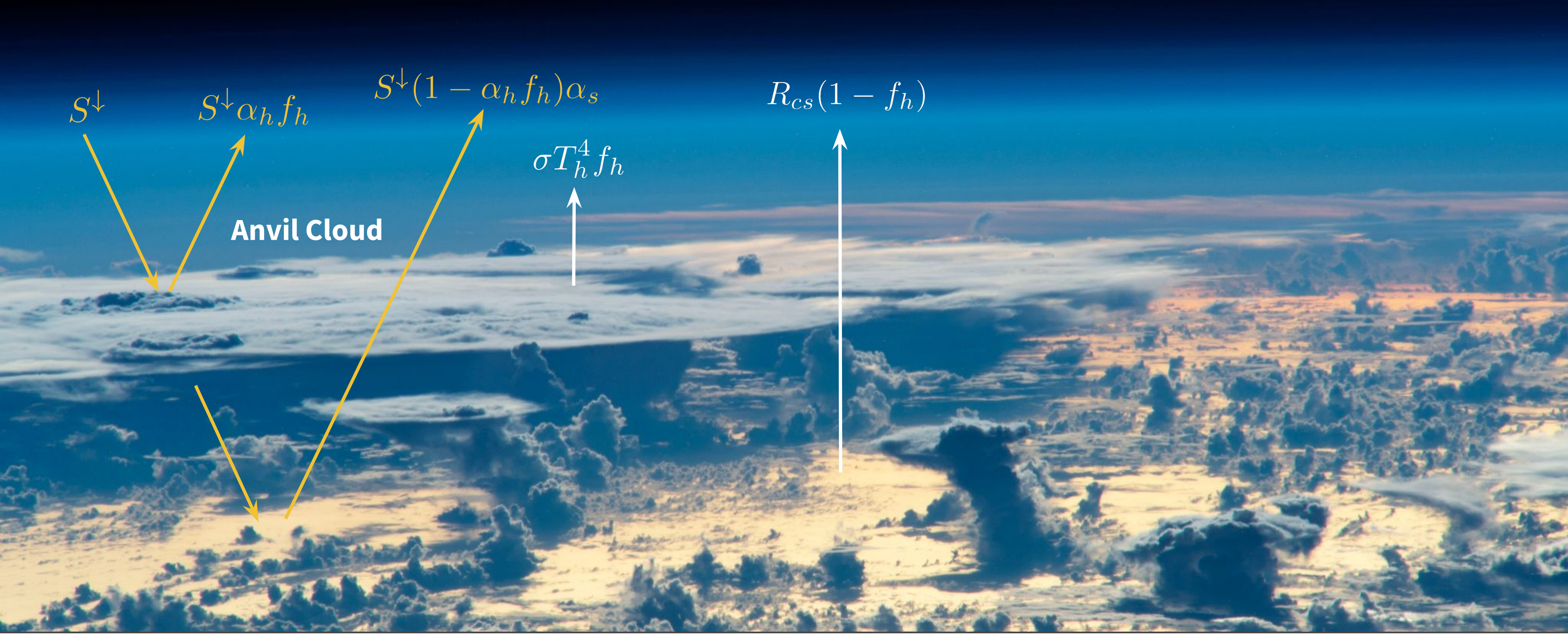
Understanding the anvil cloud area feedback



Brett McKim, Sandrine Bony, Marion Saint-Lu, Jean-Louis Dufresne, Claudia Stubenrauch

LMD | EUREC4A Meeting | 8 December 2022

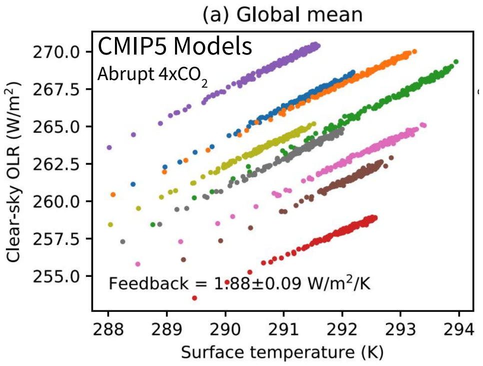
University of Exeter LMD FULBRIGHT

Image: https://eol.jsc.nasa.gov/SearchPhotos/photo.pl?mission=ISS066&roll=E&frame=37532

Knowns and unknowns in climate feedbacks

- Climate models simulate the longwave clear-sky feedback to within 5%

$$\lambda_{cs} = 1.88 \pm 0.09 \ \mathrm{Wm^{-2}K^{-1}}$$



Zhang et al, 2020; Sherwood et al, 2020

Knowns and unknowns in climate feedbacks

- Climate models simulate the longwave clear-sky feedback to within 5%

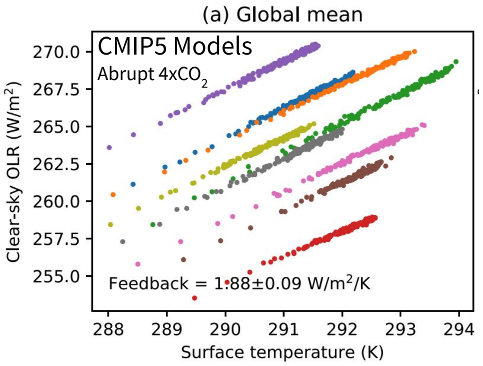
$$\lambda_{cs} = 1.88 \pm 0.09\ \mathrm{Wm^{-2}K^{-1}}$$

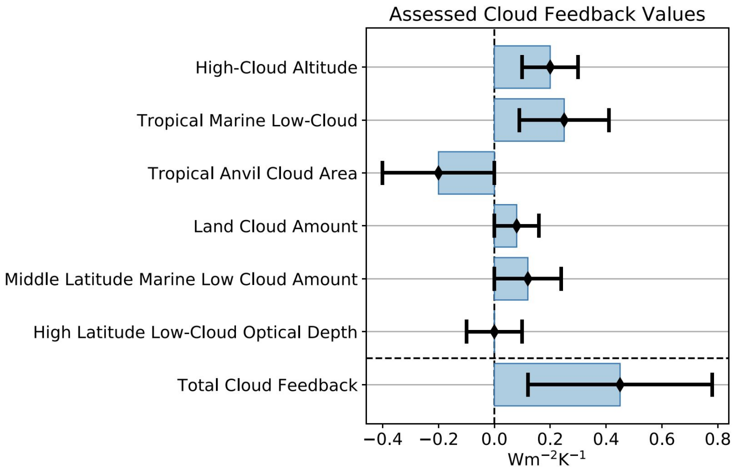
- Cloud feedback uncertainty is larger than the feedback itself

$$\lambda_{\mathrm{clouds}} = 0.45 \pm 33\ \mathrm{Wm^{-2}K^{-1}}$$

- Much uncertainty comes from the anvil cloud area feedback

$$\lambda_{\mathrm{iris}} = -0.2 \pm 0.2\ \mathrm{Wm^{-2}K^{-1}}$$



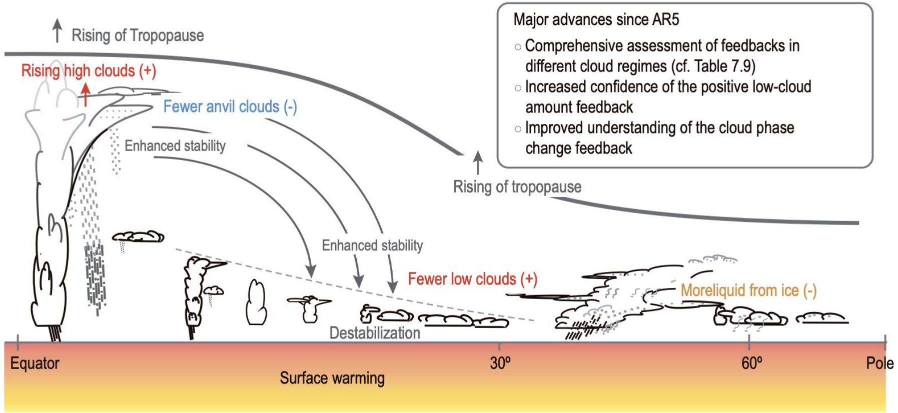


Zhang et al, 2020; Sherwood et al, 2020

Uncertainties in the anvil cloud area feedback

2 distinct questions

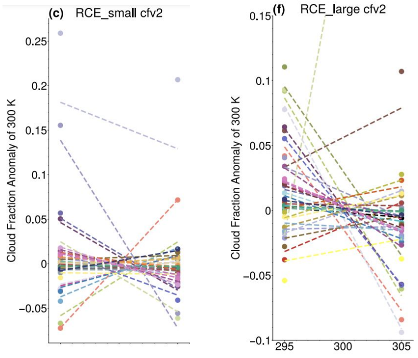
- How much does anvil cloud fraction change with warming?
- What is the the radiative feedback due to that change?



