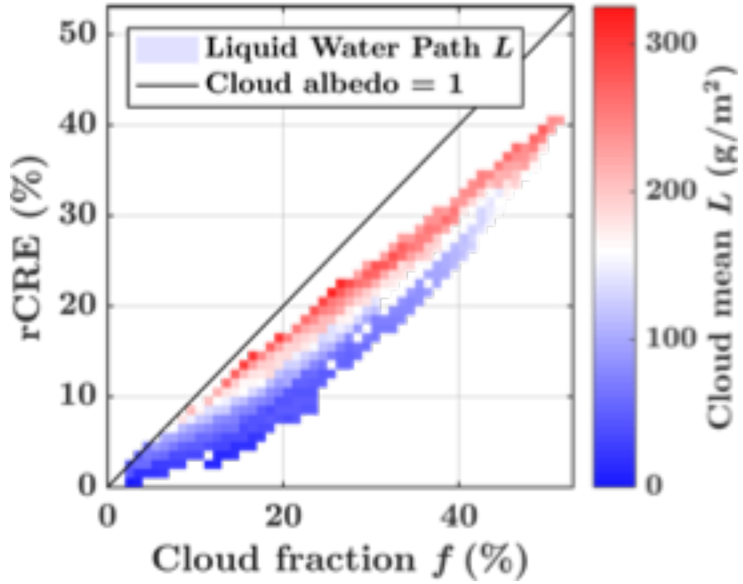
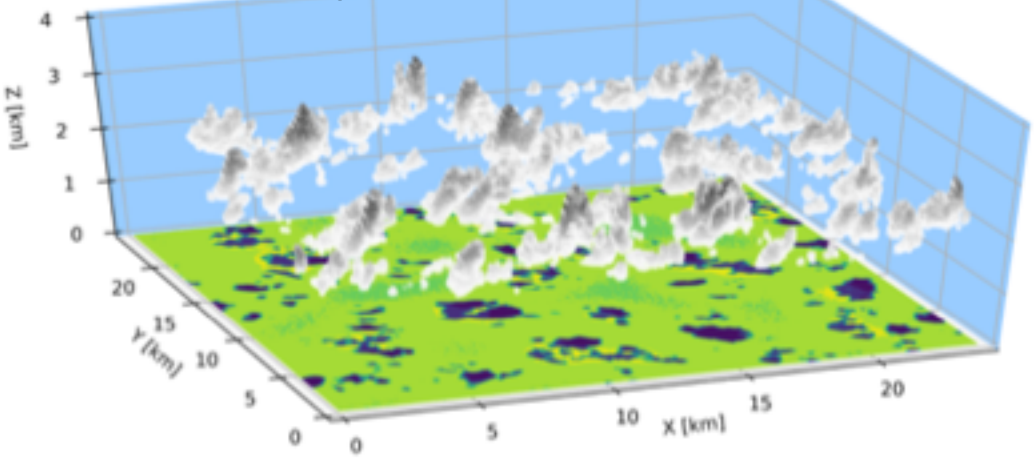
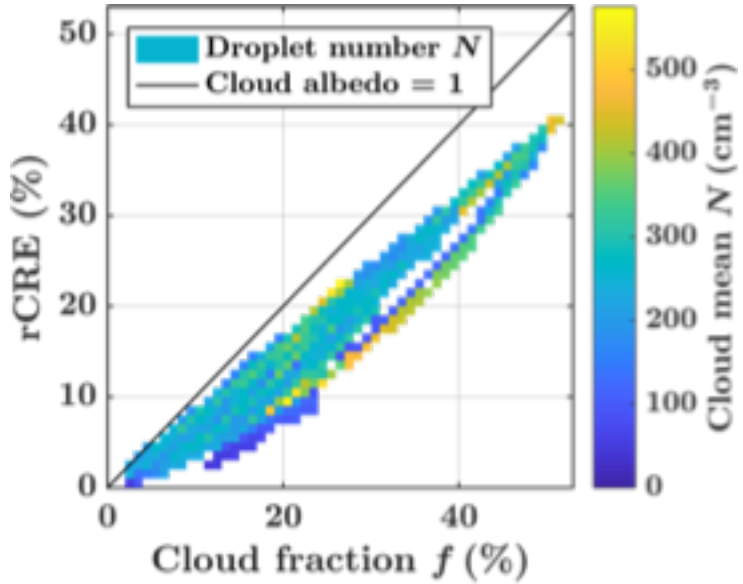




