Cloud Feedbacks:
What We Have Learned,
What We Can Measure, &
What EarthCARE May Resolve

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with contributions from Li-Wei Chao, Steve Klein, and many others
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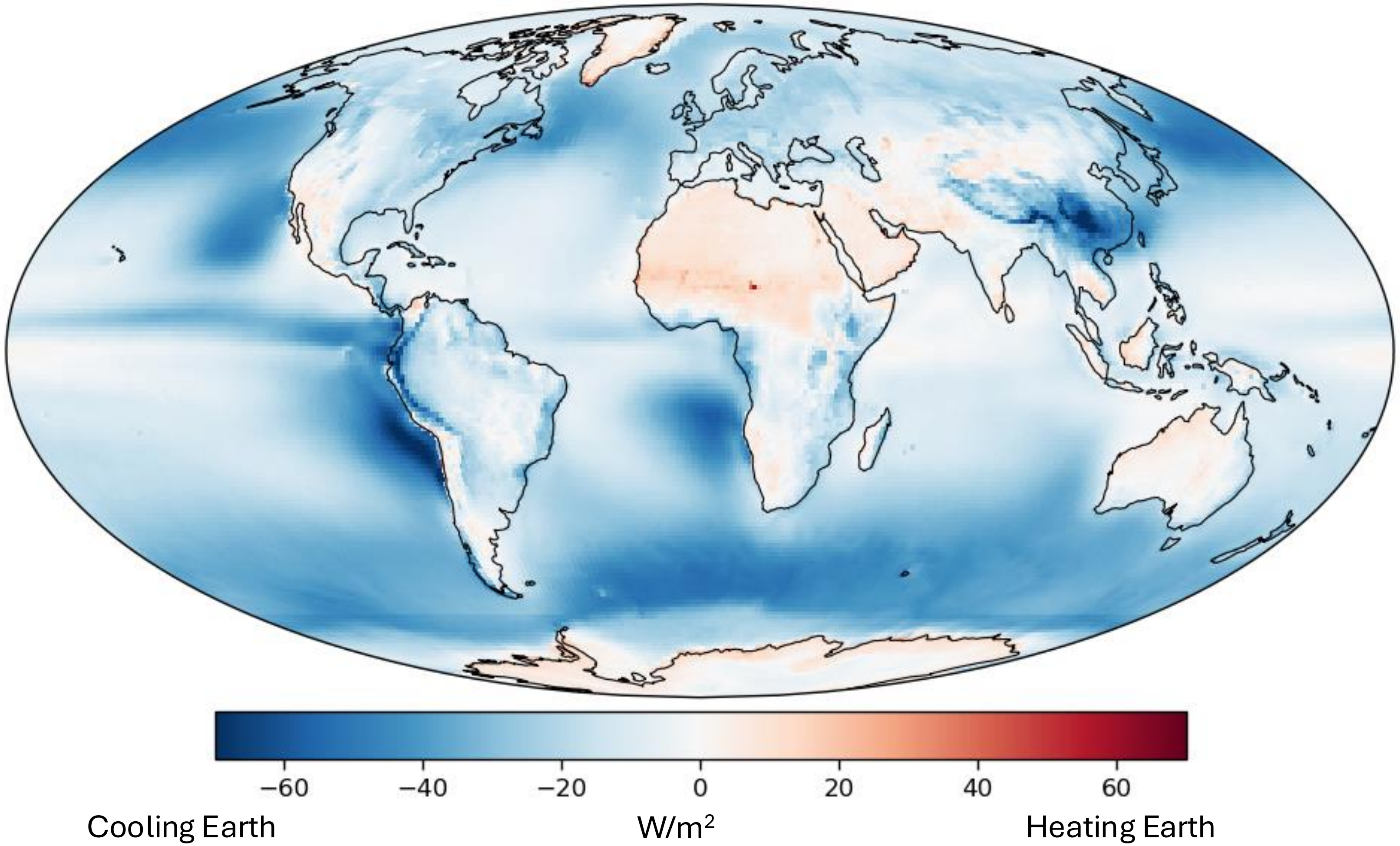
We are grateful for support from the RGMA Program at the US Department of Energy

Net Cloud Radiative Effect

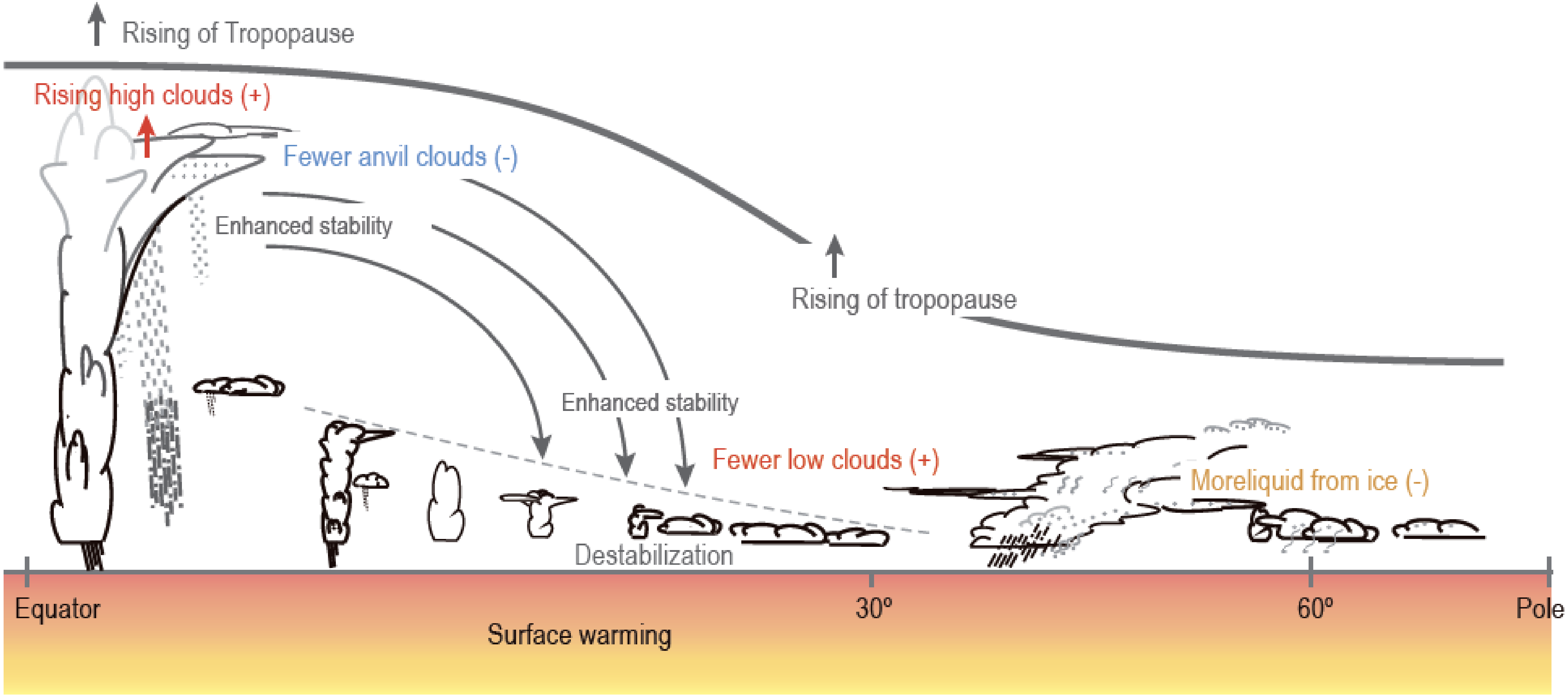
Impact of clouds on TOA radiation

Global average = -18 W/m^2



(from CERES)

The Cloud Feedback Challenge



IPCC AR6, Figure 7.9

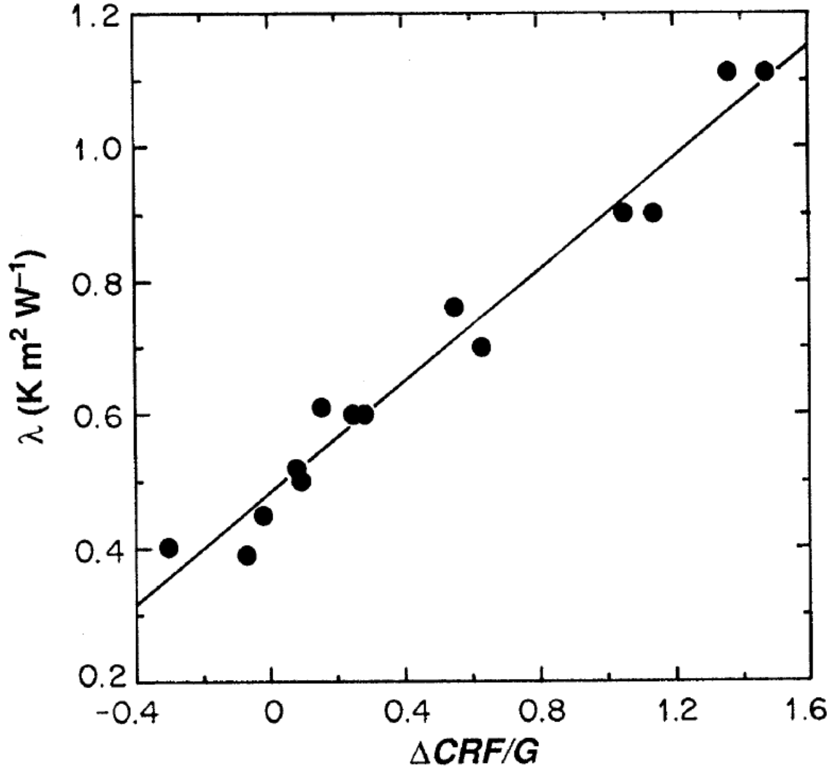
Our Evolving Understanding

1970s-1980s

-ECS differences due to cloud feedback

Interpretation of Cloud-Climate Feedback as Produced by 14 Atmospheric General Circulation Models

R. D. Cess, G. L. Potter, J. P. Blanchet, G. J. Boer, S. J. Ghan, J. T. Kiehl, H. Le Treut, Z.-X. Li, X.-Z. Liang, J. F. B. Mitchell, J.-J. Morcrette, D. A. Randall, M. R. Riches, E. Roeckner, U. Schlese, A. Slingo, K. E. Taylor, W. M. Washington, R. T. Wetherald, I. Yagai



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-Tropical marine low-clouds responsible for inter-model spread

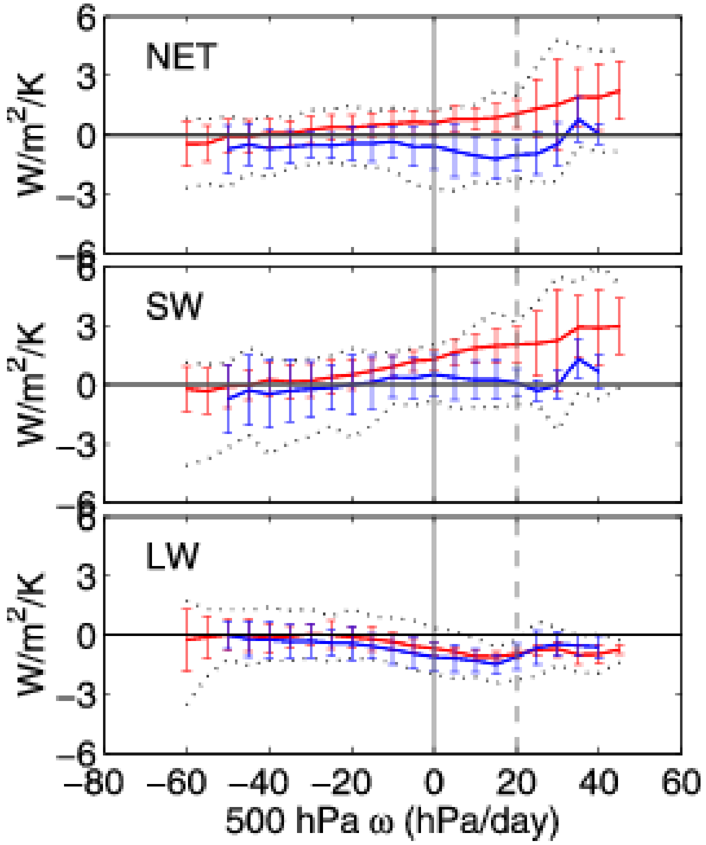
GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L20806, doi:10.1029/2005GL023851, 2005

Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models

Sandrine Bony and Jean-Louis Dufresne

Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace, Centre National de Recherche Scientifique, Paris, France

Received 24 June 2005; revised 30 August 2005; accepted 21 September 2005; published 26 October 2005.



