Observational Constraint On Low-Cloud Feedbacks Suggests Moderate Climate Sensitivity

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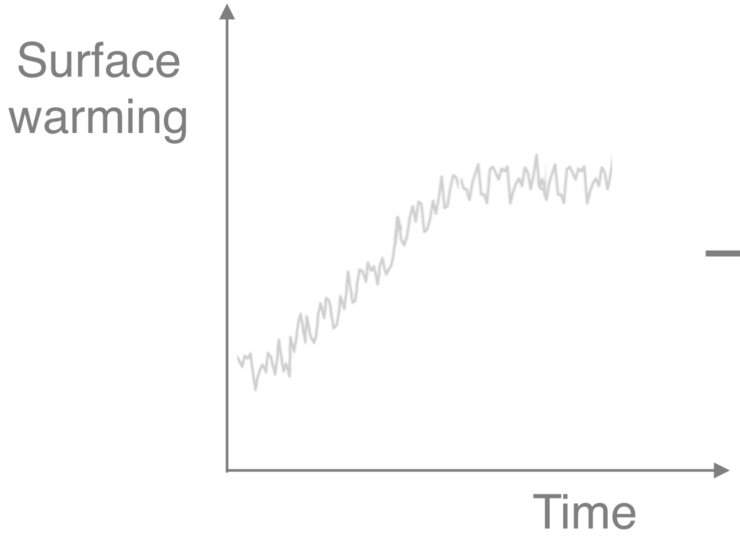
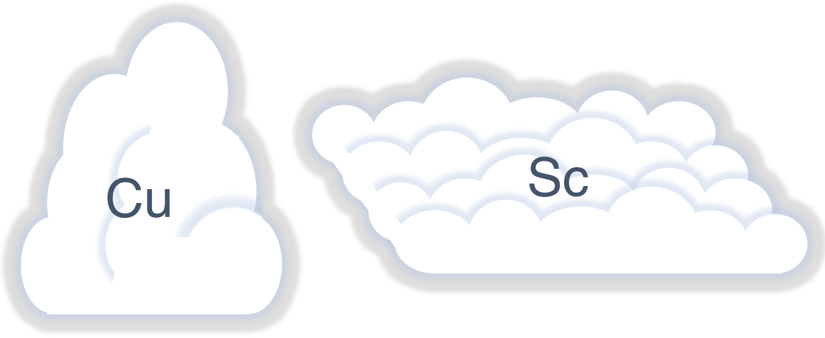