L

f





N

rCRE Budget

$$\mathrm{rCRE} = f \cdot \mathcal{A} \quad , \quad \mathcal{A}(L, N)$$

Budget analysis:

How does rCRE change as cloud drop number *N* changes?

rCRE Budget

$$\mathrm{rCRE} = f \cdot \mathcal{A} \quad , \quad \mathcal{A}(L, N)$$

<u>Budget analysis:</u>

How does rCRE change as cloud drop number *N* changes?

$$\ln(\mathrm{rCRE}) = \ln f + \ln A$$

$$\frac{\mathrm{d}\ln \mathrm{rCRE}}{\mathrm{d}\ln N} =$$

rCRE Budget

$$\mathrm{rCRE} = f \cdot \mathcal{A} \quad , \quad \mathcal{A}(L, N)$$

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

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

rCRE Budget

$$\mathrm{rCRE} = f \cdot \mathcal{A} \quad , \quad \mathcal{A}(L, N)$$

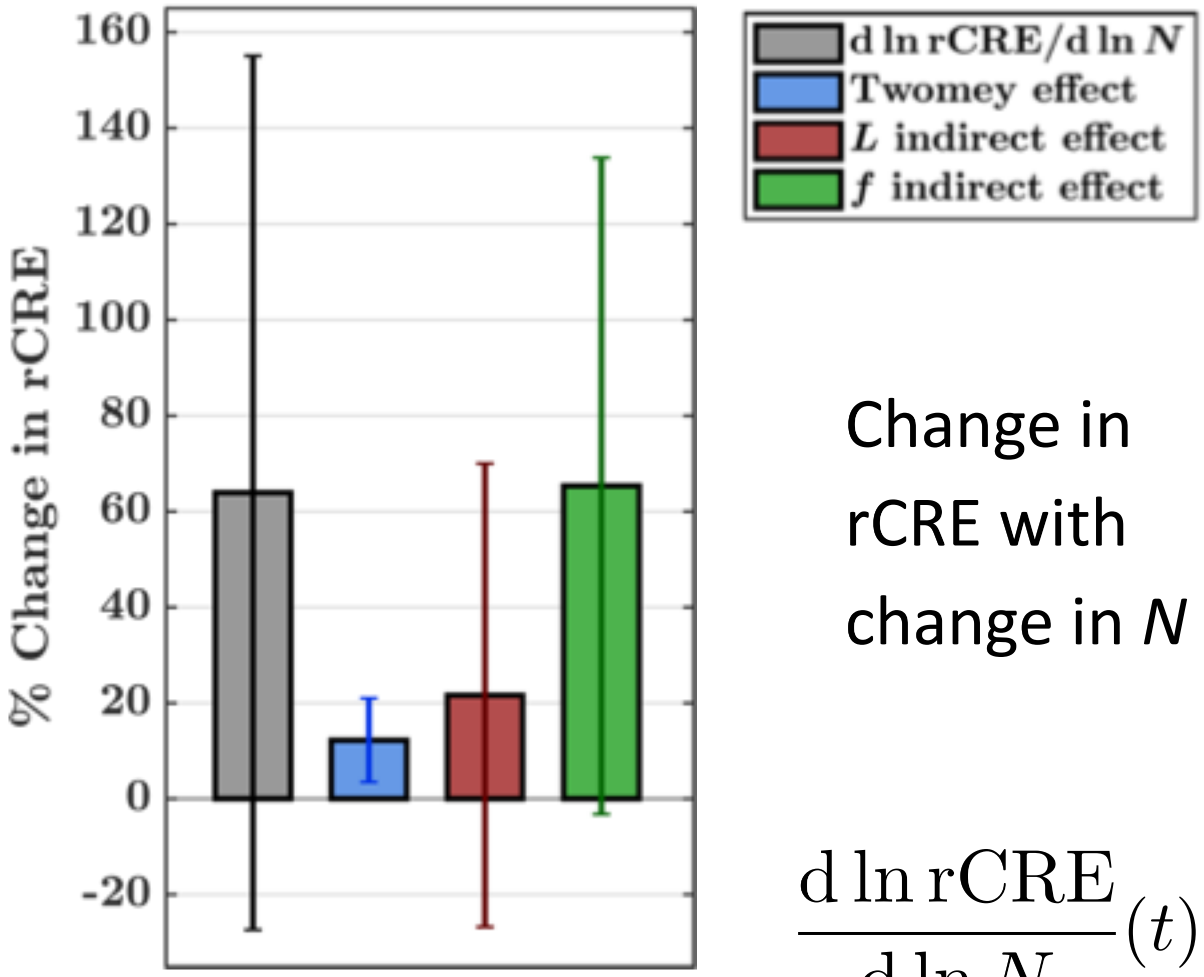
Temporal Numerical Differentiation
(*Numerical Recipes*, 2007)