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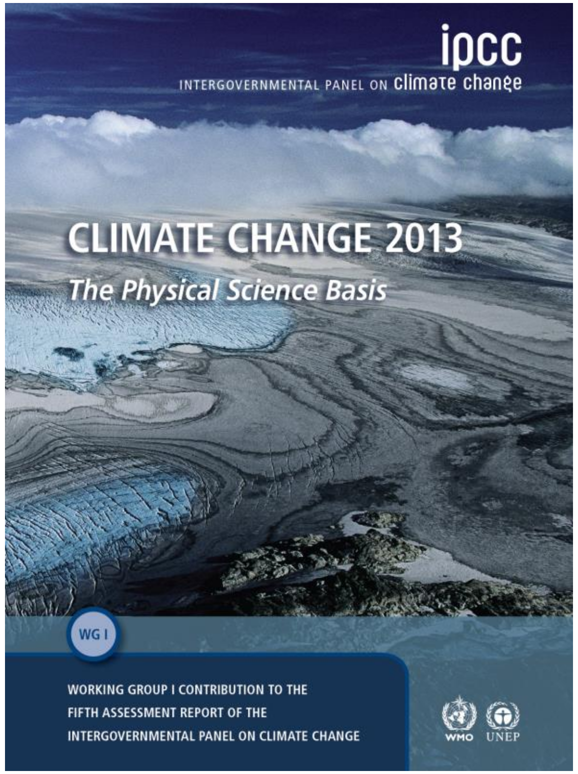
2010s

-Large-eddy simulations and observational analyses mature
-Novel diagnostic approaches developed and widely used
-Assessed positive cloud feedback: +0.6 W m^{-2} K^{-1} (range -0.2 to 2.0)



"The sign of the net radiative feedback due to all cloud types is... likely positive"

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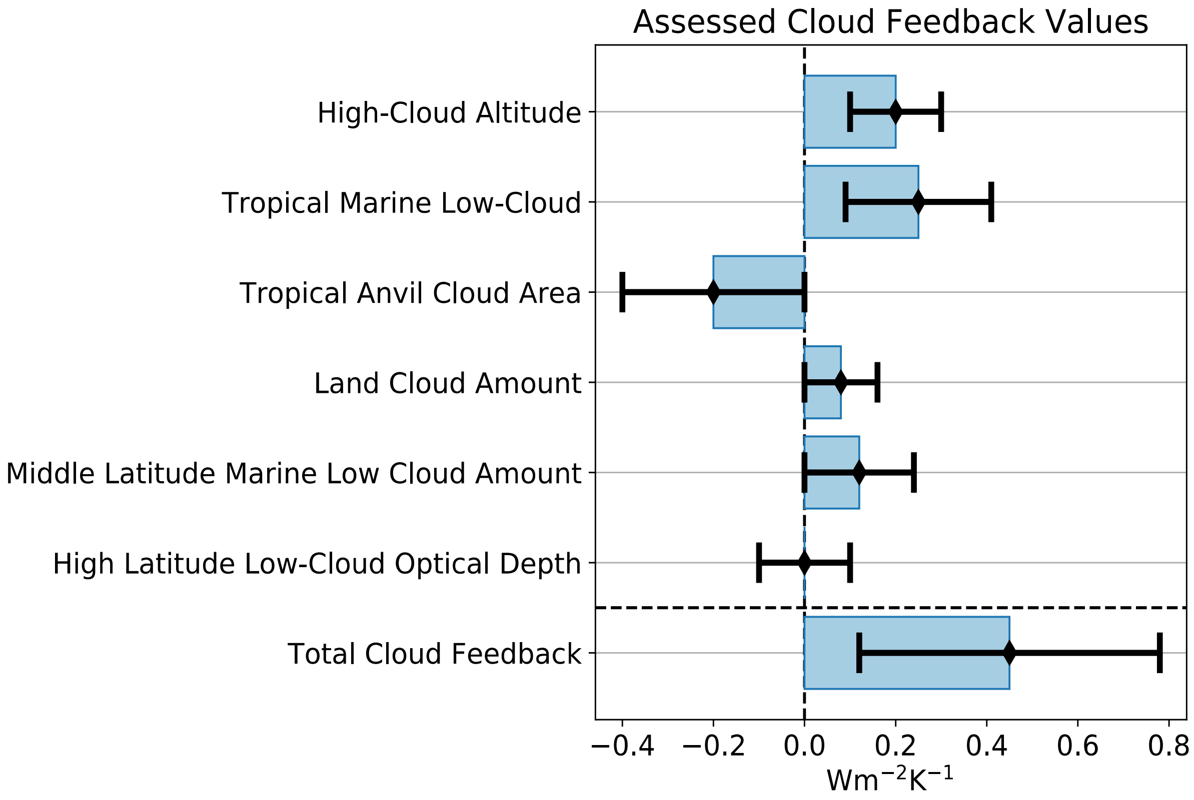
2020 WCRP ECS Assessment

-Quantified cloud feedbacks by cloud type
-Assessed total cloud feedback of +0.45 ± 0.33 W m^{-2} K^{-1}
-ECS likely range of 2.6–3.9K



WCRP Climate Sensitivity Assessment, Sherwood et al. (2020)

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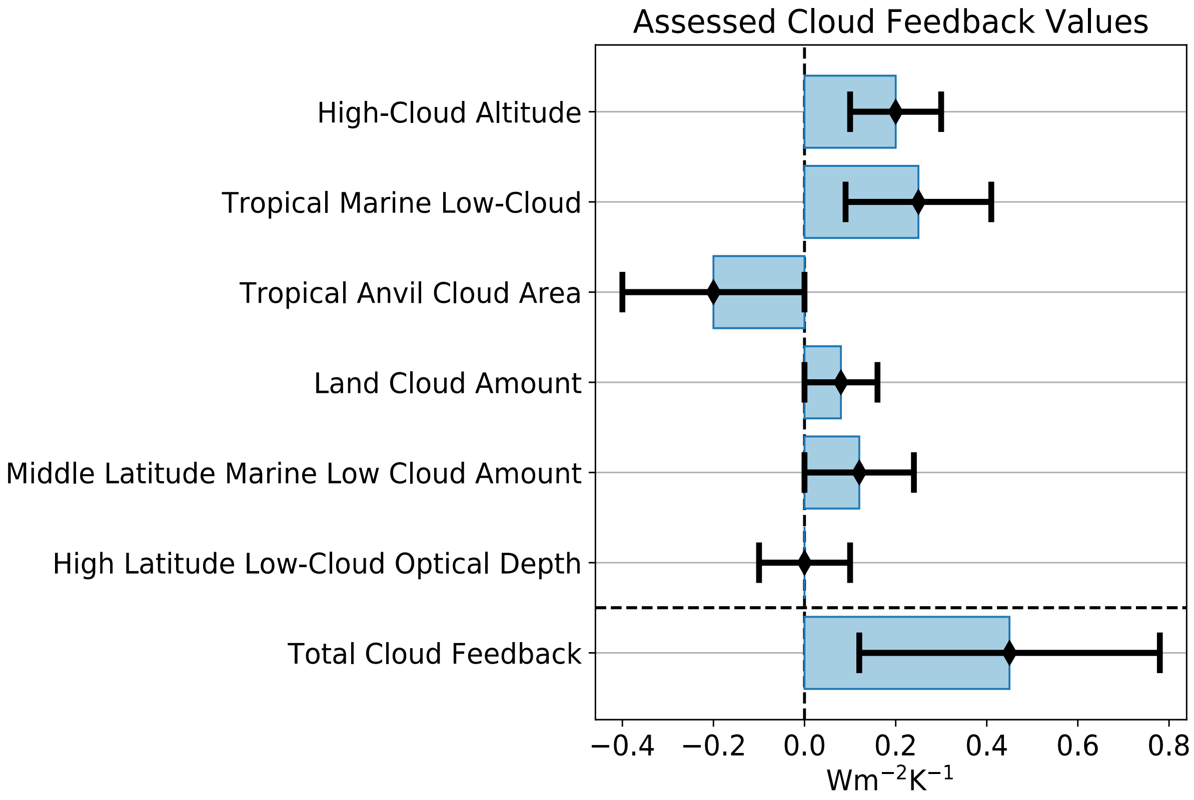
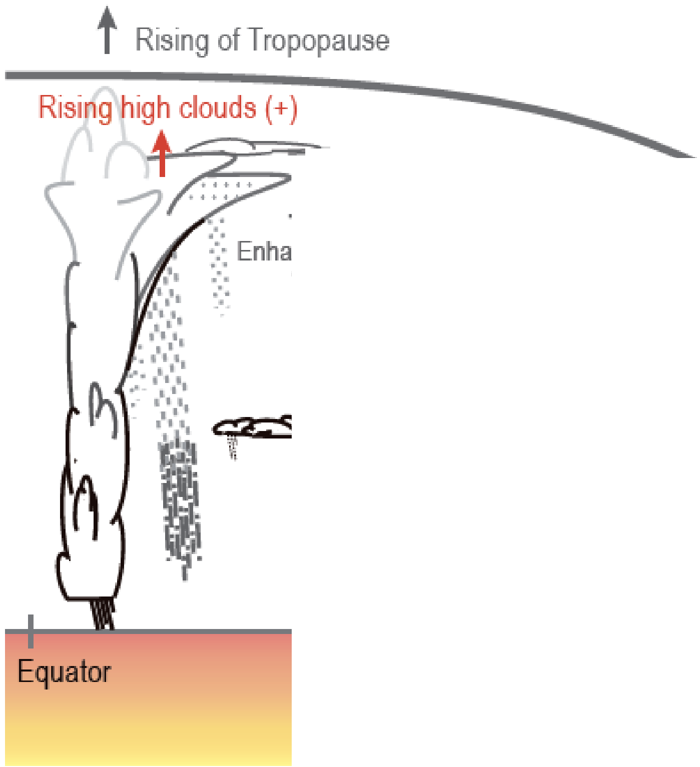
Post-WCRP Assessment

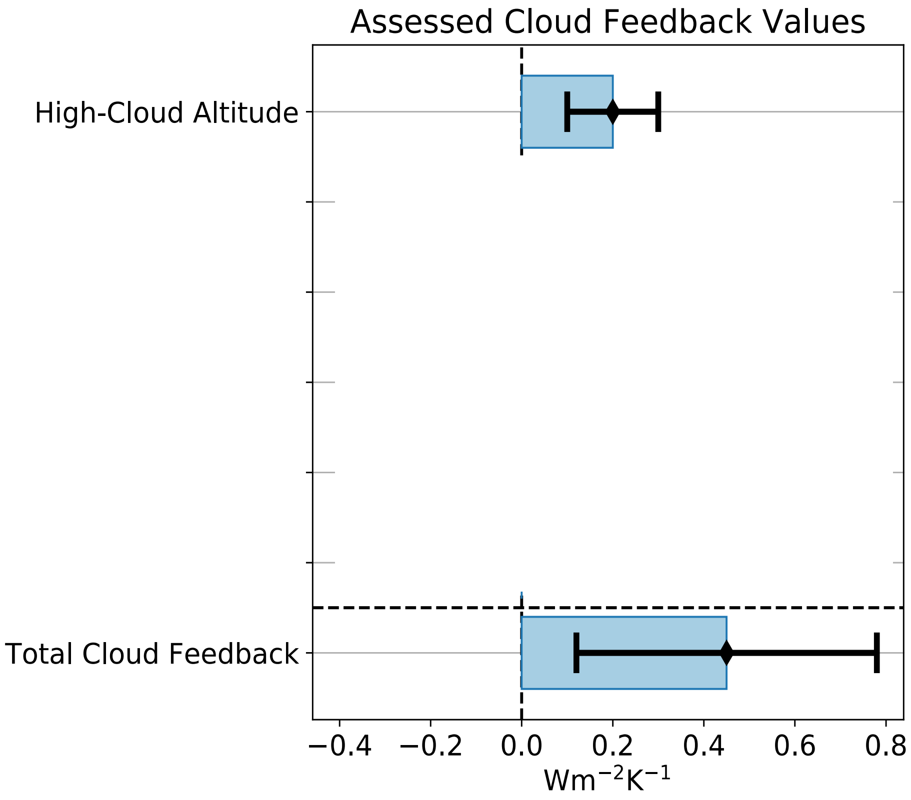
-Maturation of CCF analyses for both high- and low-cloud feedbacks
-Renewed emphasis on narrowing high cloud feedback uncertainty
-Emergence of global storm resolving models
-Questions raised by the observed EEI record from CERES



WCRP Climate Sensitivity Assessment, Sherwood et al. (2020)

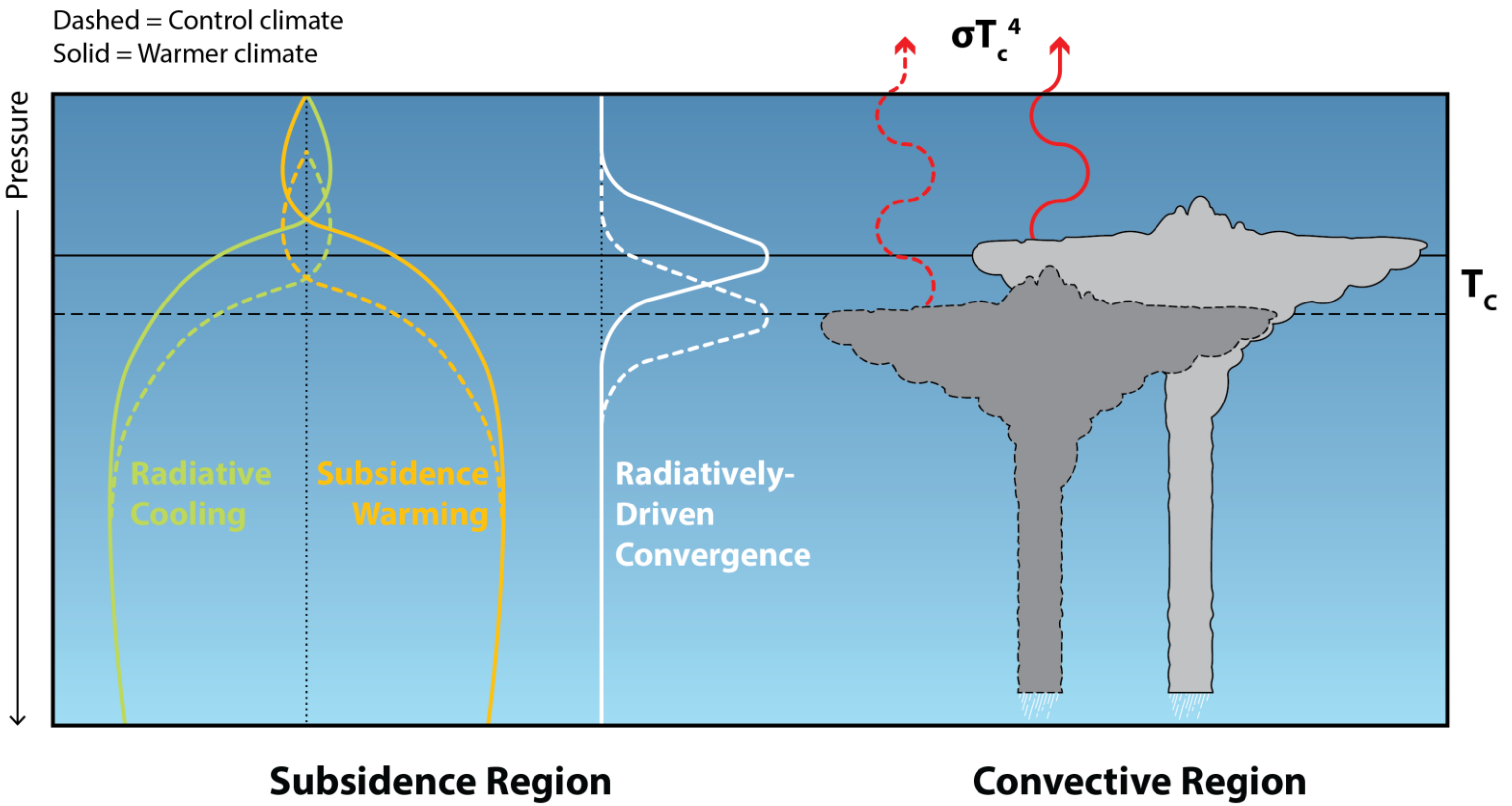
High Cloud Feedbacks: Altitude

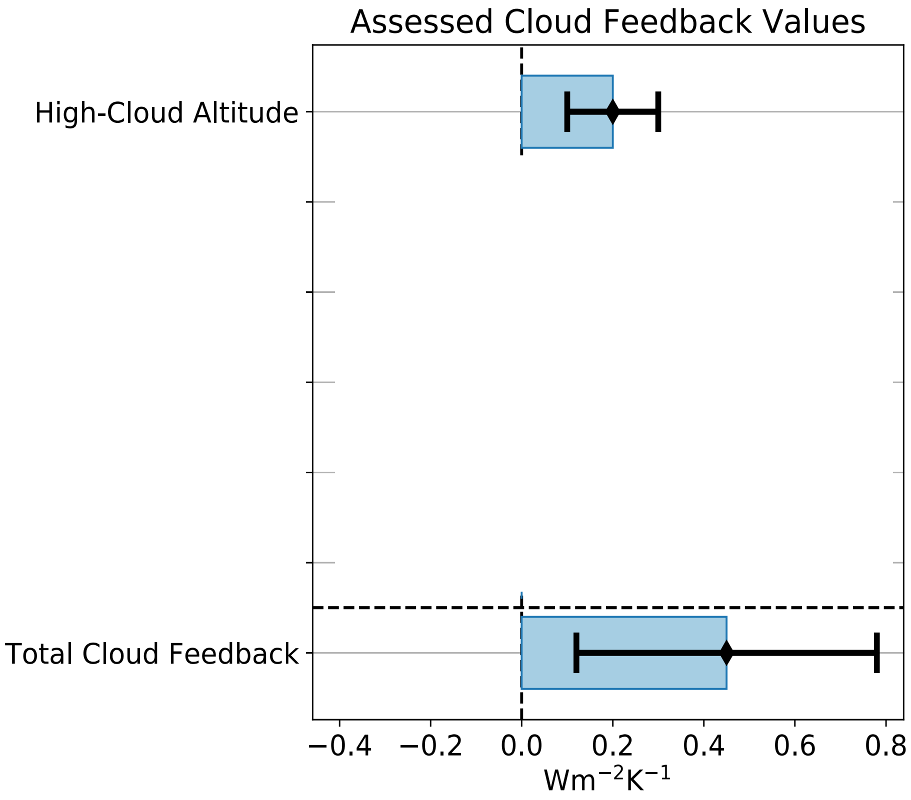




WCRP Climate Sensitivity Assessment, Sherwood et al. (2020)