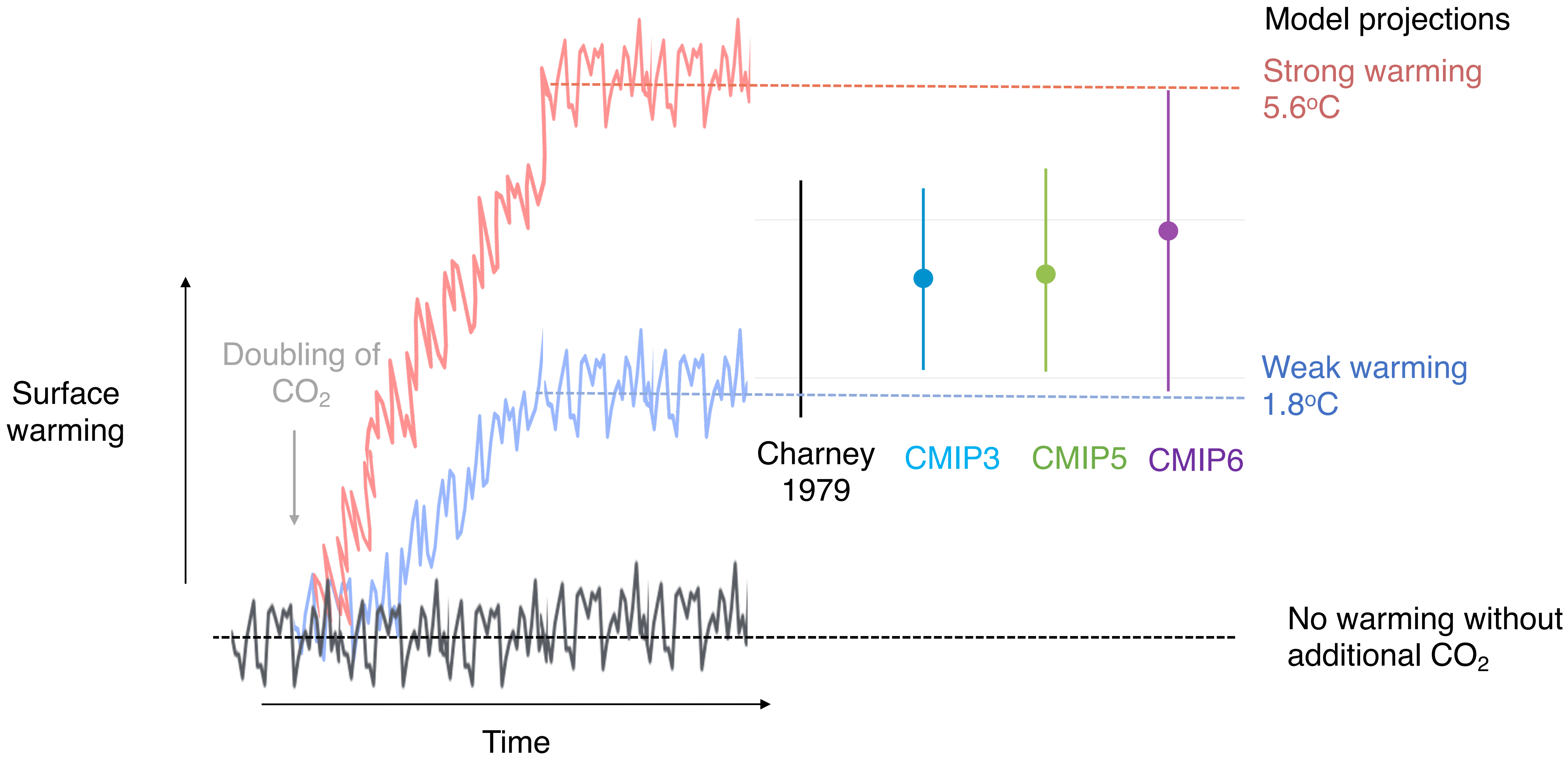
Tropical low-cloud response to global warming (feedback)



Can we observationally constrain this?

Cesana, G. and Del Genio, A. D., (2021), Observational constraint on cloud feedbacks suggests moderate climate sensitivity, Nat. Clim. Change, 11, no. 3, 213-218, doi:10.1038/s41558-020-00970-y.

The surface warming resulting from an hypothetical doubling of CO_2 (**climate sensitivity**) has remained highly uncertain over the past 40 years