Timescale of variation
$\sim$ 1 hour

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

rCRE Budget

16 days LASSO shallow cumulus



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

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

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

rCRE Budget

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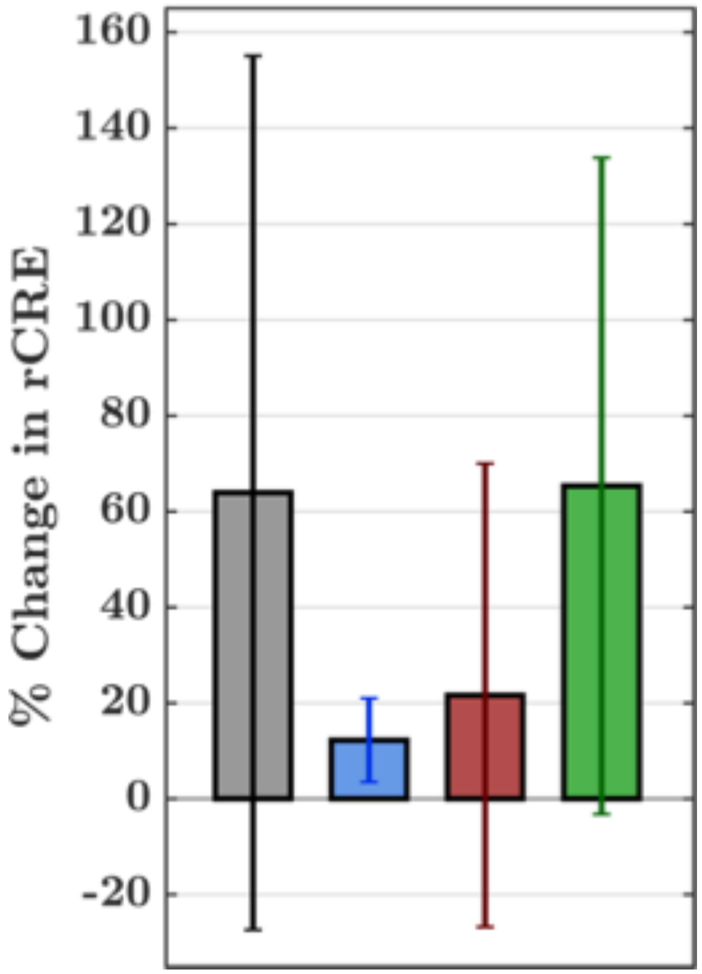

