Sensitivity of Hadley circulation changes under warming to physical parameters in CESM

Kathleen A Schiro[1], Hui Su[1], Yuan Wang[1], Baird G. Langenbrunner[2], Jonathan H. Jiang[1], and J. David Neelin[3]

[1] Jet Propulsion Laboratory, California Institute of Technology

[2] University of California, Irvine

[3] University of California, Los Angeles

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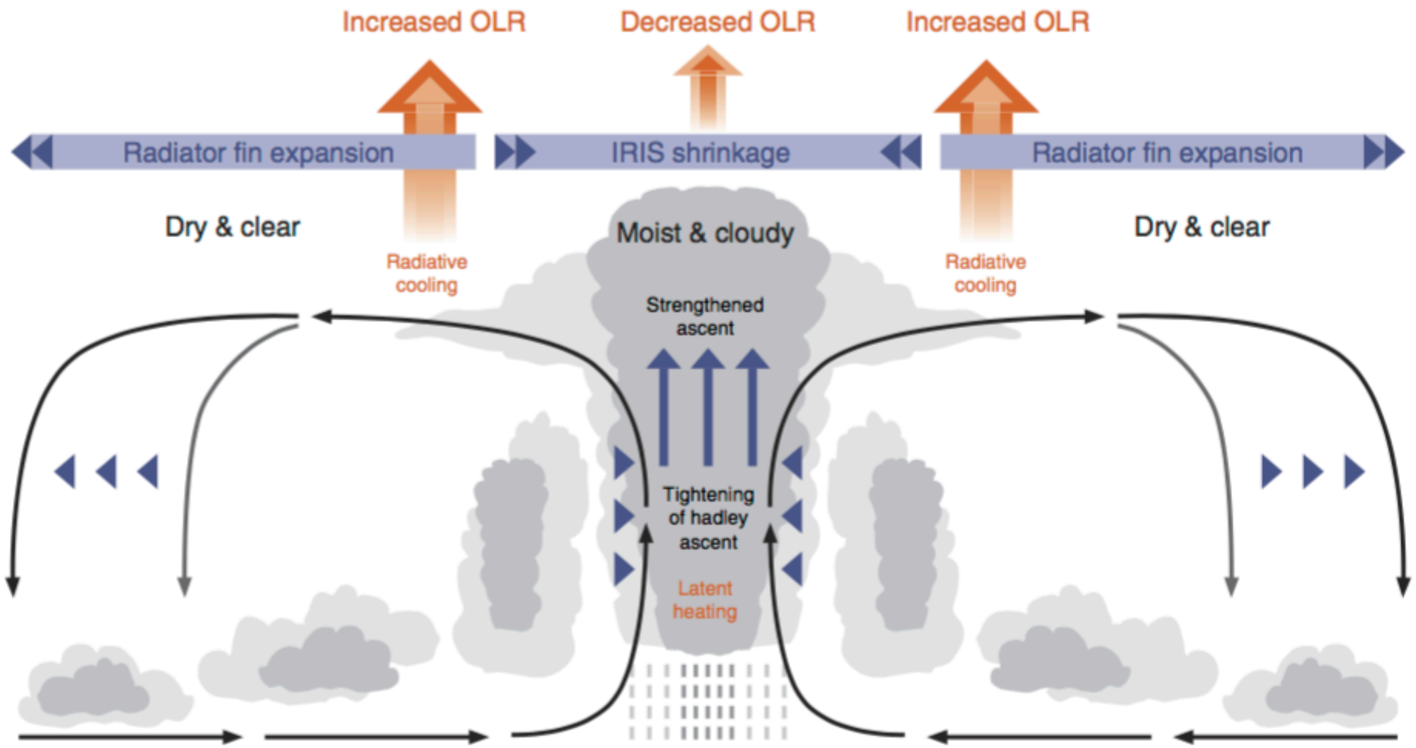
Motivation

- Hadley ascent area projected to decrease with warming



Su et al. (2017), Nat. Comm.

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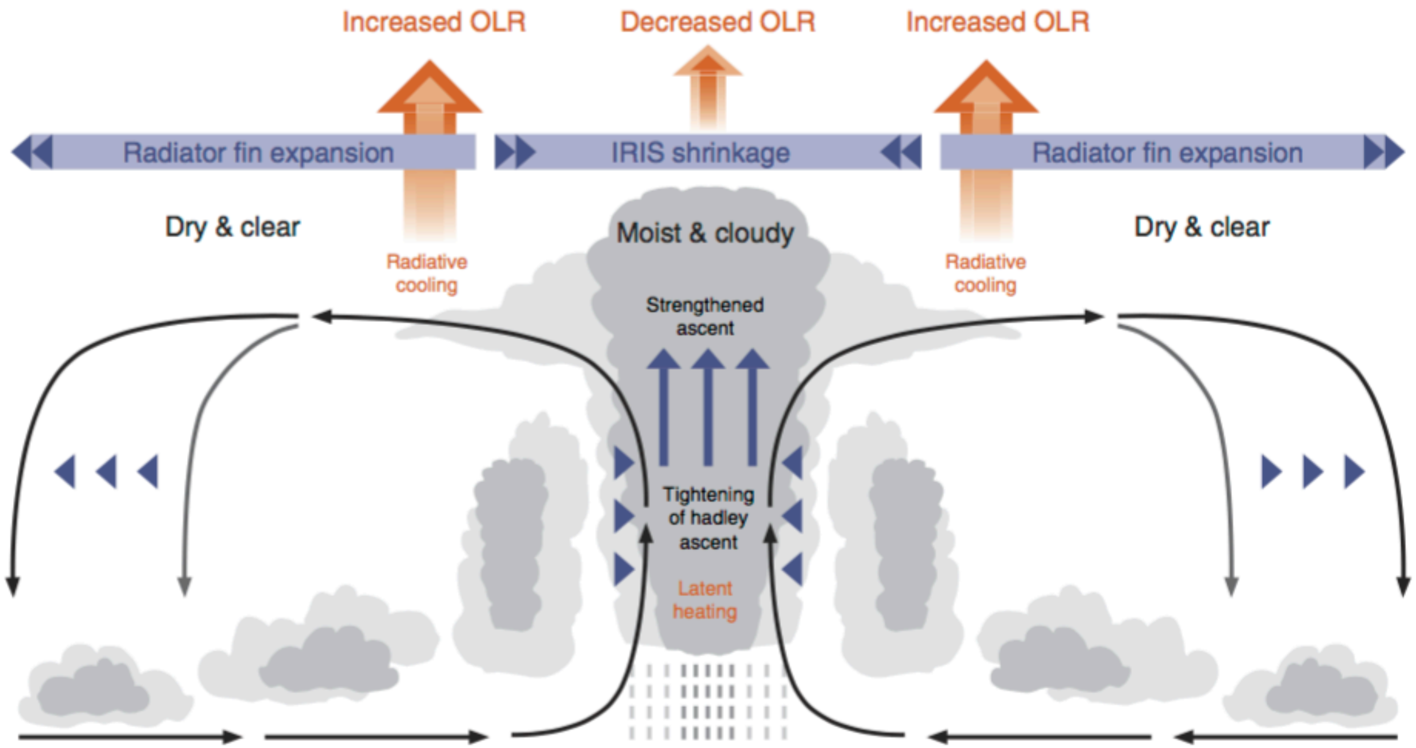
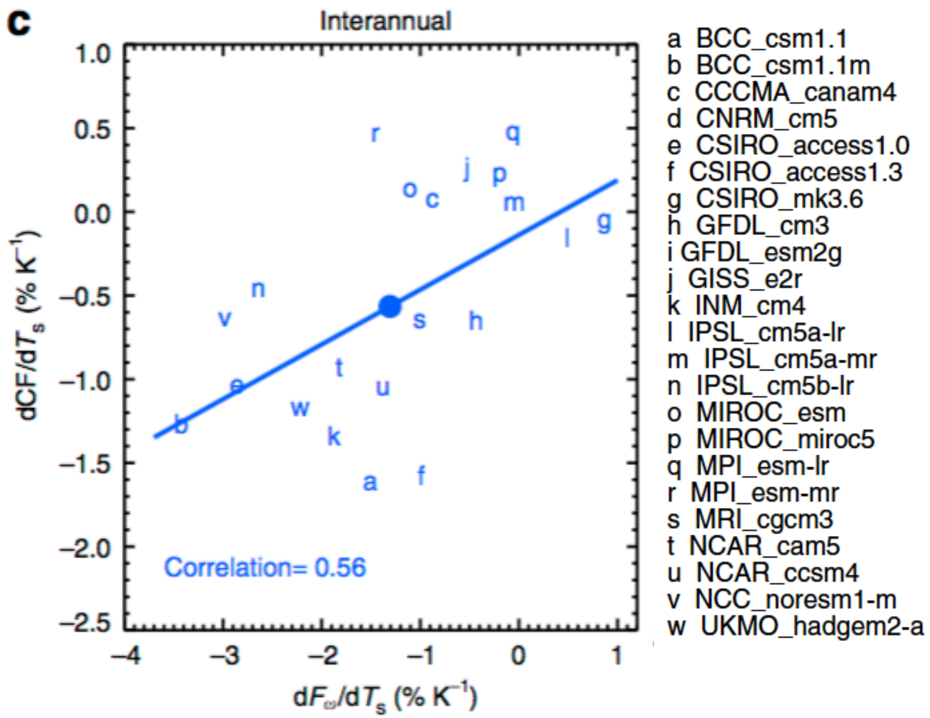
- Hadley ascent area projected to decrease with warming
- Large CMIP5 intermodel spread in tightening response





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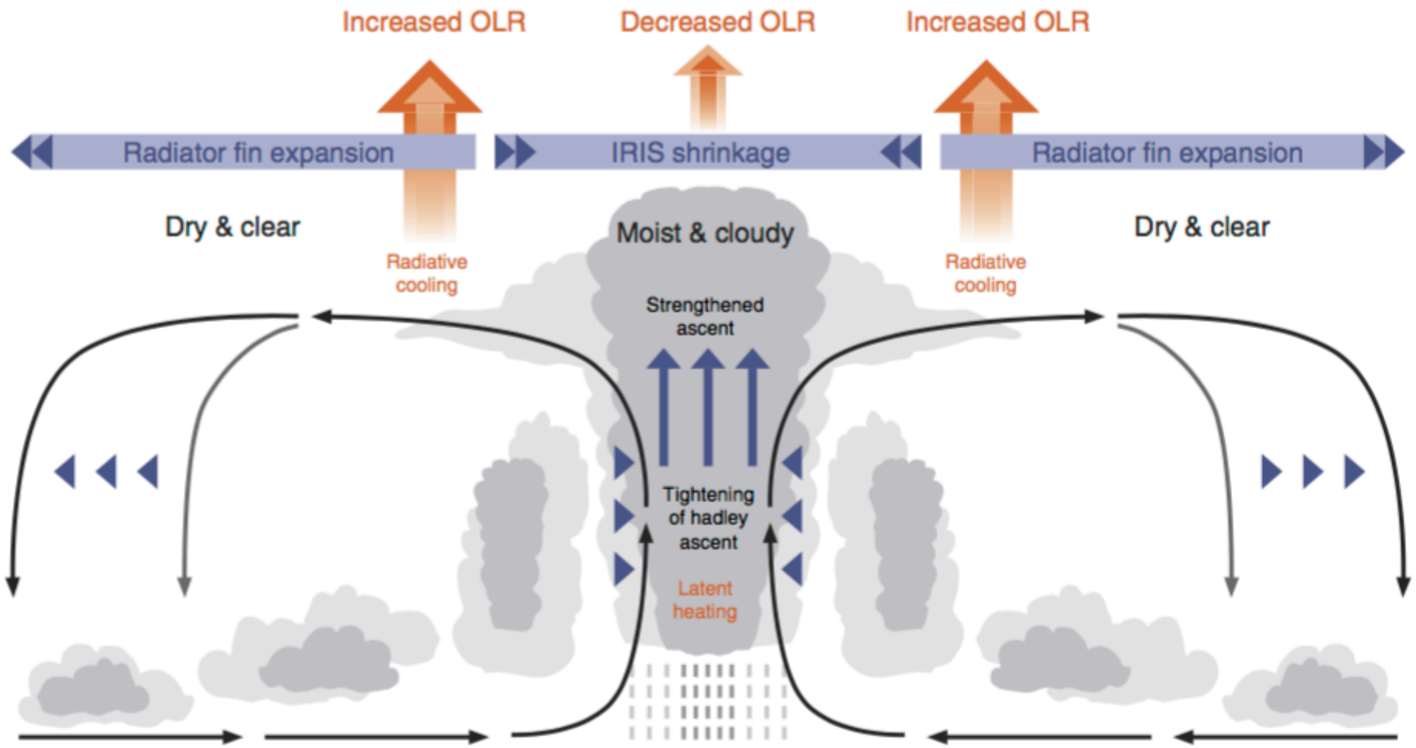