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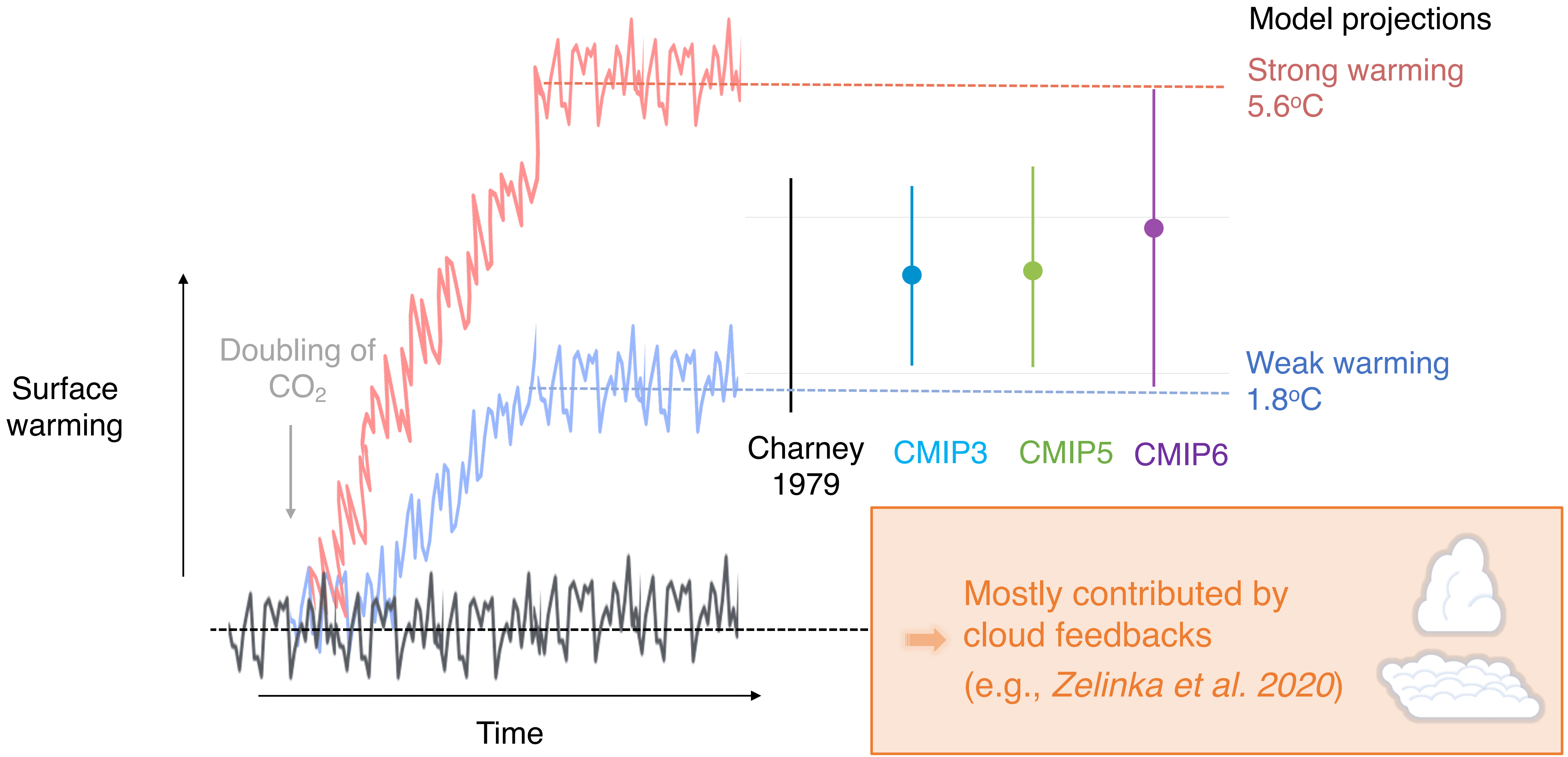