1. The radiative effect of an ***N*** perturbation is magnified by concurrent changes in cloud fraction ***f***

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

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

Mutual Information:

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

$$\mathrm{MI}(y,x) = \sum_X \sum_Y p(x,y) \log \frac{p(x,y)}{p(x) \cdot p(y)}$$

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

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

$$\mathrm{CMI}(y,x|z) = \sum_X \sum_Y \sum_Z p(x,y,z) \log \frac{p(z) \cdot p(x,y,z)}{p(x,z) \cdot p(y,z)}$$

Mutual Information:

$$\mathrm{MI}(x,y) = \sum p(x,y) \log \frac{p(x,y)}{p(x)\cdot p(y)}$$

$$\mathrm{MI}\ ::\ \mathrm{rCRE} \leftrightarrow f_c = 65\%$$

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$$\mathrm{MI} \ :: \ \mathrm{rCRE} \leftrightarrow f_c = 65\%$$

$$\mathrm{MI} \ :: \ \mathrm{rCRE} \leftrightarrow L_c = 34\%$$

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$$\mathrm{MI} \ :: \ \mathrm{rCRE} \leftrightarrow N_c = 18\%$$

Mutual Information:

$$\mathrm{MI}(x,y) = \sum p(x,y) \log \frac{p(x,y)}{p(x)\cdot p(y)}$$

$$\mathrm{CMI}(y,x|z) = \sum_X \sum_Y \sum_Z p(x,y,z) \log \frac{p(z)\cdot p(x,y,z)}{p(x,z)\cdot p(y,z)}$$

$$\mathrm{MI} \;::\; \mathrm{rCRE} \leftrightarrow f_c = 65\%$$

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

$$\mathrm{MI} \;::\; \mathrm{rCRE} \leftrightarrow L_c = 34\%$$

$$\mathrm{MI} \;::\; \mathrm{rCRE} \leftrightarrow N_c = 18\%$$

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

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$$\mathrm{MI}(x,y) = \sum p(x,y) \log \frac{p(x,y)}{p(x)\cdot p(y)}$$

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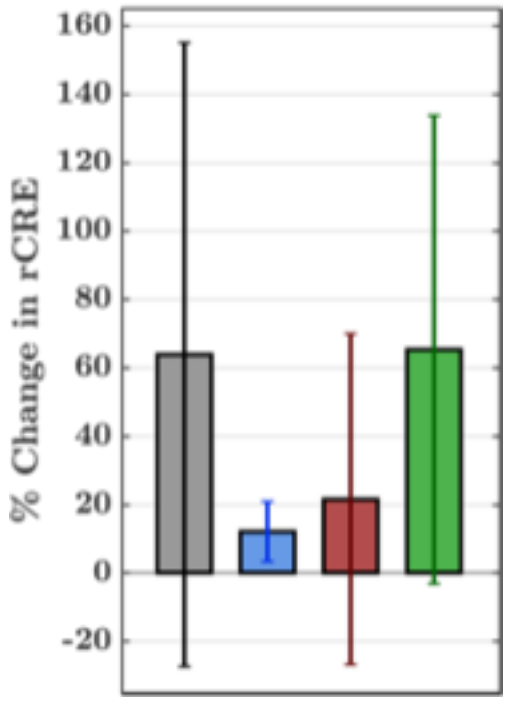
CMI (rCRE, *f*|*N*) = *80%*

Explanation?