Fixed Anvil Temperature (FAT)



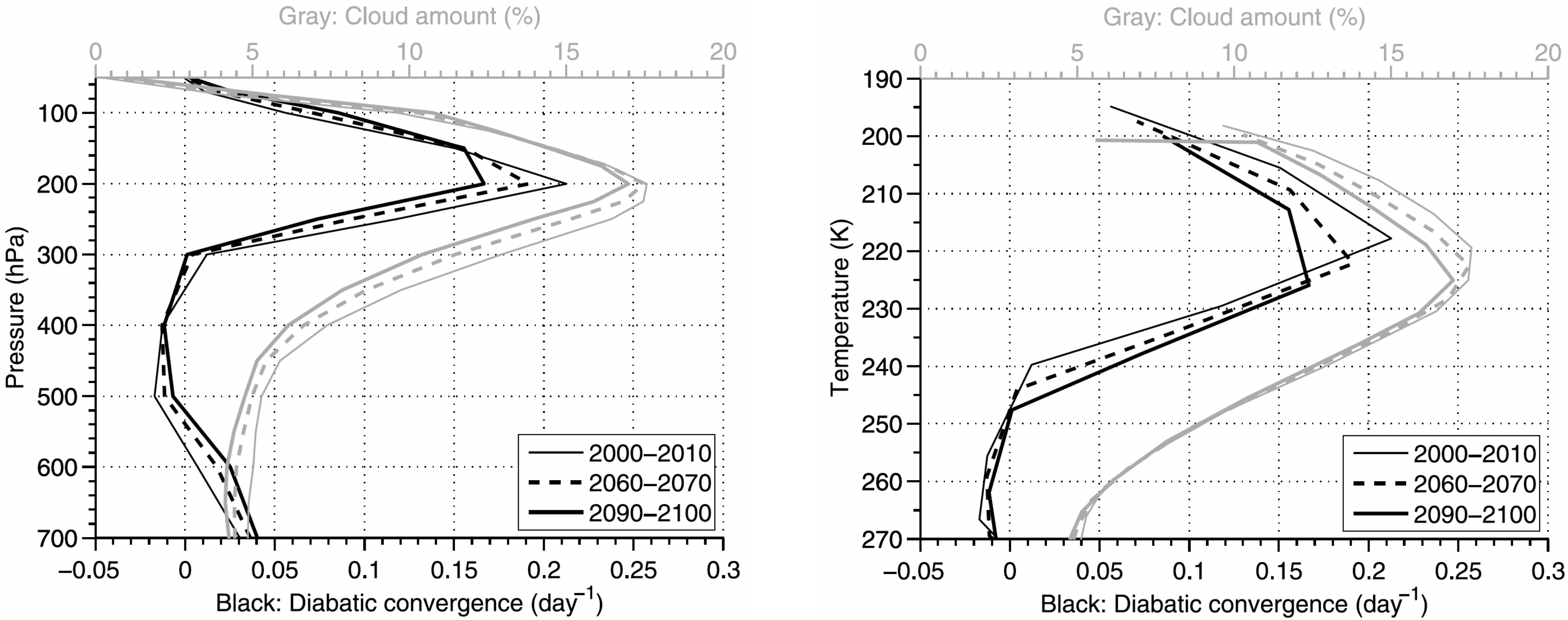


WCRP Climate Sensitivity Assessment, Sherwood et al. (2020)

Hartmann and Larson (2002)

PHAT Clouds in CMIP

Not quite a fixed anvil temperature, but still a strong positive altitude feedback

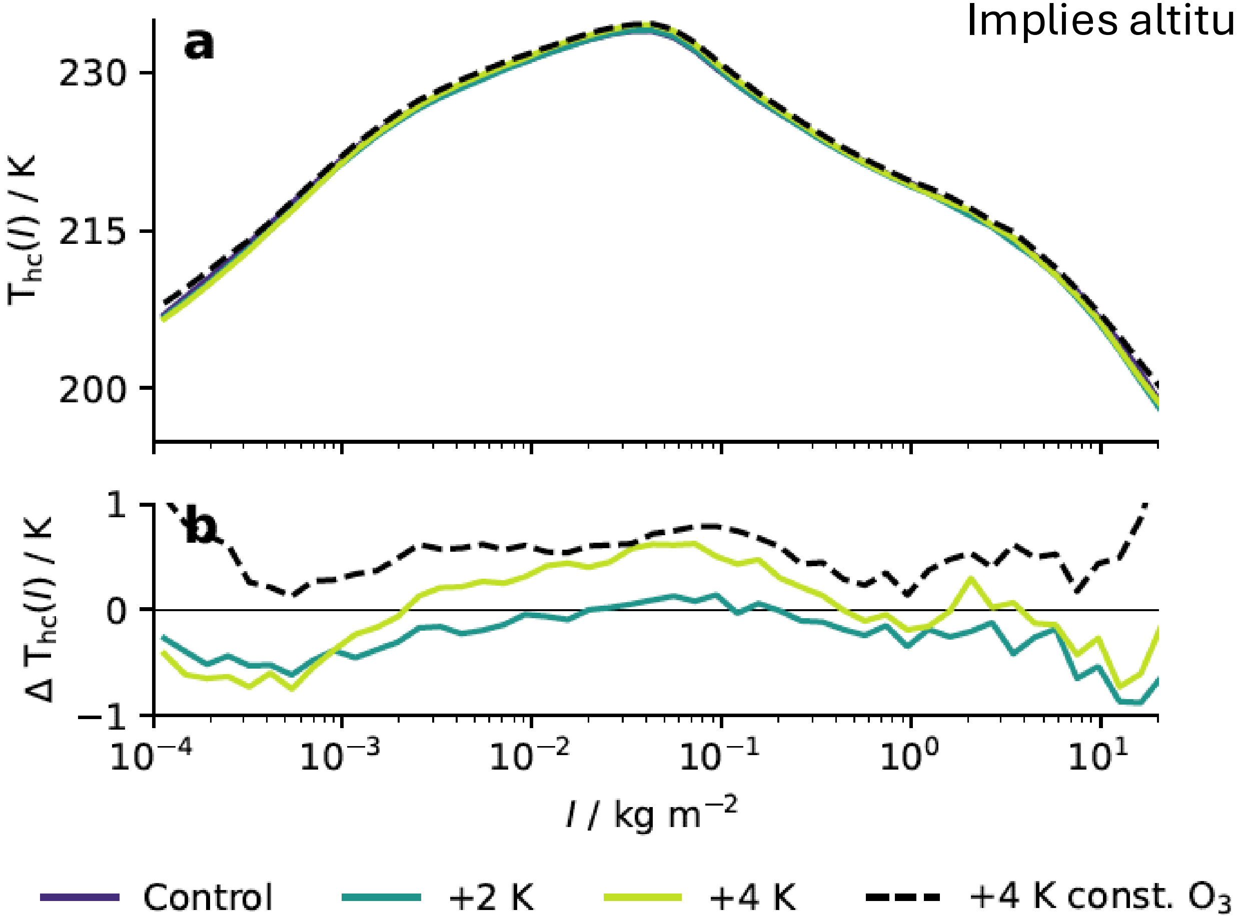


Zelinka and Hartmann (2010)

~~PHAT~~ FAT Clouds in ICON

Fixed anvil temperature in a km-scale model; larger positive altitude feedback

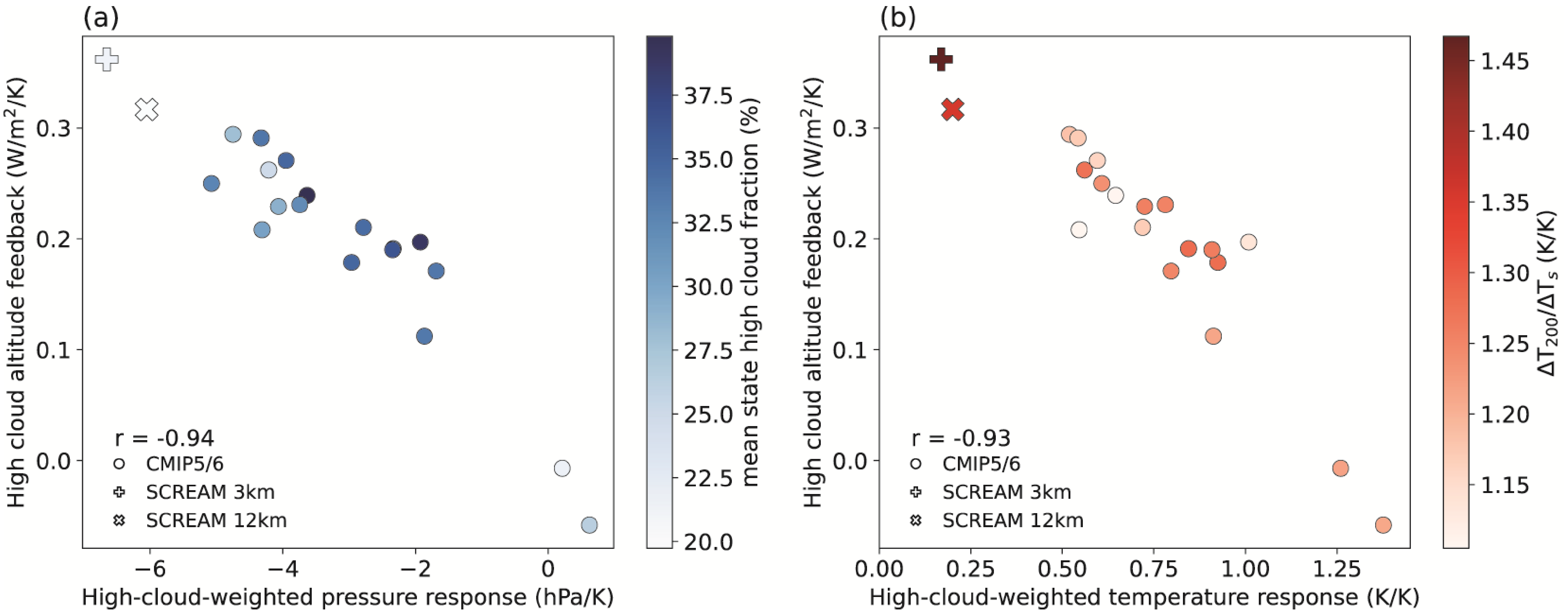
Implies altitude feedback of ~0.3 W/m²/K



Deutloff et al (submitted)

~~PHAT~~ FAT Clouds in SCREAM

Fixed anvil temperature in a km-scale model; larger positive altitude feedback



Chao et al. (2026)

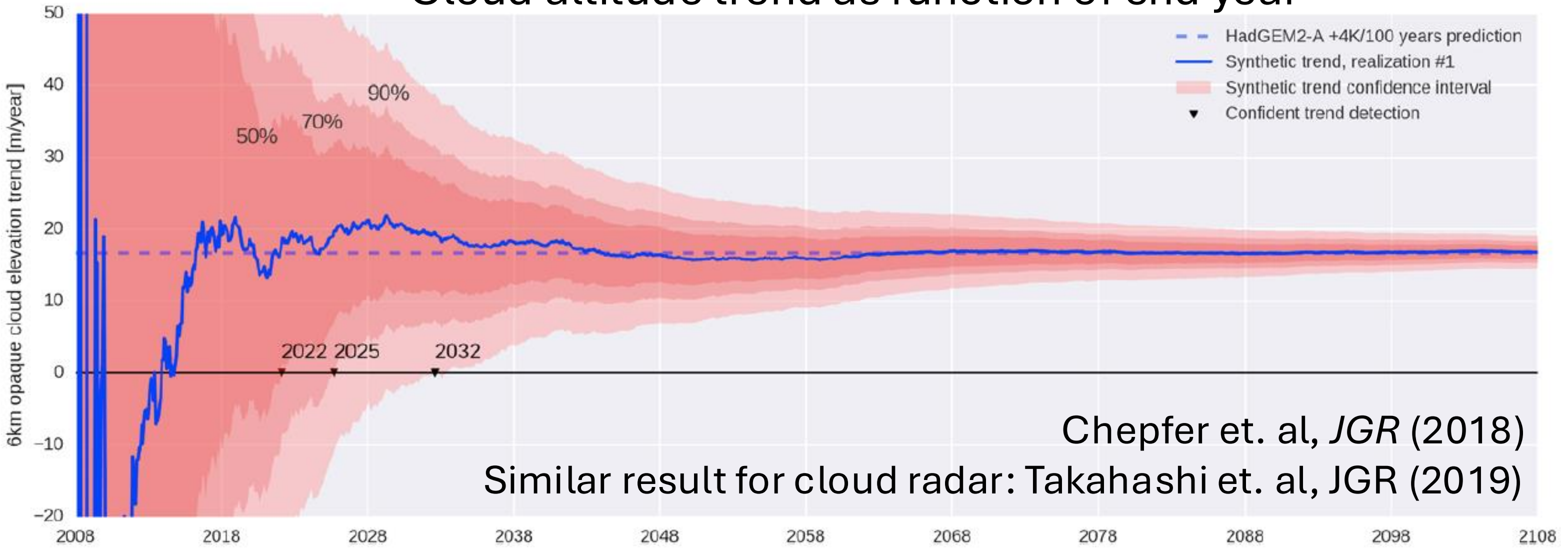
Cloud Altitude Trends

- Small global-warming induced changes in cloud properties that we care about for cloud feedback will only emerge from the noise on multi-decadal timescales.
  → need measurement accuracy and stability! [*Winker et al. Surv. Geophys. 2017*]