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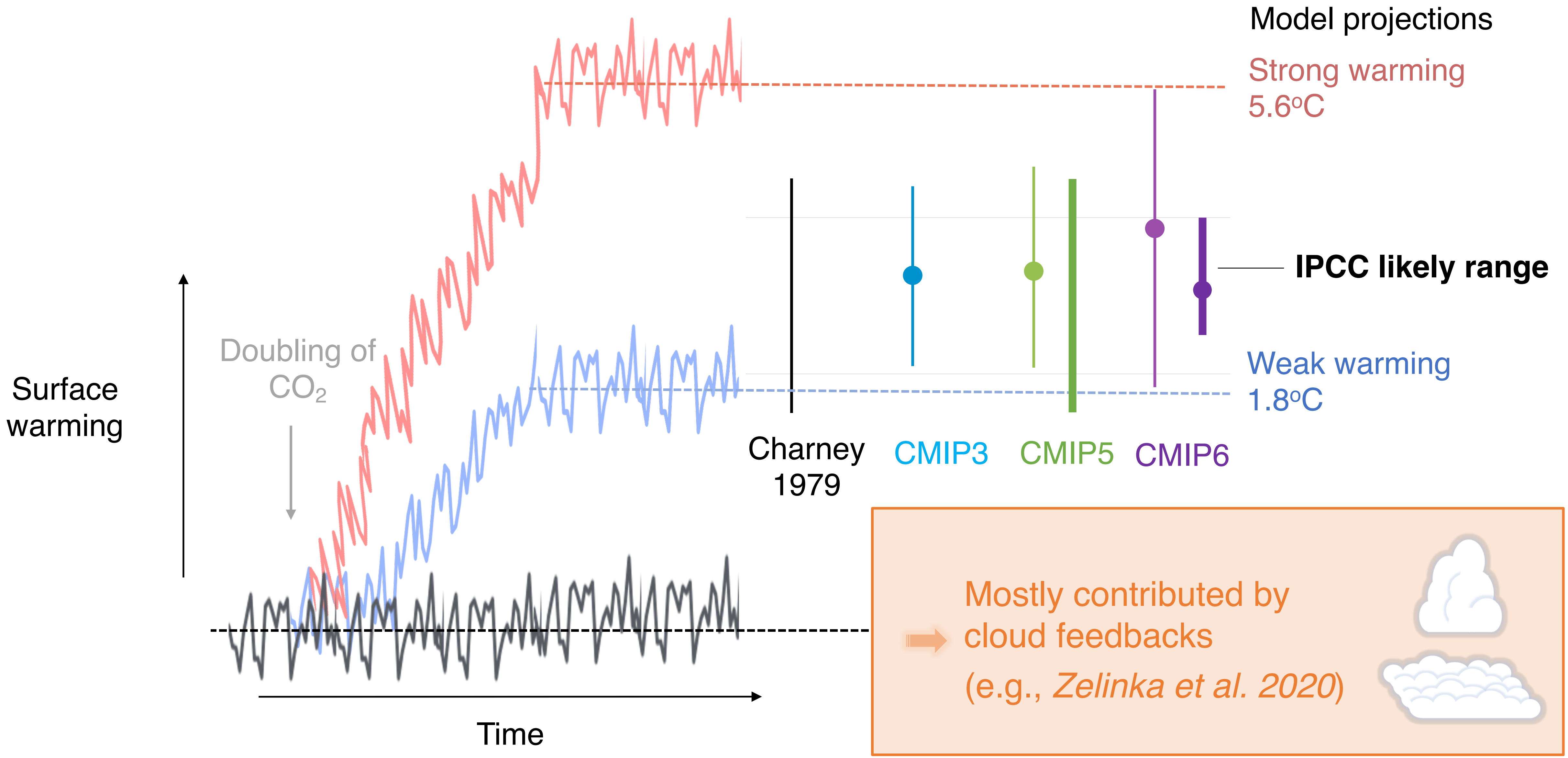
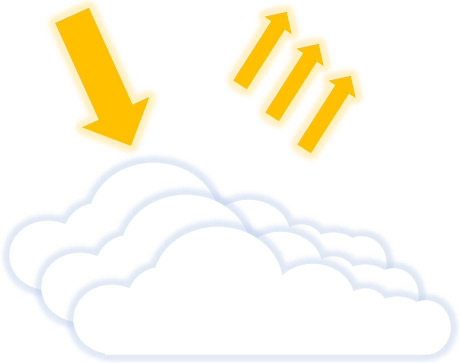


Mostly contributed by cloud feedbacks (e.g., *Zelinka et al. 2020*)

Low clouds cool the Earth by reflecting SW radiation back to space

Cloud Radiative Effect (CRE)

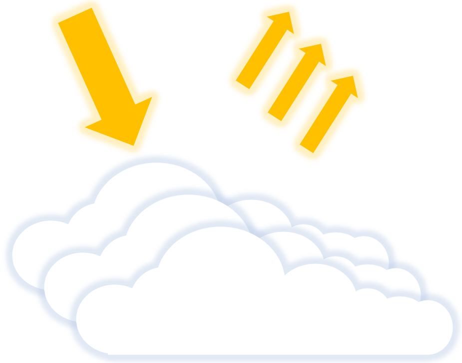


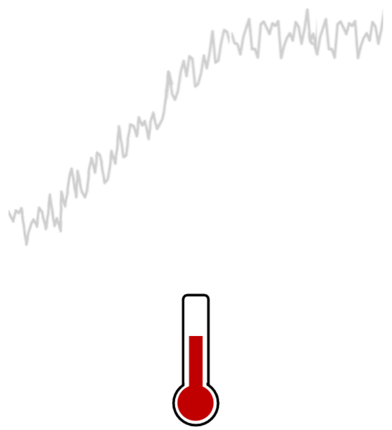
Cooling

In response to global warming…

Cloud Radiative Effect (CRE)