rCRE Budget



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

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

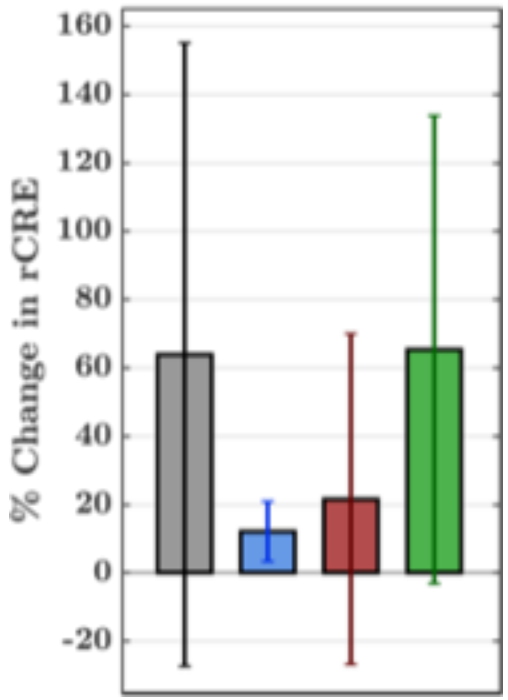
Mutual Information:

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

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

Co-variability between terms

rCRE Budget



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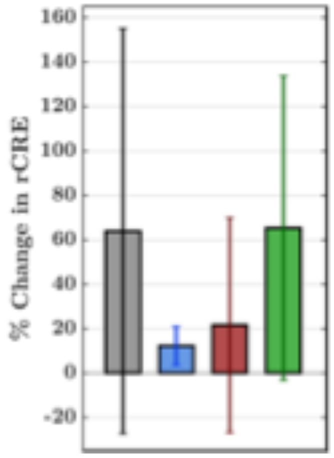

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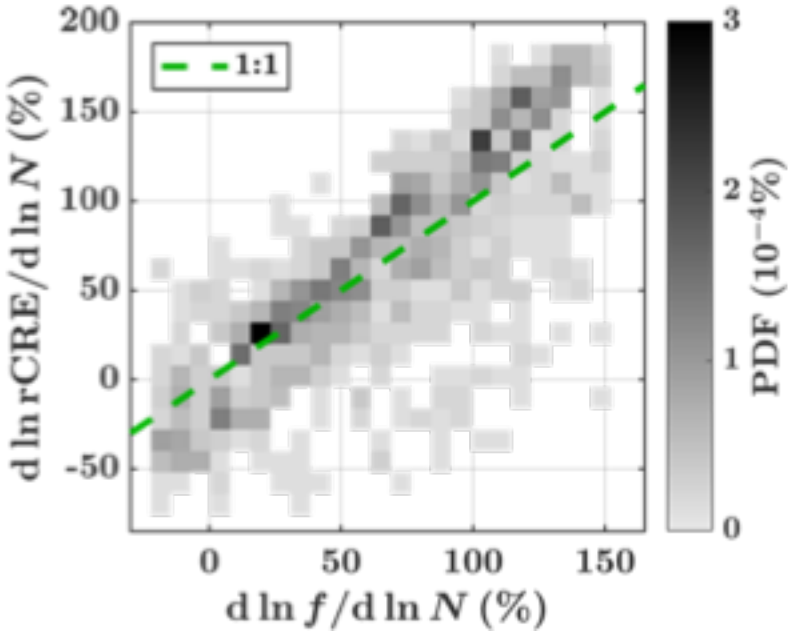
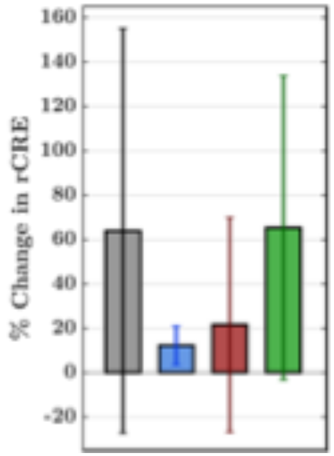