Does anvil cloud fraction change with warming?

- Models of RCE simulate a diversity of f_h changes—some positive, some negative.

Change in f_h with warming in RCEMIP



Stauffer and Wing, 2022; Jeevanjee 2022; Beydoun et al, 2021

Does anvil cloud fraction change with warming?

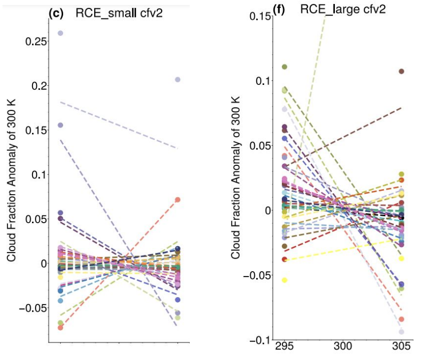
- Models of RCE simulate a diversity of f_h changes—some positive, some negative.

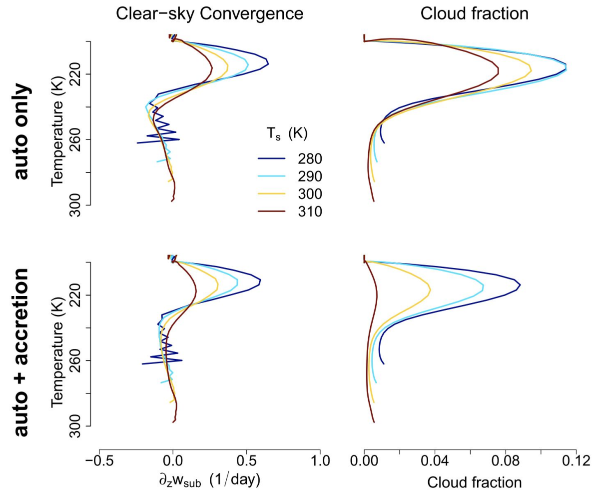
- This diversity might stem from microphysical parameterizations.

$$f_h = \mathrm{CSC} \cdot \mathrm{microphyisical\ tendencies}$$

- It is a problem that models can't agree on this aspect of climate change.

Change in f_h with warming in RCEMIP





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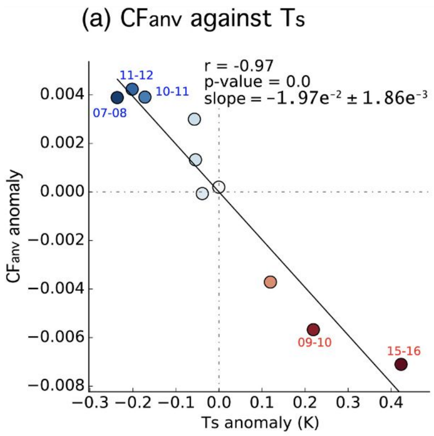
Does anvil cloud fraction change with warming?

- Observations of interannual variability show that tropical mean f_h decreases with warming.
  $$\frac{df_h}{dT_s} = -0.02 \text{ K}^{-1}$$



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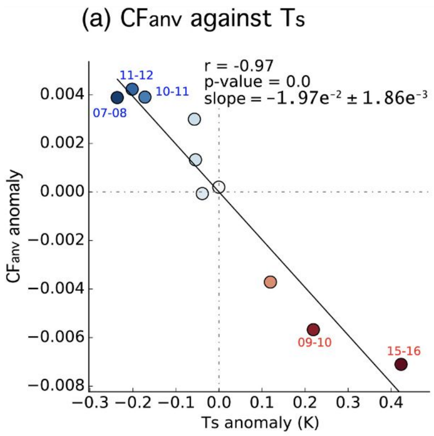
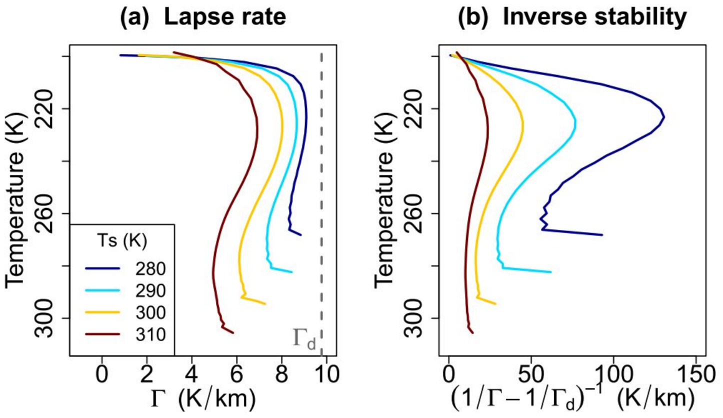
$$\frac{df_h}{dT_s} = -0.02\ \mathrm{K}^{-1}$$

- This change ultimately comes from decreased static stability with warming (outweighing the increased radiative cooling)

$$f_h \propto \mathrm{CSC} = \partial_z w_{\mathrm{sub}} = \partial_z \left(\frac{\mathcal{H}}{\Gamma_d - \Gamma} \right)$$

"Stability Iris" (Bony et al, 2016)





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Does anvil cloud fraction change with warming?

- A human iris changes area to counteract changes in light intensity.

- Do anvil area changes counteract changes in surface temperature?

https://www.scientificamerican.com/article/seeing-in-the-dark1/, Image: https://eol.jsc.nasa.gov/SearchPhotos/photo.pl?mission=ISS066&roll=E&frame=37532

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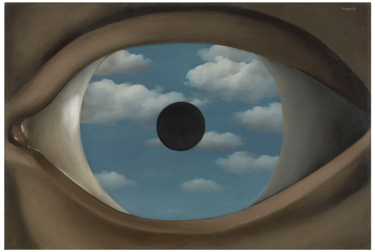


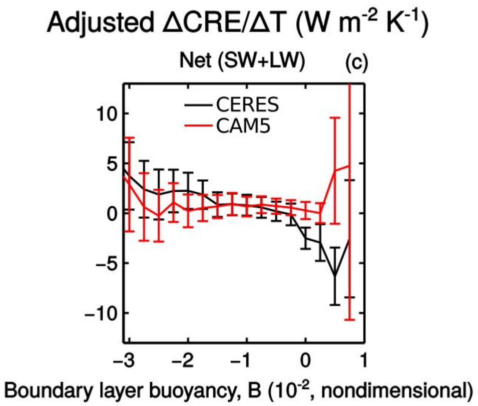
?

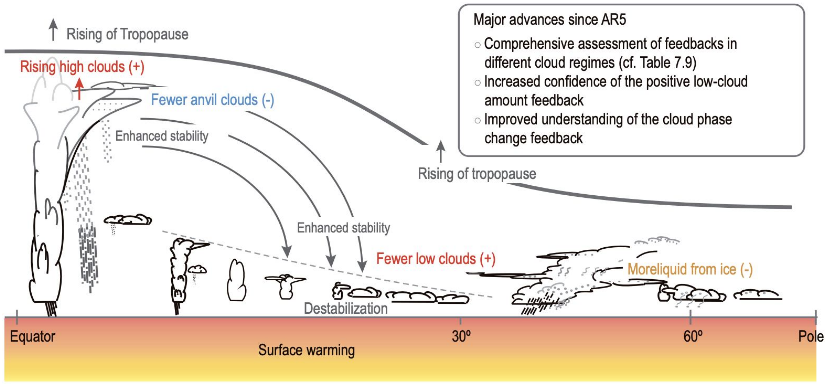
Credit: Rene Magritte, "The False Mirror," 1929 © 2020 C. Herscovici / Artists Rights Society (ARS), New York

https://www.scientificamerican.com/article/seeing-in-the-dark1/, Image: https://eol.jsc.nasa.gov/SearchPhotos/photo.pl?mission=ISS066&roll=E&frame=37532

What is the the radiative feedback due to a decreasing f_h?

- The anvil cloud area can be estimated with the change in cloud radiative effect (CRE) with warming, but the interpretation is complicated.





