The Basic Physics of High Cloud Feedbacks

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GEWEX UTCC PROES
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How much does the Earth warm in response to increased CO_2?

$$\mathrm{ECS} = \frac{\mathcal{F}_{2\times}}{|\lambda|}.$$

$$N \equiv S - \mathrm{OLR} \qquad (\text{net radiation, W/m}^2),$$

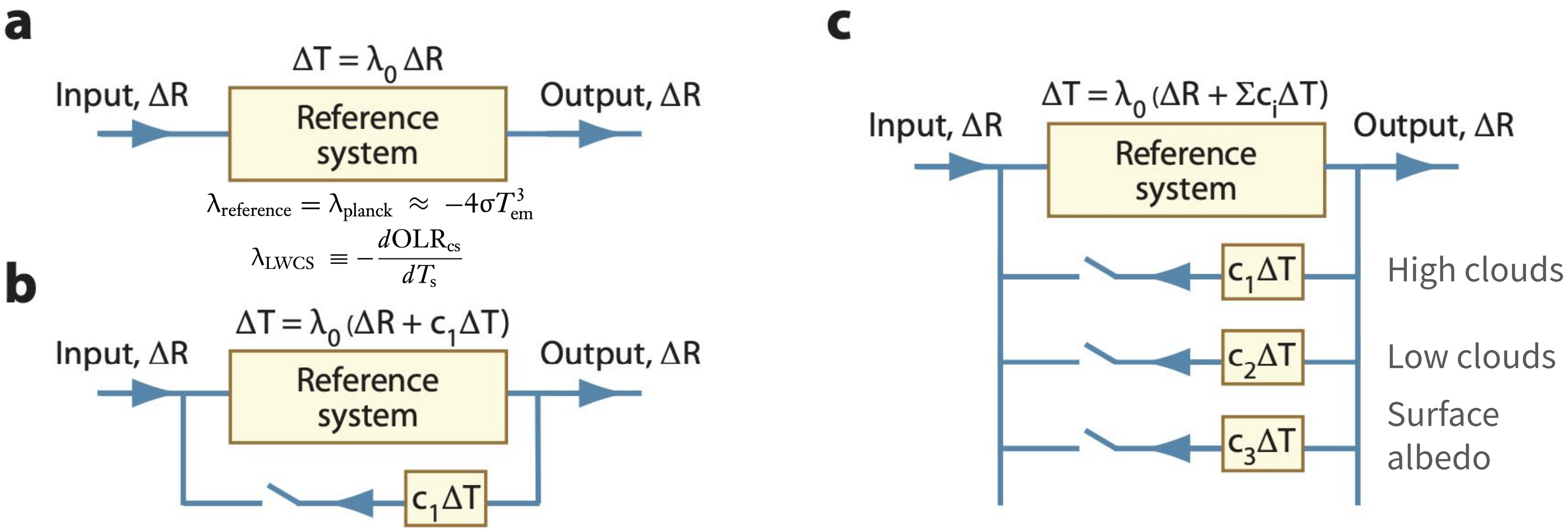
$$\lambda \equiv \frac{dN}{dT_s} \quad (\mathrm{W/m^2/K},\ \lambda < 0).$$

$$N = \mathcal{F} + \lambda T_s$$

- TOA budget is simpler to observe and constrain than the surface energy budget
- The total feedback is ultimately negative, but how it is partitioned among different processes requires a model of the climate system

Taken from various sources

Feedback analysis is one way to unravel this complexity



$$\lambda_{\text{reference}} = \lambda_{\text{planck}} \approx -4\sigma T_{\text{em}}^3$$

$$\lambda_{\text{LWCS}} \equiv -\frac{d\text{OLR}_{\text{cs}}}{dT_{\text{s}}}$$

- In a system in which everything influences everything else, feedback analysis provides a framework for separating and quantifying the processes that contribute to the overall feedback.

Roe, 2009

Feedback analysis is one way to unravel this complexity

Term	Value
Effective radiative forcing from a CO_2 doubling ΔF_{2xCO2}	$N(+4.00, 0.30)$
Planck feedback	$N(-3.20, 0.10)$
Water vapor + lapse rate feedback	$N(+1.15, 0.15)$
Surface albedo feedback	$N(+0.30, 0.15)$
Individual cloud feedbacks	
High-cloud altitude	$N(+0.20, 0.10)$
Tropical marine low cloud	$N(+0.25, 0.16)$
Tropical anvil cloud area	$N(-0.20, 0.20)$
Land cloud amount	$N(+0.08, 0.08)$
Middle-latitude marine low-cloud amount	$N(+0.12, 0.12)$
High-latitude low-cloud optical depth	$N(+0.00, 0.10)$
Total cloud feedback λ_{clouds}	$N(+0.45, 0.33)$
Stratospheric feedback	$N(+0.00, 0.10)$
Feedbacks induced by atmospheric composition changes	$N(+0.00, 0.15)$
Climate feedback parameter λ	$N(-1.30, 0.44)$

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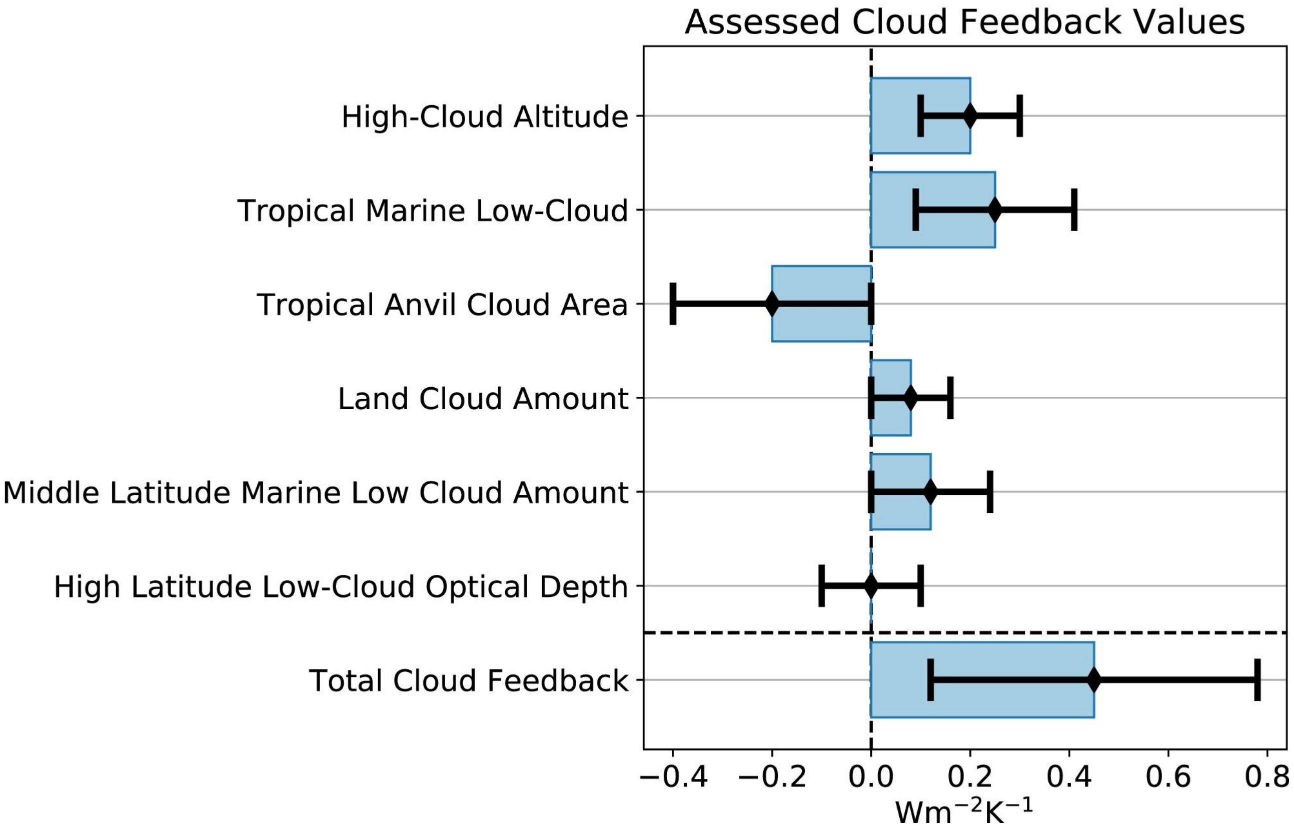
Roe, 2009

Quantifying uncertainties helps motivate targeted research



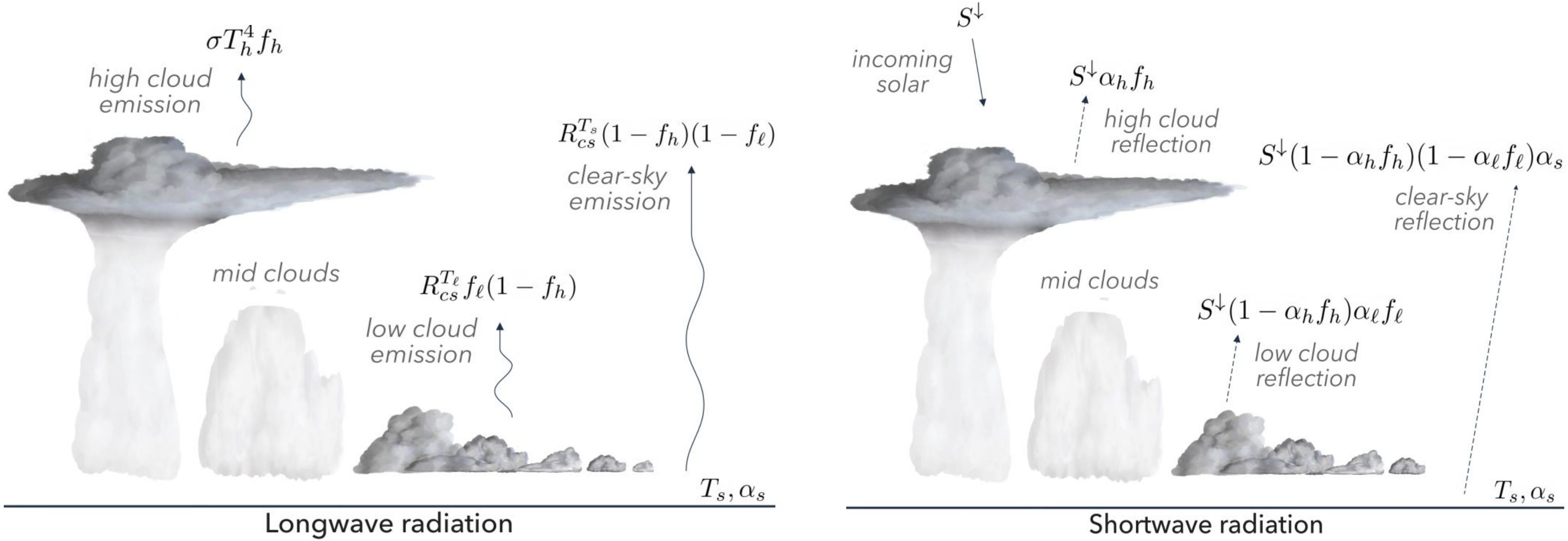
- Decomposing feedbacks and quantifying uncertainty is triage for researchers of Earth's climate system

- How many times have you seen this figure at the beginning of a talk?