$$\frac{\mathrm{d}\ln f}{\mathrm{d}\ln N}$$



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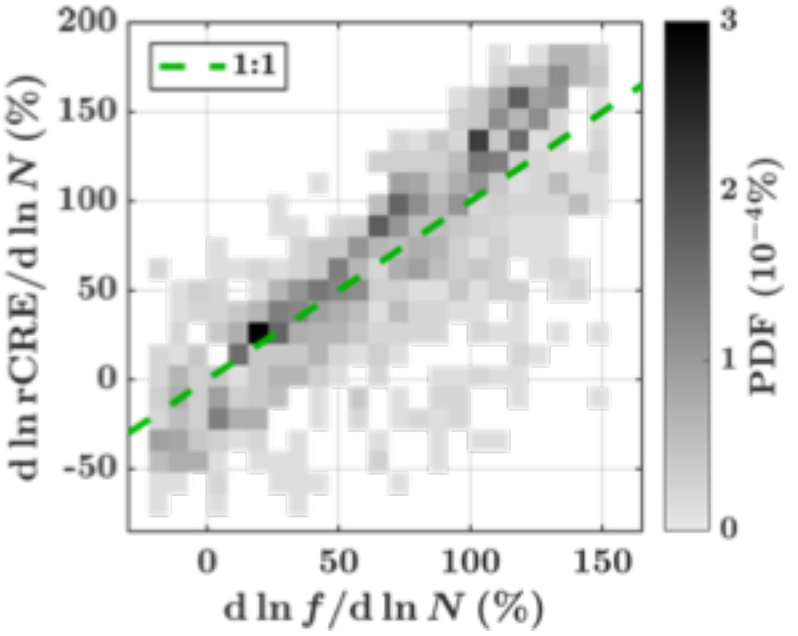

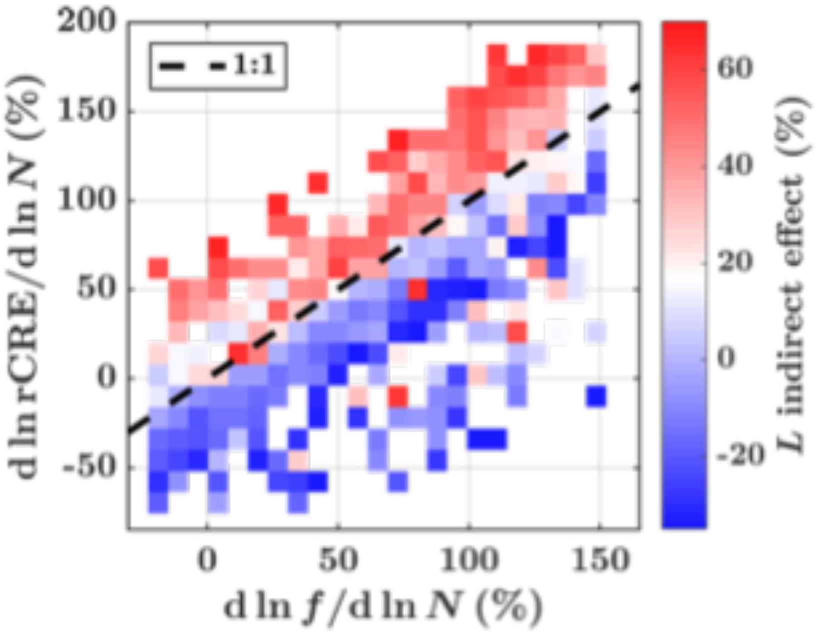

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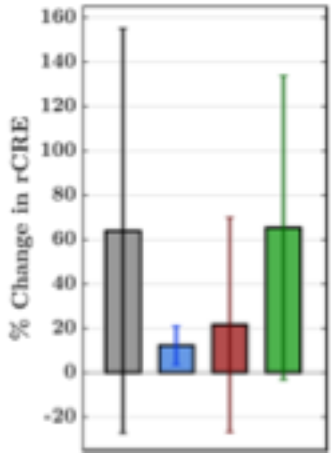