Cloud Altitude Trends

- Small global-warming induced changes in cloud properties that we care about for cloud feedback will only emerge from the noise on multi-decadal timescales.
  → need measurement accuracy and stability! [*Winker et al. Surv. Geophys. 2017*]
- Secular changes in cloud altitude from active sensors
  - High cloud altitude feedback has good signal-to-noise characteristics
  - Lidar-derived cloud altitude retrievals have inherently high accuracy, so ATLID could be related to A-train, even if temporal gaps exist

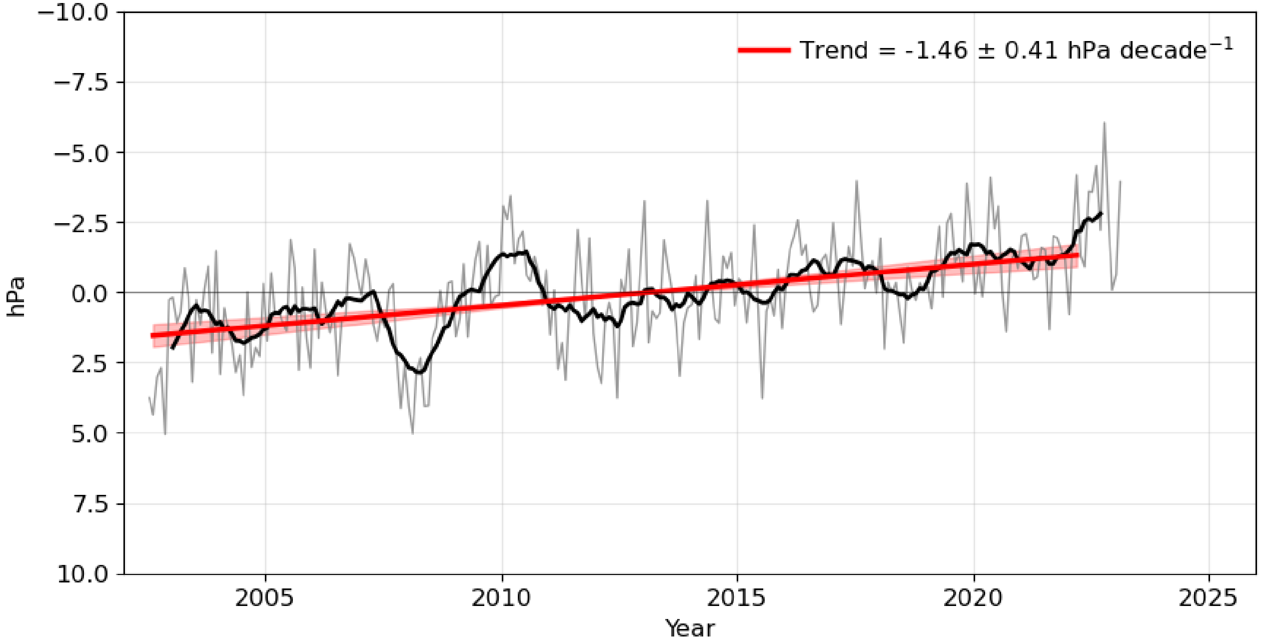
Cloud altitude trend as function of end year



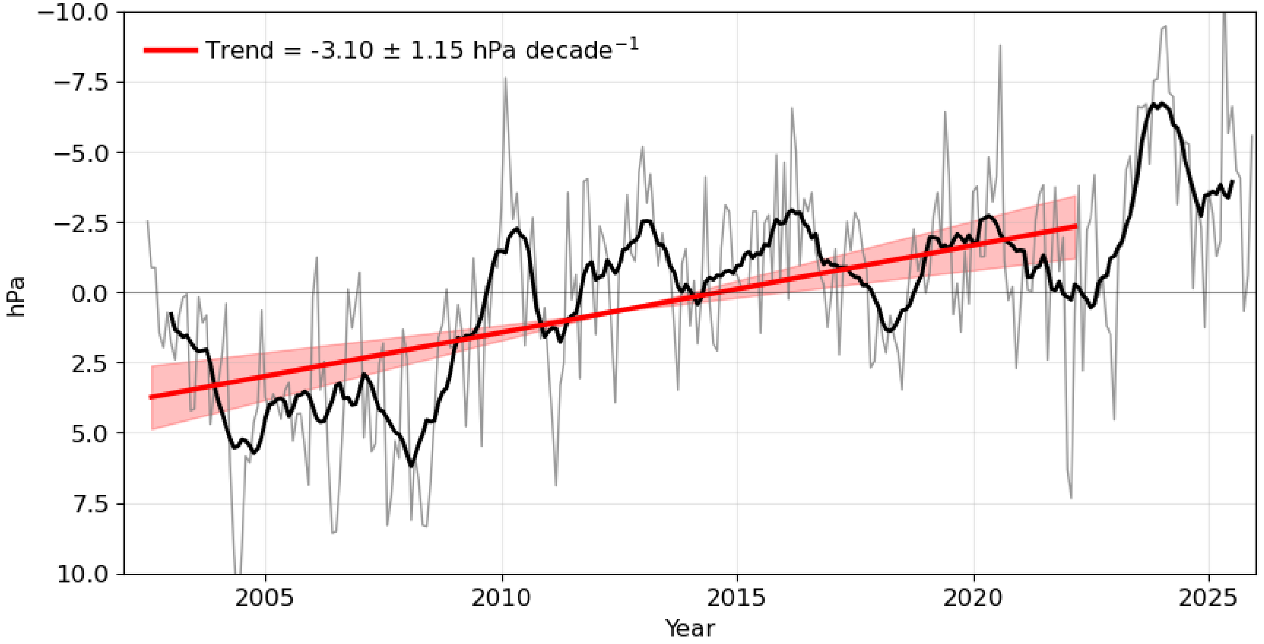
Chepfer et. al, *JGR* (2018)
Similar result for cloud radar: Takahashi et. al, JGR (2019)

Observed High Cloud Top Pressure Trends

MODIS (CERES-FBCT)



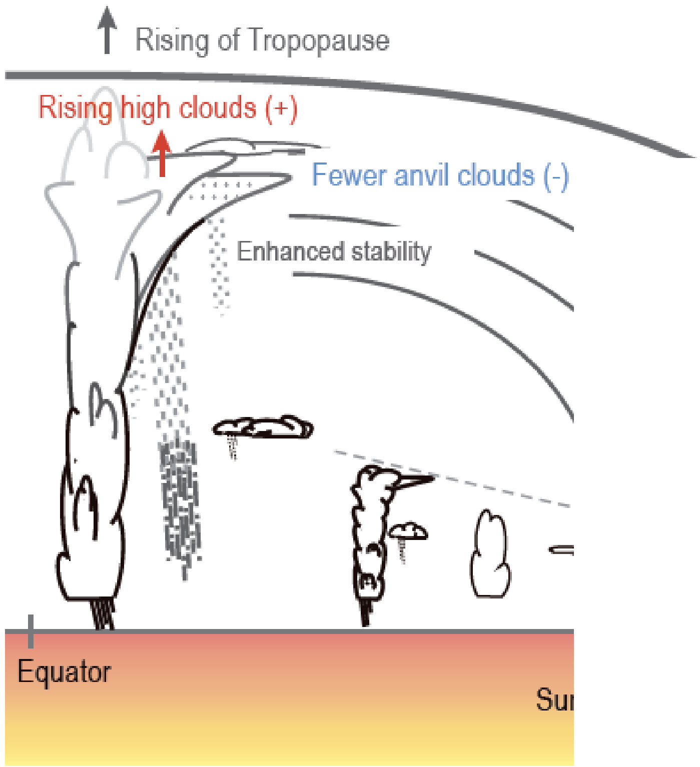
MODIS-COSP

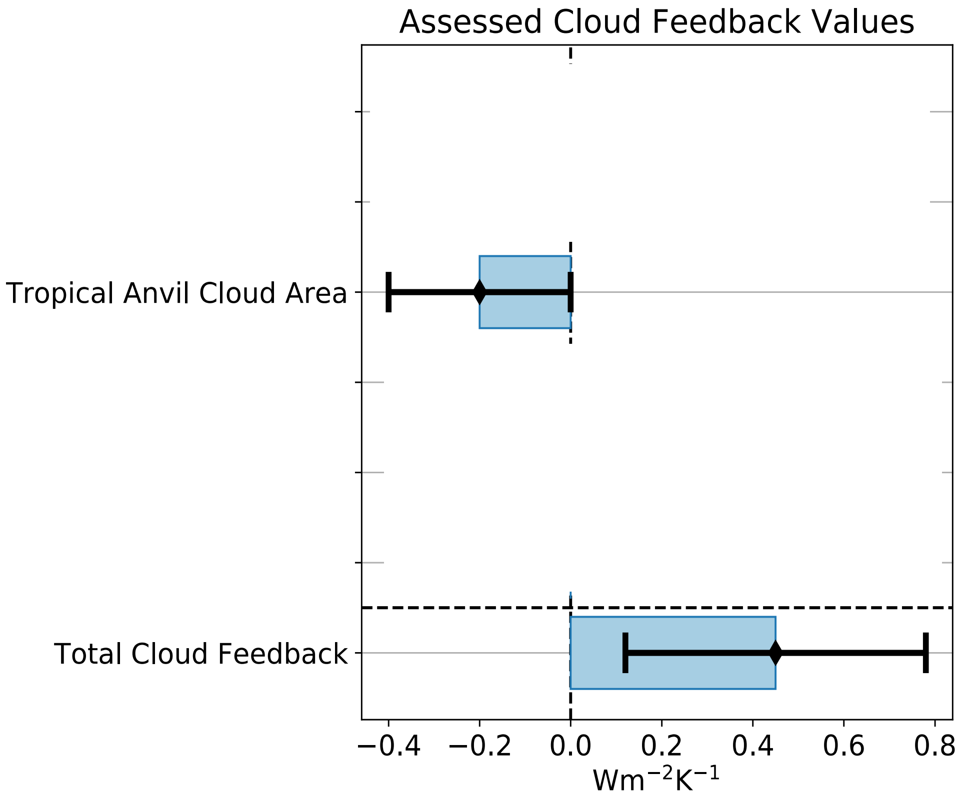


CTP < 560hPa

See also Richardson et al (2022)

High Cloud Feedbacks: Amount + Optical Depth

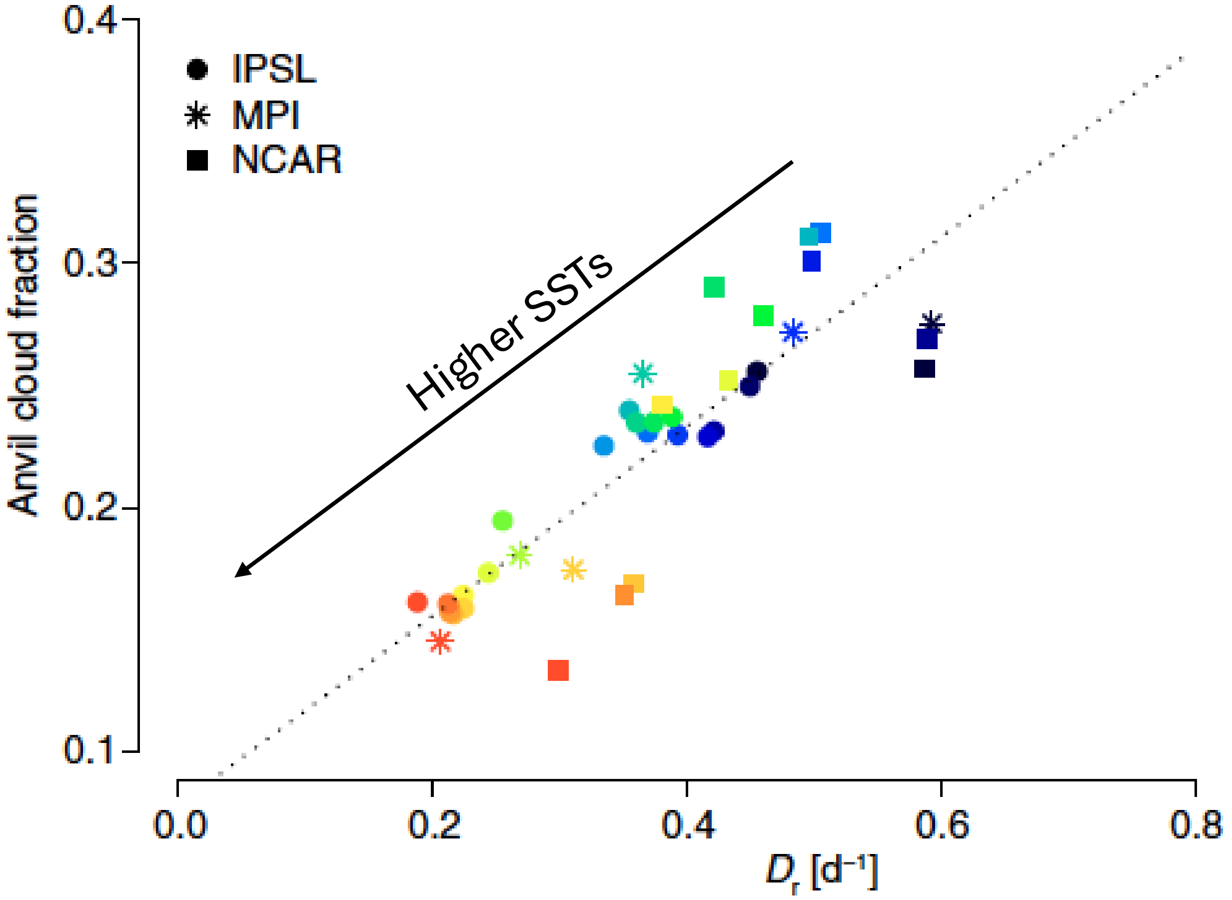




WCRP Climate Sensitivity Assessment, Sherwood et al. (2020)