Sherwood et al, 2020

An idealized model of the climate system for feedback analysis

- Simple model provides expressions for TOA energy balance and cloud radiative effect (CRE) in terms of bulk parameters that can be diagnosed from observations.



$$R = R_{\text{cs}}^{T_s}(1-f_h) + \sigma T_h^4 f_h + \lambda_{\text{cs}}(T_s - T_\ell)(1-f_h) f_\ell$$

$$S = S^{\downarrow}(1-\alpha_h f_h)(1-\alpha_\ell f_\ell)(1-\alpha_s)$$

McKim et al, 2024

An idealized model of the climate system for feedback analysis

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- If we can observe and/or derive theories for these quantities, then we can constrain cloud feedbacks.

$$S = S^{\downarrow}(1 - \alpha_h f_h)(1 - \alpha_\ell f_\ell)(1 - \alpha_s)$$ ---------- All-sky shortwave

$$R = R_{cs}^{T_s}(1 - f_h) + \sigma T_h^4 f_h + \lambda_{cs}(T_s - T_\ell)(1 - f_h) f_\ell$$ ---------- All-sky longwave

$$C_h = \Big(- S_{cs}\alpha_h + R_{cs} - \sigma T_h^4 \Big) f_h$$ ---------- Anvil cloud CRE

$$C_\ell = \Big(- S_{cs}\alpha_\ell - \lambda_{cs}(T_s - T_\ell) \Big) f_\ell$$ ---------- Low cloud CRE

$$m_{\ell h} = \Big(S_{cs}\alpha_\ell\alpha_h + \lambda_{cs}(T_s - T_\ell) \Big) f_\ell f_h$$ ---------- Cloud overlap effect

An idealized model of the climate system for feedback analysis

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$$\lambda = \lambda_0 + \lambda_s^{\text{albedo}} + \sum_{i=h,\ell} \lambda_i^{\text{area}} + \lambda_i^{\text{temp}} + \lambda_i^{\text{albedo}}$$

$\lambda_0 = \lambda_{cs}(1 - f_h)$ — Reference feedback (note anvil cloud masking)

$\lambda_{\alpha_s} = \frac{d \ln \alpha_s}{dT_s} C_s$ — Surface albedo feedback

$\lambda_i^{\text{area}} = \frac{d \ln f_i}{dT_s} \left(C_i + m_{\ell h} \right)$ — Cloud area feedbacks

$\lambda_i^{\text{albedo}} = \frac{d \ln \alpha_i}{dT_s} \left(C_i^{sw} + m_{\ell h}^{sw} \right)$ — Cloud albedo feedbacks

$\lambda_h^{\text{temp}} = -4 \frac{dT_h}{dT_s} \sigma T_h^3 f_h$ — Anvil cloud temp feedback

$\lambda_\ell^{\text{temp}} = -\frac{d(T_s - T_\ell)}{dT_s} \lambda_{cs}(1 - f_h) f_\ell$ — Low cloud temp feedback

Hypothesis testing for cloud feedbacks

Derivation provides key insights

- The smaller the CRE, the larger the cloud change required to produce a given feedback
- Using observed cloud radiative effects can help constrain the area feedback

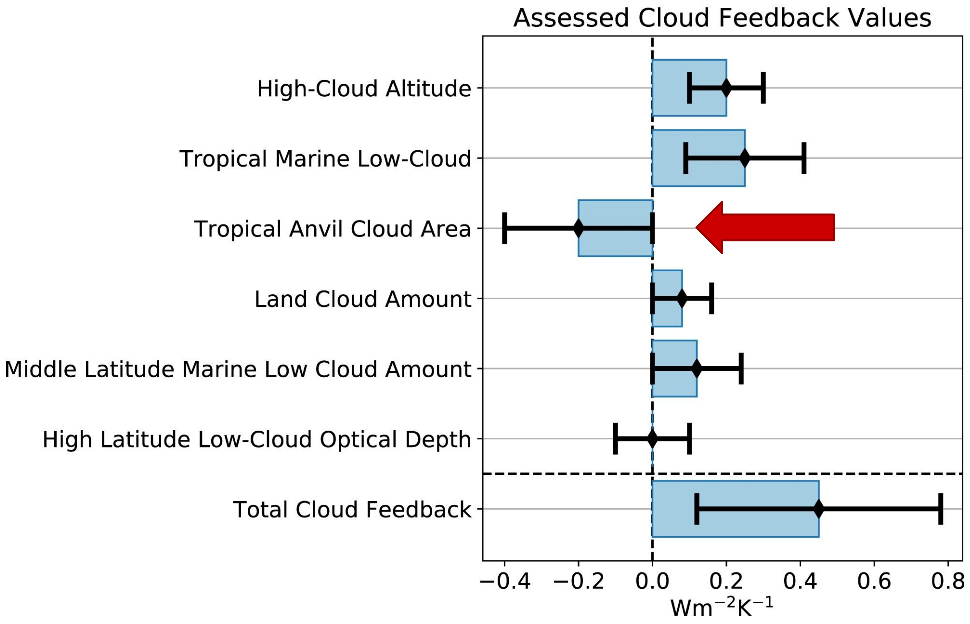
$$\lambda_h^{\text{area}} = \underbrace{\frac{d \ln f_h}{dT_s}}_{\text{Fractional change in anvil area with warming}} \underbrace{\left(C_h + m_{\ell h}\right)}_{\text{Present day anvil CRE and cloud overlap effect}}$$

Fractional change in anvil area with warming

Present day anvil CRE and cloud overlap effect

Hypothesis testing for cloud feedbacks

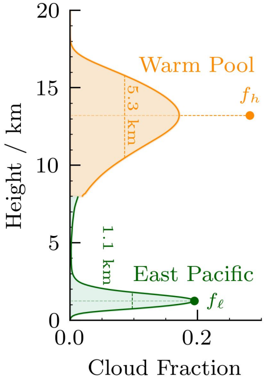
- $\lambda_h^{\text{area}} = \frac{1}{2} \frac{d \ln f_h}{dT_s} \left(C_h + m_{\ell h} \right)$
- $\lambda_h^{\text{area}} = -0.4 \text{ Wm}^{-2}\text{K}^{-1}$
- $C_h + m_{\ell h} \approx -1.5 \text{ Wm}^{-2}$
- **Required for lower bound** $\Rightarrow \frac{d \ln f_h}{dT_s} \approx 50\% \text{ K}^{-1}$

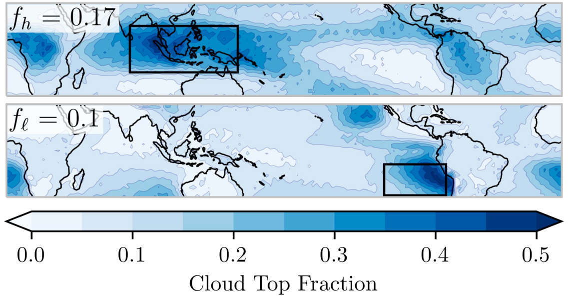


Sherwood et al 2020

An idealized model of the climate system for feedback analysis

Data
CALIPSO - Cloud fraction
CERES - TOA Clear-sky, All-Sky
ERA5 - atmospheric/cloud temp
HadCRUT5 - surface temp

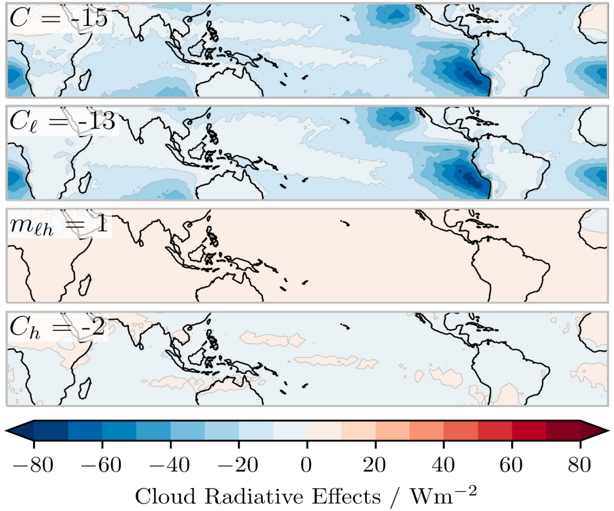




+ **Clear-sky radiation**
+ **Simple model**

=

Net CRE
Low cloud CRE
Cloud overlap effect
Anvil CRE

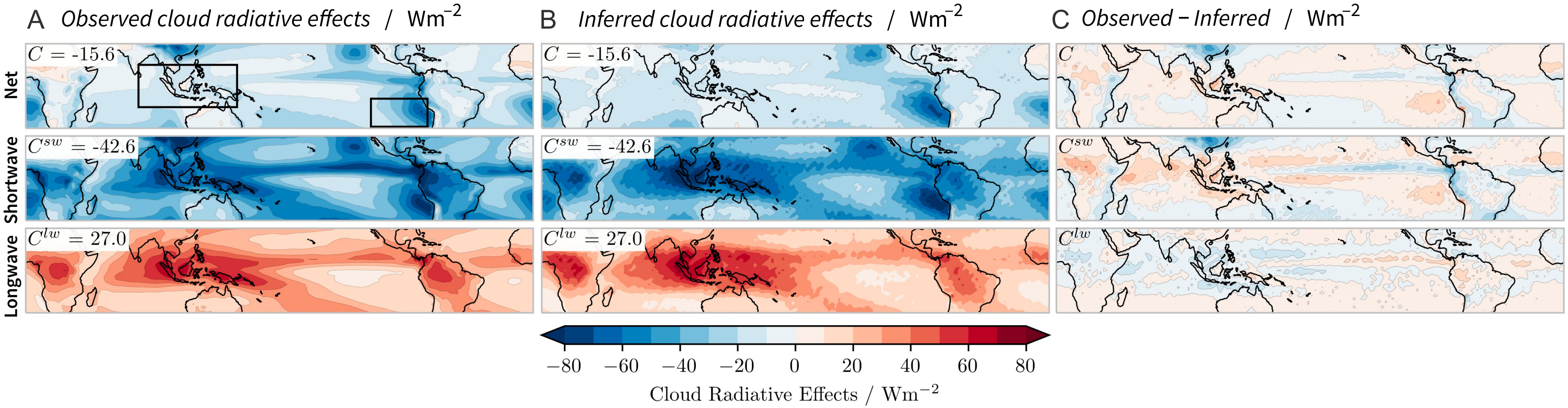


Anvil CRE and cloud overlap can't be observed directly, but they can be inferred from our equations