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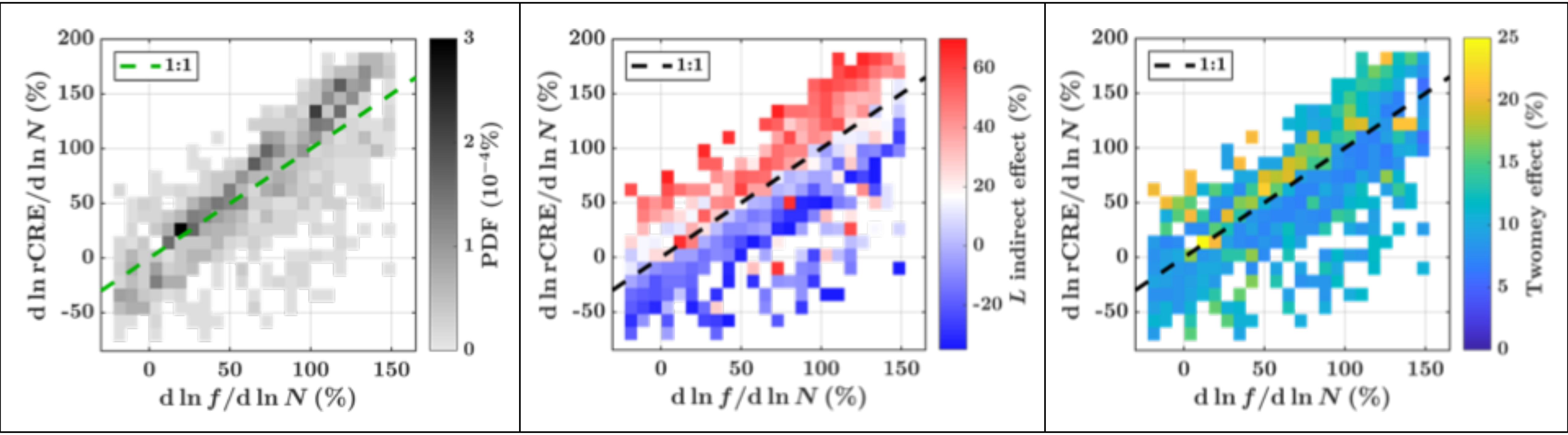
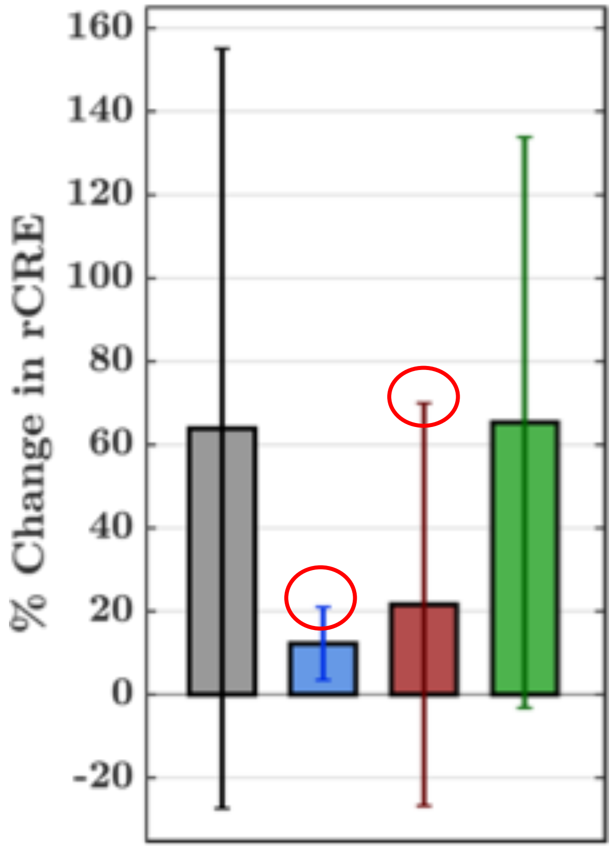


$$\frac{\mathrm{d}\ln f}{\mathrm{d}\ln N}$$

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**.