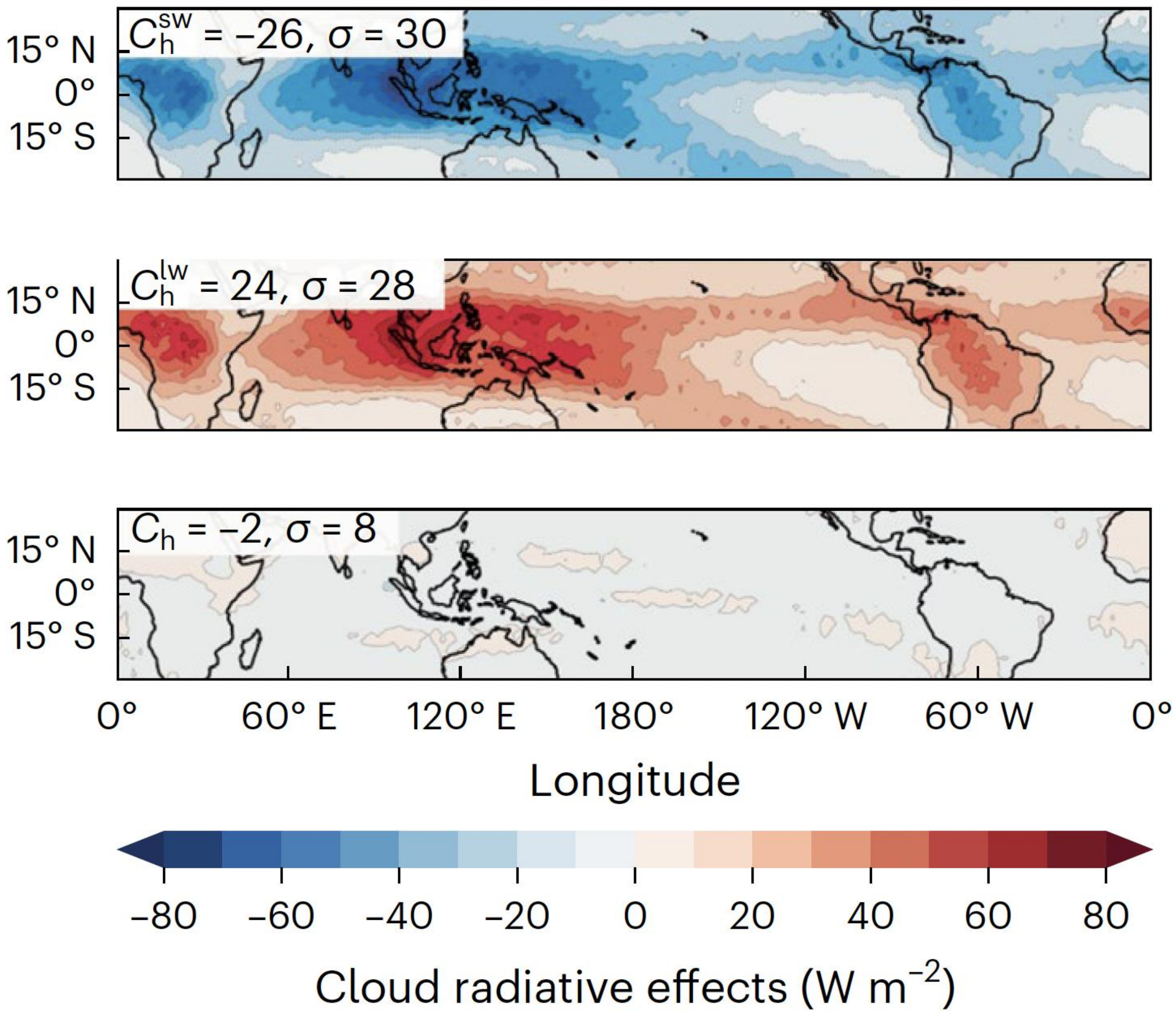
The Stability Iris

Enhanced stability at anvil level demands less convective outflow



Bony et al (2016)

Amount changes alone can't do much



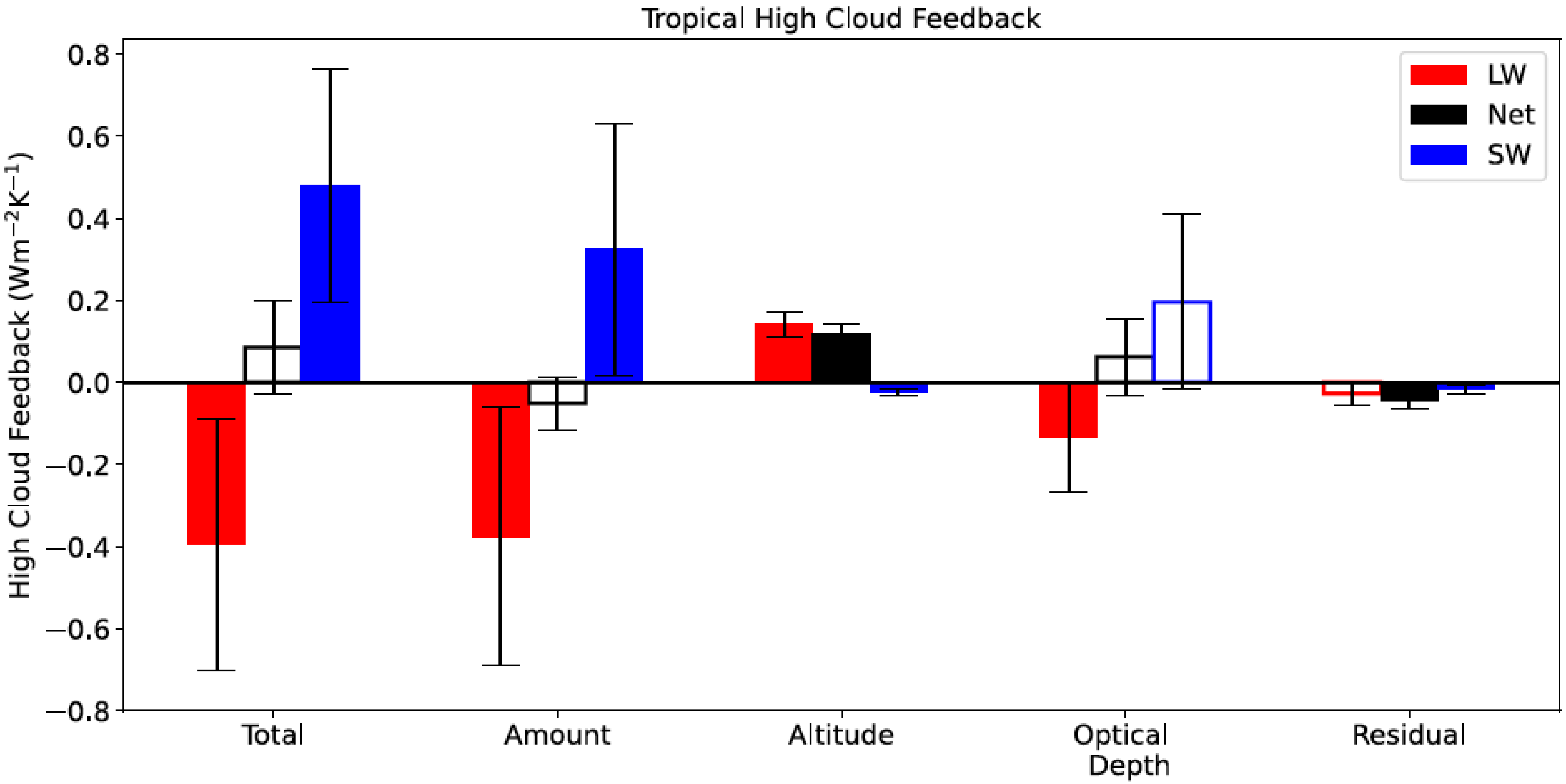
High cloud SWCRE

High cloud LWCRE

High cloud NetCRE

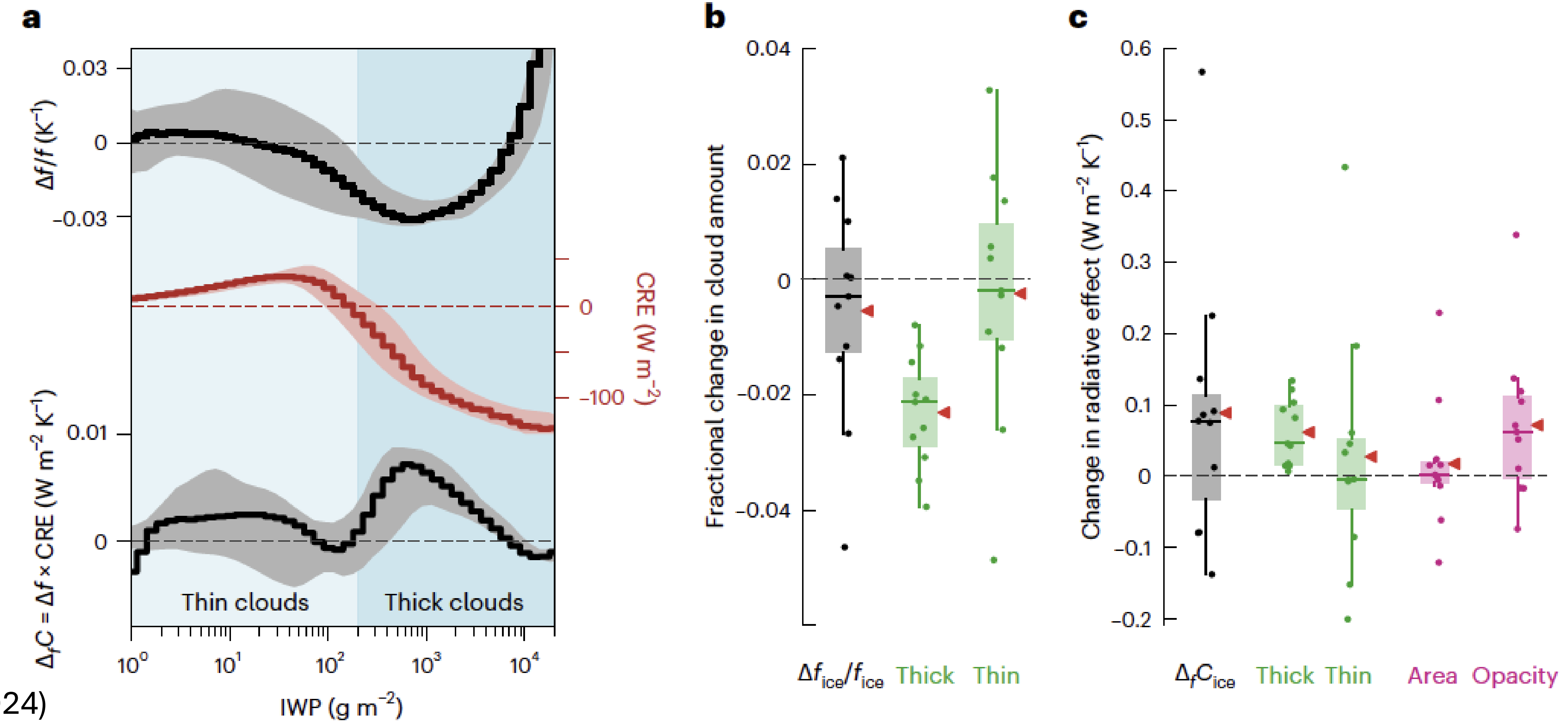
McKim et al. (2024)

Amount changes alone don’t do much



Raghuraman et al (2024)

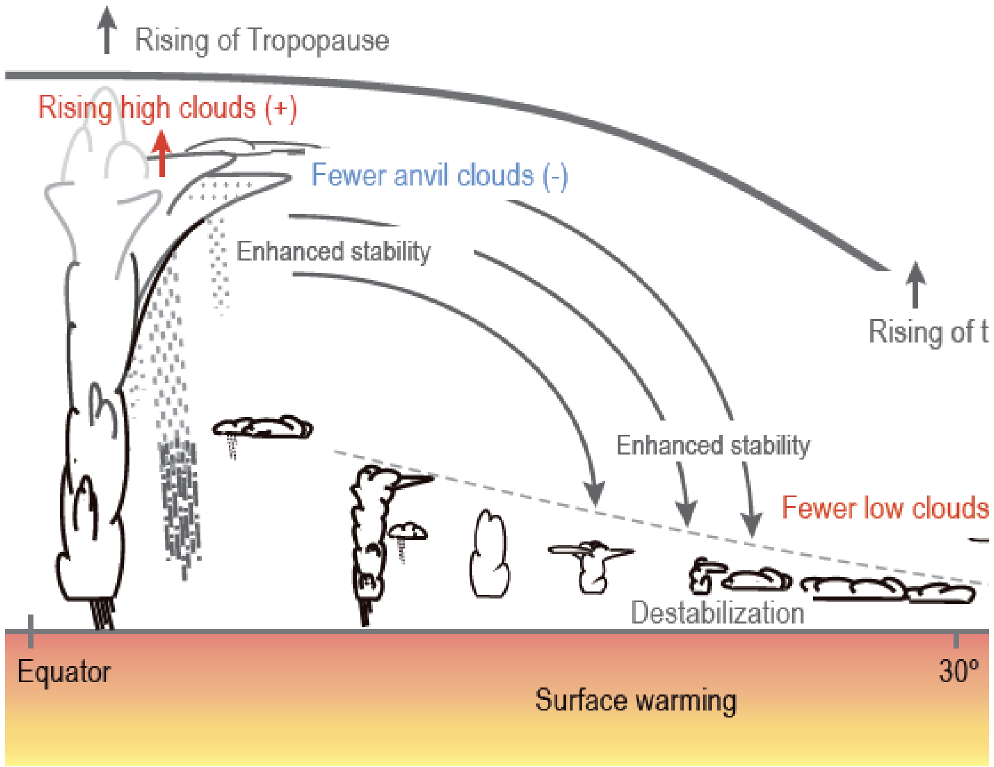
Changes in relative amount of thick vs thin can break the LW – SW balance