- $C_h + m_{\ell h} \approx -1.5 \text{ Wm}^{-2}$

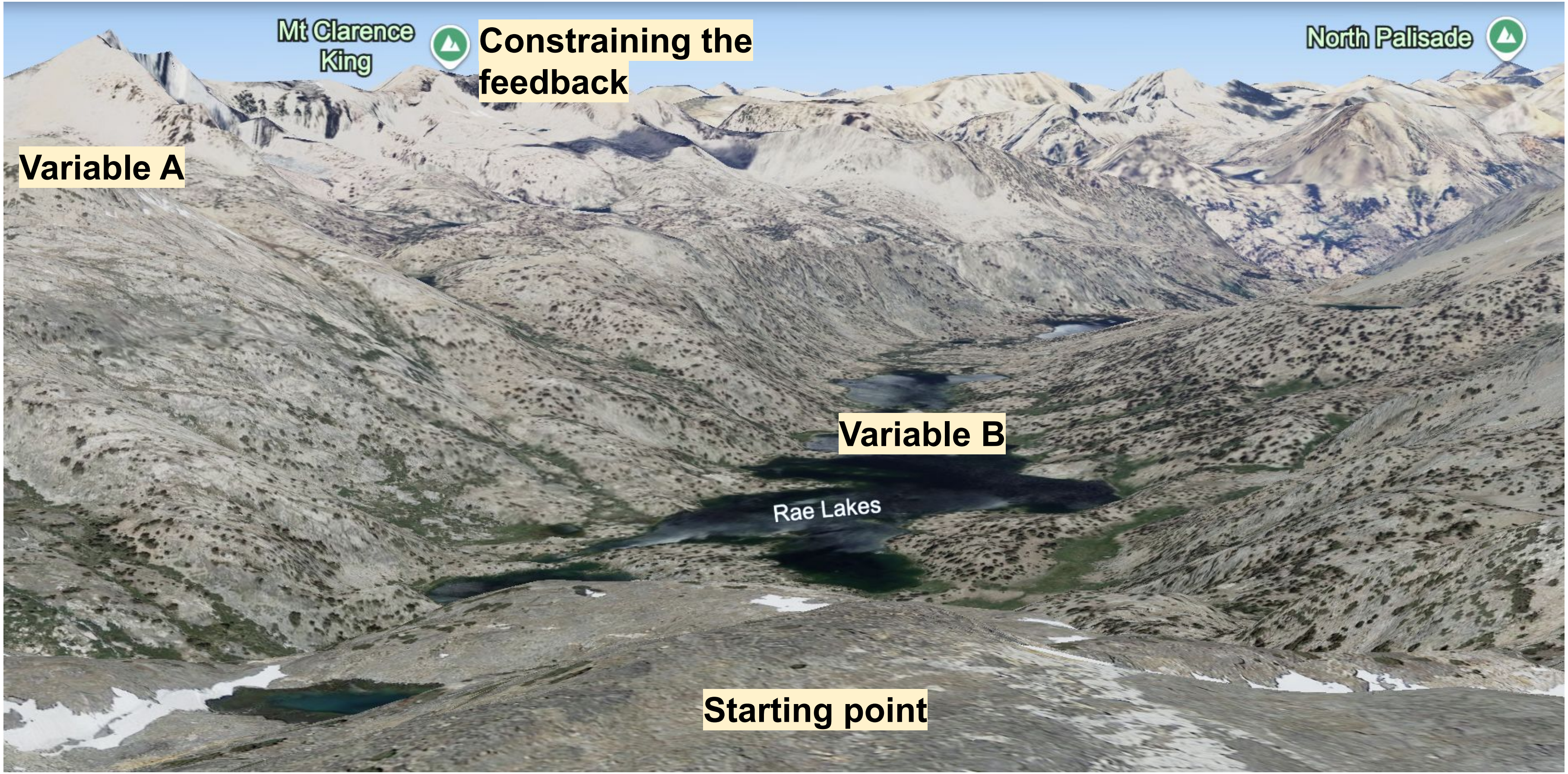
McKim et al, 2024

An idealized model of the climate system for feedback analysis



McKim et al, 2024

What is the more efficient path?



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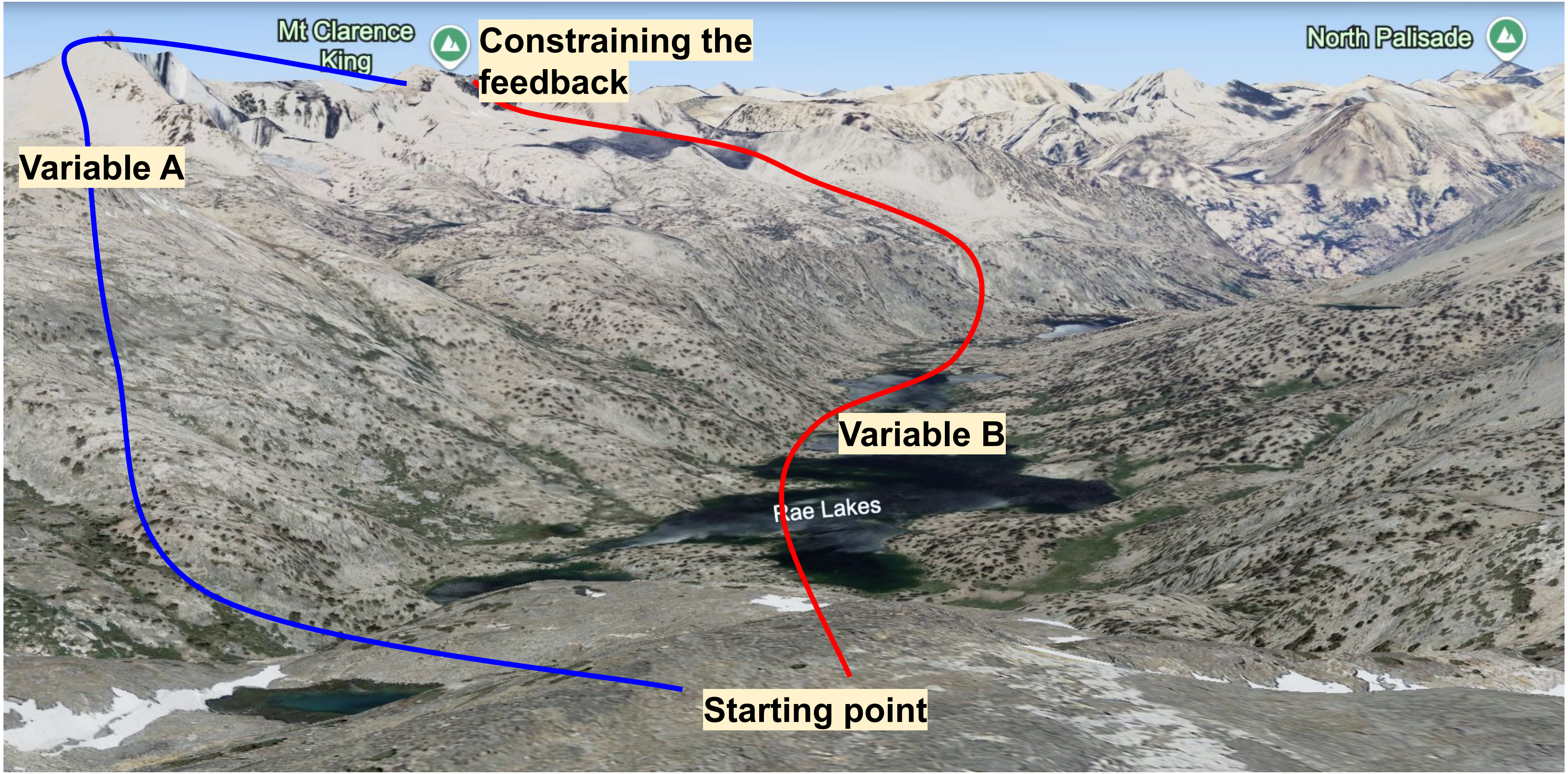
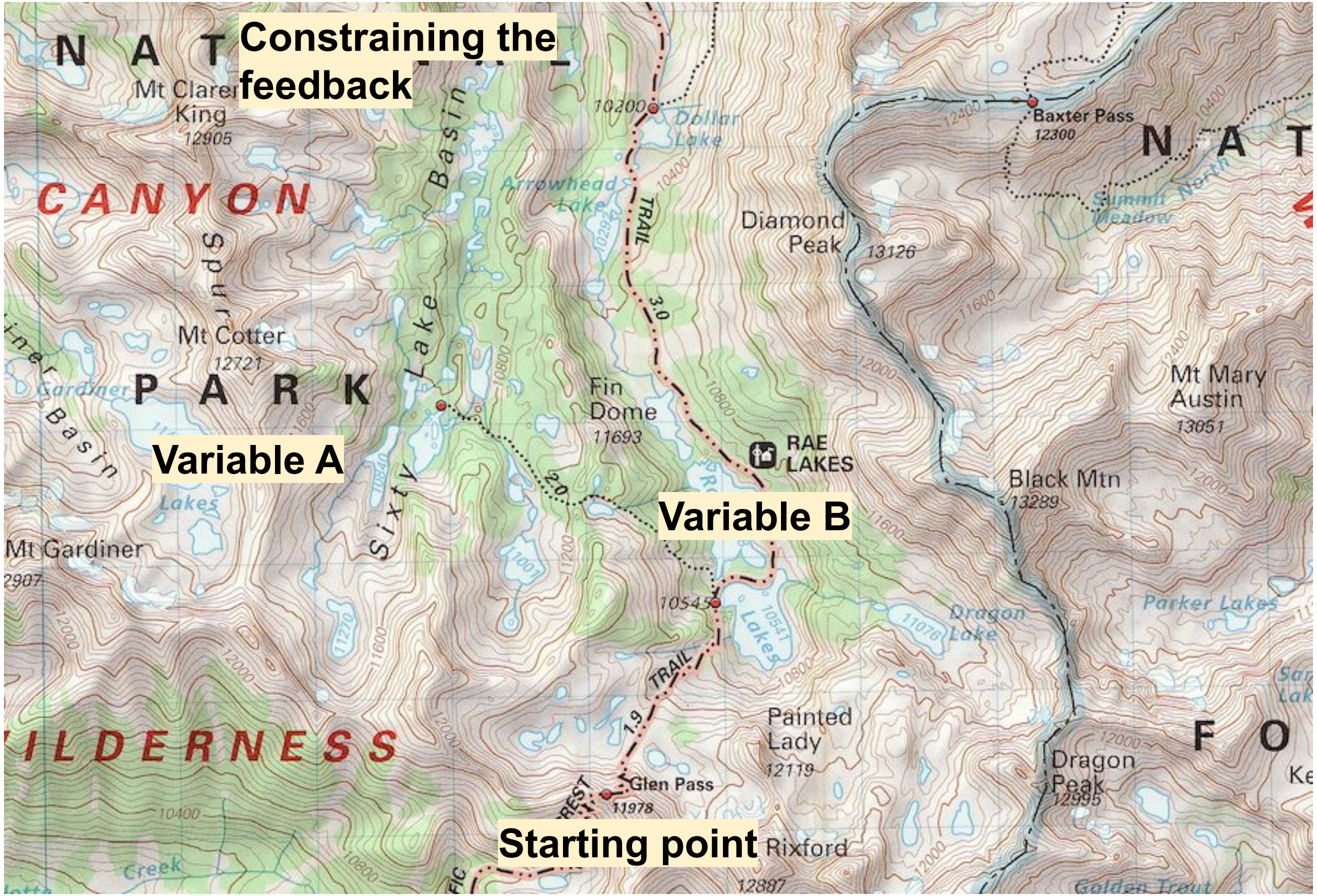
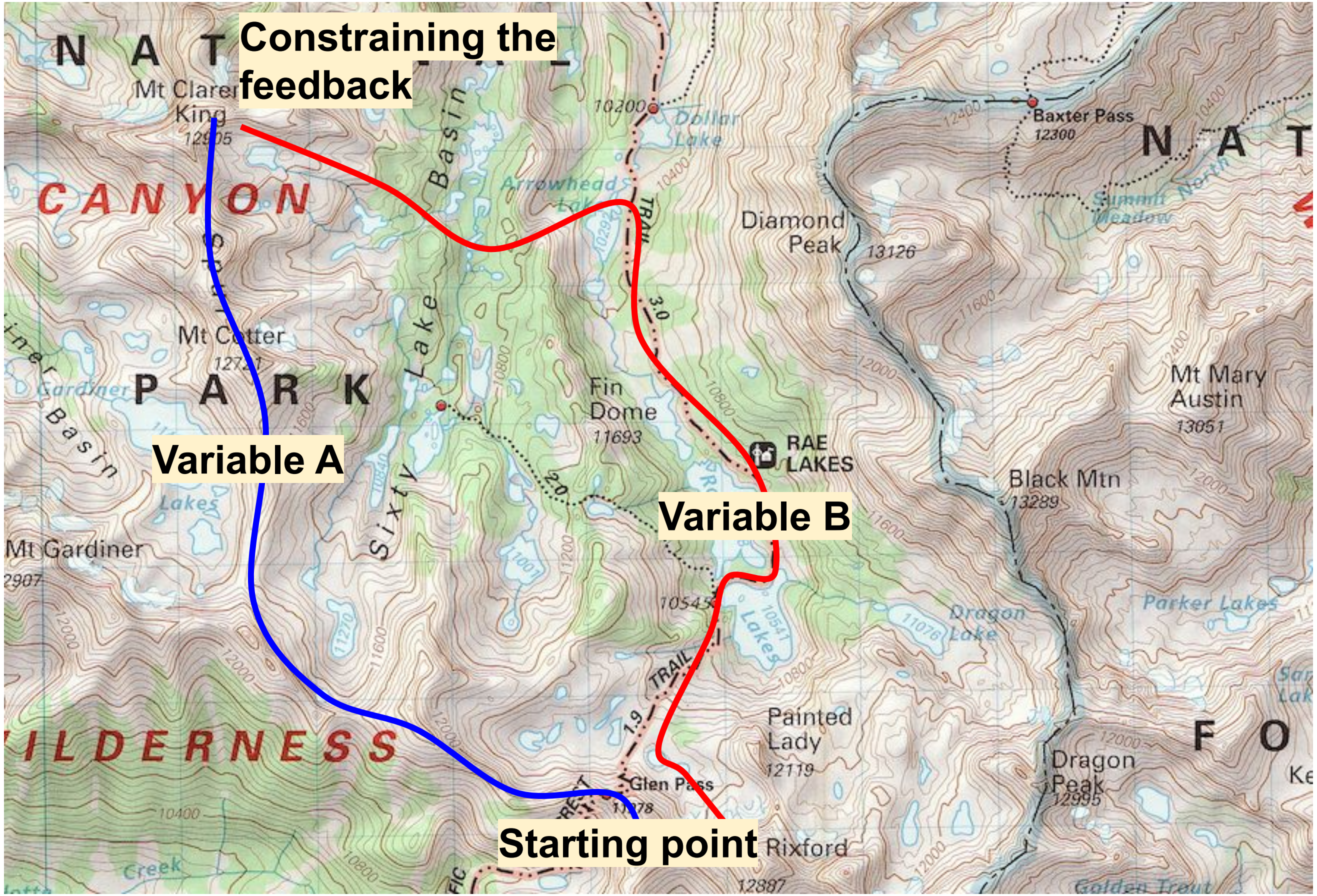