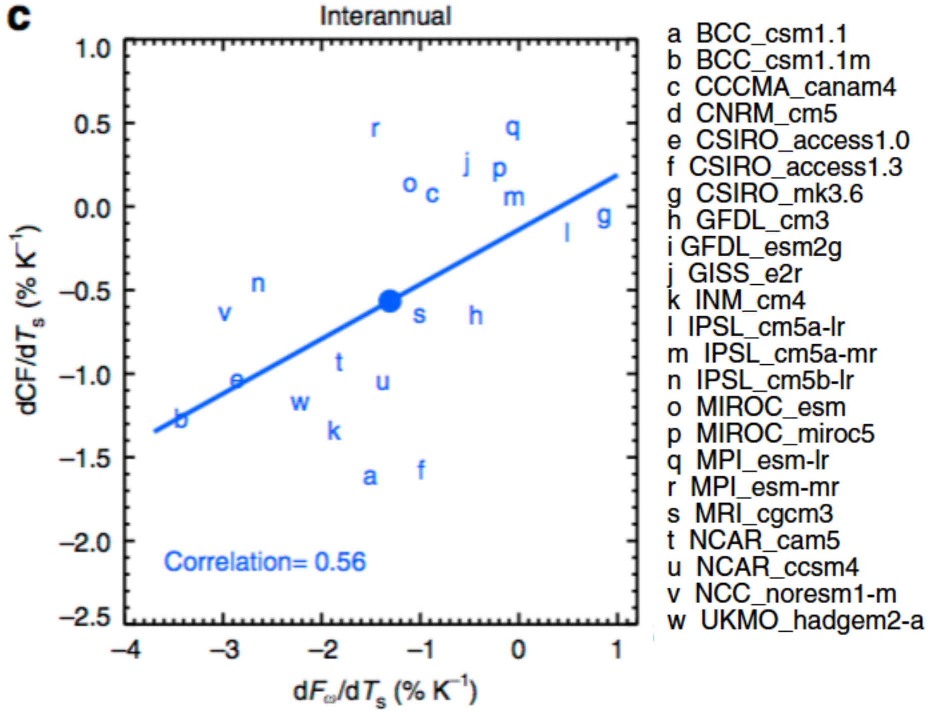

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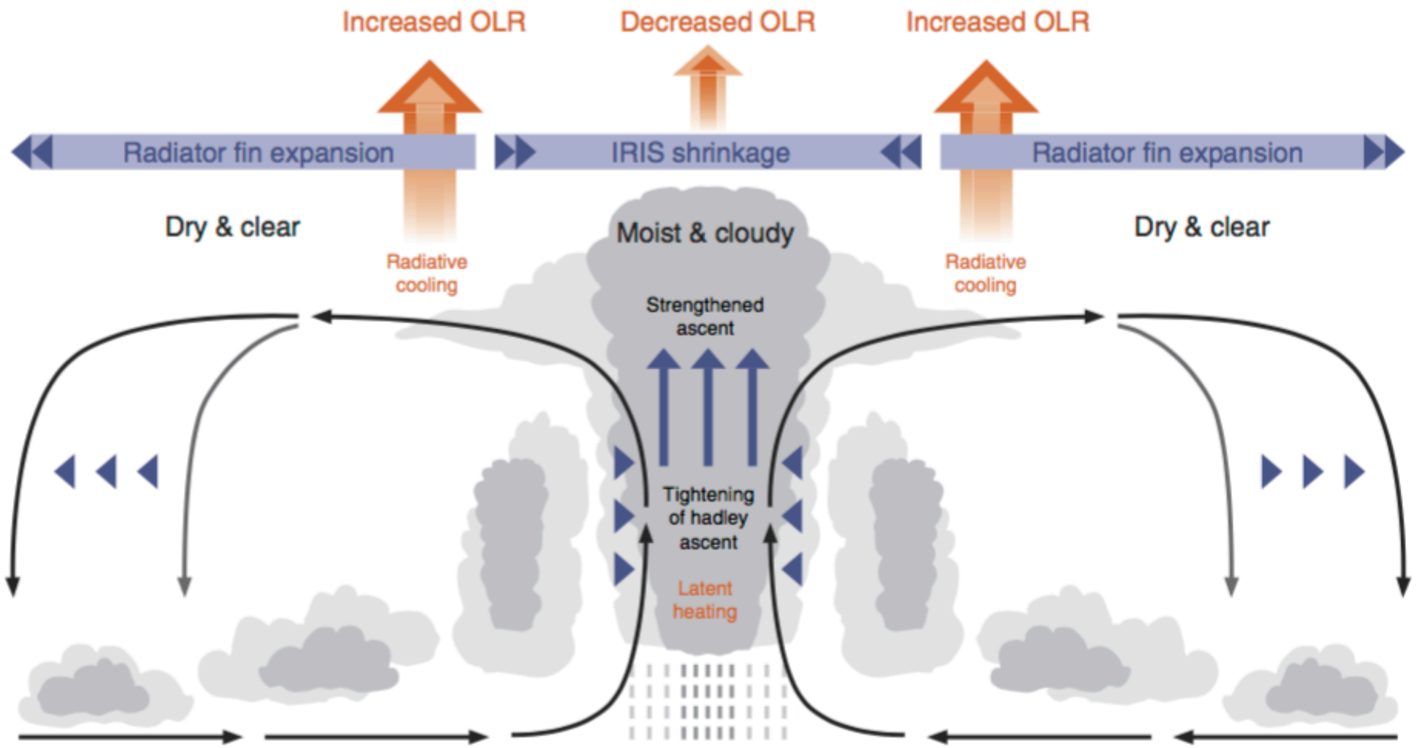

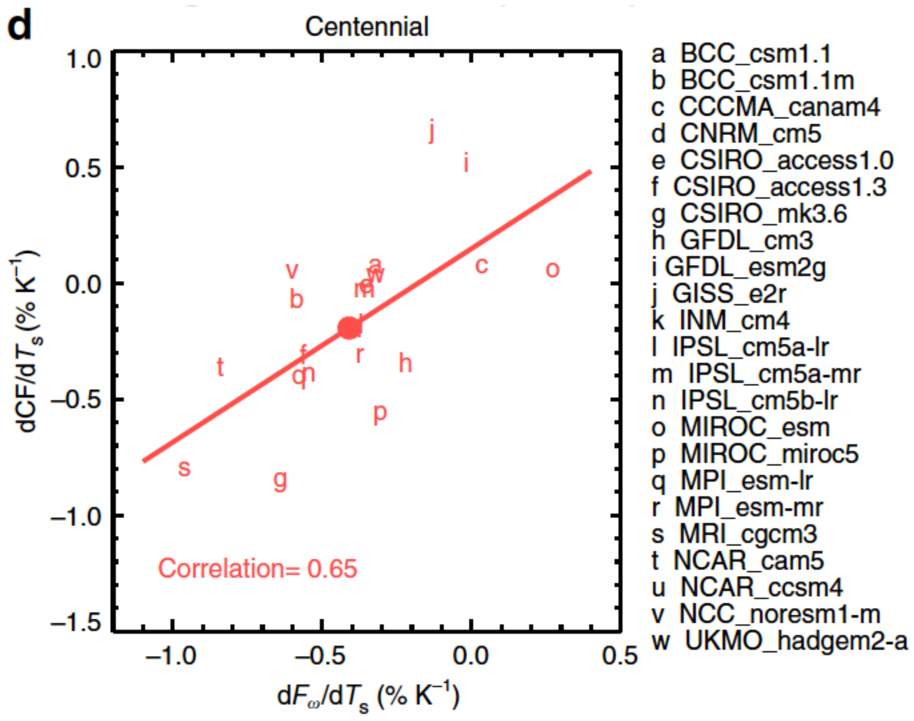

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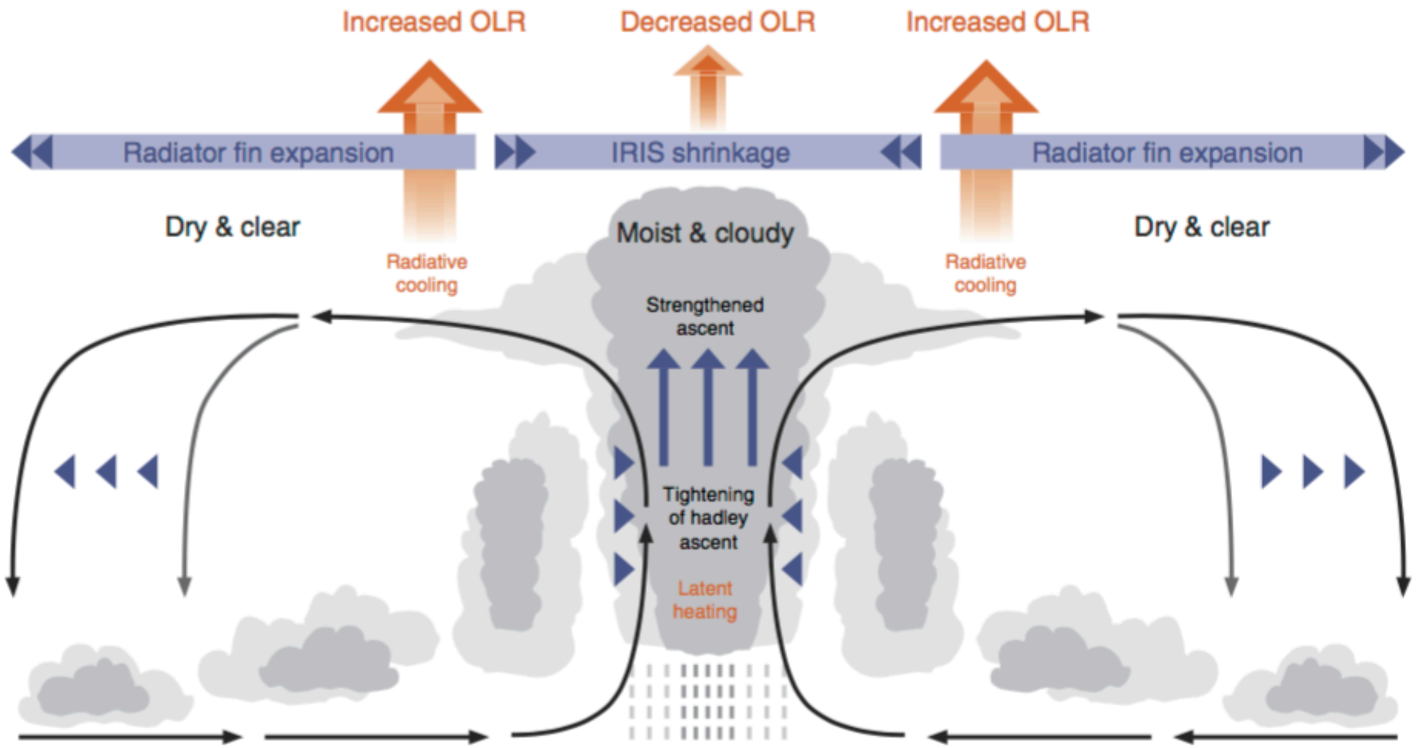
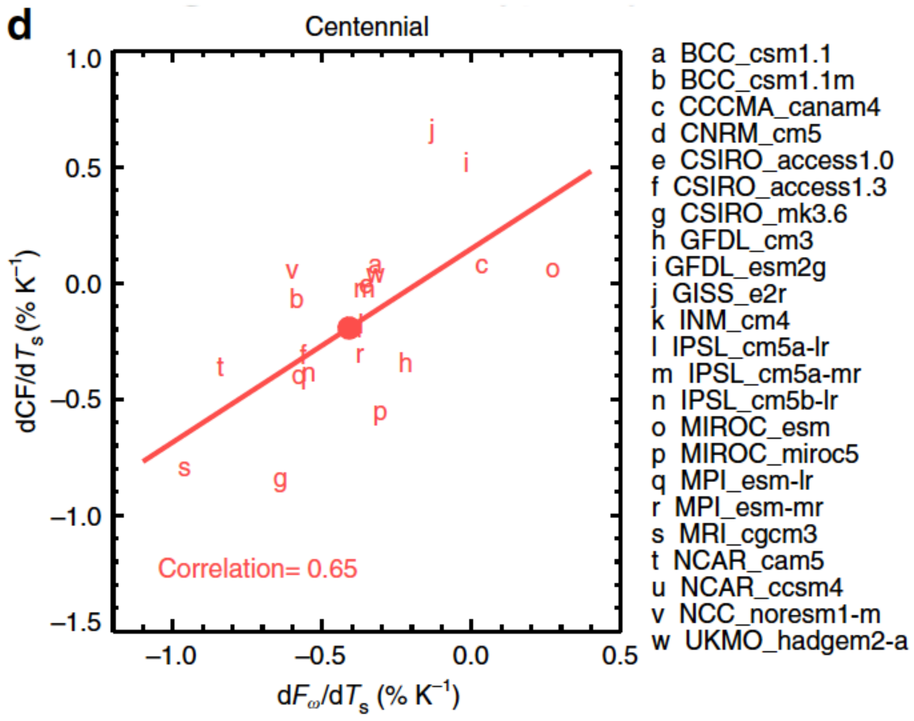
- Cloud-circulation coupling – similar interannual vs. forced warming
- Imperative to regional and global precipitation changes





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Questions

- What physical processes contribute most to the intermodel spread in Hadley ascent area and high cloud changes under warming in CMIP5 models?
- What are the dominant physics linking Hadley ascent area and high cloud changes under warming?