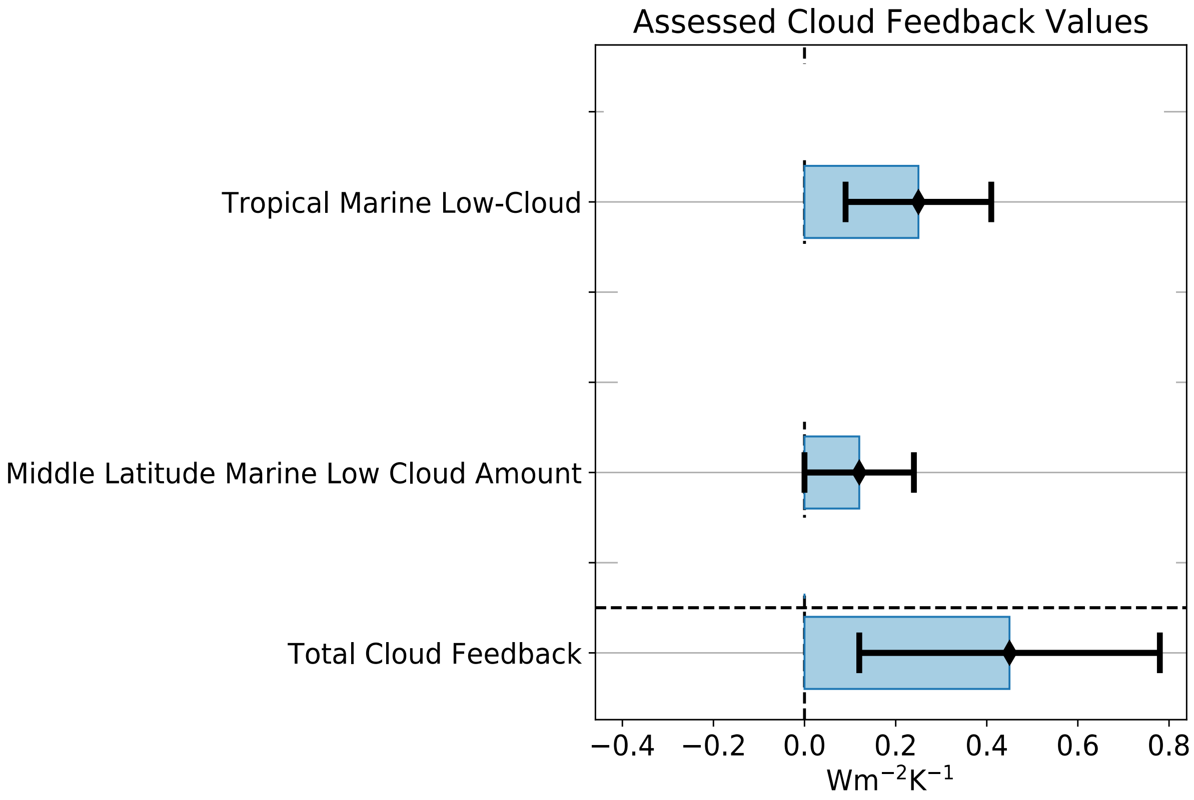


Sokol et al (2024)

Process / Property	EarthCARE Observable	Questions
Cloud radiative properties	Radiative properties from spectrometer	How does the balance of thin cirrus vs thick anvils change with warming?
Convective Detrainment	Radar vertical velocity	Does the mass of condensate detrained from convective updrafts increase with warming?
Radiatively Driven Turbulence in Cirrus	Radar vertical velocity Radiative cooling profile	Does the amount of thin cirrus increase with the level of turbulence in the anvil?
Convective Aggregation	Arrangement of radar convective updrafts	Do cumulus updrafts become more concentrated with warming?

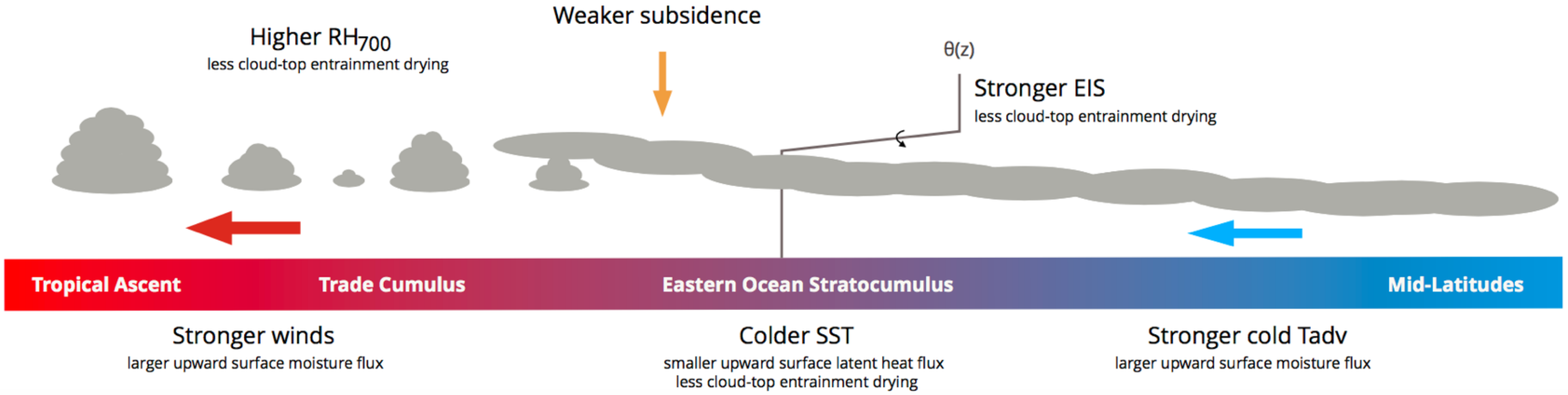
Low Cloud Feedbacks: Amount





WCRP Climate Sensitivity Assessment, Sherwood et al. (2020)

Looking at cloud changes through the lens of their *controlling factors*



$$\lambda_{cloud} = \frac{dR_{cloud}}{dT_g} = \sum_i \frac{\partial R_{cloud}}{\partial x_i} \frac{dx_i}{dT_g} \qquad x_i \in \{\mathrm{SST}, \text{inversion strength}, \text{advection}, \dots\}$$

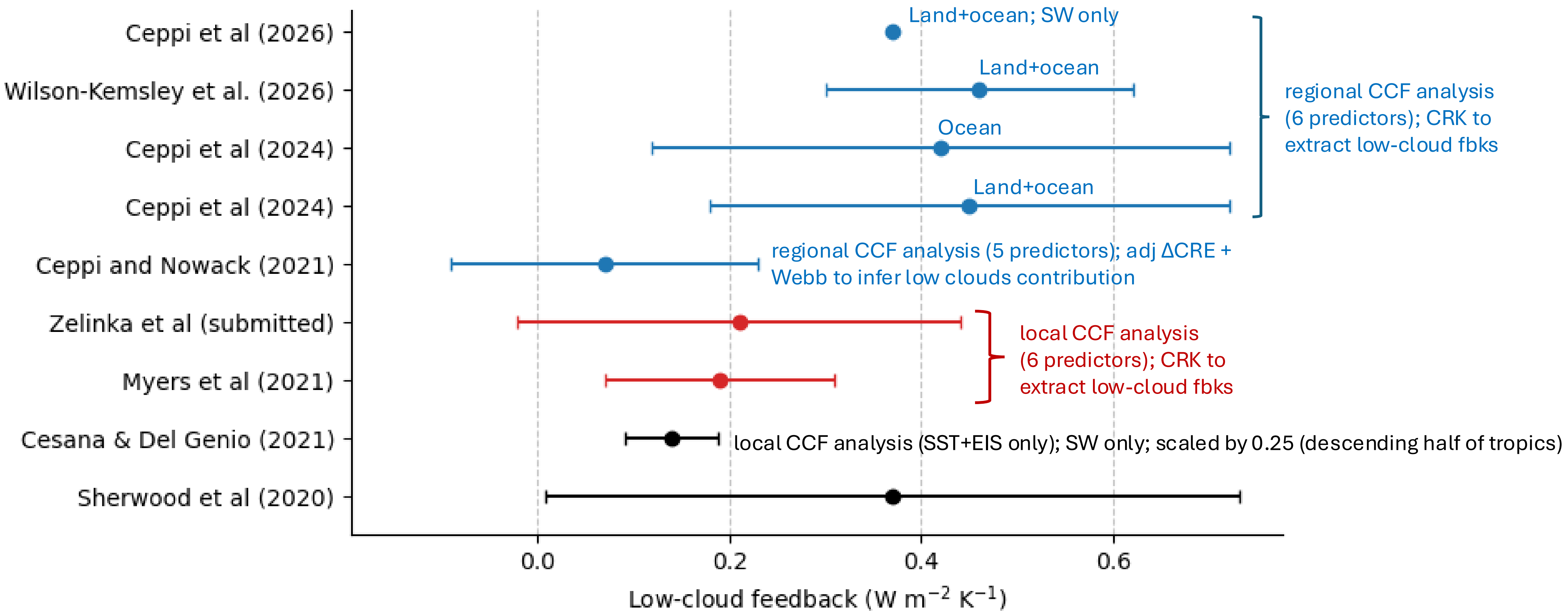
R_{cloud} Sensitivity to CCFs
[from satellite observations]

Climate Change in CCFs
[from abrupt-4xCO_2 exps]

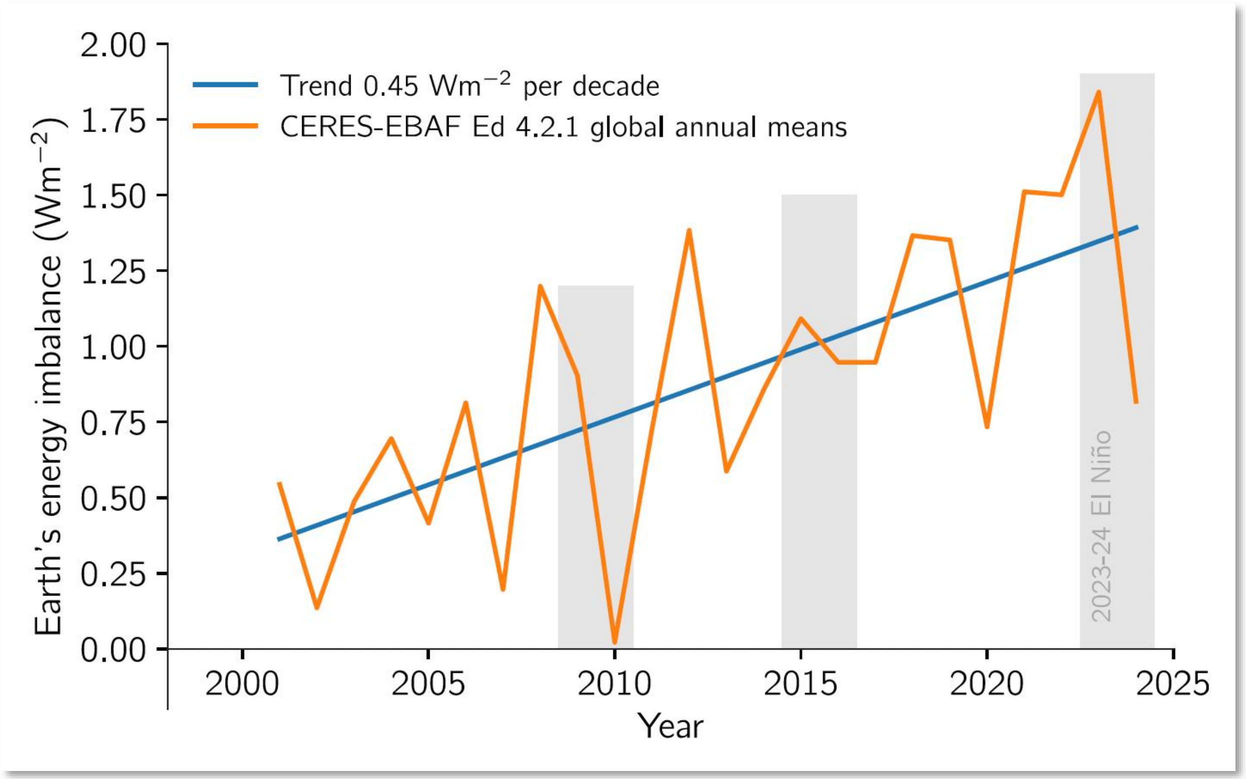
Scott et al. (2020)
Myers et al. (2021)

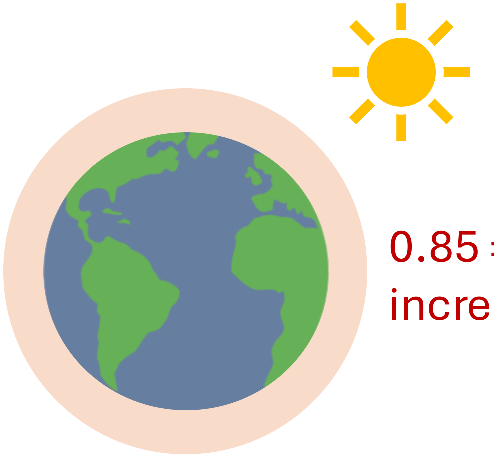
Obs-constrained low cloud feedback estimates

Generally in the ballpark of the WCRP Assessed values

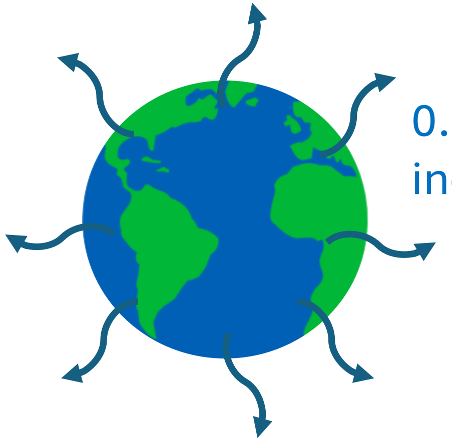


Earth's Growing Energy Surplus





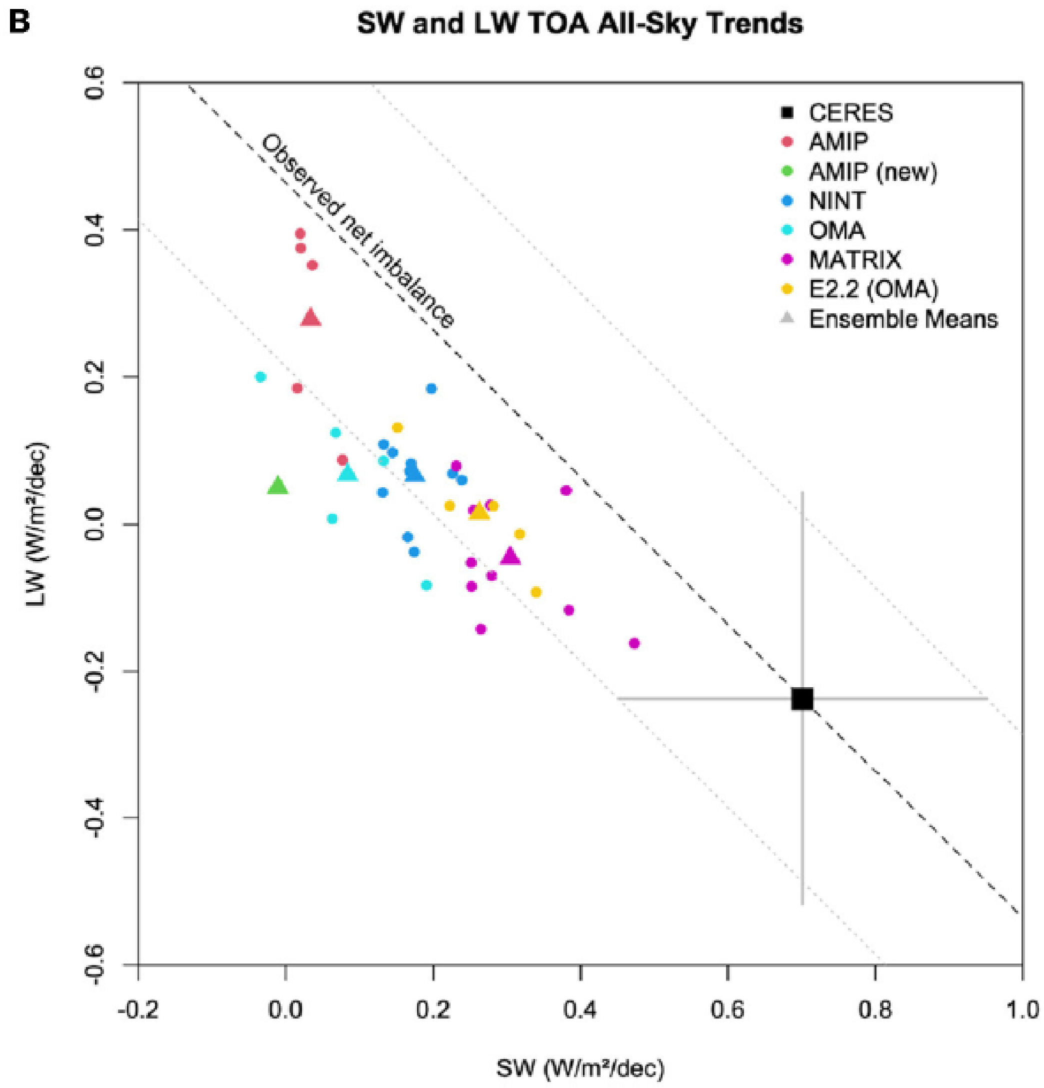
0.85 ± 0.22 W/m²/dec
increased solar heating