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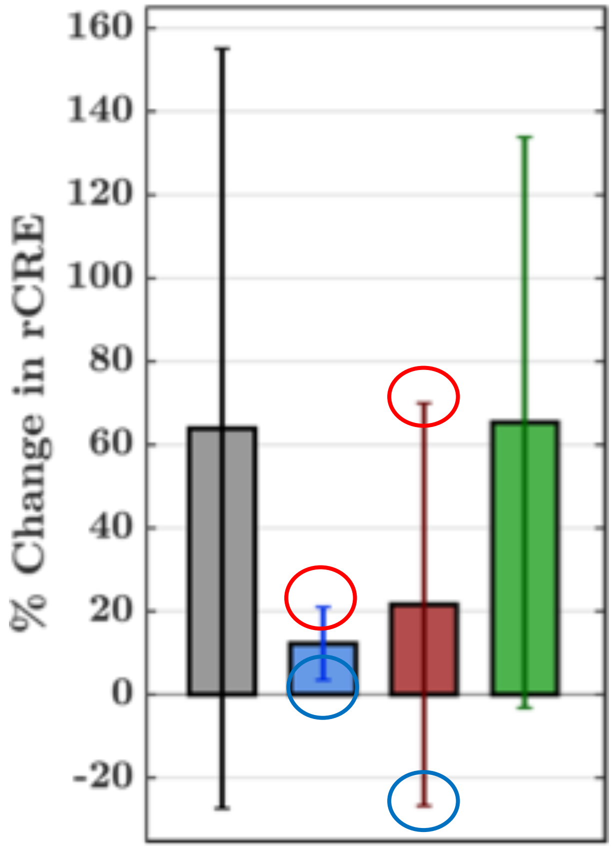
CMI (rCRE, *f*) | *N* = *80%*

Summary:



Magnifying the radiative effect

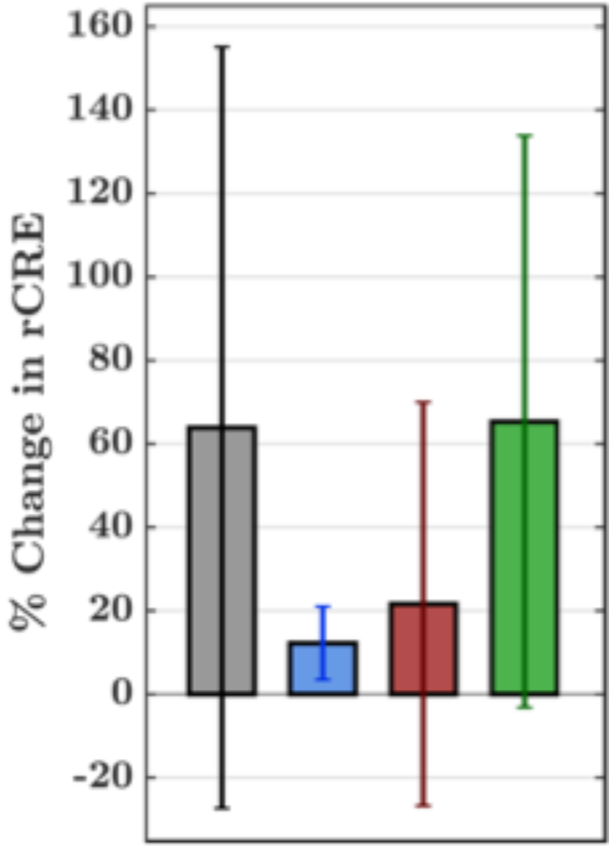
(Most common case)
A given ***N*** perturbation is able to increase the albedo a relatively **large** amount. The ***L*** response is **positive**.

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.

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

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



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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!