Williams and Pierrehumbert 2017, AR6 Chapter 7

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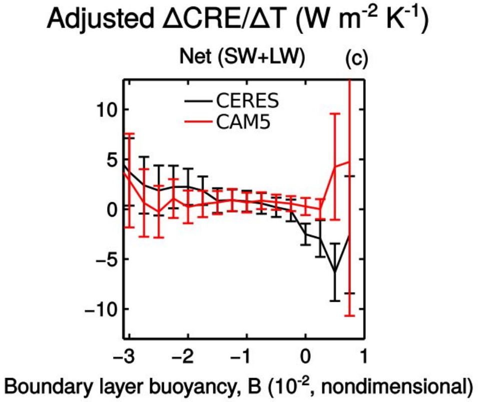
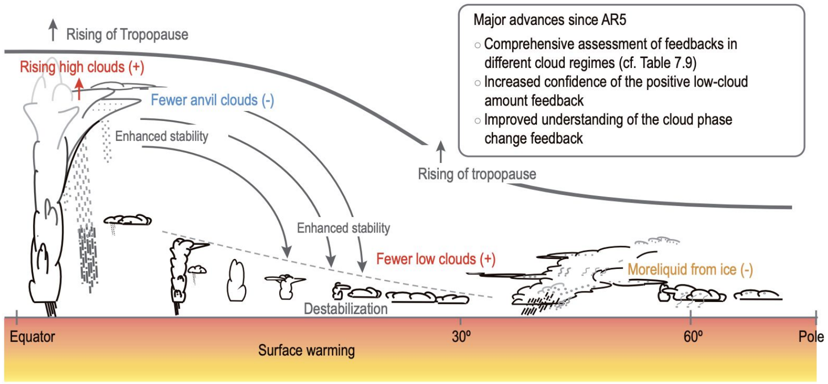
$$\mathrm{CRE_{LW}} = -(R - R_{cs})$$
$$\mathrm{CRE_{SW}} = S - S_{cs}$$

  - Clouds *and* clear-skies change
  - Other cloud properties change
  - Different reference response than traditional feedback decompositions





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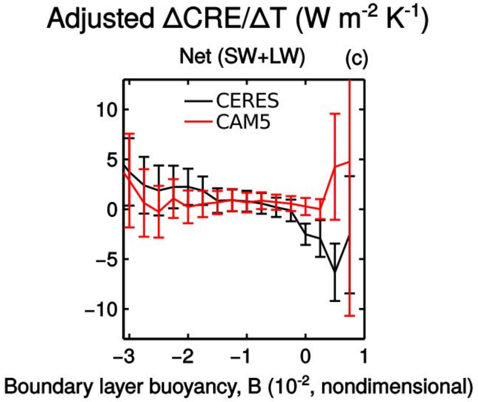
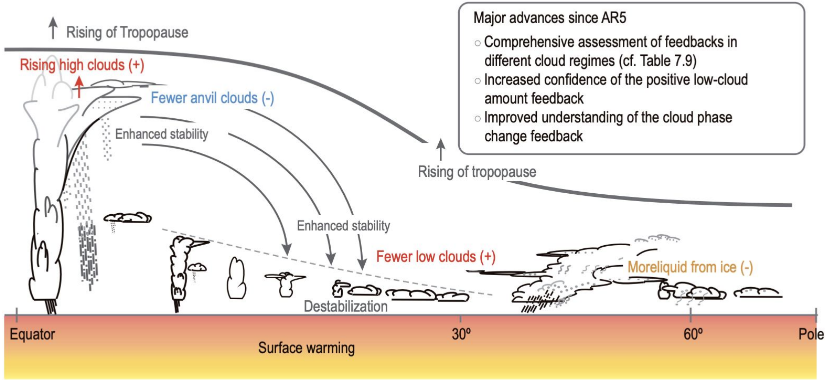
- Can we approach this problem in another, simpler way?





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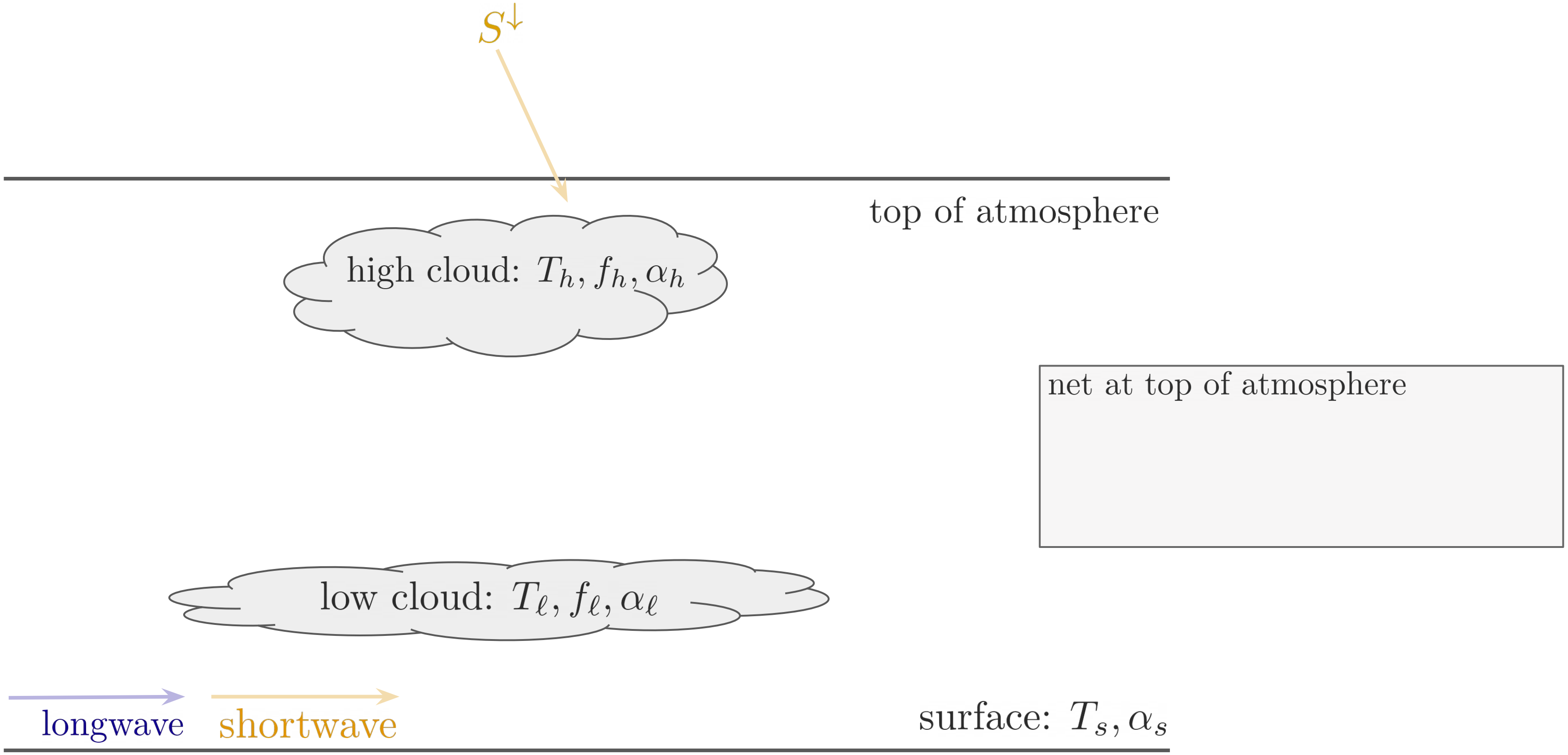
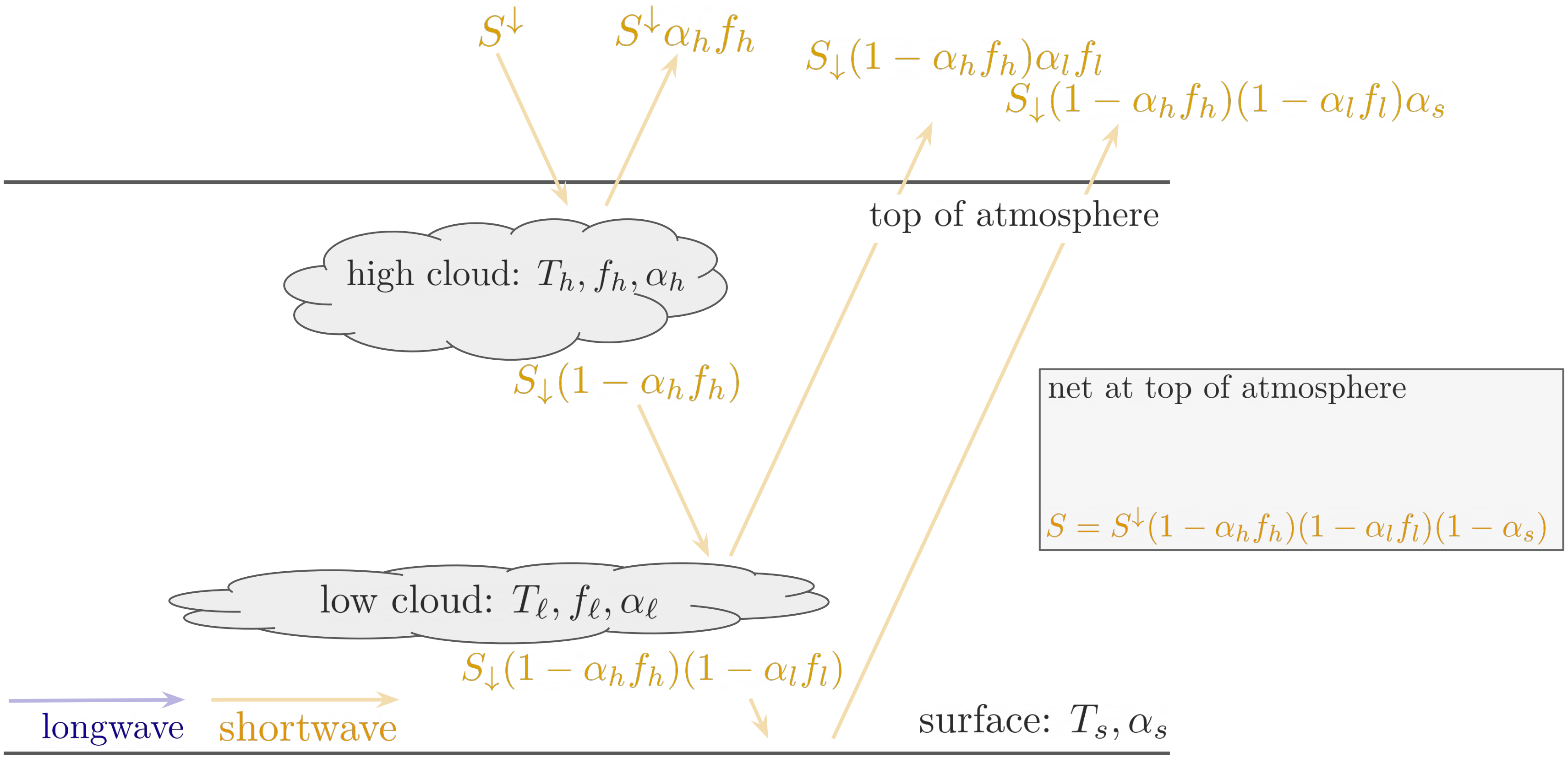
A two layer model of cloud radiative effects