0.41 ± 0.23 W/m²/dec
increased outgoing LW radiation

Mauritsen et al (2025)

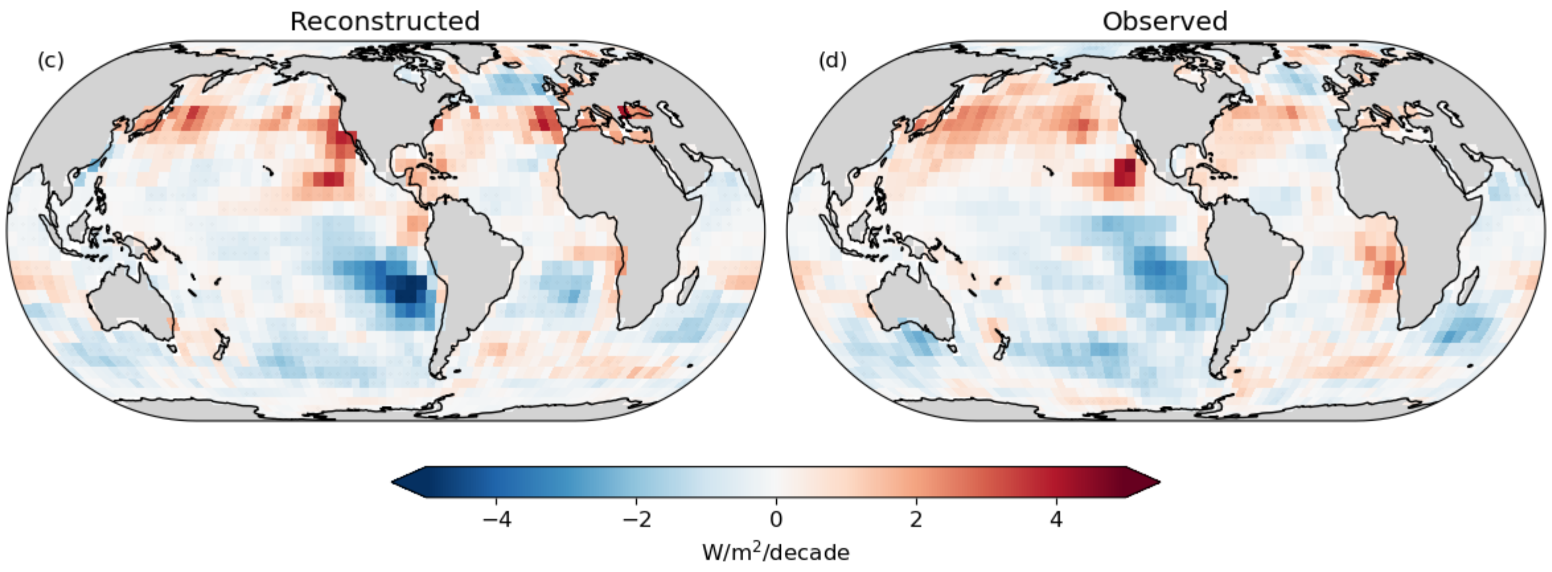
Even when given observed SSTs and SICs, models struggle to get SW and LW trends as large as seen in CERES Observations



This has led to speculation that we've underestimated cloud feedback and ECS.

Schmidt et al (2023)

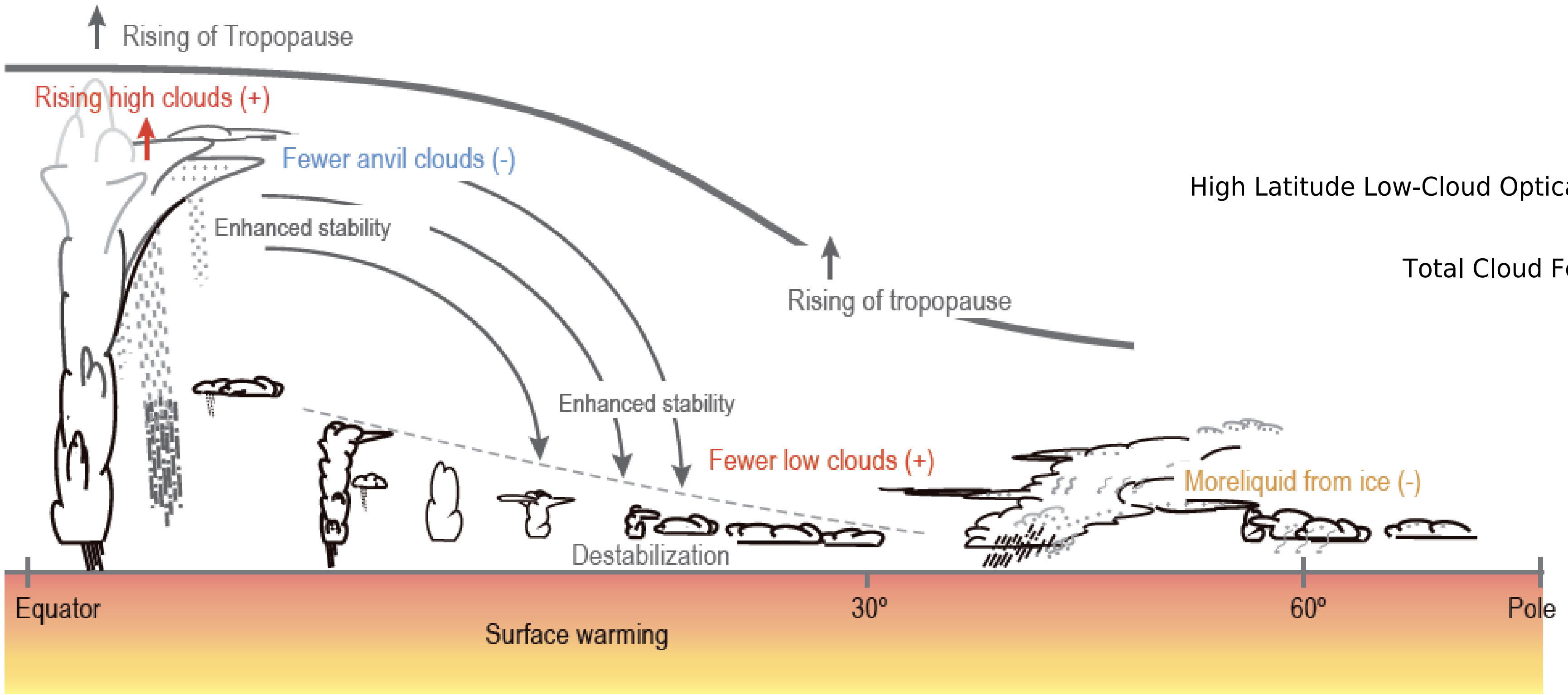
Don’t blame low-cloud feedback

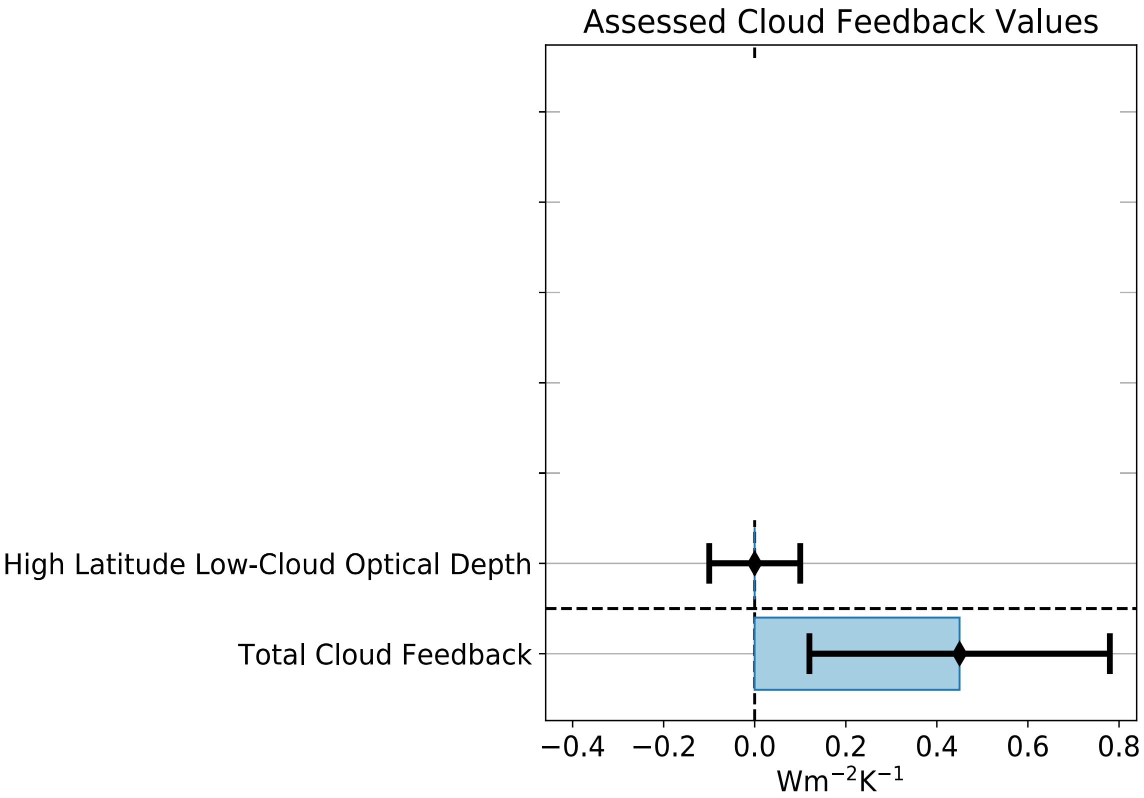


Zelinka et al (2026)
Ceppi et al (2026)

- Trends in cloud-radiative effects can be reconstructed via summing contributions from controlling factors, using the same sensitivities that have been used to observationally constrain low-cloud feedback.
- We do not need to invoke some emergence of a stronger-than-expected low-cloud feedback to understand what is happening in nature.
- While cloud-radiative anomalies and trends over the past 22 years are within expectations, continued global monitoring of clouds, aerosols, and radiation remains crucial.
- **Coincident lidar, radar, imager, and radiometer measurements are essential.**