Idealizations help guide us



- But they are not a replacement for simulations or observations!

Idealizations help guide us



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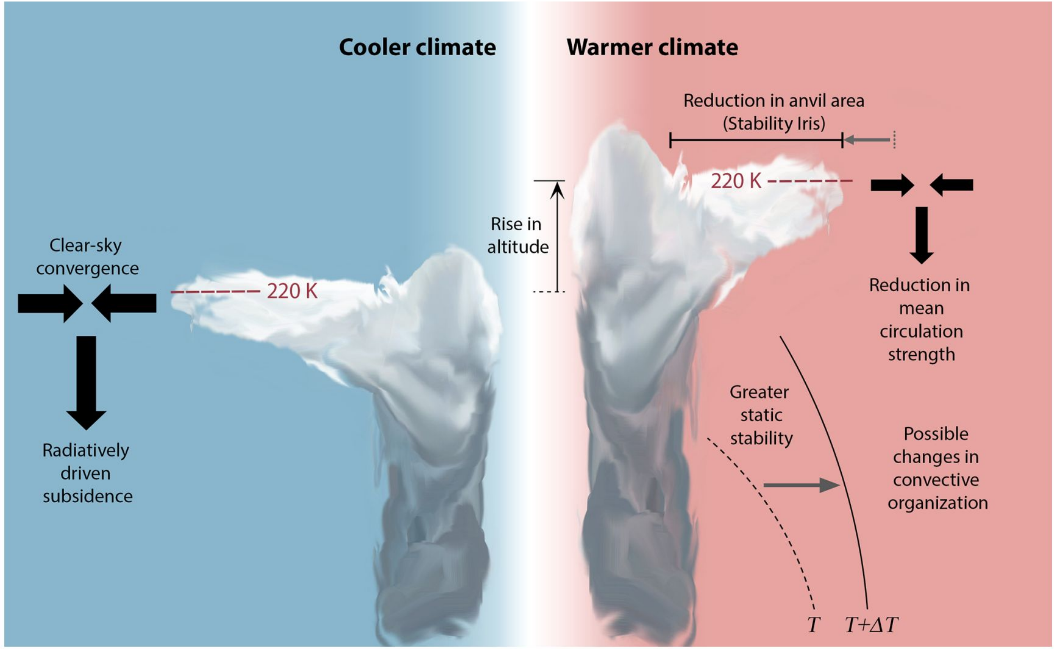
General circulation constraints on cloudiness

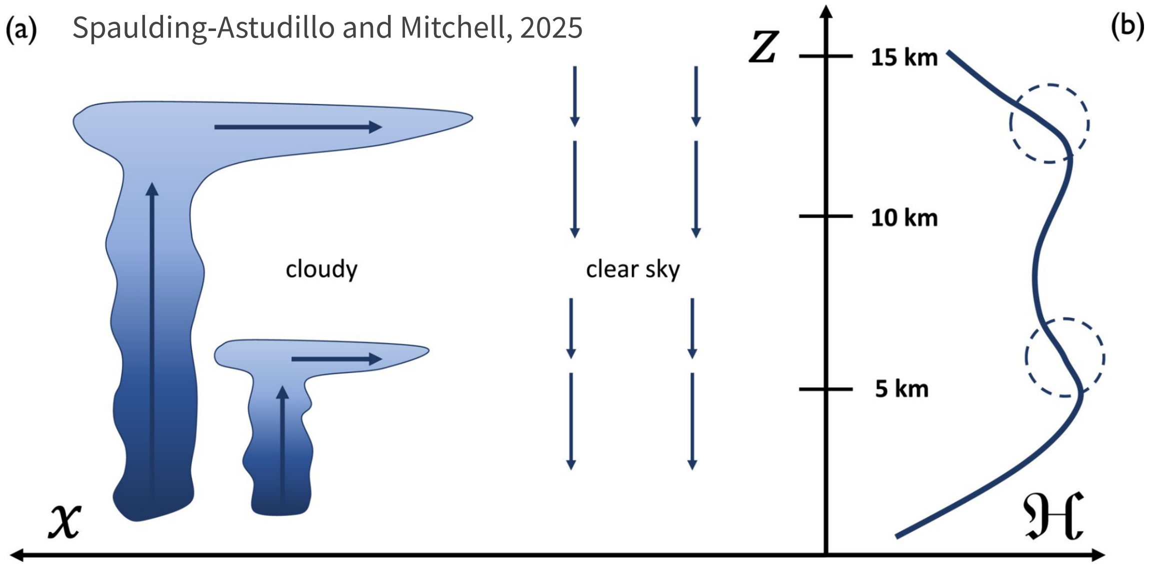


- Clouds are both a driver and a product of the general circulation (Riehl and Malkus, 1958)
- Clouds can be regarded as balance between sources and sinks of condensates (Seeley et al, 2019; Beydoun et al, 2021)

Gasparini et al, 2023

The Fixed Anvil Temperature Hypothesis (FAT)