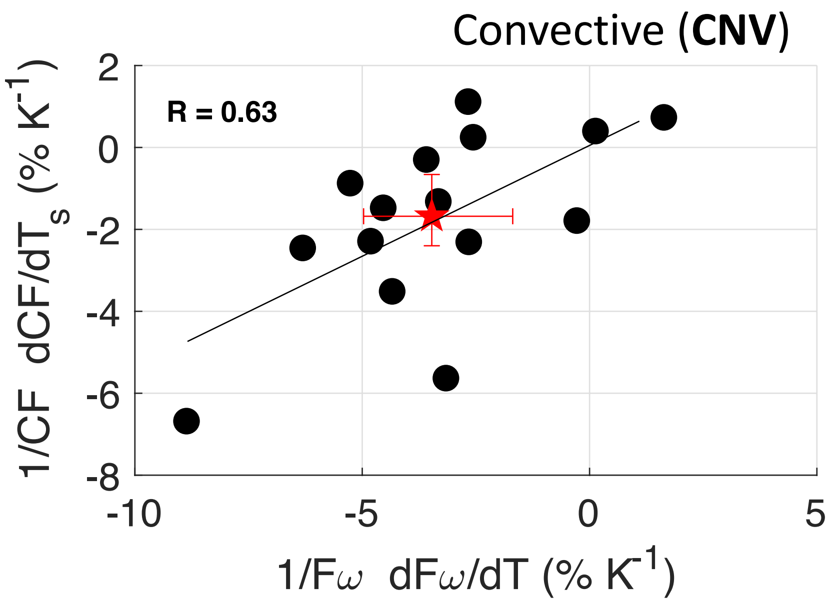
Experiment

- Two parameter perturbation experiments
  - ***Cloud physics*** experiment (**CLD**)
  - ***Convective*** experiment (**CNV**)

  **Perturbed one at a time within ranges cited in Zhao et al. (2013), Qian et al. (2015)*
- NCAR CESM1.2.2 Atmosphere-Only (CAM5.3) at 2^o
- Results shown from 1995-2005 monthly output (interannual only)
- Analysis performed from 20^oS-20^oN

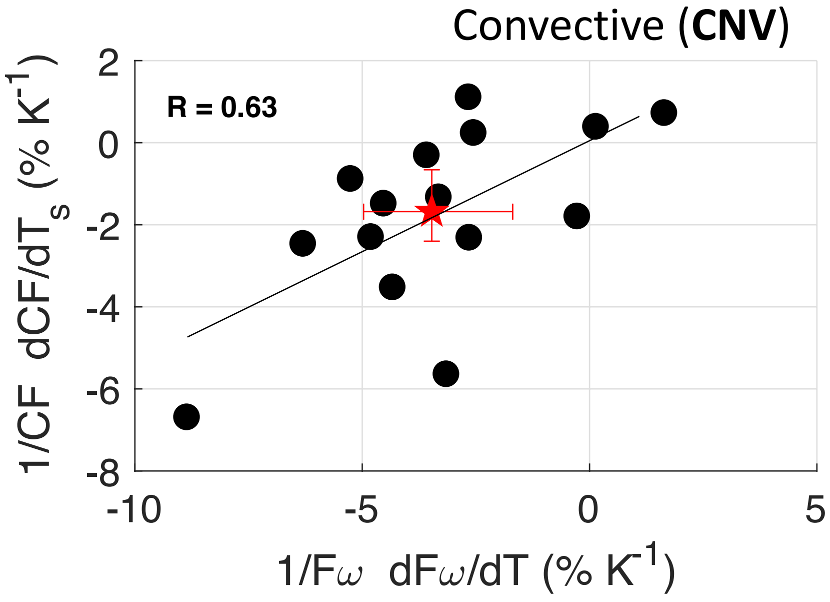
Parameter	Description	Category	Values (units)
dmpdz	Fractional rate of entrainment	Deep convection	0.08, 0.16, 0.25, 0.5, **1***, 1.5 (km^{-1})
alpha	Downdraft fraction	Deep convection	**0.1***, 0.25, 0.5, 0.75
tau	Convective timescale	Deep convection	30, **60***, 120, 180 (min)
ke	Evaporation efficiency	Deep convection	0.1, 0.5, **1***, 5, 10 ($(10^{-6}$ kg $m^{-2}s^{-1})^{-1/2}s^{-1}$)
cldfrc_rhminh	Threshold RH for high-level clouds	macrophysics	0.65, **0.8***, 0.85
cldfrc_rhminl	Threshold RH for low-level clouds	macrophysics	0.8, **0.8875***, 0.99
cldwatmi_ai	Fall speed parameter for stratiform ice	microphysics	350, **700***, 1400 (s^{-1})
cldwatmi_as	Fall speed parameter for stratiform snow	microphysics	5.86, **11.72***, 23.44 ($m^{0.59}$ s−1)
cldwatmi_dcs	Autoconversion size threshold ice - snow	microphysics	0.0001, **0.0004***, 0.0005 (m)
cldwatmi_eii	Collection efficiency, ice aggregation	microphysics	0.001, **0.1***, 1
cldwatmi_qcvar	Inverse relative variance of cloud water	microphysics	0.5, **2***, 5
micropa_wsubimax	Max subgrid scale w for ice nucleation	microphysics	0.1, **0.2***, 1 (m s^{-1})
micropa_wsubmin	Min subgrid scale w for liquid nucleation	microphysics	0, **0.2***, 1 (m s^{-1})
D_ice	Radius of detrained ice, deep convection	microphysics	10, **25***, 50 (um)

RESULTS



RESULTS

- Perturbing convection produces very similar cloud-circulation response as CMIP5 models



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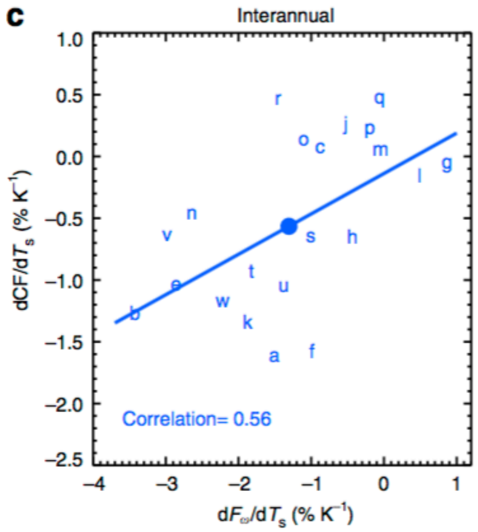

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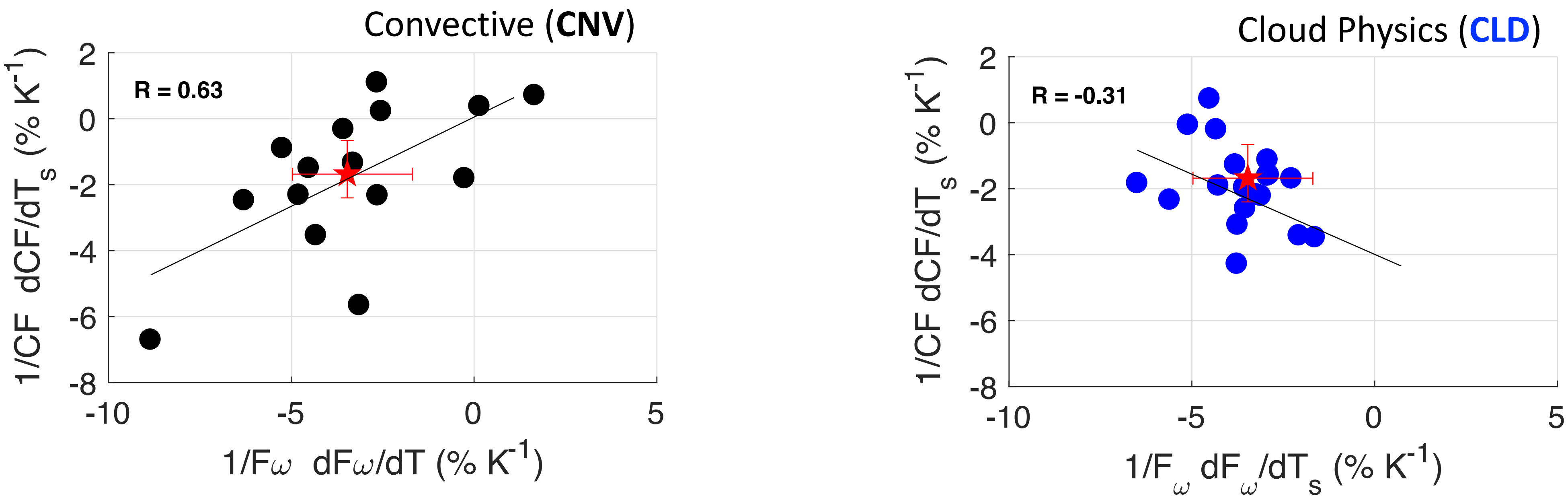
- Perturbing convection produces very similar cloud-circulation response as CMIP5 models
- Cloud response different



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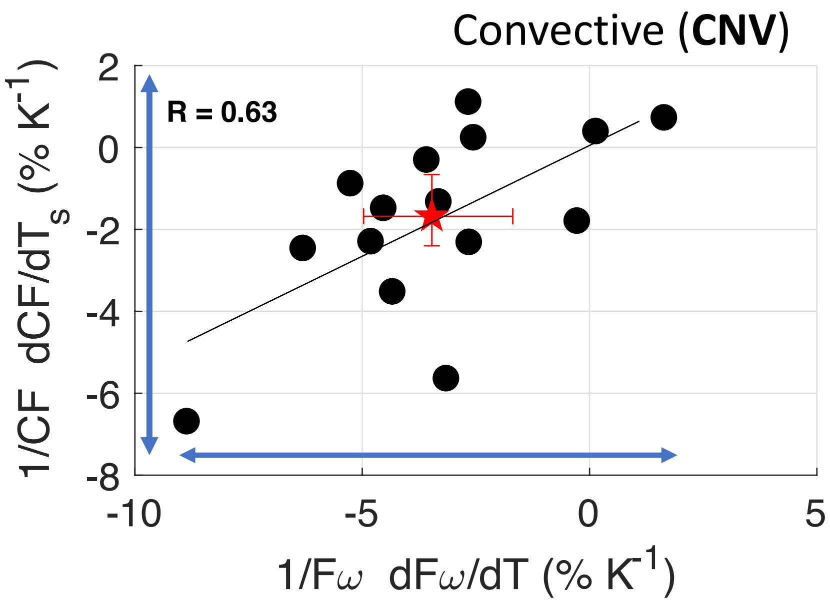

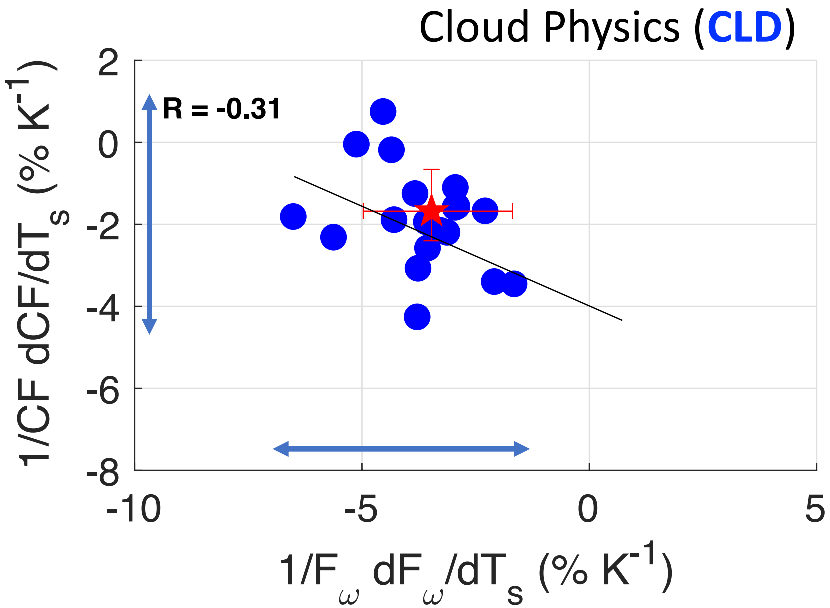

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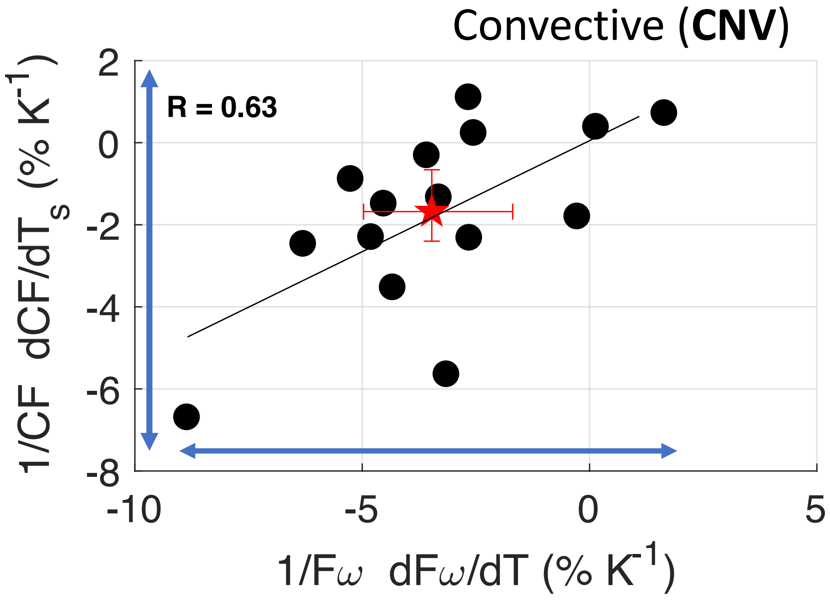