One Grid Cell

A two layer model of cloud radiative effects



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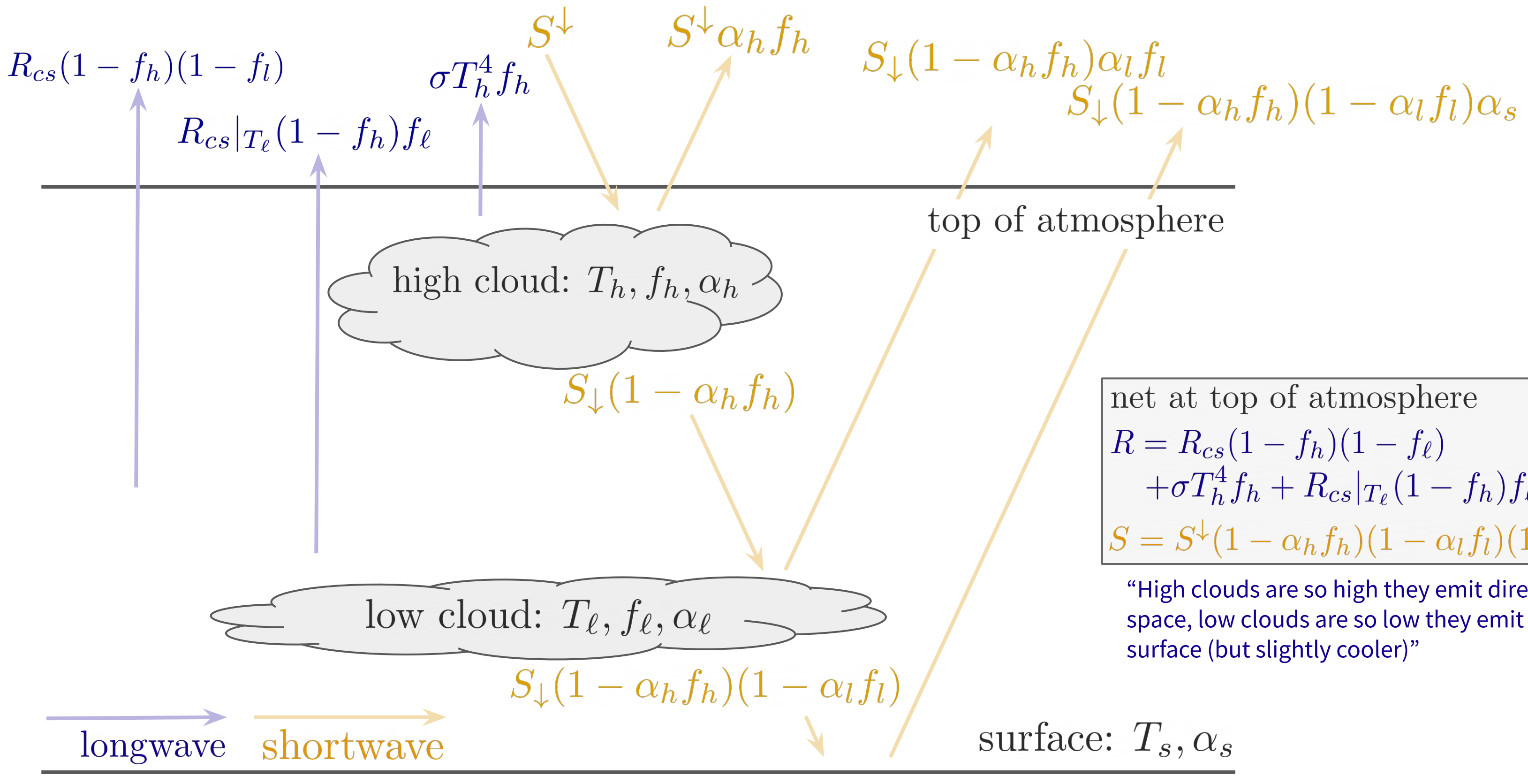

One Grid Cell

net at top of atmosphere

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

$$S = S^{\downarrow}(1-\alpha_h f_h)(1-\alpha_l f_l)(1-\alpha_s)$$

"High clouds are so high they emit directly to space, low clouds are so low they emit like the surface (but slightly cooler)"

A two layer model of cloud radiative effects

$$\lambda = \frac{dN}{dT_s} = \frac{d[S - R]}{dT_s}$$

A two layer model of cloud radiative effects

$$\lambda = \frac{dN}{dT_s} = \frac{d[S-R]}{dT_s}$$

$$= \underbrace{\lambda_{cs}(1-f_h)}_{\text{cloud-masked clear-sky feedback}} - \underbrace{\frac{dT_h}{dT_s}4\sigma T_h^3 f_h}_{\text{PHAT feedback}} + \underbrace{\frac{1}{f_h}\frac{df_h}{dT_s}\left[\mathrm{CRE}_h + \lambda_{cs}(T_s - T_\ell)f_\ell f_h + S^{\downarrow}(1-\alpha_s)\alpha_\ell f_\ell \alpha_h f_h\right]}_{\text{iris feedback}}$$

$$+ \ldots(\text{low cloud feedbacks})$$

A two layer model of cloud radiative effects

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A number of questions arise:

- What can we learn from this equation?
- How do we validate it?
- Can we estimate the iris feedback?
- What is missing from or assumed in this model?

What can we learn from this equation?

$$\lambda_{\text{iris}} = \frac{1}{f_h}\frac{df_h}{dT_s}\left[\text{CRE}_h + \lambda_{cs}(T_s - T_\ell)f_\ell f_h + S^{\downarrow}(1-\alpha_s)\alpha_\ell f_\ell \alpha_h f_h\right]$$

The iris feedback owes to 3 contributions:

*Others have anticipated this coupling between high and low clouds (e.g. Lindzen et al, 2001; Kang et al, 2020) but lacked an intuitive *and* quantitative description of it.