Spaulding-Astudillo and Mitchell, 2025



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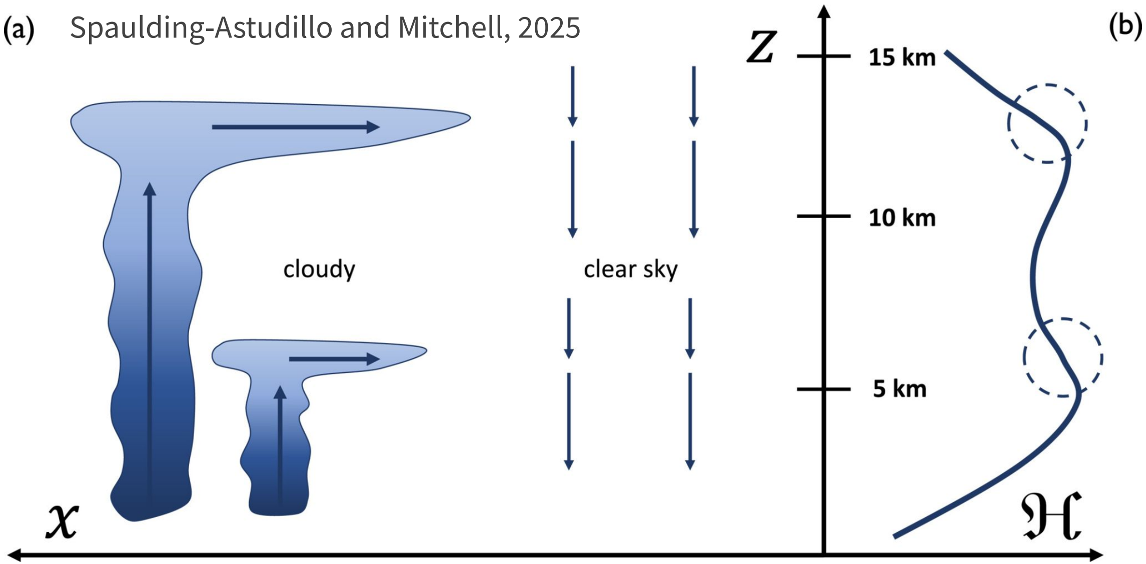

$$M_{\mathrm{clr}} = \frac{\mathscr{H}}{c_p \sigma}.$$

$$\mathrm{CSC} \approx \max\left(0, \frac{-1}{c_p \rho \sigma} \frac{\partial \mathscr{H}}{\partial z}\right).$$

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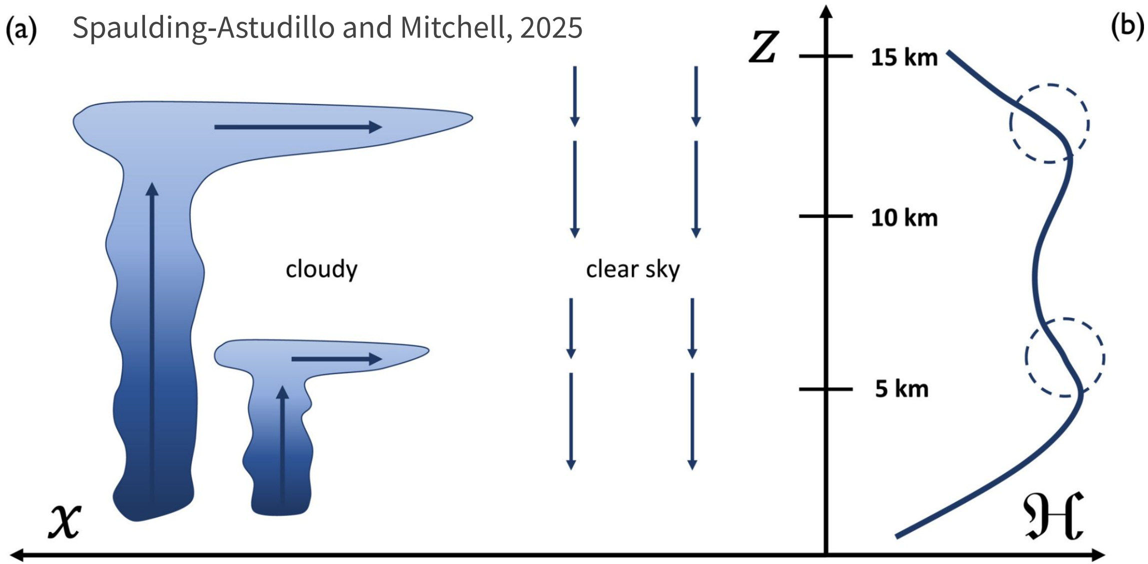

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Detrainment $\propto$ CSC

Cloud fraction = detrainment
x cloud lifetime

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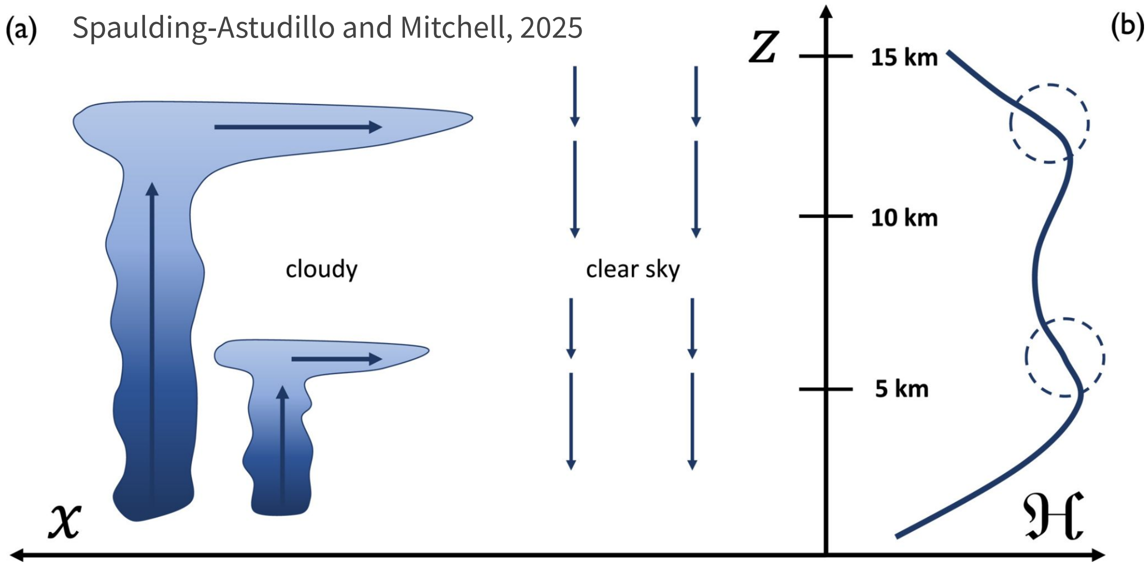

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$$\frac{dT_h}{dT_s} = \frac{T_h}{T_s} \frac{1}{\frac{L R_d \Gamma}{g R_v T_h} - 1} \approx 1/7$$

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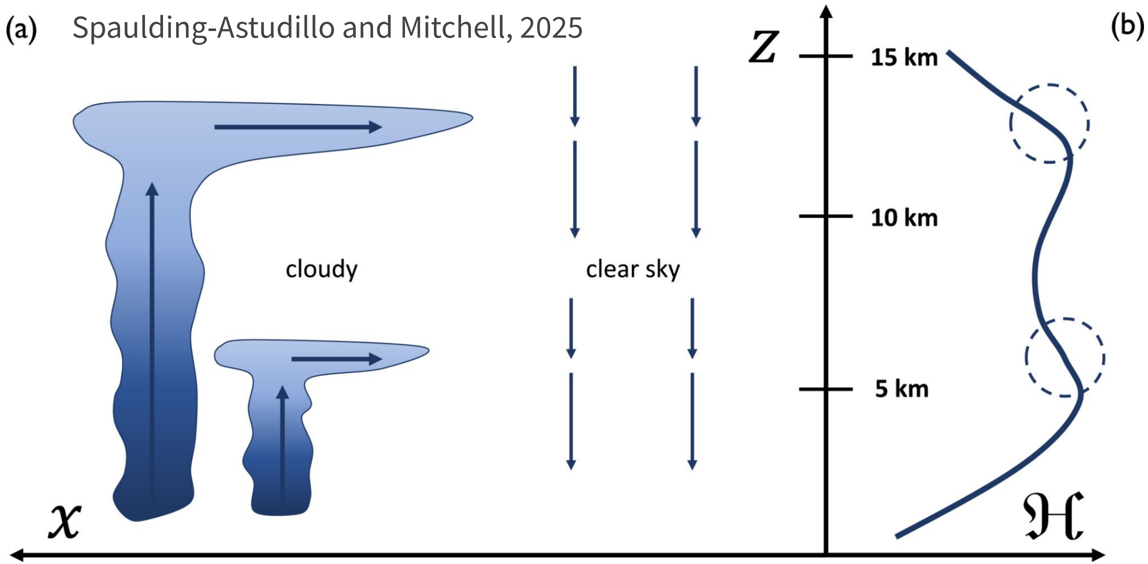

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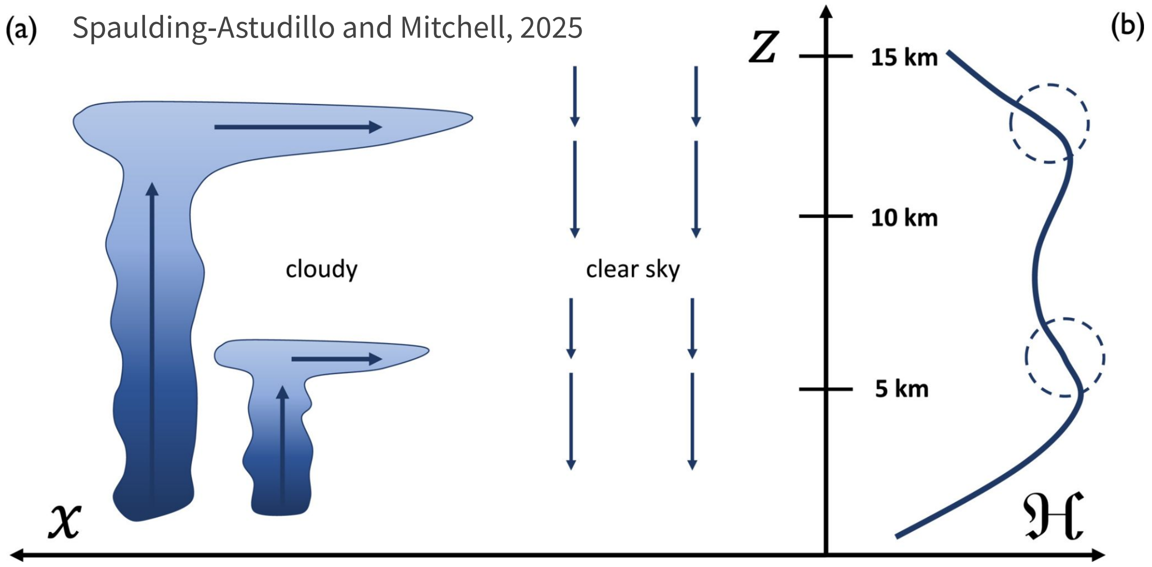
- Anvil clouds appear where the vertical profile of radiative cooling changes sharply in the upper troposphere due to mass conservation (Manabe and Strickler, 1964)
- This cooling is sourced from water vapor, and so the temperature of anvil clouds are thermodynamically constrained like water vapor (Hartmann and Larson, 2002)