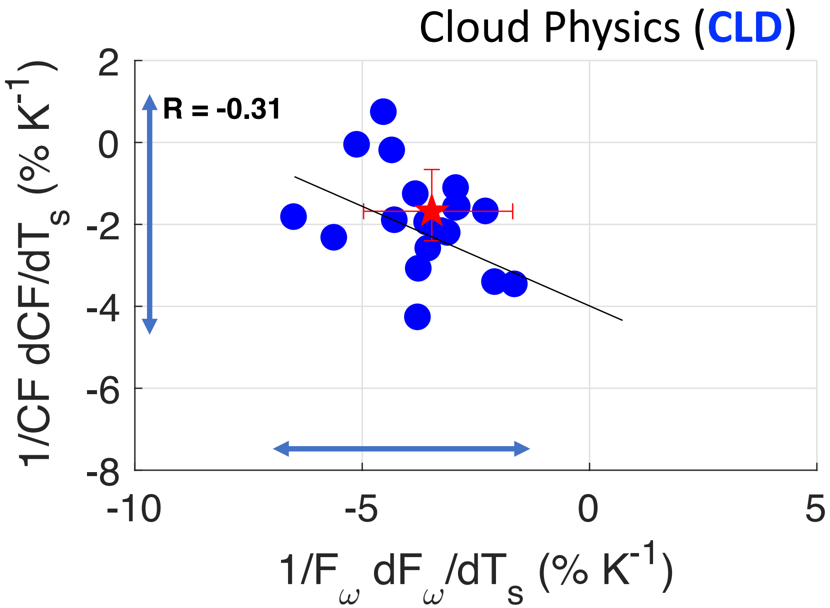

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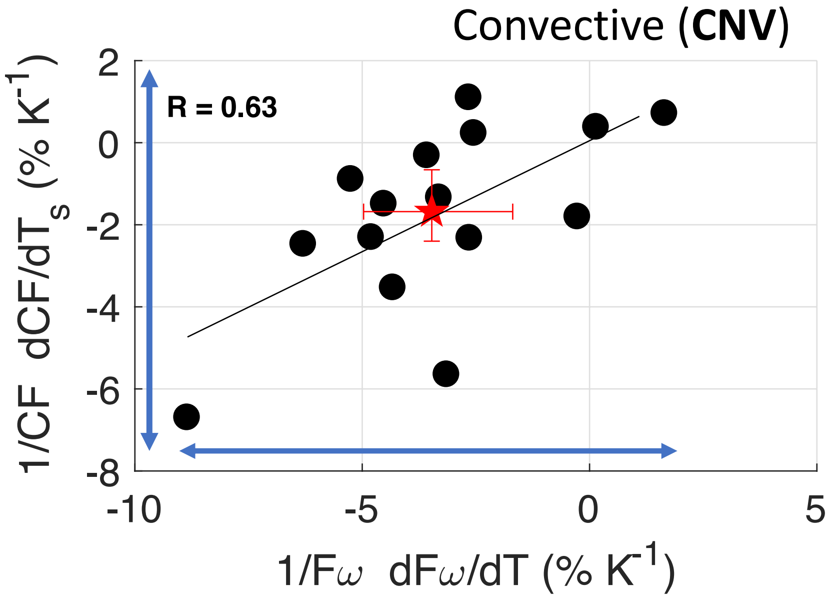
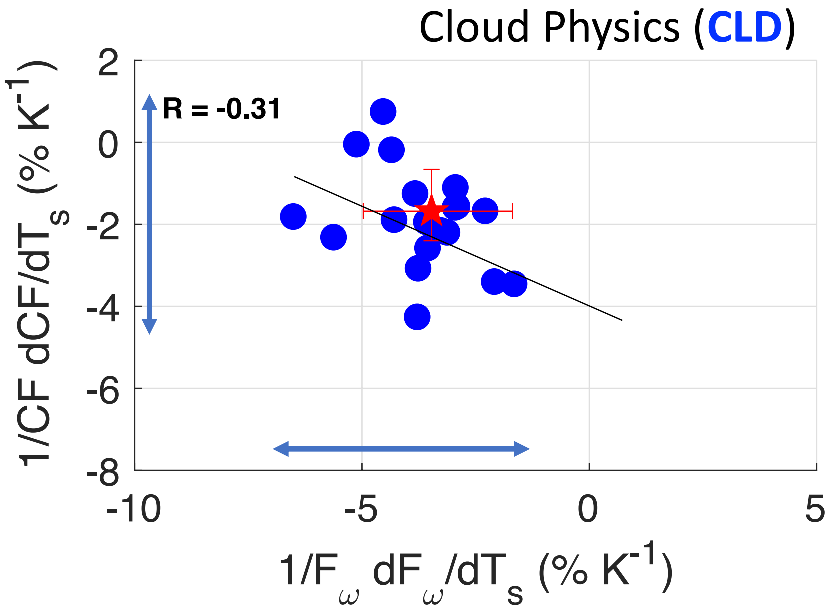
- Suggests differing strengths of physical pathways linking clouds and convection to circulation



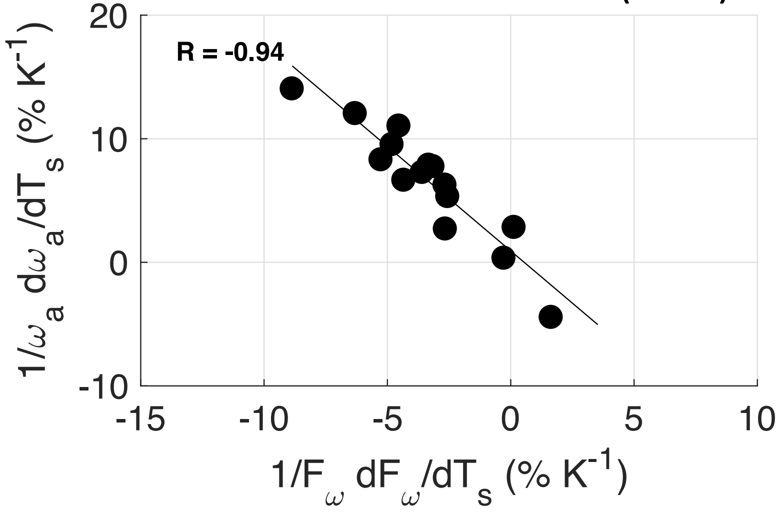


RESULTS

Strong coupling between Hadley cell ascent strength and ascent area.

Physical processes within ascent region likely dominant in determining ascent width (e.g. Byrne and Schneider 2016; Popp and Silvers 2017; Su et al. 2018; Byrne et al. 2018; Albern et al. 2018)

Convective (**CNV**)



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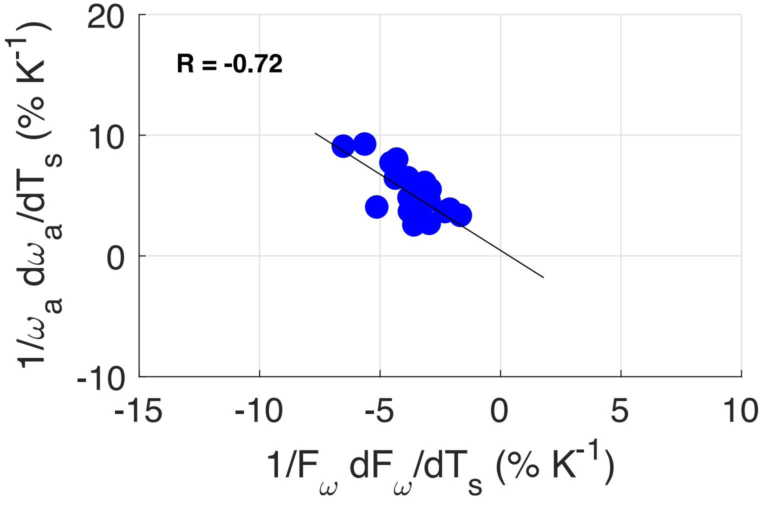

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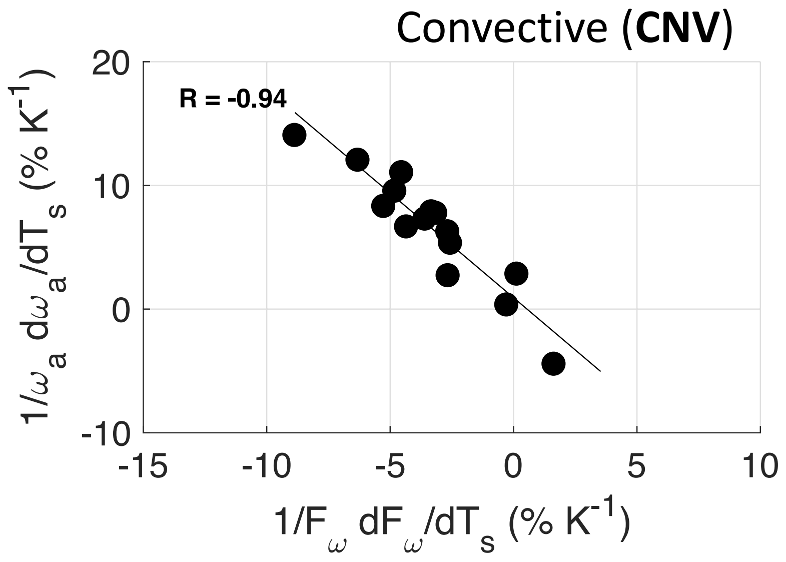
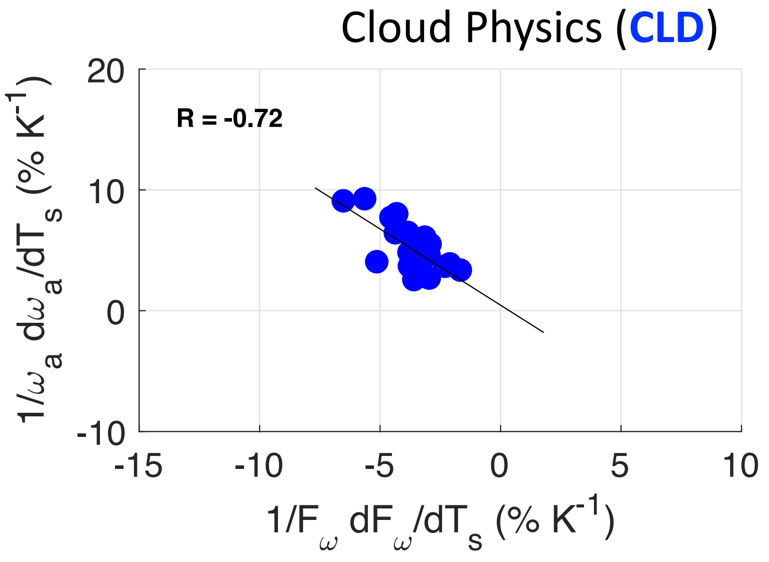


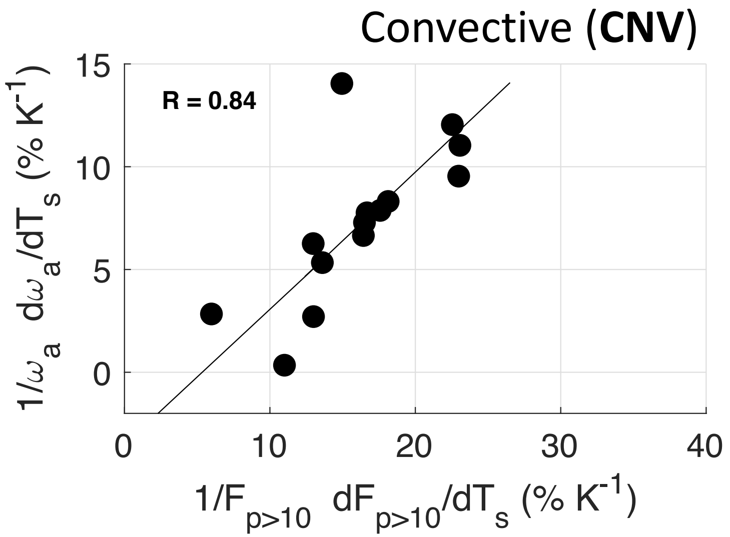


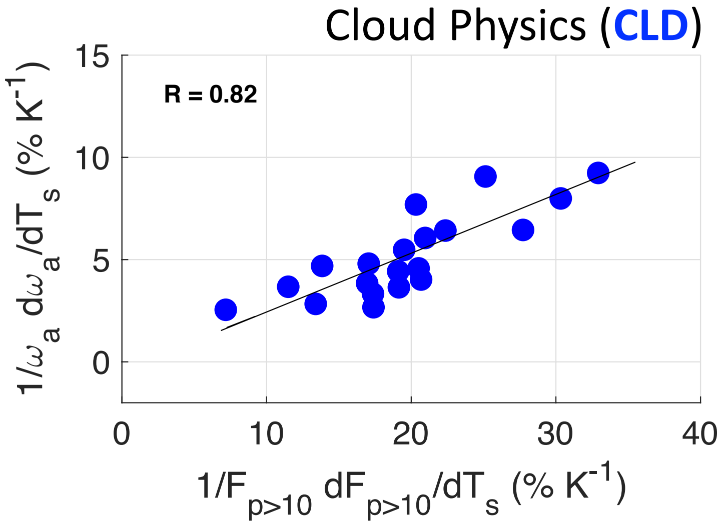
*Larger range in the response for CNV than CLD

RESULTS

Ascent strength and convection strength tightly coupled in both experiments.