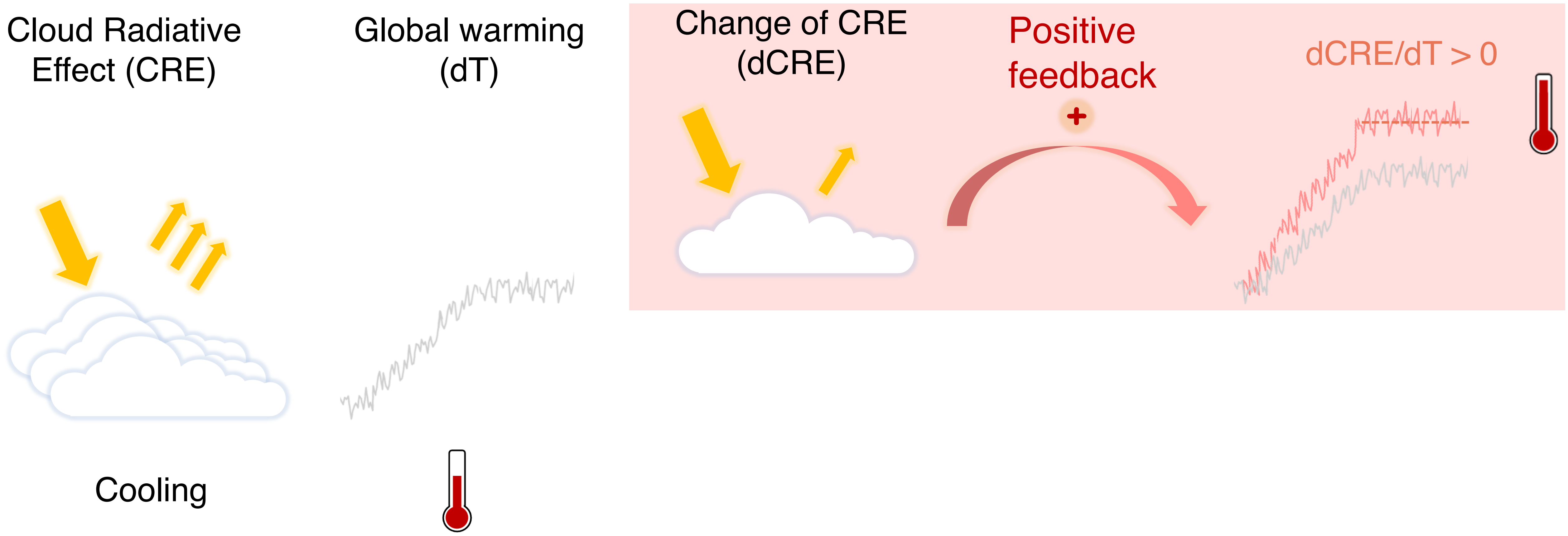
Global warming (dT)