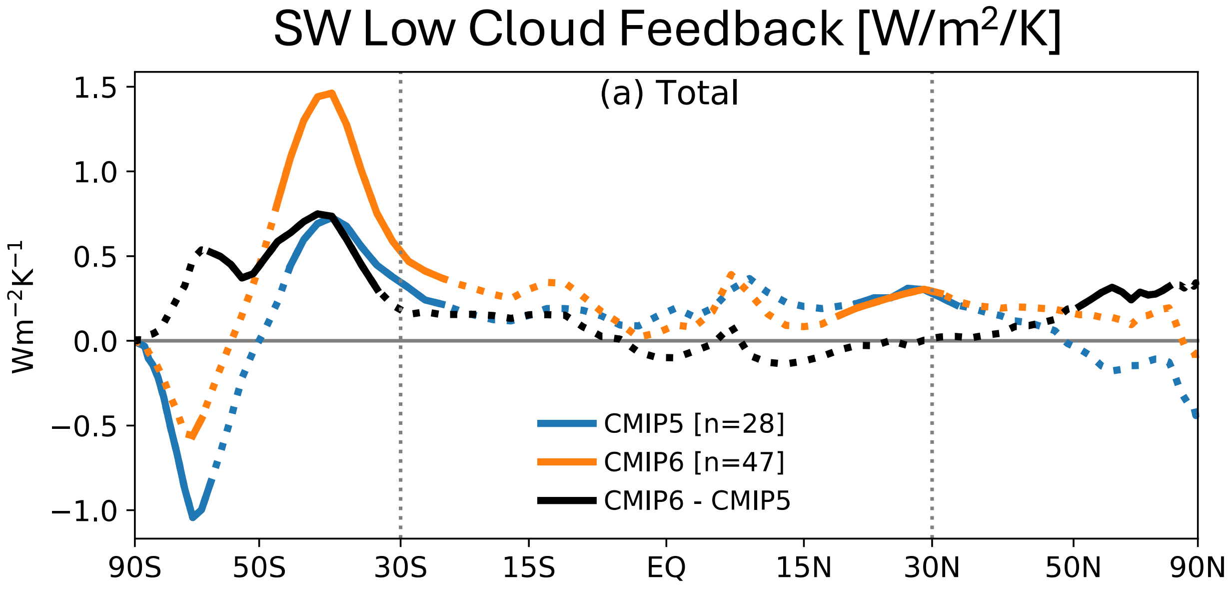
Low Cloud Feedbacks: Optical Depth



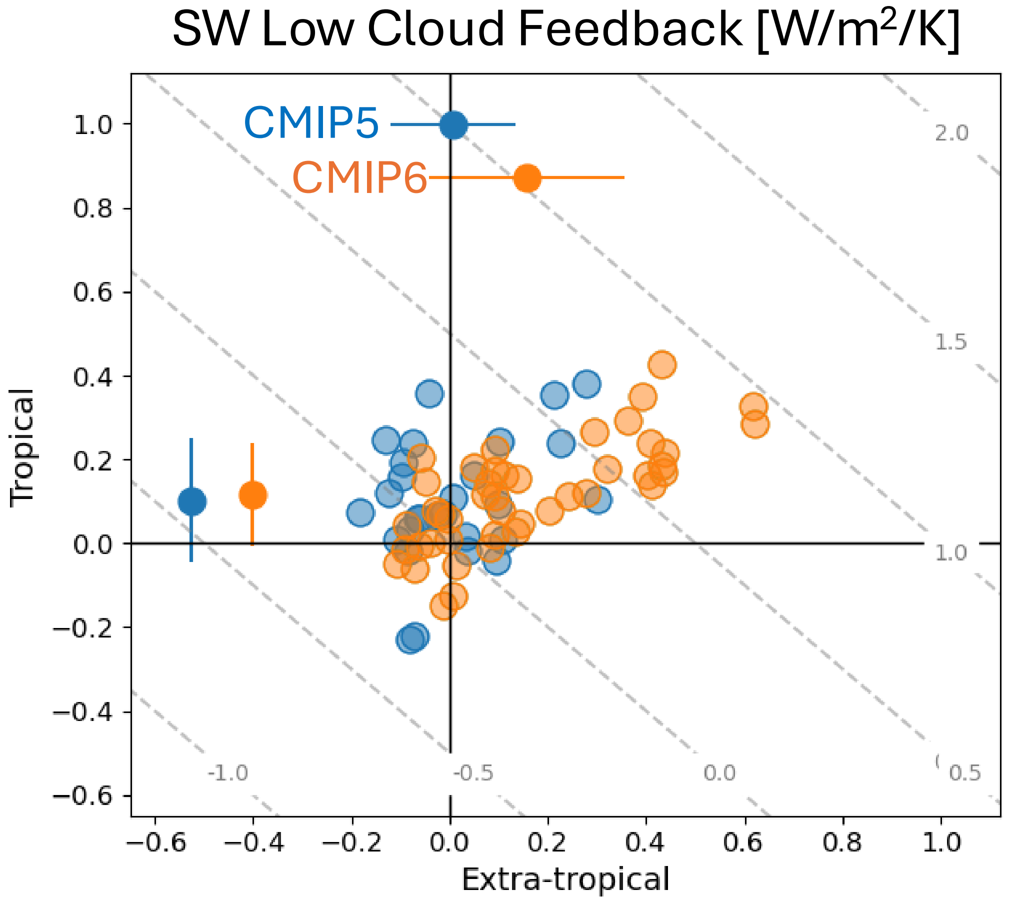


WCRP Climate Sensitivity Assessment, Sherwood et al. (2020)

Higher ECS in CMIP6 comes from stronger positive **extra-tropical low** cloud feedbacks.



This increase is due to larger reductions in cloud cover and cloud albedo in CMIP6.

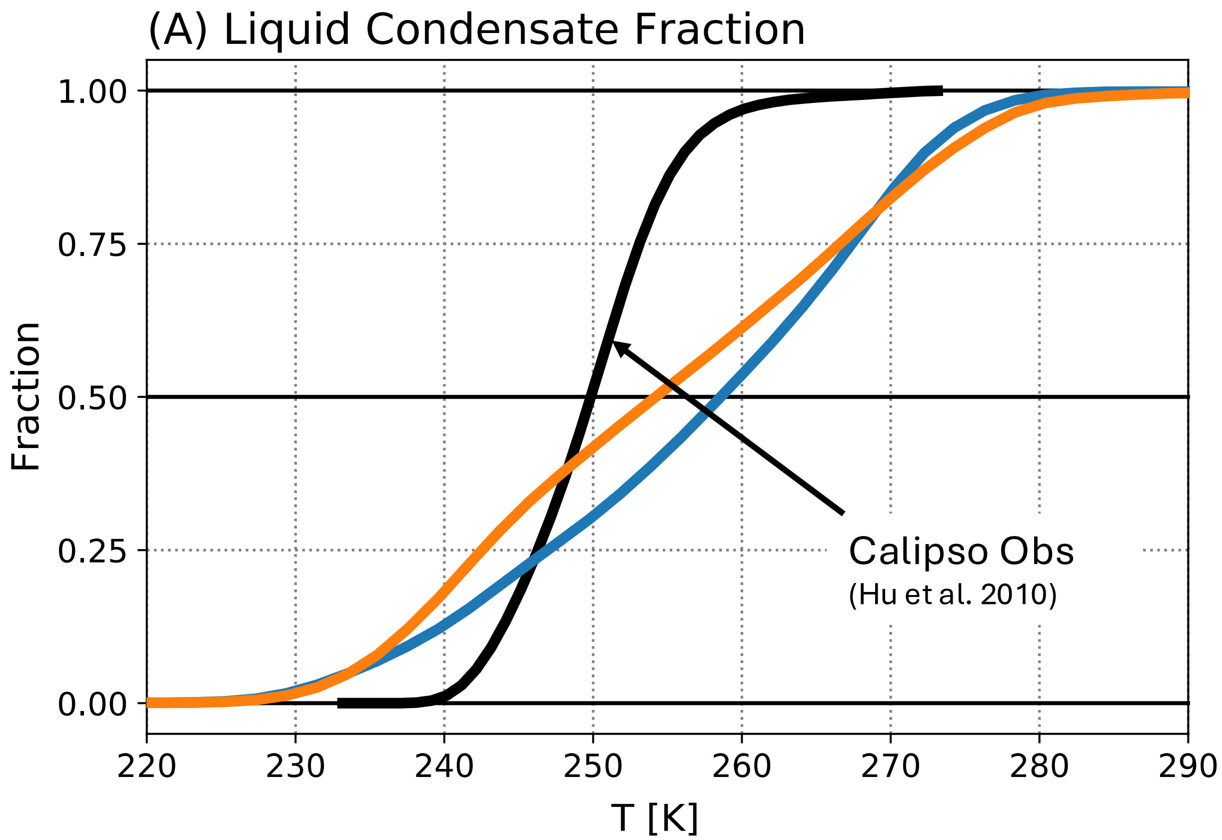


Zelinka et al (2020)

Larger extratropical cloud feedback from improved mean-state cloud phase?

Conventional Wisdom:

- Phase feedback: clouds transition from ice- to liquid-dominated
- Liquid clouds reflect more sunlight than ice clouds (for same total water), so this is a negative radiative feedback
- More mean-state liquid implies weaker negative phase feedback
- Cloud phase is simulated better in latest models
- Hence increased extratropical cloud feedback is more realistic



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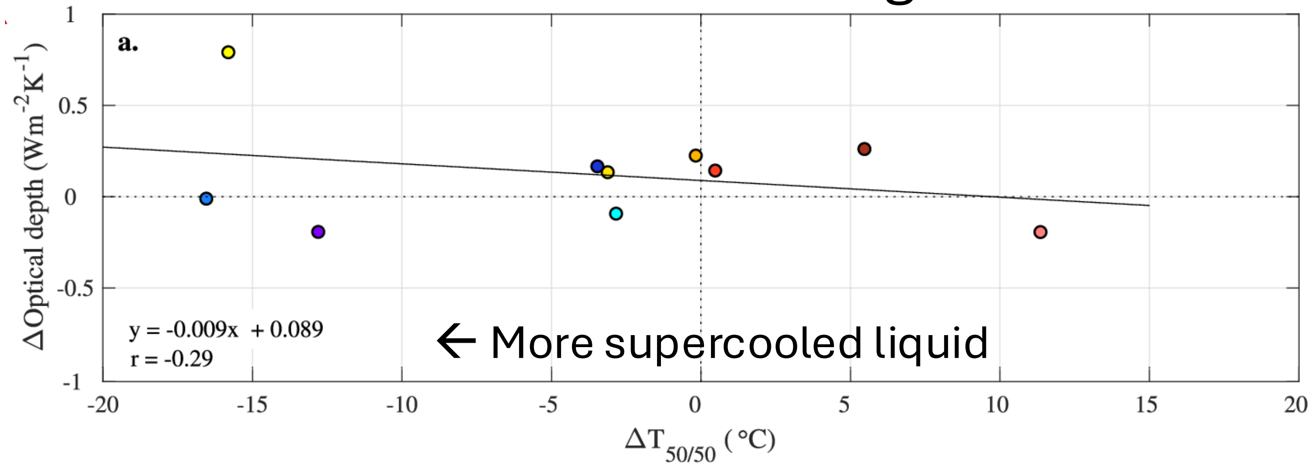
CMIP5→6 Change



Cesana et al (2024)

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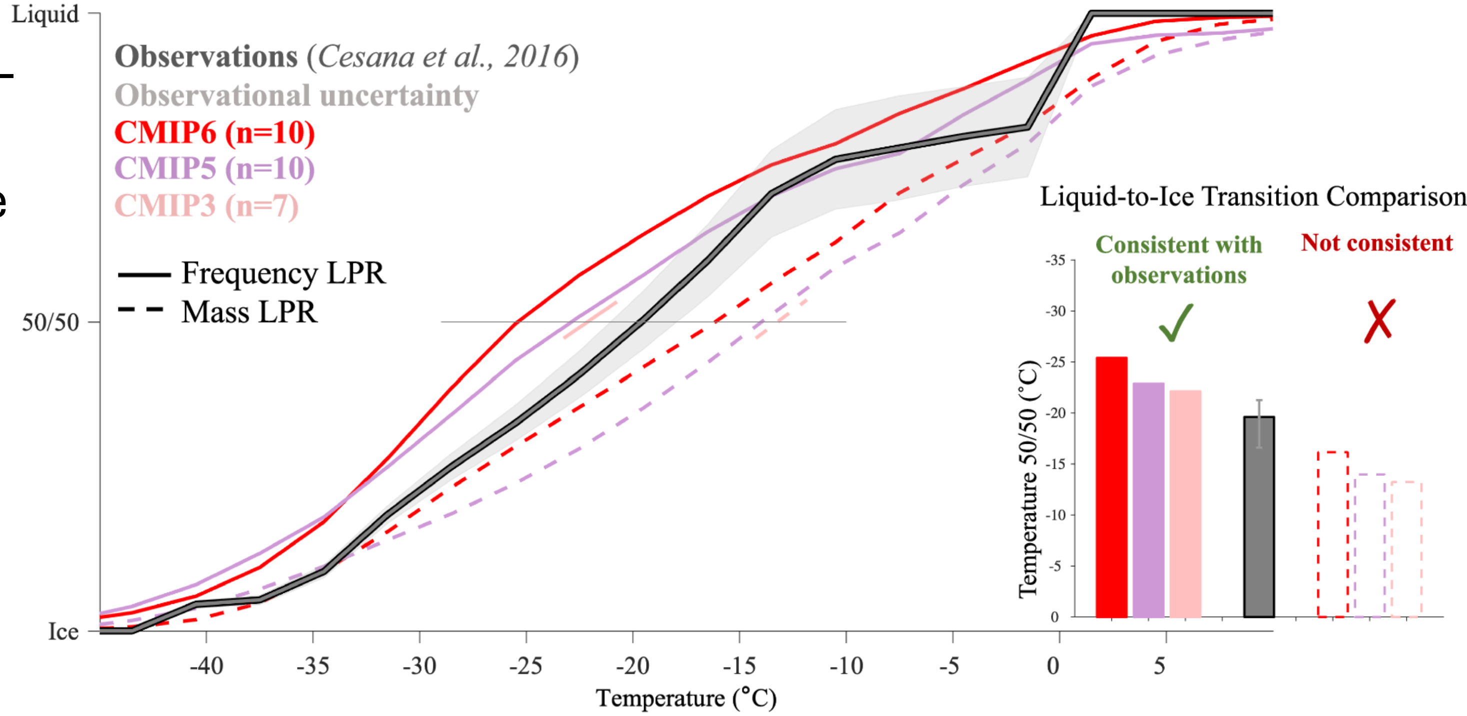

Cesana et al (2024)

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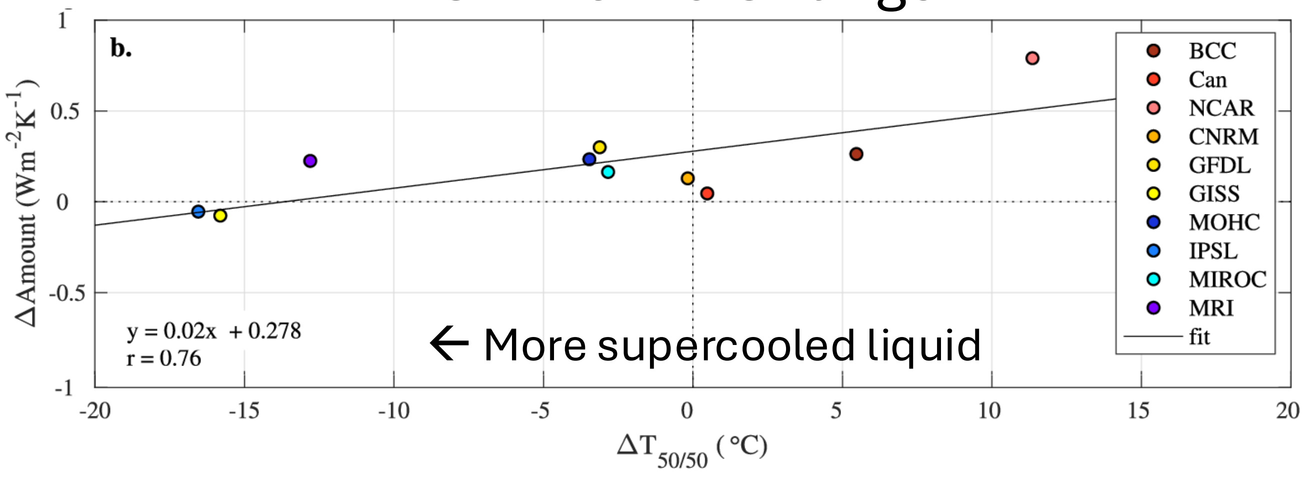

- Transition to warm clouds w/ less efficient precipitation increases cloud lifetime → weaker positive amount feedback
- This increase in cloud lifetime may be underestimated because warm clouds rain too efficiently in models (Mülmenstädt et al. 2021)

Cesana et al (2024)

Larger extratropical cloud feedback from improved mean-state cloud phase?

Warm rain probability is a process-oriented metric observable from satellite radar/lidar.

Measuring both ***state*** and ***process*** is essential.

This increase in cloud lifetime may be underestimated because warm clouds rain too efficiently in models (Mülmenstädt et al. 2021)

Concluding Remarks

- Lack of convergence in cloud feedback and ECS across models belies substantial theoretical, observational, and modeling advances that have improved our understanding of cloud feedbacks.

- But there is still much work to be done to narrow uncertainty, reconcile disparate observational results, and improve models.

- Two primary ways EarthCARE can help reduce uncertainty in cloud feedbacks:

  - Better observations of the processes that determine cloud radiative properties and how they vary with temperature

  - Accurately observing temporal changes in clouds and their properties