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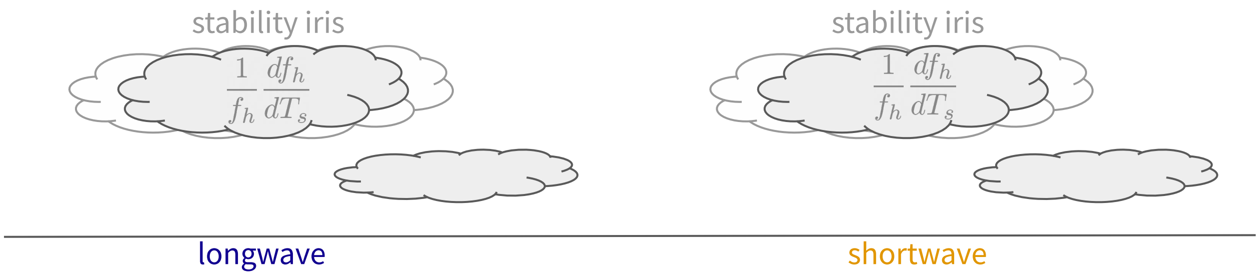
The iris feedback owes to 3 contributions:

1. The fractional change in high cloud area



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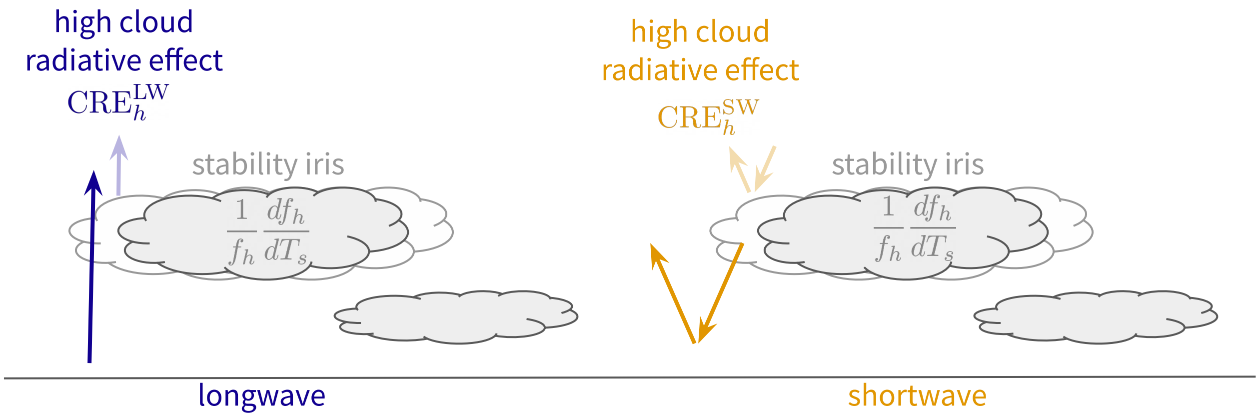
The iris feedback owes to 3 contributions:

1. The fractional change in high cloud area
2. The high cloud radiative effect in the absence of low clouds



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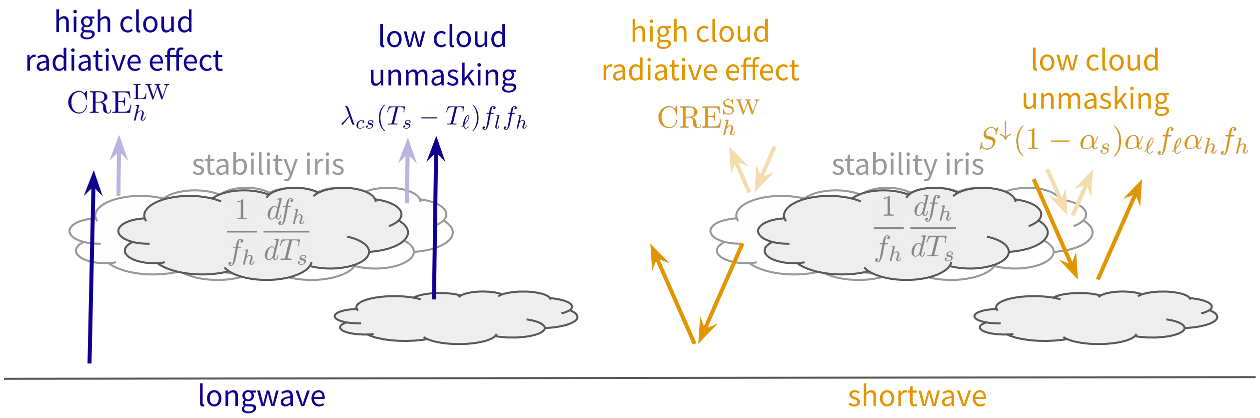
The iris feedback owes to 3 contributions:

1. The fractional change in high cloud area
2. The high cloud radiative effect in the absence of low clouds
3. The radiative effect of low clouds *no longer* blocked by the high clouds



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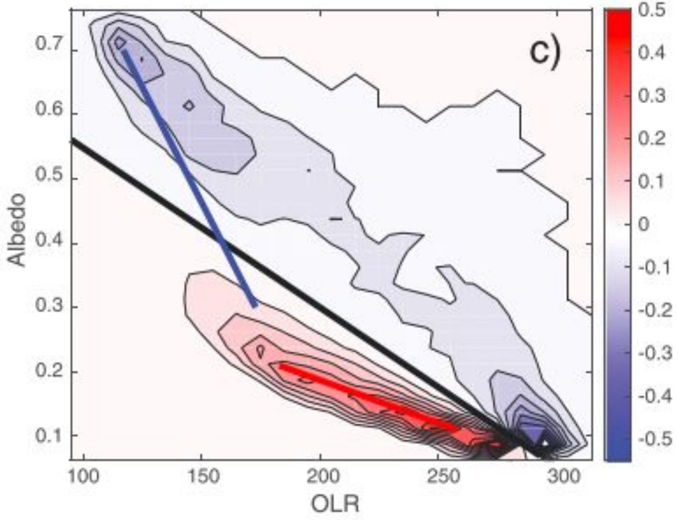
$$\text{CRE}_h \approx -4 \text{ Wm}^{-2}\text{K}^{-1}$$

CRE_h distribution in equatorial western Pacific Ocean region



CRE_h(normalized by f_h)

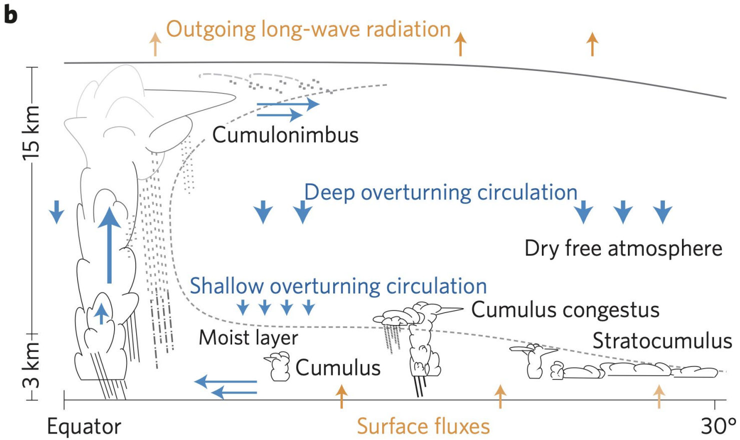
Hartmann et al, 2017

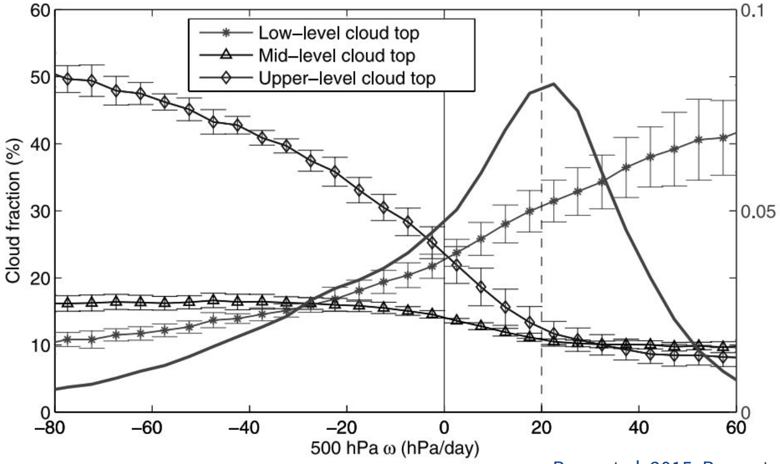
What can we learn from this equation?

$$\lambda_{\text{iris}} = \frac{1}{f_h}\frac{df_h}{dT_s}\left[\text{CRE}_h + \lambda_{cs}(T_s - T_\ell)f_\ell f_h + S^{\downarrow}(1-\alpha_s)\alpha_\ell f_\ell \alpha_h f_h\right]$$

$$\lambda_{cs}(T_s - T_\ell)f_\ell f_h \approx -2\ \text{Wm}^{-2}\text{K}^{-1} \cdot 15\ \text{K} \cdot 0.1 \cdot 0.15 \approx -0.5\ \text{Wm}^{-2}$$

$$S^{\downarrow}(1-\alpha_s)\alpha_\ell f_\ell \alpha_h f_h \approx 340\text{Wm}^{-2} \cdot 0.87 \cdot 0.5 \cdot 0.1 \cdot 0.5 \cdot 0.15 \approx 1.1\ \text{Wm}^{-2}\text{K}^{-1}$$