Stronger precip





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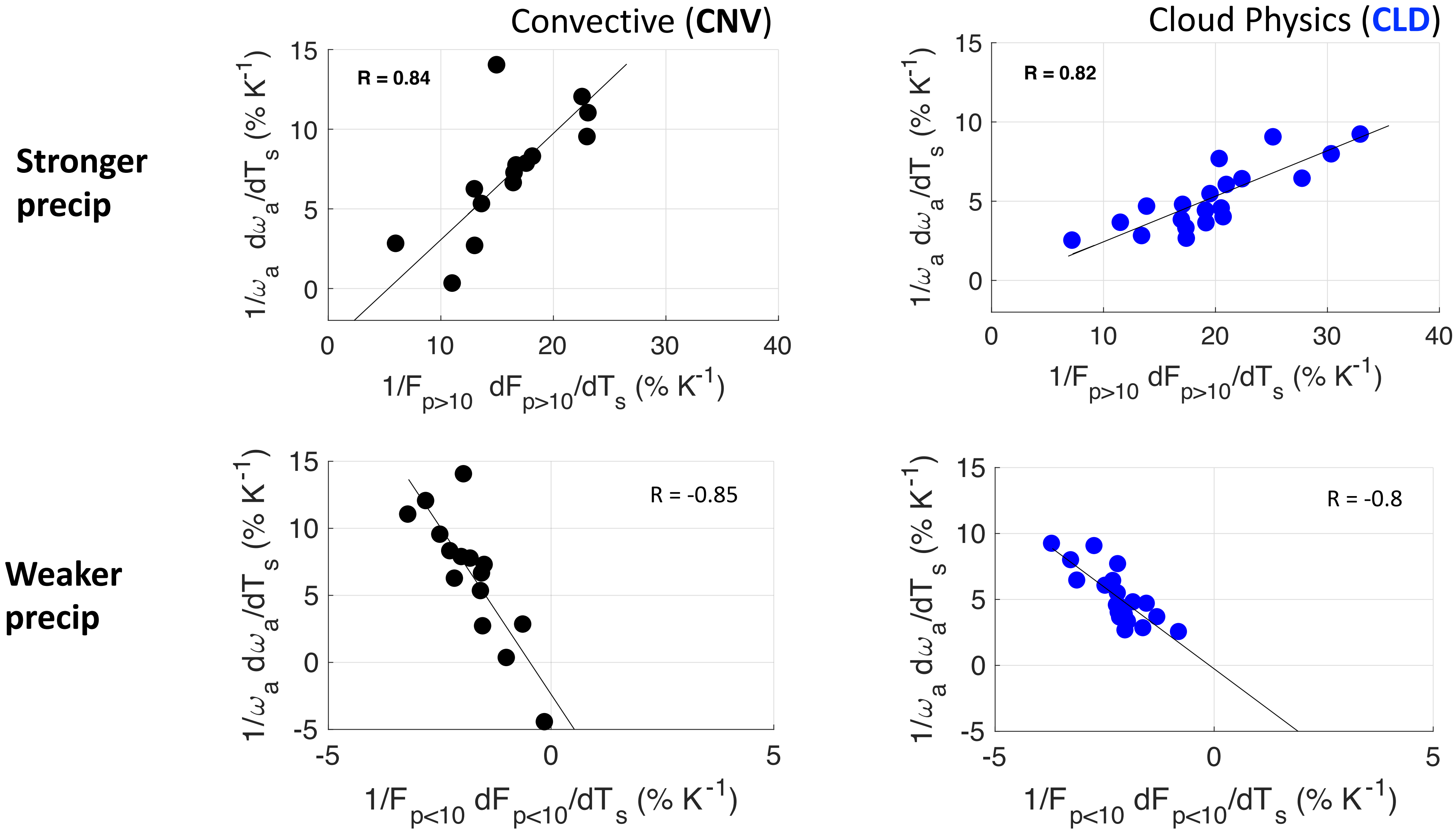


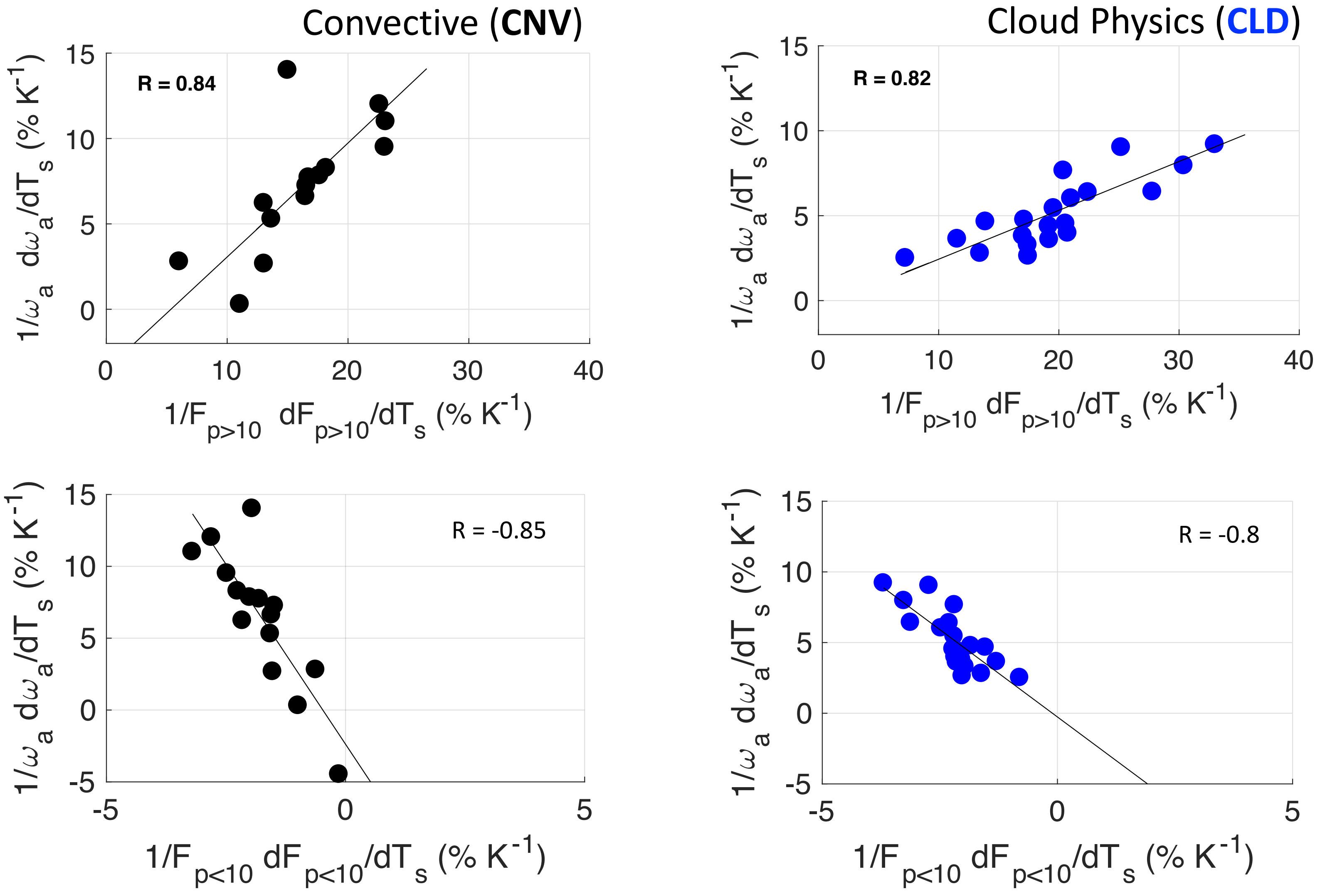
RESULTS

Ascent strength and convection strength tightly coupled in both experiments.

Stronger precip

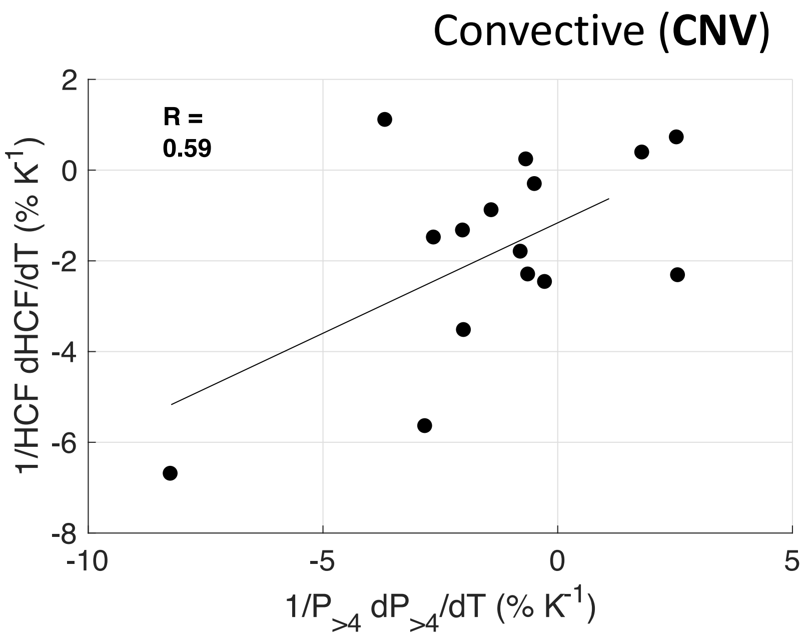
Weaker precip

* Mean state (e.g. moisture, temperature) matters



RESULTS

- Increasing deep convective frequency correlated to increase in cloud fraction in CNV



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- Increasing deep convective frequency correlated to increase in cloud fraction in CNV
- Relation weaker in CLD

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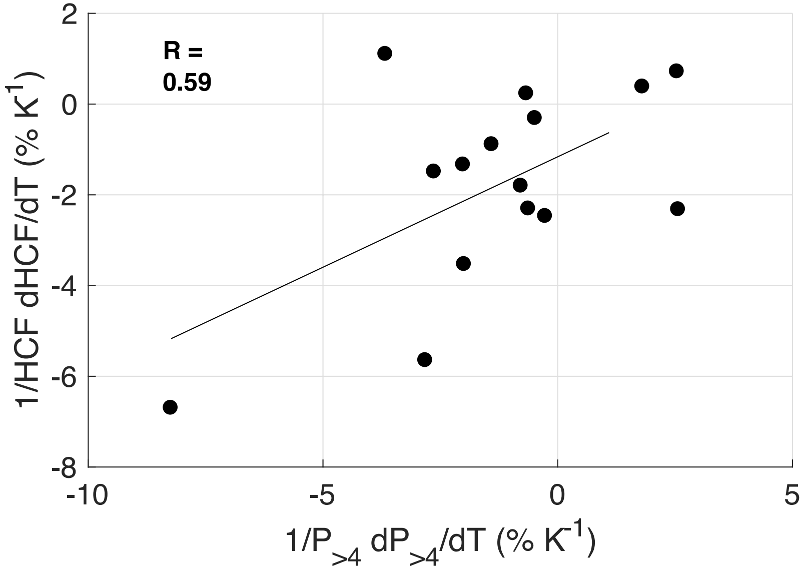

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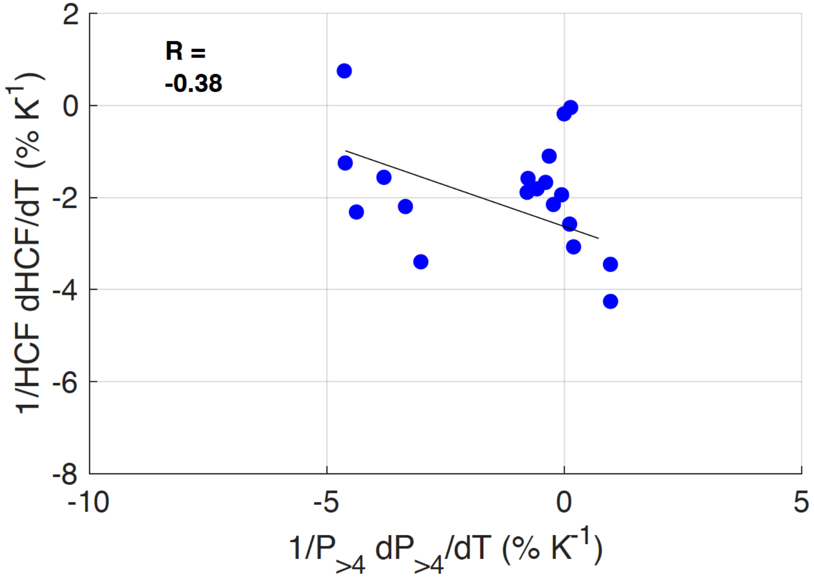