The Stability Iris Hypothesis



$$M_{\mathrm{clr}} = \frac{\mathscr{H}}{c_p \sigma}.$$

$$\mathrm{CSC} = \partial_z\left(\frac{H}{\Gamma_d - \Gamma}\right)$$

Detrainment $\propto$ CSC

Cloud fraction = detrainment x cloud lifetime

$$\frac{\mathrm{d}\ln f_{\mathrm{h}}}{\mathrm{d}T_s} = -\frac{\mathrm{d}\ln(1/\Gamma_{\mathrm{h}} - 1/\Gamma_{\mathrm{d}})}{\mathrm{d}T_s} \approx -1 \text{ to } -4\%\ \mathrm{K}^{-1},$$

$$\frac{d\ln(1/\Gamma - 1/\Gamma_d)^{-1}}{dT_s} \approx -\frac{d\ln q_v^*(T)}{dT_s}$$

- Moist adiabatic lapse rates decrease at a fixed isotherm with surface warming (Williams et al, 2025) so CSC should decrease (Bony et al., 2016).

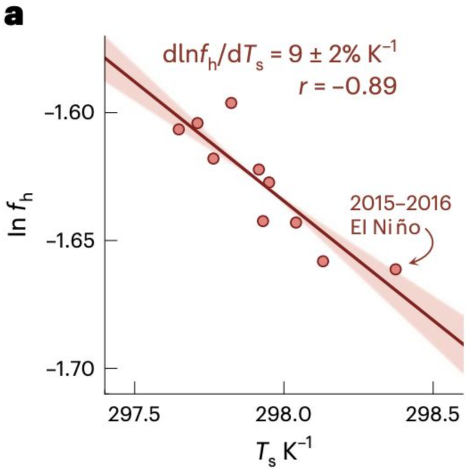
Multiple lines of evidence constrain the high cloud area feedback

Theory

$$\frac{d\ln f_h}{dT_s} = -\frac{d\ln(1/\Gamma_h - 1/\Gamma_d)}{dT_s}$$

$$\approx -1 \text{ to } -4\%\,K^{-1},$$

Observations



$$C_h + m_{\ell h} = -1 \pm 3\,W\,m^{-2}$$

Simple Feedback Framework

$$\lambda_h^{\text{area}} = \frac{1}{2}\frac{d\ln f_h}{dT_s}\left(C_h + m_{\ell h}\right)$$

$$\lambda_h^{\text{area}} = -0.02 \pm 0.07 \text{Wm}^{-2}\text{K}^{-1}$$

McKim et al, 2024

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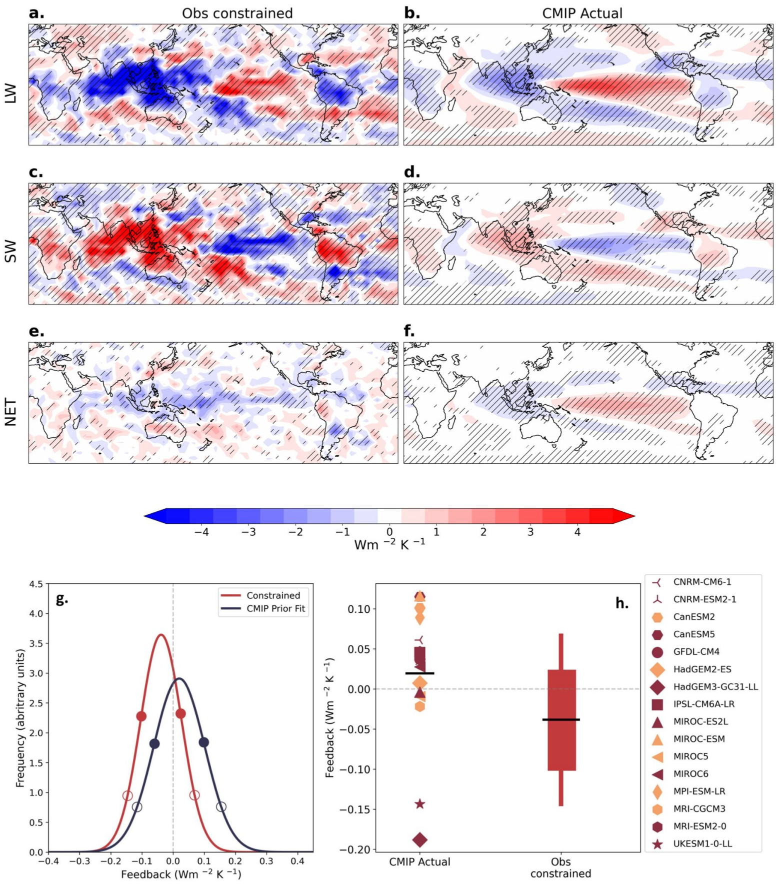

Cloud Controlling Factor Analysis

(Upper tropospheric stability is now included as a CCF)

$$\frac{dR(r)}{dT} \approx \sum_{i=1}^{M} \boldsymbol{\Theta}_i \frac{d\boldsymbol{X}_i(r)}{dT},$$

$$\lambda_h^{\mathrm{area}} = -0.04 \pm 0.07\ \mathrm{Wm^{-2}K^{-1}}$$

Wilson-Kemsley and Ceppi, 2025; Raghuraman et al, 2024; Stauffer and Wing, 2023

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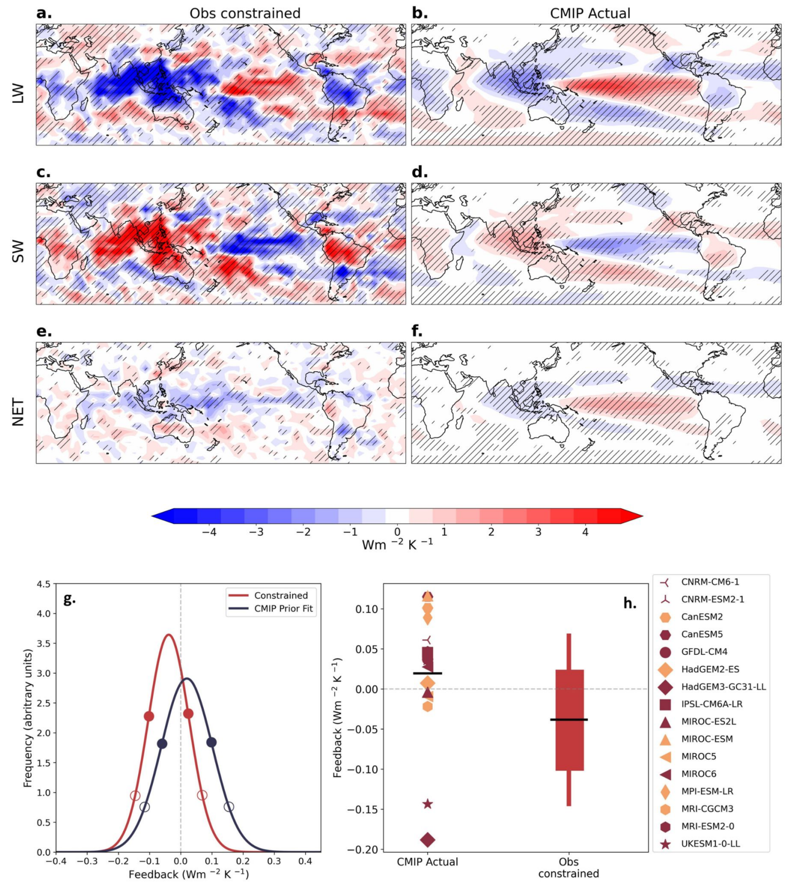

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Cloud Radiative Kernels from Observations

$$\lambda_h^{\text{area}} = -0.03 \pm 0.05\ \text{Wm}^{-2}\text{K}^{-1}$$

Wilson-Kemsley and Ceppi, 2025; Raghuraman et al, 2024; Stauffer and Wing, 2023

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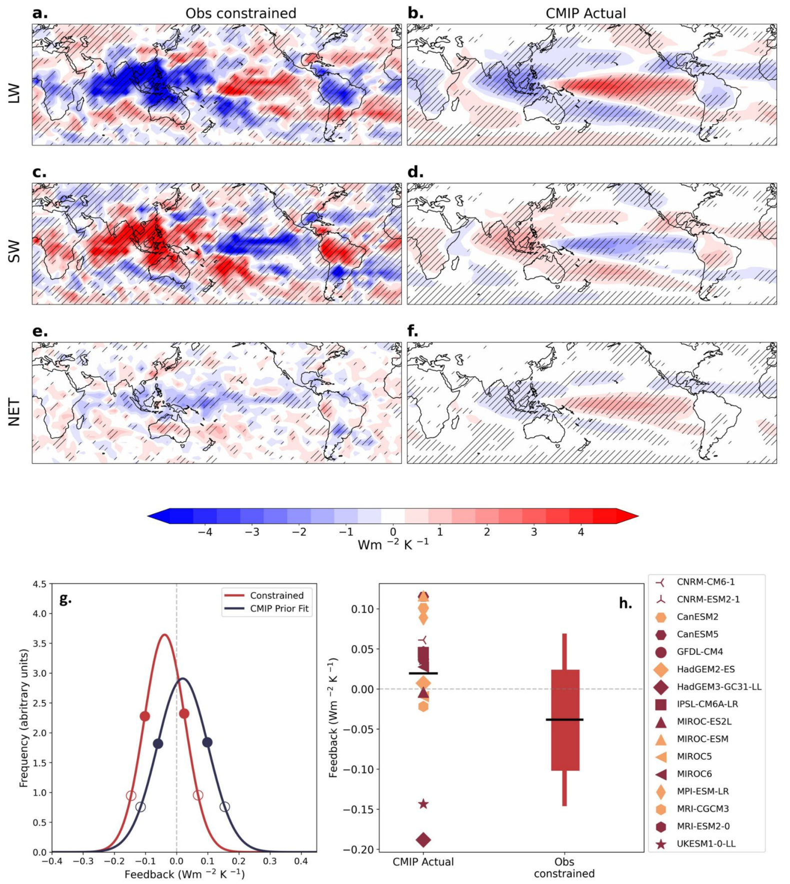