Bony et al, 2015; Bony et al, 2005

Estimating the tropical mean anvil cloud area feedback

$$\langle \lambda_{\text{iris}} \rangle = \frac{\langle \overline{A_h} \rangle}{\langle \overline{f_h} \rangle} \frac{d\langle f_h \rangle}{d\langle T_s \rangle} \left[\langle \overline{\text{CRE}_h + \lambda_{cs}(T_s - T_\ell) f_\ell f_h + S^{\downarrow}(1-\alpha_s)\alpha_\ell f_\ell \alpha_h f_h} \rangle \right]$$

Estimating the tropical mean anvil cloud area feedback

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- What do the terms mean?
  - $\langle\cdot\rangle$ Tropical average (+/- 30 deg N)
  - $\overline{\cdot}$ Temporal average over all years

Estimating the tropical mean anvil cloud area feedback

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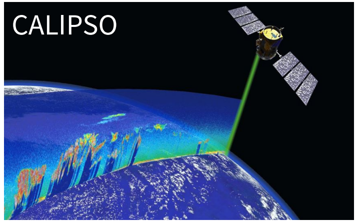
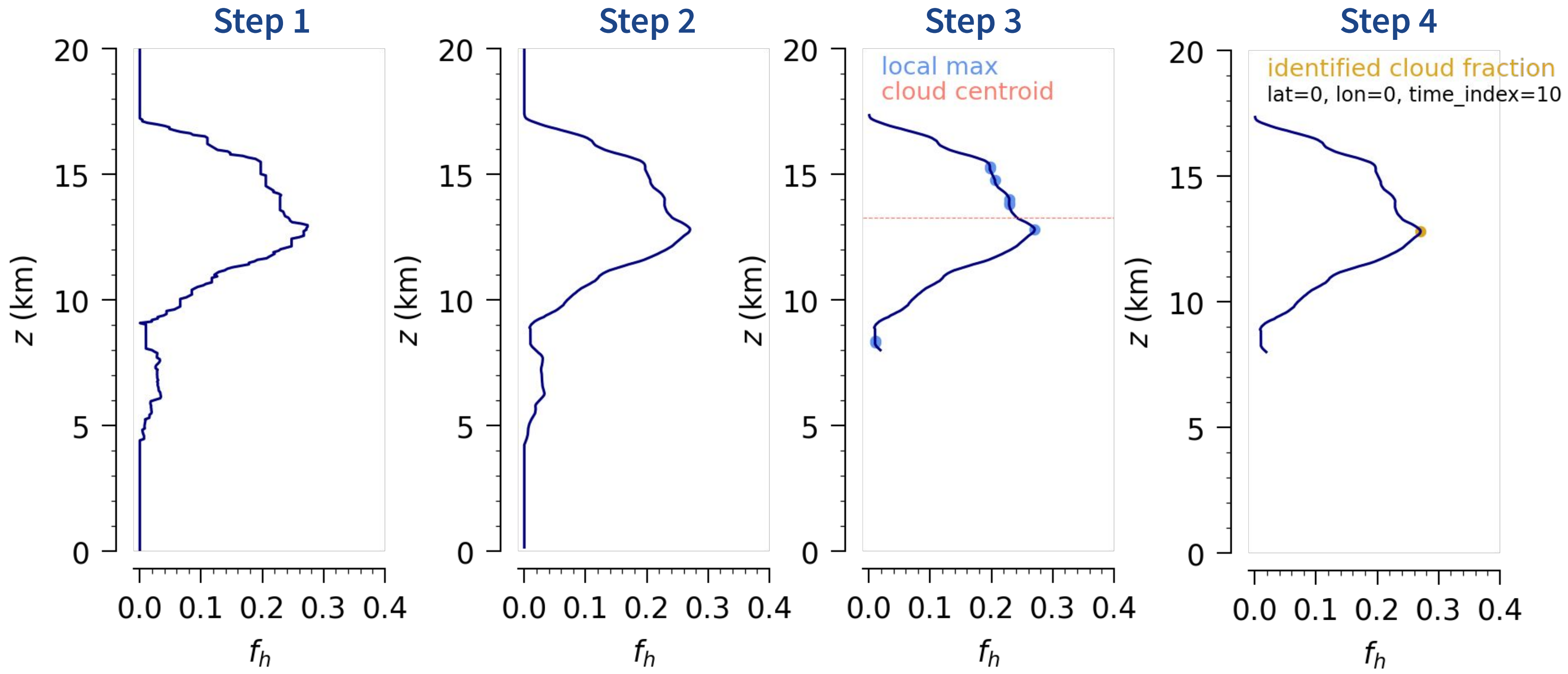
- What do the terms mean?
  - $\langle \cdot \rangle$ Tropical average (+/- 30 deg N)
  - $\overline{\cdot}$ Temporal average over all years
- Let's validate using …
  - HadCRUT for T_s, ERA5 for atmospheric T
  - CALIPSO for f_h and f_l, CERES for CRE and surface albedo
  - Estimate clear-sky feedback as -2
  - Estimate cloud albedo by fitting predictions of *S* and *R*



Validating the two layer model

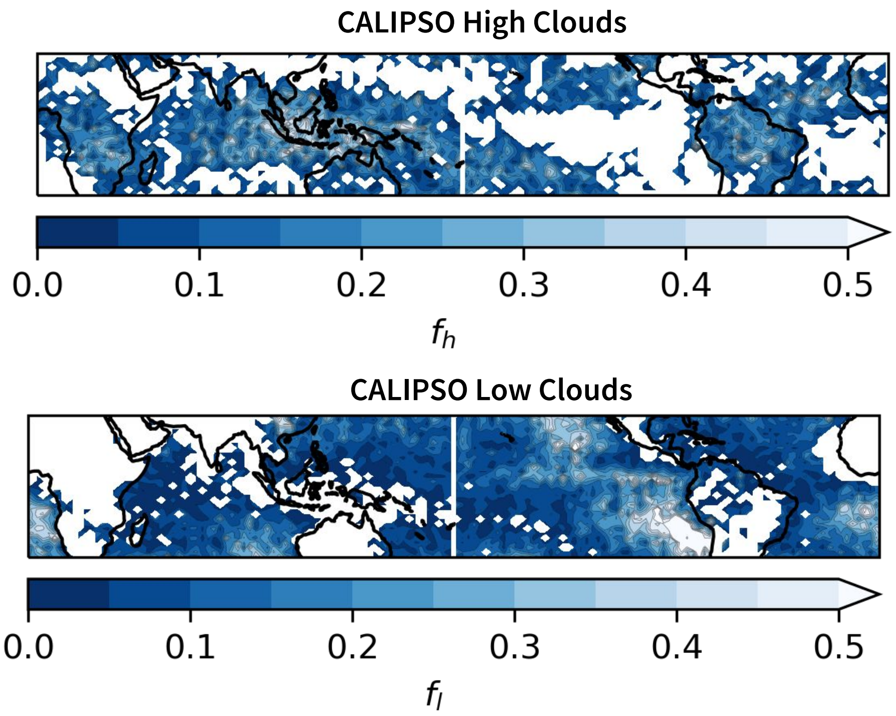
Following Saint-Lu et al, 2020: Use cloud fraction of clouds with optical depth 0.3 < tau < 5



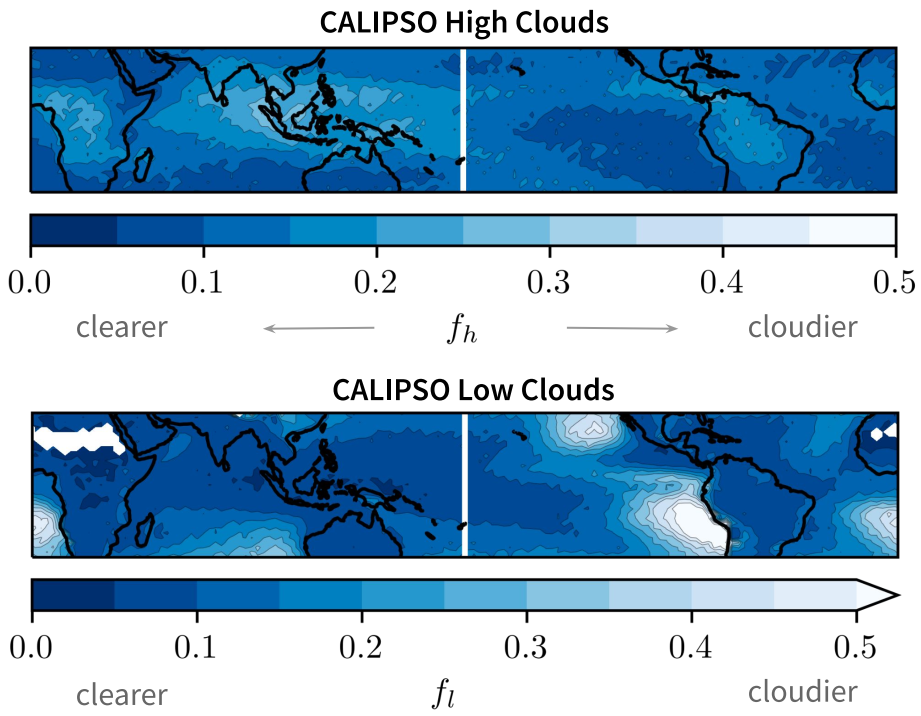
* This definition of anvils excludes clear-sky regions, as well as subvisible cirrus clouds, and the cores of deep convective clouds.