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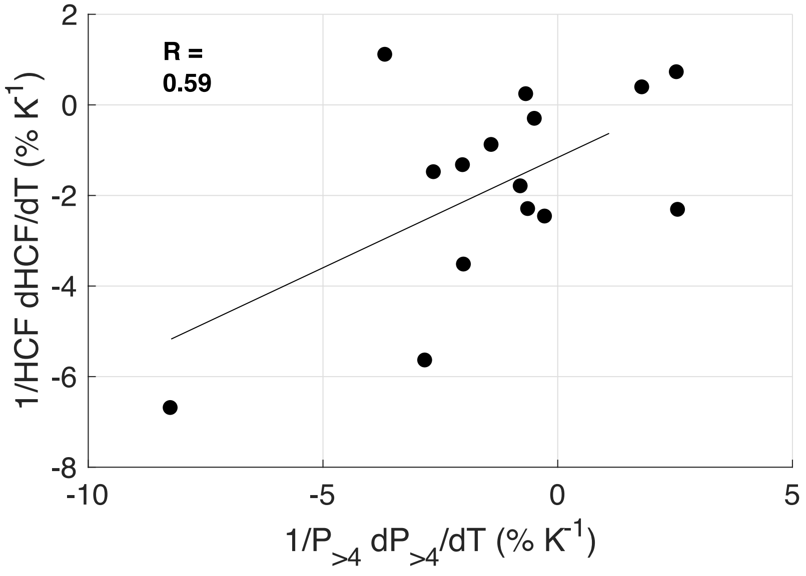

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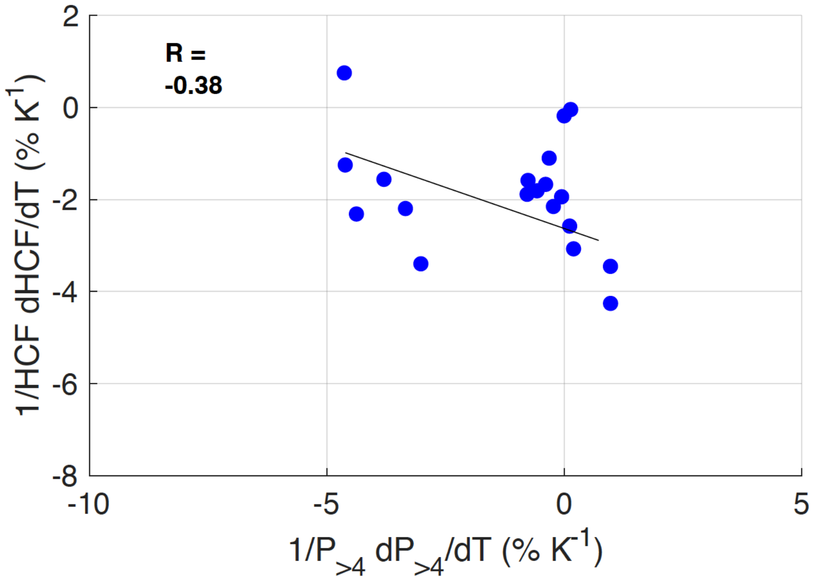

*Increase convective frequency in warming, increase high cloud fraction in convective experiment.

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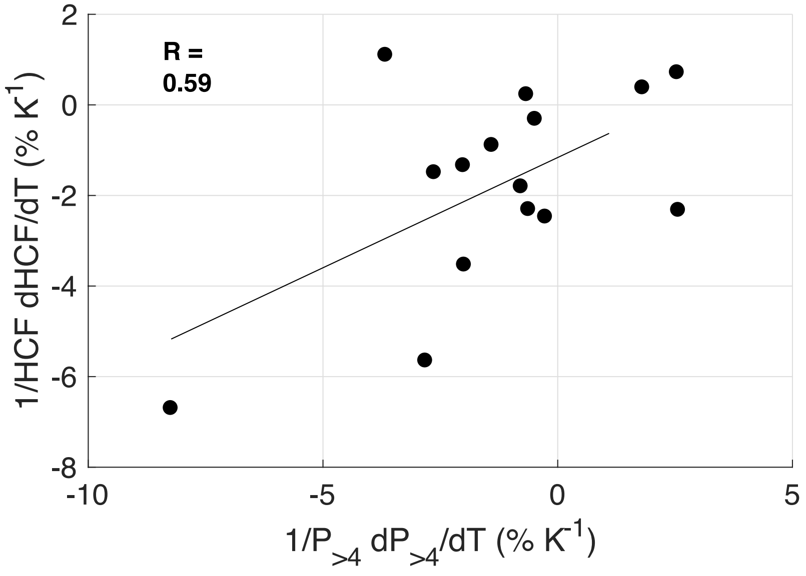

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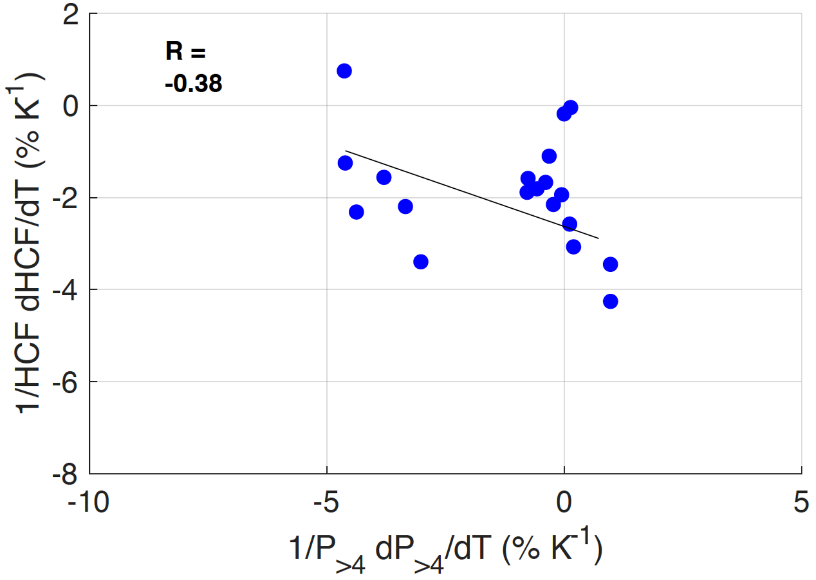


*Increase convective frequency in warming, increase high cloud fraction in convective experiment. *Why doesn't this occur in the cloud physics experiment?*

convection

$$\frac{dF_p}{dTs}$$

→

clouds

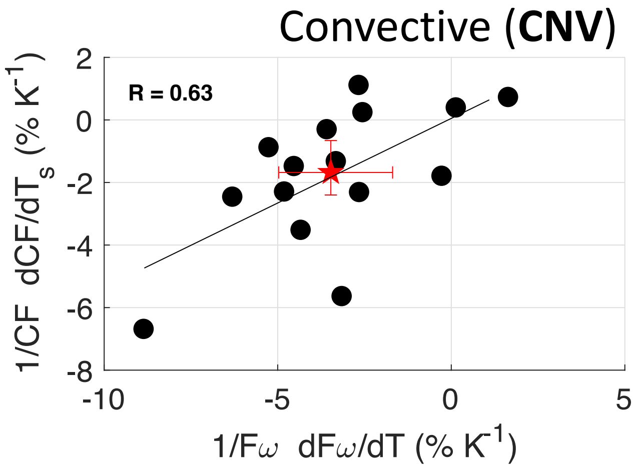
$$\frac{dCF}{dTs}$$

strength

$$\frac{d\omega_a}{dTs}$$

width

$$\frac{dF_\omega}{dTs}$$



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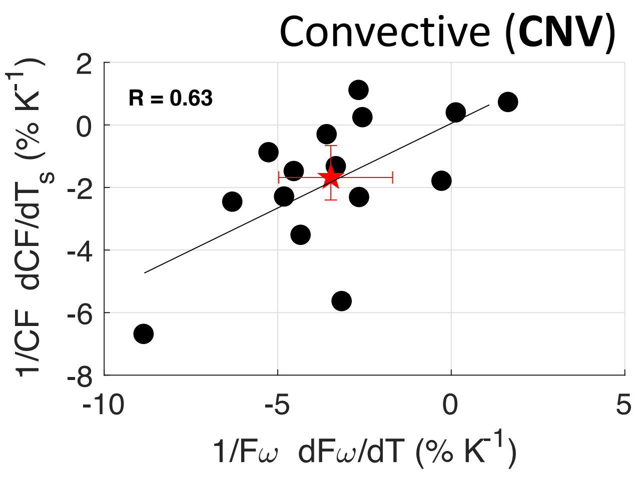

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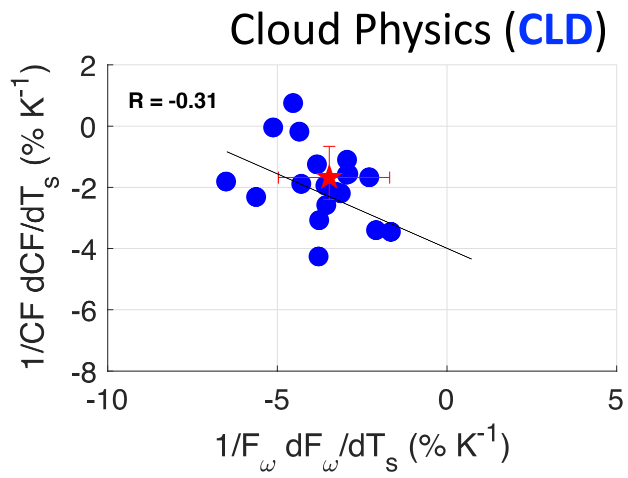

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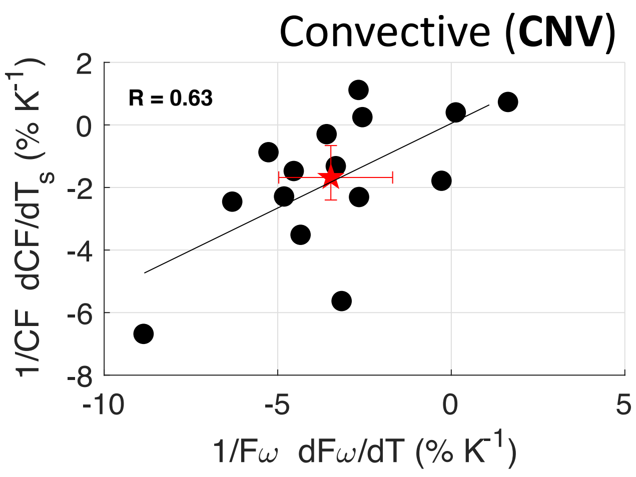

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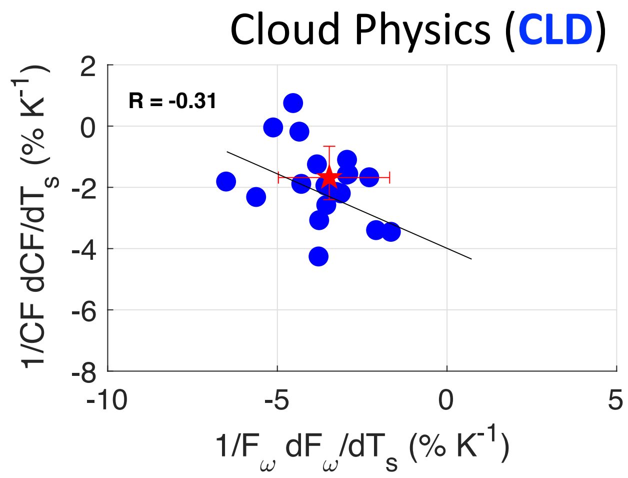
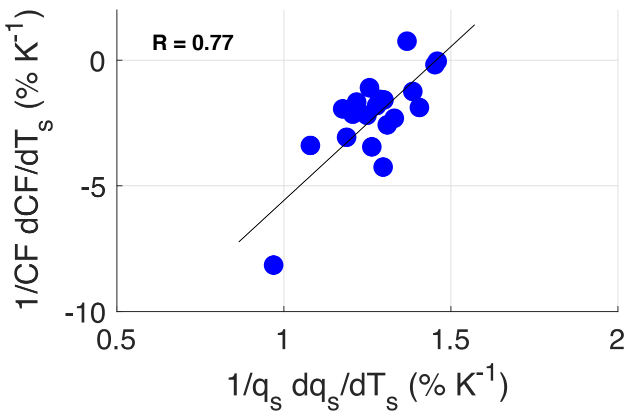


How do clouds modify circulation?