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Cloud Radiative Kernels from Observations

$$\lambda_h^{\text{area}} = -0.03 \pm 0.05 \ \text{Wm}^{-2}\text{K}^{-1}$$

RCEMIP

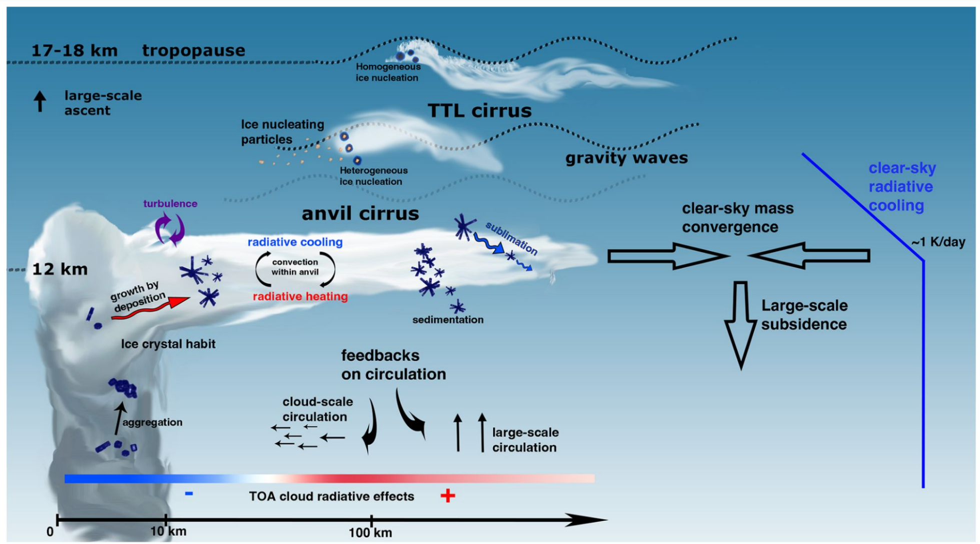
$$\lambda_h^{\text{area}} = -0.07 \pm 0.12 \ \text{Wm}^{-2}\text{K}^{-1}$$

Wilson-Kemsley and Ceppi, 2025; Raghuraman et al, 2024; Stauffer and Wing, 2023

Limitations of theories of anvil clouds

- Both theories are highly idealized and ignore other sources/sinks of cloudiness. How reasonable is this?

- In practice, these theories can explain a large amount of the observed variability in high cloud height and area (Saint-Lu et al, 2020; 2022) and the average model response in RCEMIP (Stauffer et al, 2022), but not necessarily intermodel spread (Jeevanjee et al, 2022).



Gasparini et al, 2023

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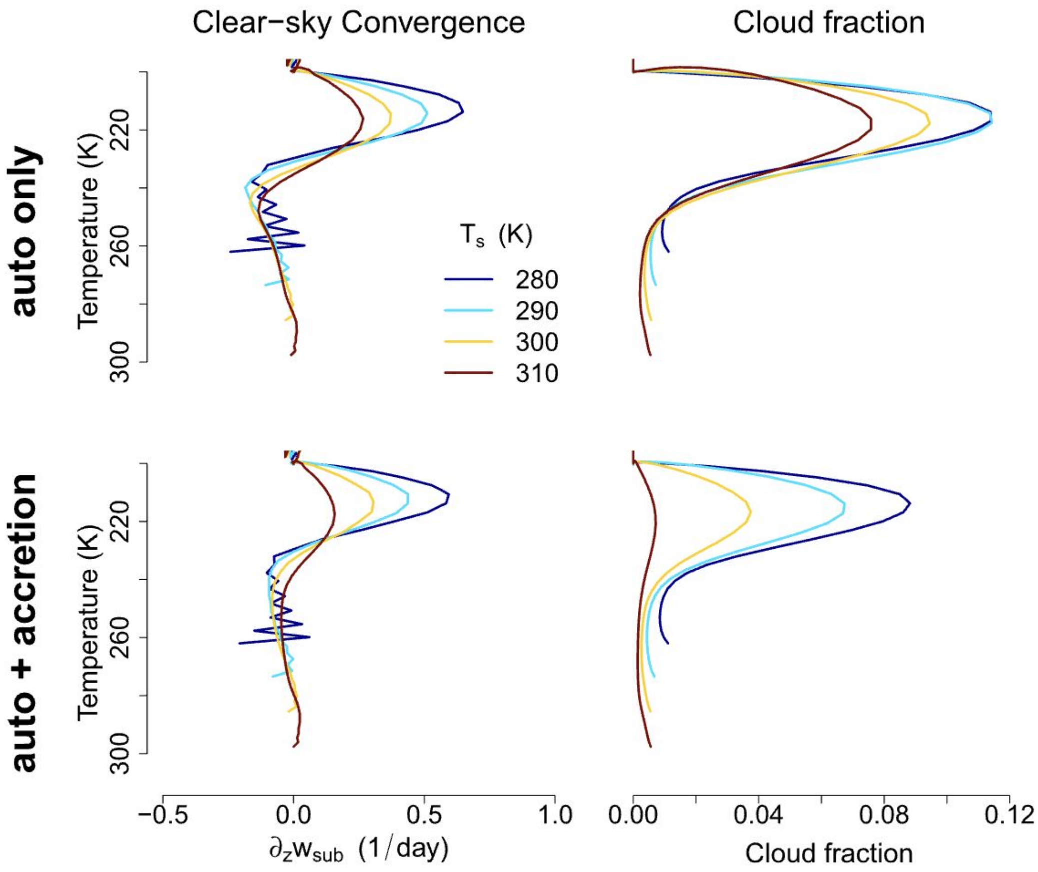


Jeevanee et al, 2022

Anvil cloudy albedo feedback is more uncertain

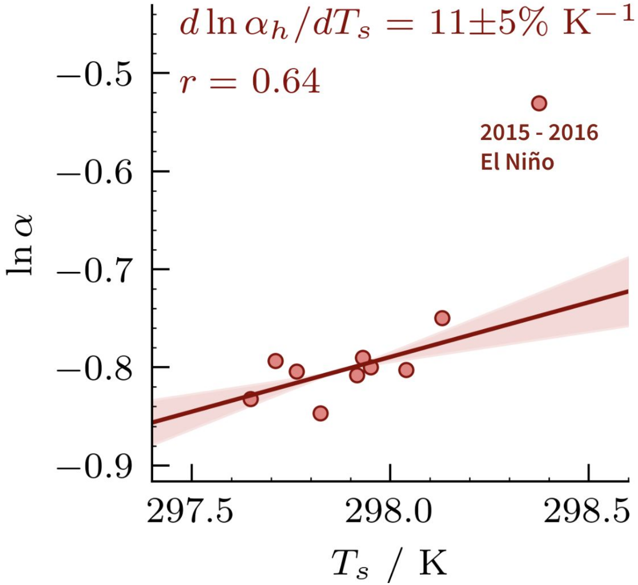
$$\lambda_h^{\text{albedo}} = \frac{1}{2}\frac{d\log\alpha_h}{dT_s}\left(C_h^{sw} + m_{\ell h}^{sw}\right)$$

- $C_h^{sw} = -27\ \text{Wm}^{-2}$, $\lambda_h^{\text{albedo}} = -0.2\ \text{Wm}^{-2}\text{K}^{-1}$

- **Required for lower bound**

$$\frac{d\log\alpha_h}{dT_s} = 1 \text{ to } 2\ \%\ \text{K}^{-1}$$

Cloudy albedo



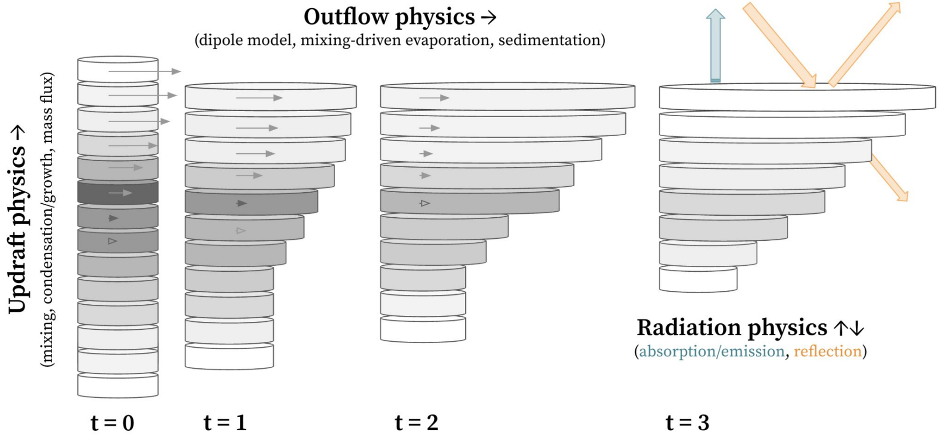
How plausible is this?

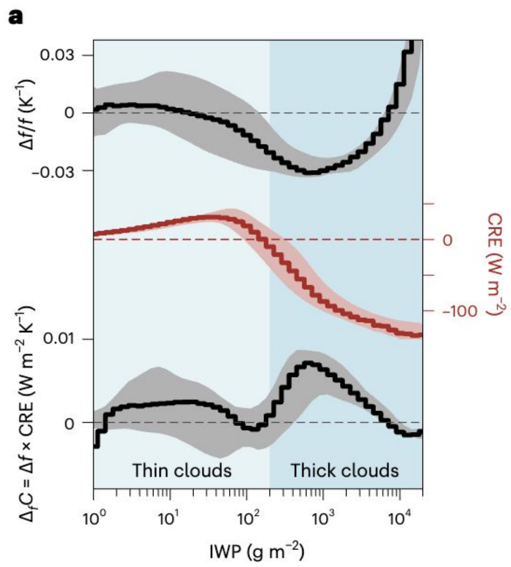
- No good theory yet for optical depth or cloudy albedo changes
- We diagnose changes in cloud reflectivity from CERES observations and find changes that imply a large feedback

Limitations of theories of anvil clouds

- No theory for the optical depth of anvil clouds, despite its importance for feedbacks (Sokol et al, 2024; McKim et al, 2024)

- A more refined model of the sources and sinks of condensates is needed to predict changes in the optical depth / ice water path distribution of high clouds. How do we translate meso- , km-, and micro-scale processes lead to macroscale predictions?