Validating the two layer model

MONTHLY SNAPSHOT

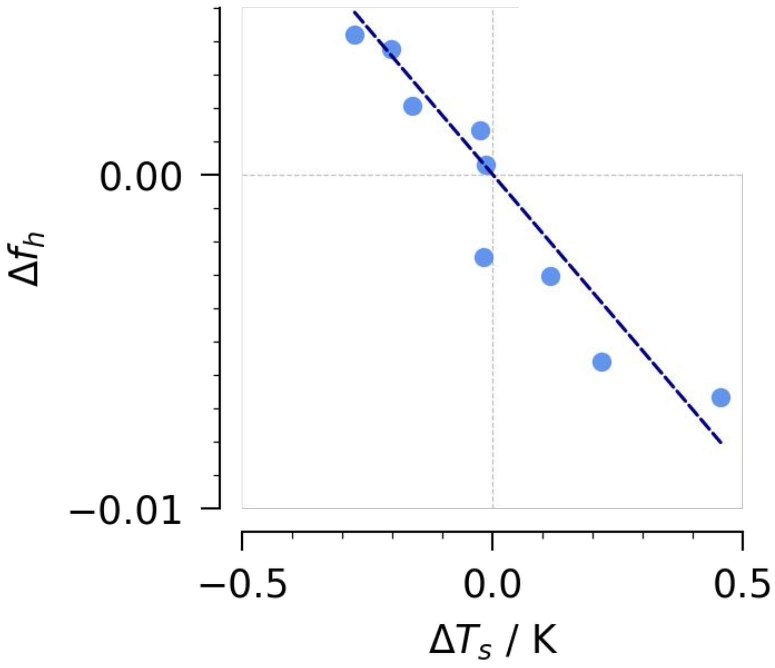


10 YEAR AVERAGE



Validating the two layer model

- Each circle is a different year (averaged from July to June)
- We get a decrease in f_h over the 10-year record, consistent with Saint-Lu et al, 2020



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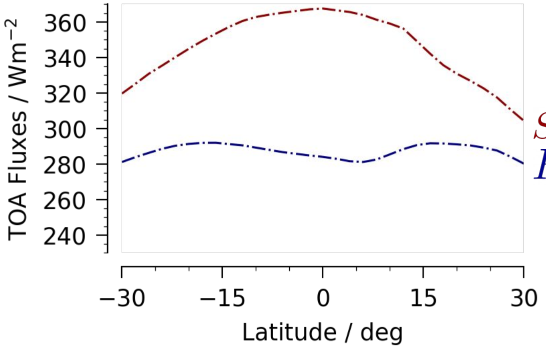

$S^{\downarrow}(1 - \alpha_s)$ $\alpha_s = \frac{S_{cs}^{\uparrow}}{S^{\downarrow}}$

R_{cs}

Validating the two layer model

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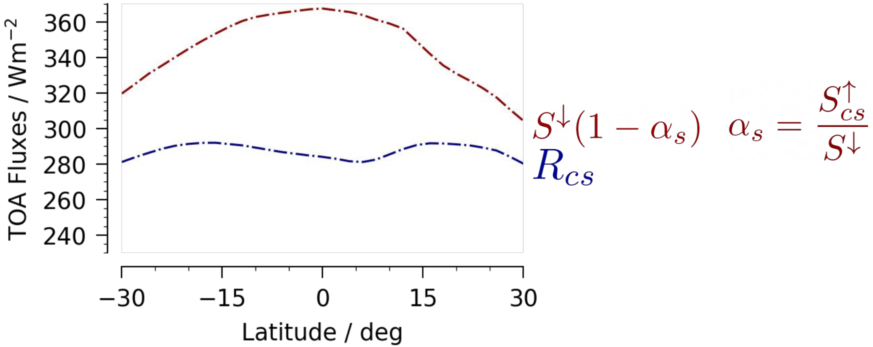

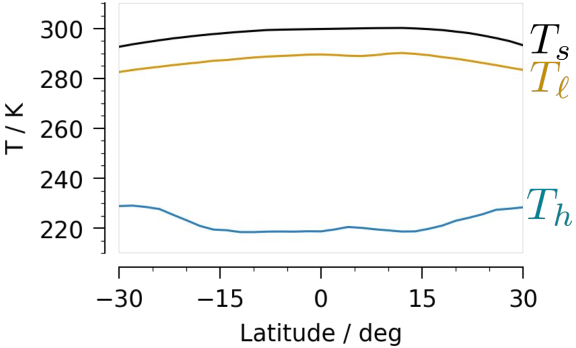

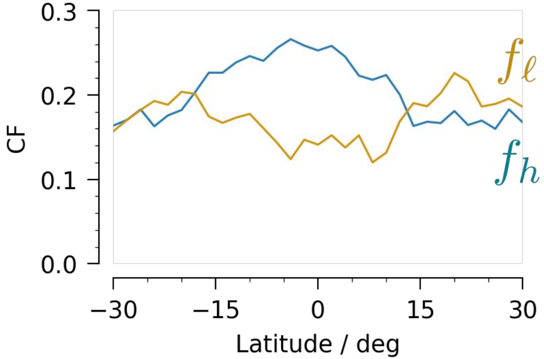

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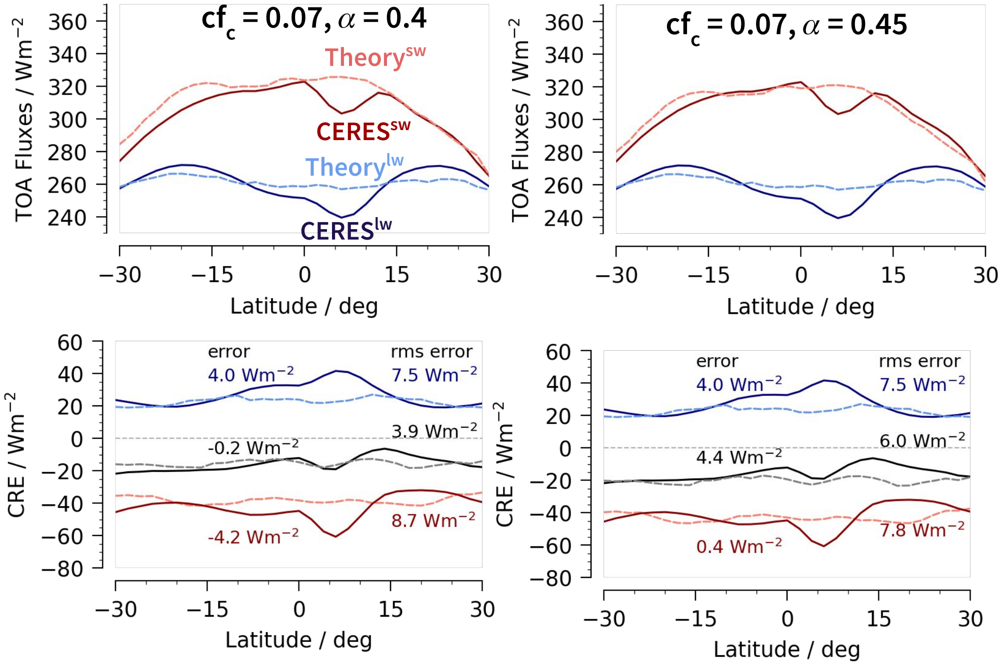
- We don't have cloud albedo data, so we tune it
- Fit albedo to minimize mean CRE error



"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk"

\- John von Neumann

Estimating the tropical mean anvil cloud area feedback

$$\langle\lambda_{\text{iris}}\rangle = \frac{\langle\overline{A_h}\rangle}{\langle\overline{f_h}\rangle}\frac{d\langle f_h\rangle}{d\langle T_s\rangle}\left[\langle\overline{\text{CRE}_h + \lambda_{cs}(T_s - T_\ell)f_\ell f_h + S^{\downarrow}(1-\alpha_s)\alpha_\ell f_\ell \alpha_h f_h}\rangle\right]$$