RESULTS

Cloud changes modify stability, which is coupled to circulation and convection changes (c.f. Voigt and Shaw 2015; Harrop and Hartmann 2016)

Fewer clouds = more unstable



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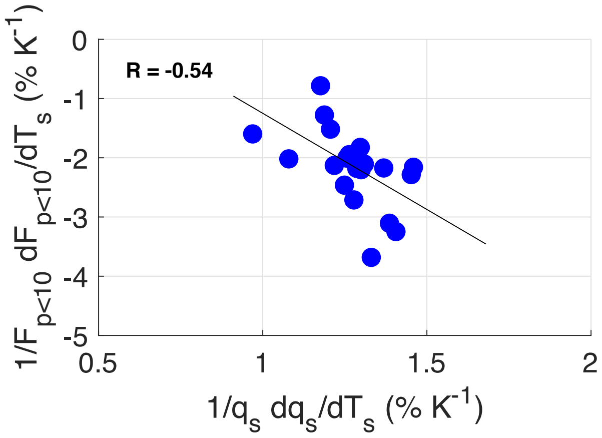
More unstable = more weak convection



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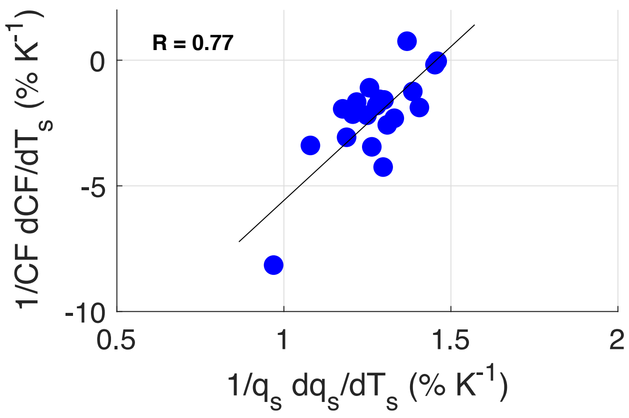

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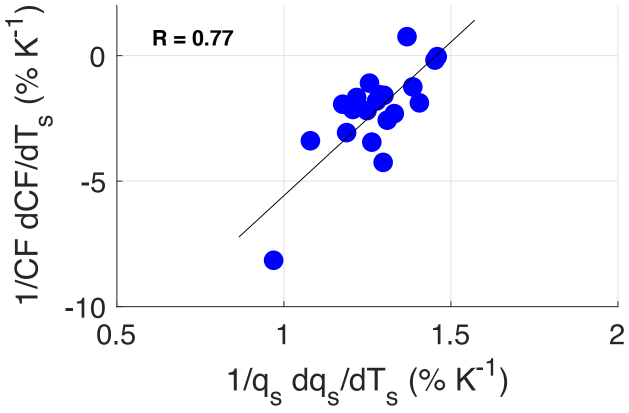

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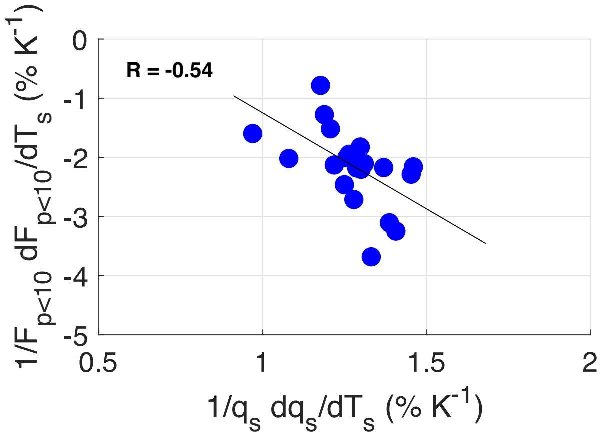
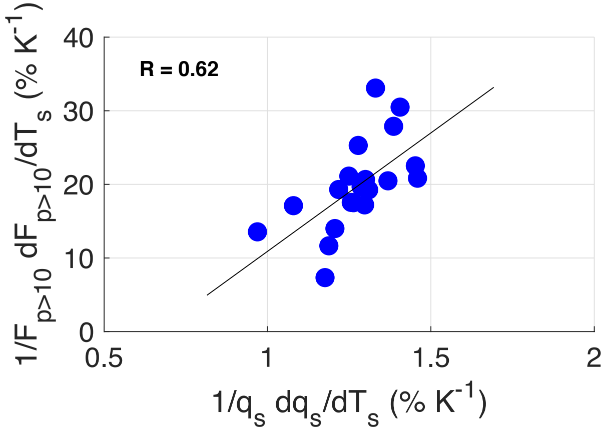


More unstable = less intense convection



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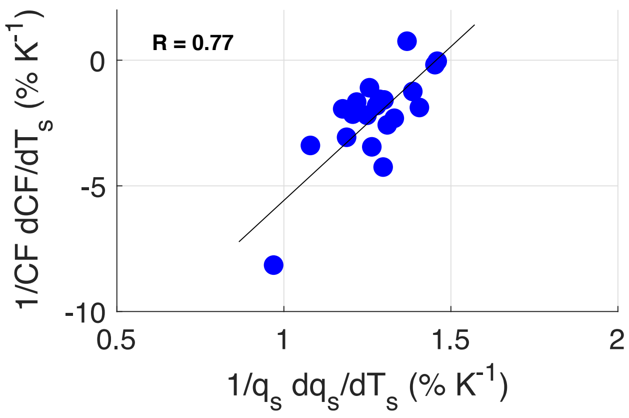

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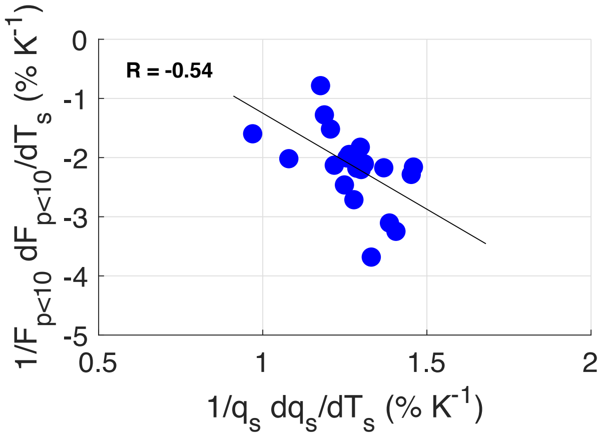

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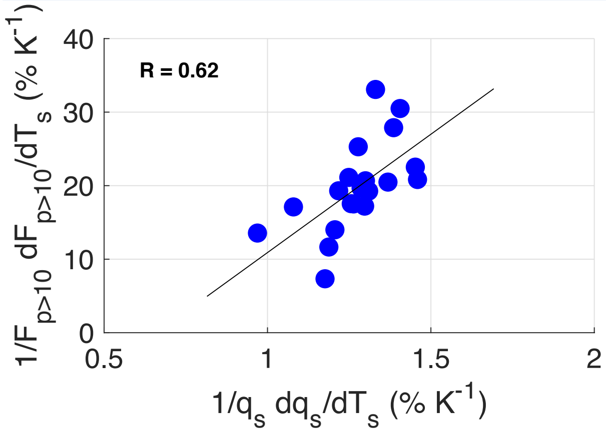
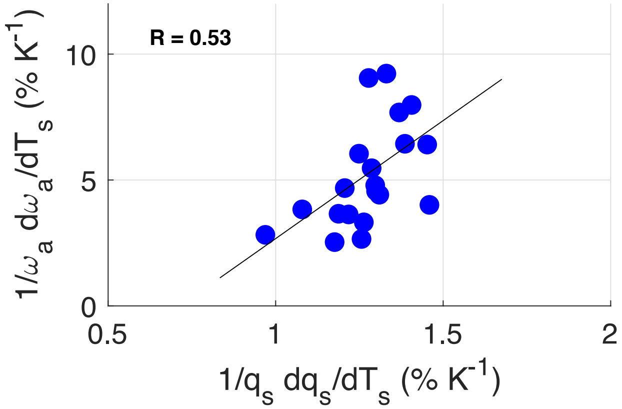


More unstable = weaker ascent, larger area



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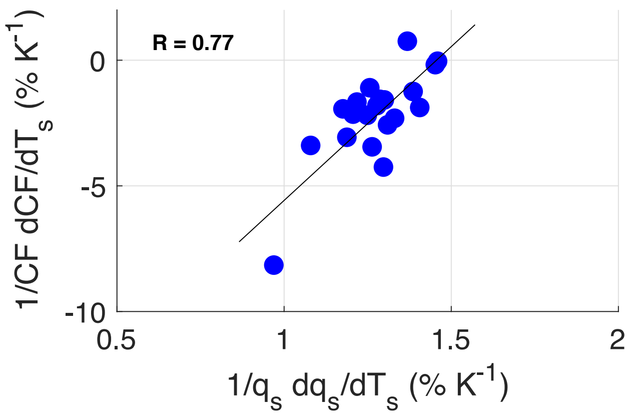

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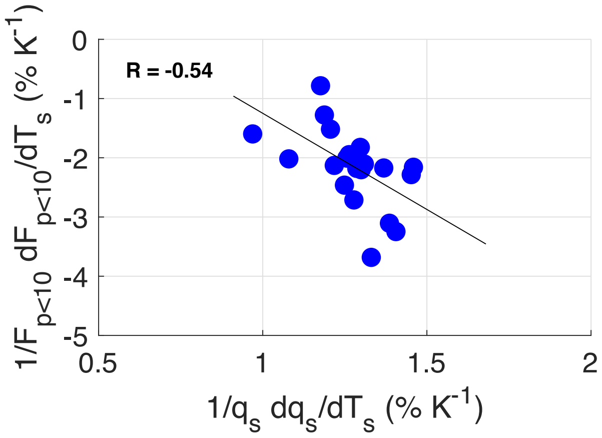

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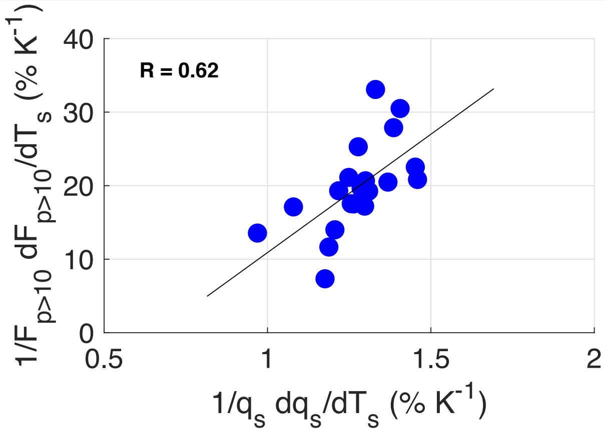

*Not present in CNV experiment

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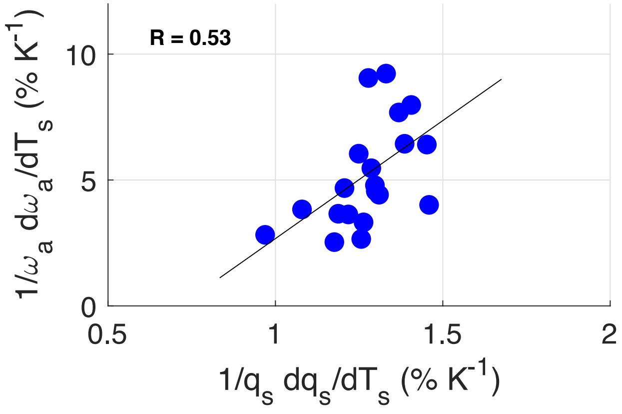
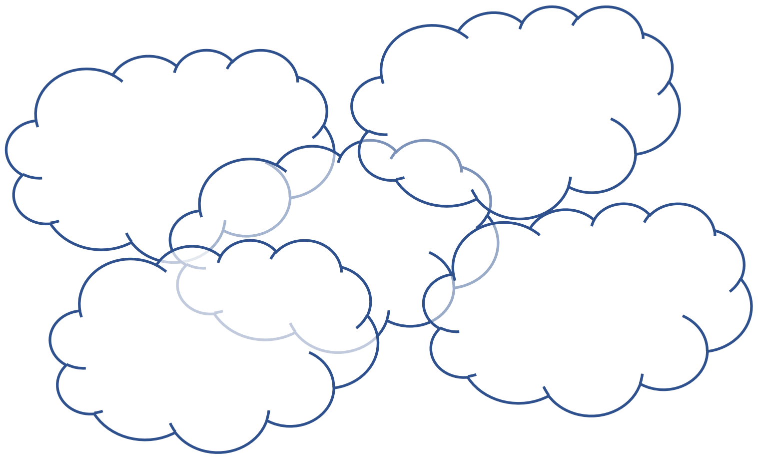
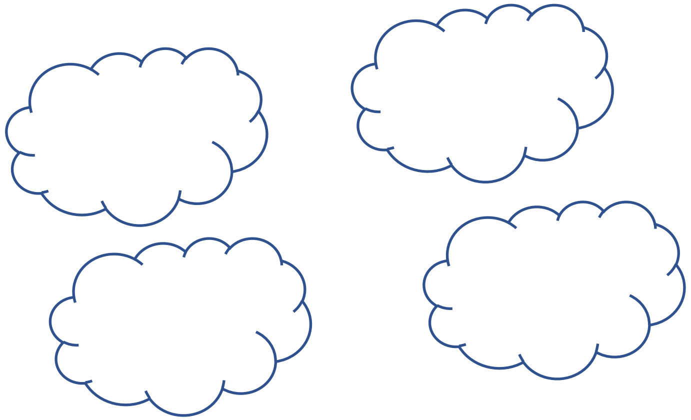