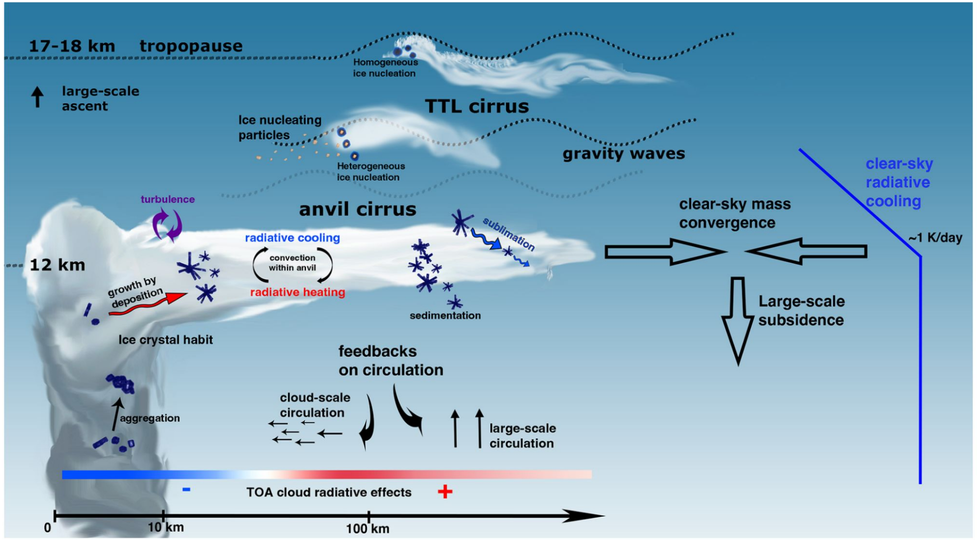




Sokol et al, 2024

Limitations of theories of anvil clouds

- What about in-situ cirrus? Or convective organization?



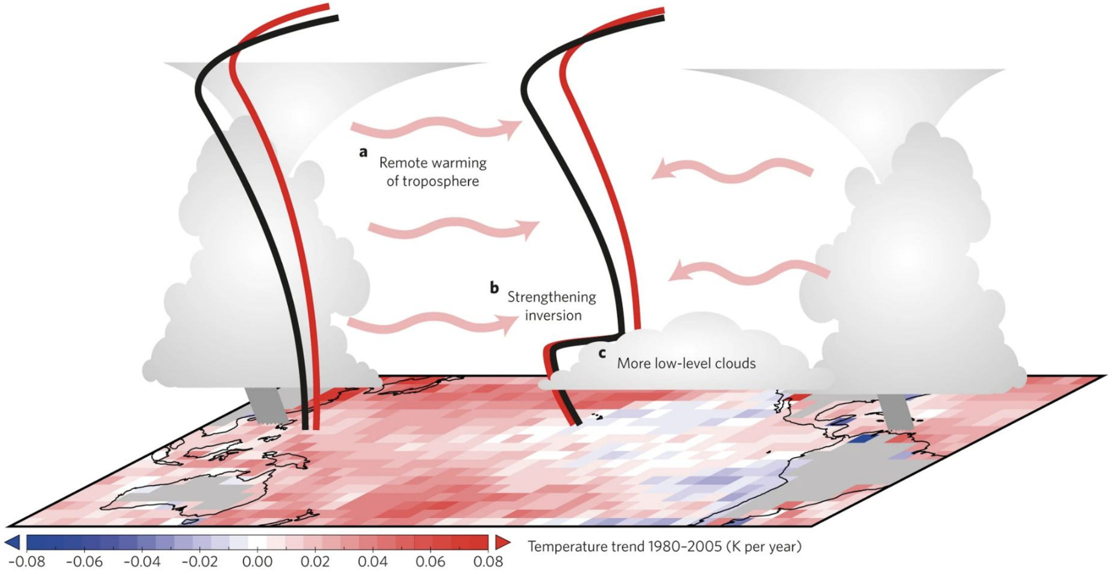
Gasparini et al, 2023

Limitations of feedback analysis

- Not all feedbacks are independent (e.g. area and temperature feedback of anvil clouds)

- The radiative response depends also on the pattern of warming, due to cloud-circulation coupling. Among other things, this complicates how we extrapolate long term feedbacks from interannual variability

$$\lambda = \lambda[\Delta \mathrm{SST}(\mathbf{x})]$$



Mauritsen, 2016

Looking ahead

- New resources at our disposal (GSRMs, EarthCare/upcoming satellite missions)

- Longer term observations and new retrievals (~40 years of geostationary data, MCS tracking, clear-sky vertical velocity, etc…)

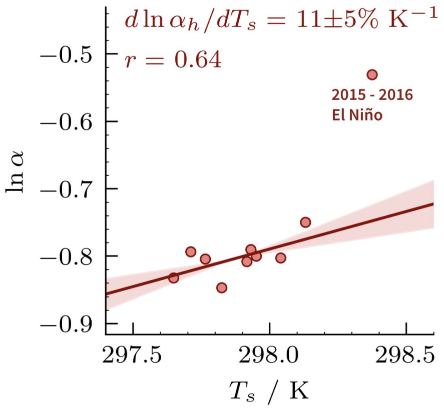
- Targeted observational campaigns on cloud-circulation coupling (EUREC4A, ORCESTRA)

- New theoretical frameworks for clouds and convective organization (Ice water path distributions, thermal merging, etc…)

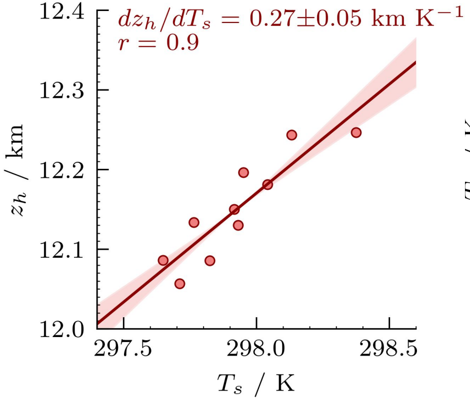
- All will help to understand the timing of convection, its growth and decay, the portioning of cirrus into thick and thin components…

Interannual Changes in Anvil Clouds

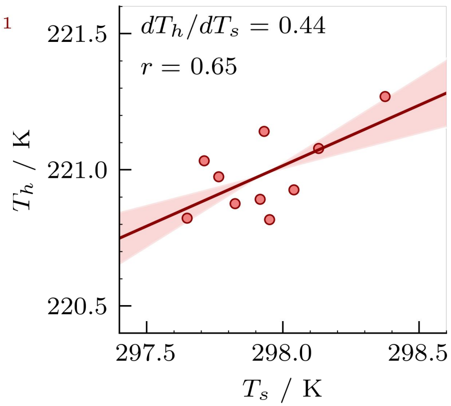
Cloudy Albedo



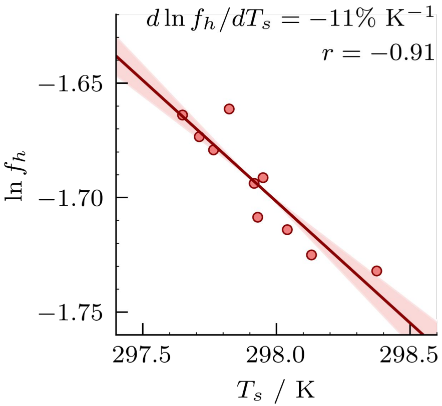
Height



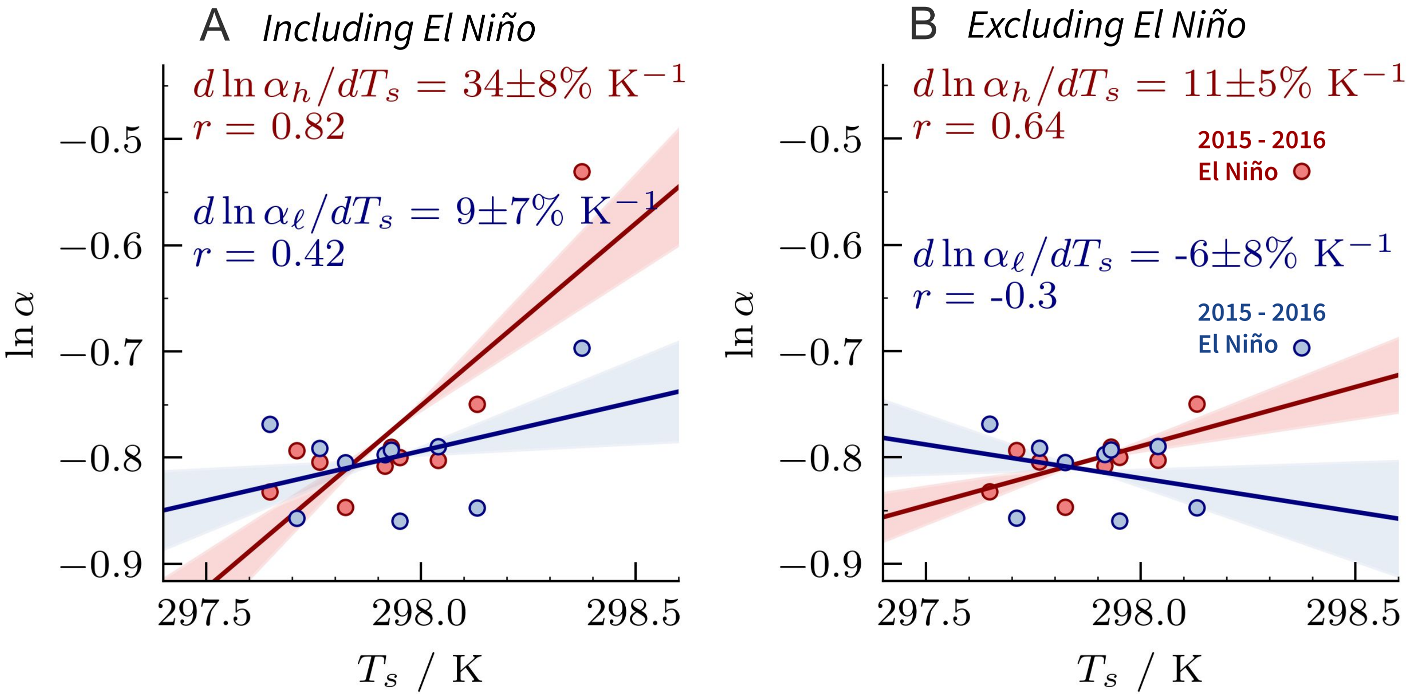
Temperature



Area



Interannual Changes in Cloudy Albedo



Identifying clouds