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0.26 + -0.37 + 1.07

Predicted values

{'**iris_feedback**': **-0.05**
'**cre_h**': **0.26**
'**lowcloud_lw**': **-0.37**
'**lowcloud_sw**': **1.07**
'cf_c': '7'
'albedo': 0.4
'fh_avg': 0.17
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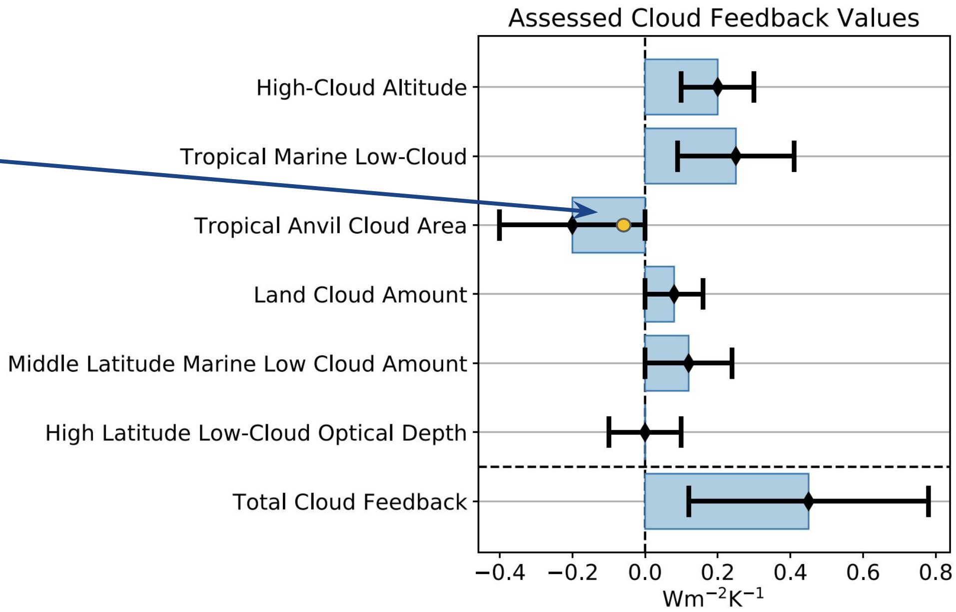

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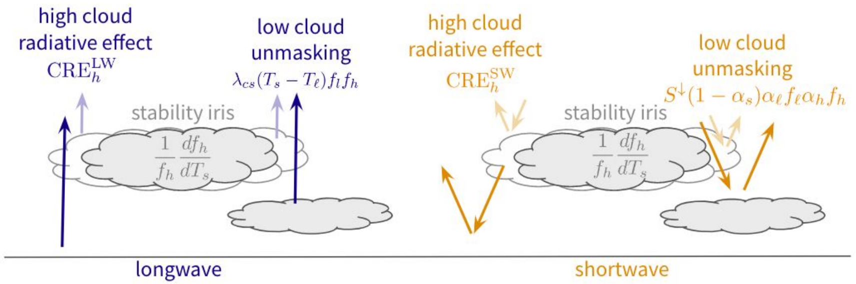

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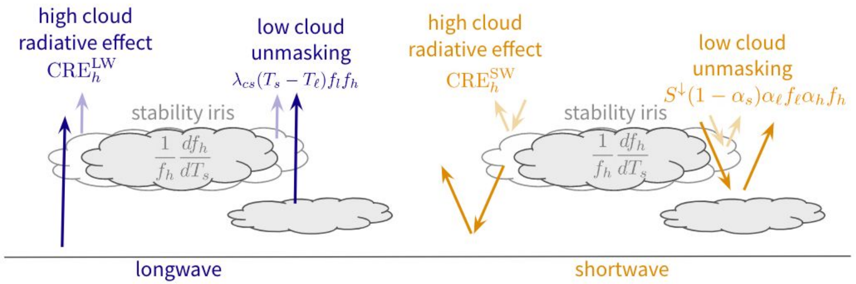


Questions and Follow ups

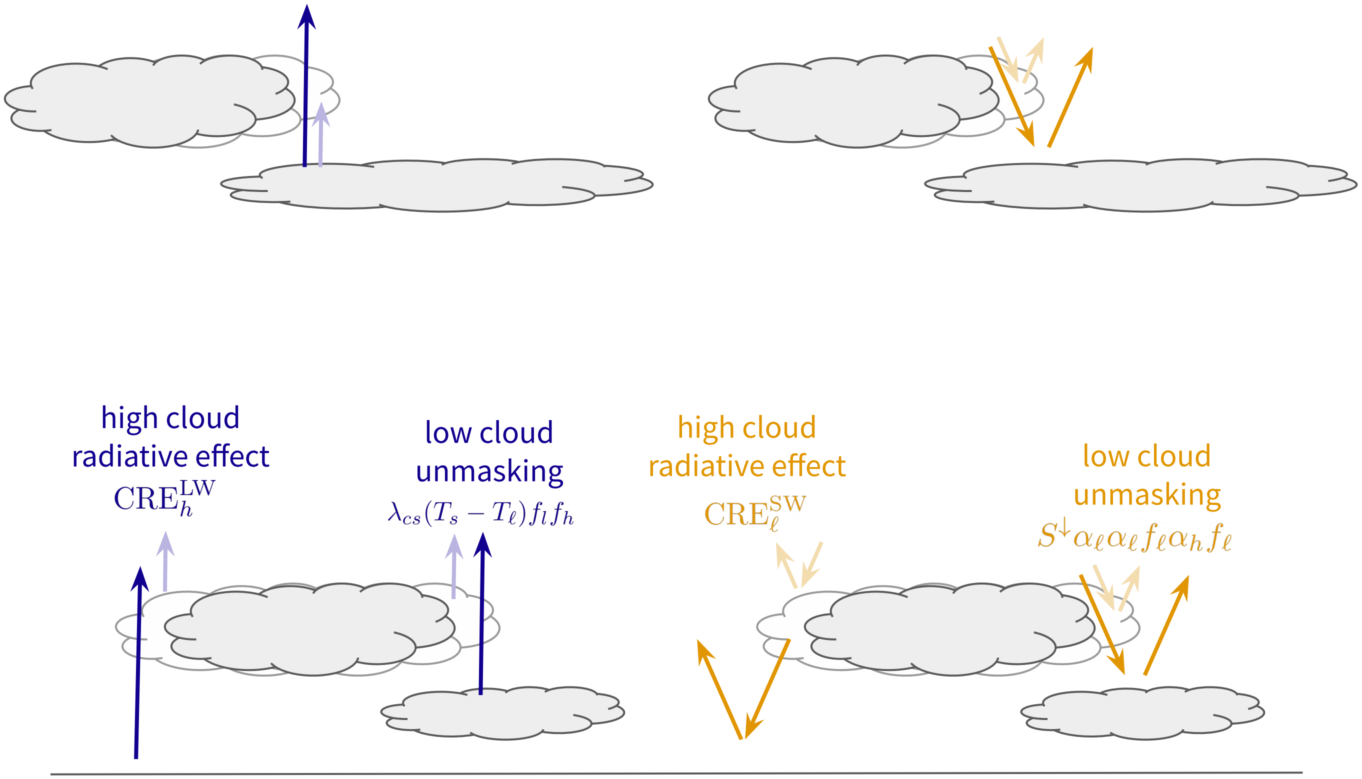
- We miss middle clouds, thin cirrus, etc. Does that matter? Does the optical depth considered matter?
- Error/uncertainty analysis?
- Can we use this model to understand intermodel spread in the anvil area feedback?
- Can we understand why Lindzen et al 2001 thought the feedback was so important?
- Why is CRE_h small in the first place?
- Do low clouds ever matter for the iris feedback?
- Can we understand if the stability iris radiative effect influences low cloud cover or the circulation?

Other directions

- Apply to low clouds feedbacks by distinguish cloud types, introducing cloud-controlling factors, etc.
- Apply to forcings, i.e. “cloud masking” (*a-la* Jeevanjee et al, 2021)
- Motivate a new feedback decompositions that more clearly distinguish clear sky and cloud feedbacks (*a-la* Yoshimori et al, 2020)
- Use to calculate priors more objectively in ECS estimates (by diagnosing the feedbacks from observations)

Thanks to…

- Nicolas, Anna-Lea
- Sandrine, Marion, Jean-Louis, Claudia


high cloud
radiative effect
$\mathrm{CRE}_h^{\mathrm{LW}}$
low cloud
unmasking
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