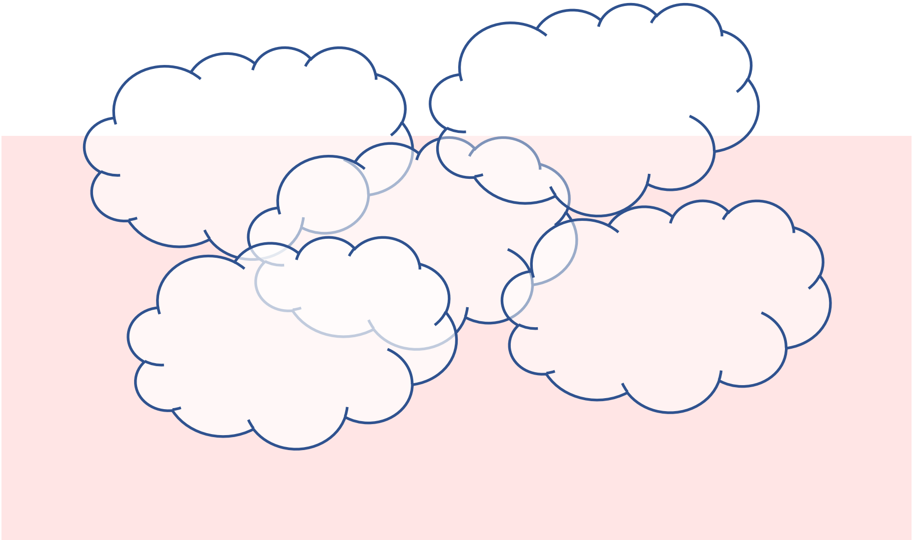


clouds

$\frac{dCF}{dT_s}$ ⇧

clouds

$\frac{dCF}{dT_s}$ ⇩



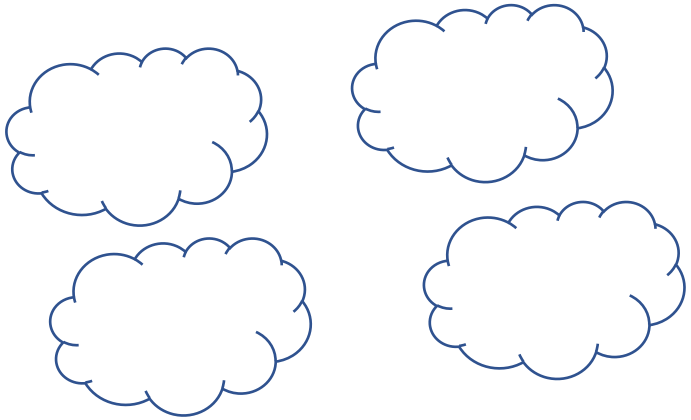
clouds

$\frac{dCF}{dT_s}$ ⇧

→

stability

$\frac{dq_s}{dT_s}$ ⇧



clouds

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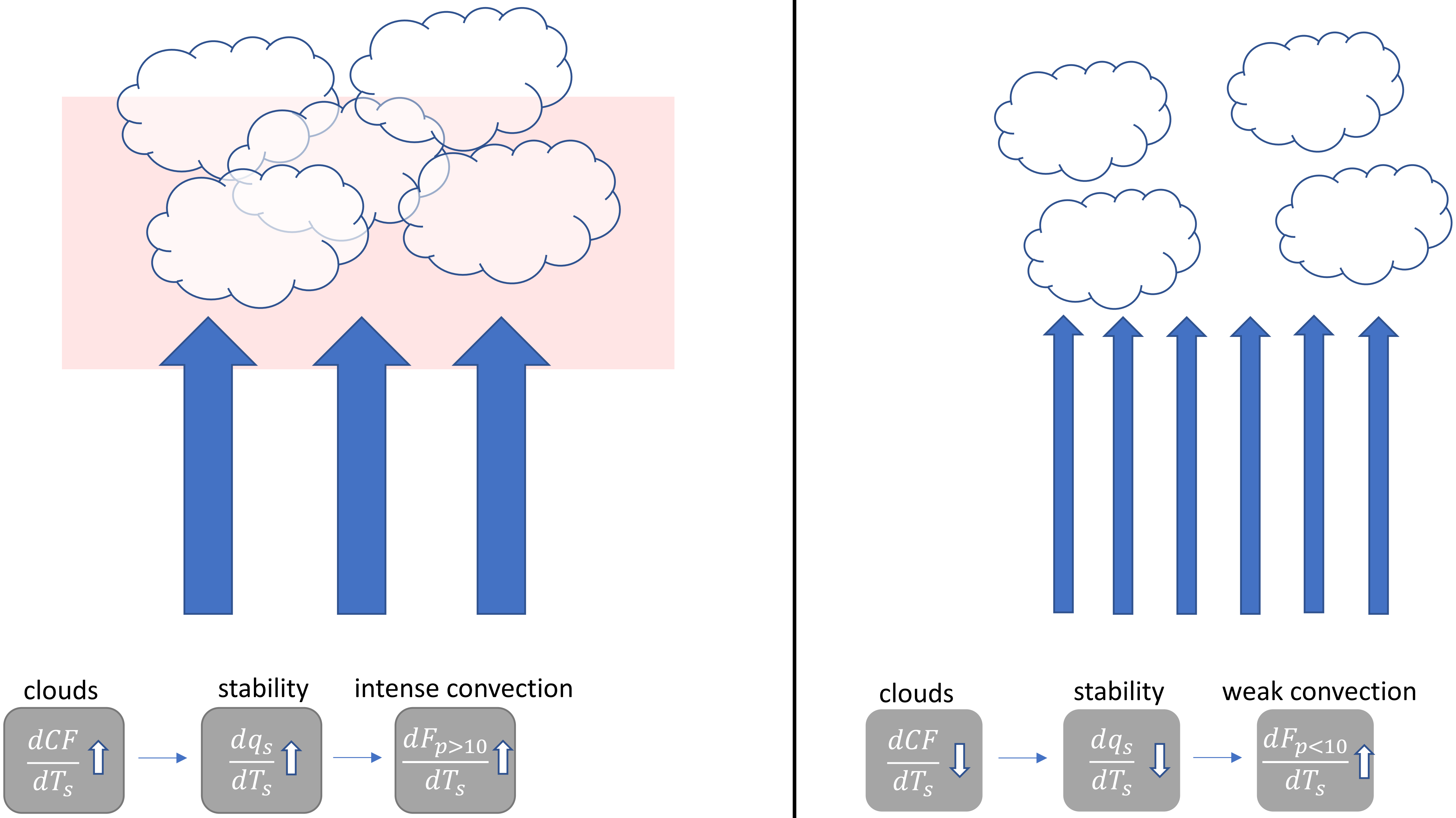
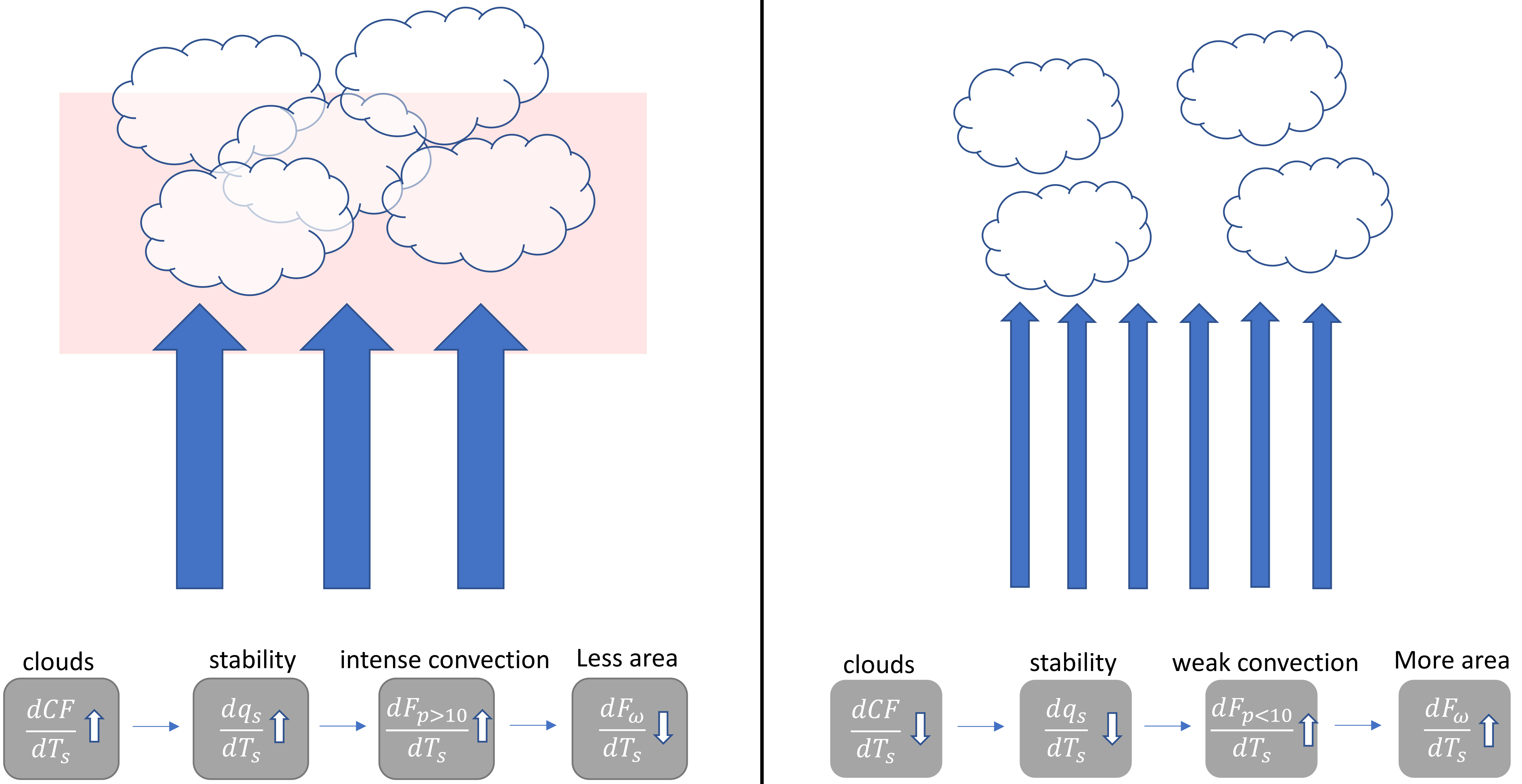

clouds
$\frac{dCF}{dT_s}$ ⇧
stability
$\frac{dq_s}{dT_s}$ ⇧
intense convection
$\frac{dF_{p>10}}{dT_s}$ ⇧
clouds
$\frac{dCF}{dT_s}$ ⇩
stability
$\frac{dq_s}{dT_s}$ ⇩
weak convection
$\frac{dF_{p<10}}{dT_s}$ ⇧


clouds
stability
intense convection
Less area
$\frac{dCF}{dT_s}$ ⇧
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$\frac{dF_{p>10}}{dT_s}$ ⇧
$\frac{dF_\omega}{dT_s}$ ⇩
clouds
stability
weak convection
More area
$\frac{dCF}{dT_s}$ ⇩
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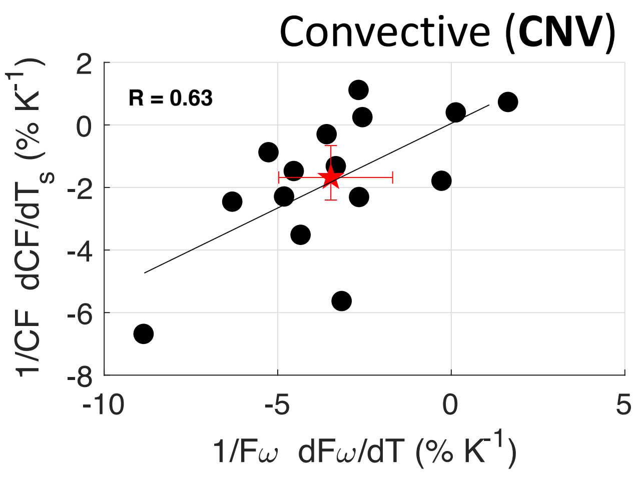
$\frac{dF_{p<10}}{dT_s}$ ⇧
$\frac{dF_\omega}{dT_s}$ ⇧

convection

$$\frac{dF_p}{dTs}$$

→

clouds	strength	width
$\frac{dCF}{dTs}$	$\frac{d\omega_a}{dTs}$	$\frac{dF_\omega}{dTs}$

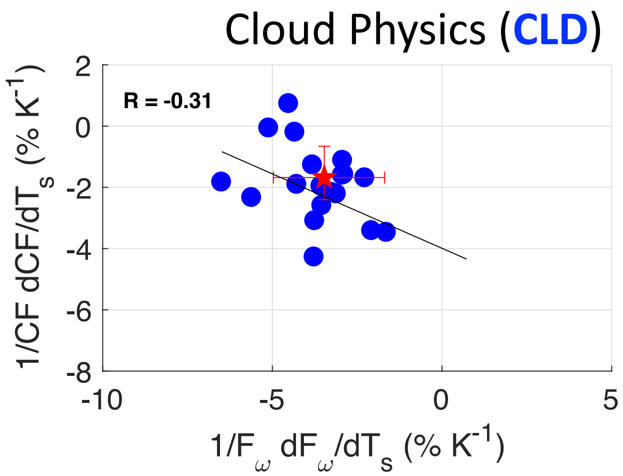


clouds

$$\frac{dCF}{dTs}$$

convection	strength	width
$\frac{dF_p}{dTs}$	$\frac{d\omega_a}{dTs}$	$\frac{dF_\omega}{dTs}$

stability



Questions

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Thank you!

Questions/Comments/Ideas:
kathleen.a.schiro@jpl.nasa.gov