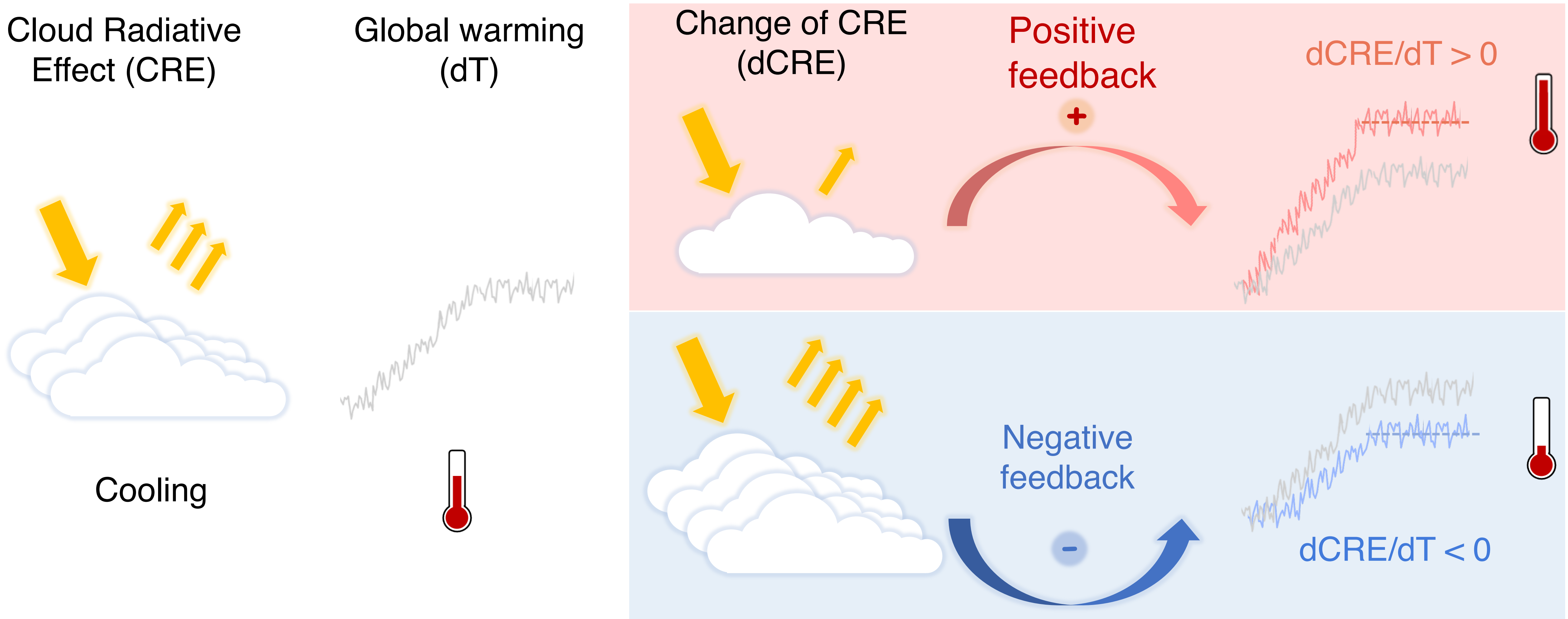


Cooling

In response to global warming…
They may dissipate, resulting in less SW radiation reflection, reinforcing the surface warming through a positive feedback



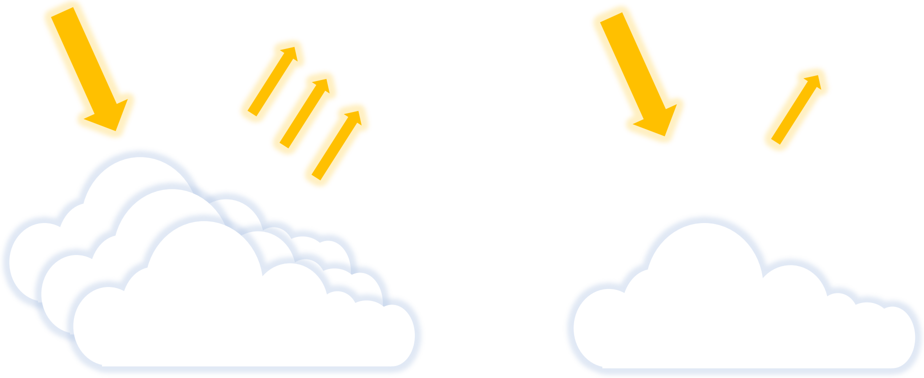
In response to global warming…
They grow larger, resulting in more SW radiation reflection, weakening the surface warming through a negative feedback



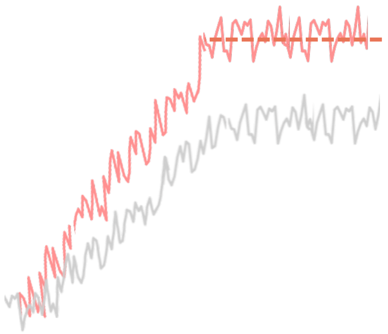
Cloud Feedback (dCRE/dT):
Change of cloud radiative effect at TOA
in response to global surface warming

$$\text{Cloud Feedback} = \frac{d\text{CRE}}{dT}$$

Change of TOA
Cloud Radiative
Effect (CRE)

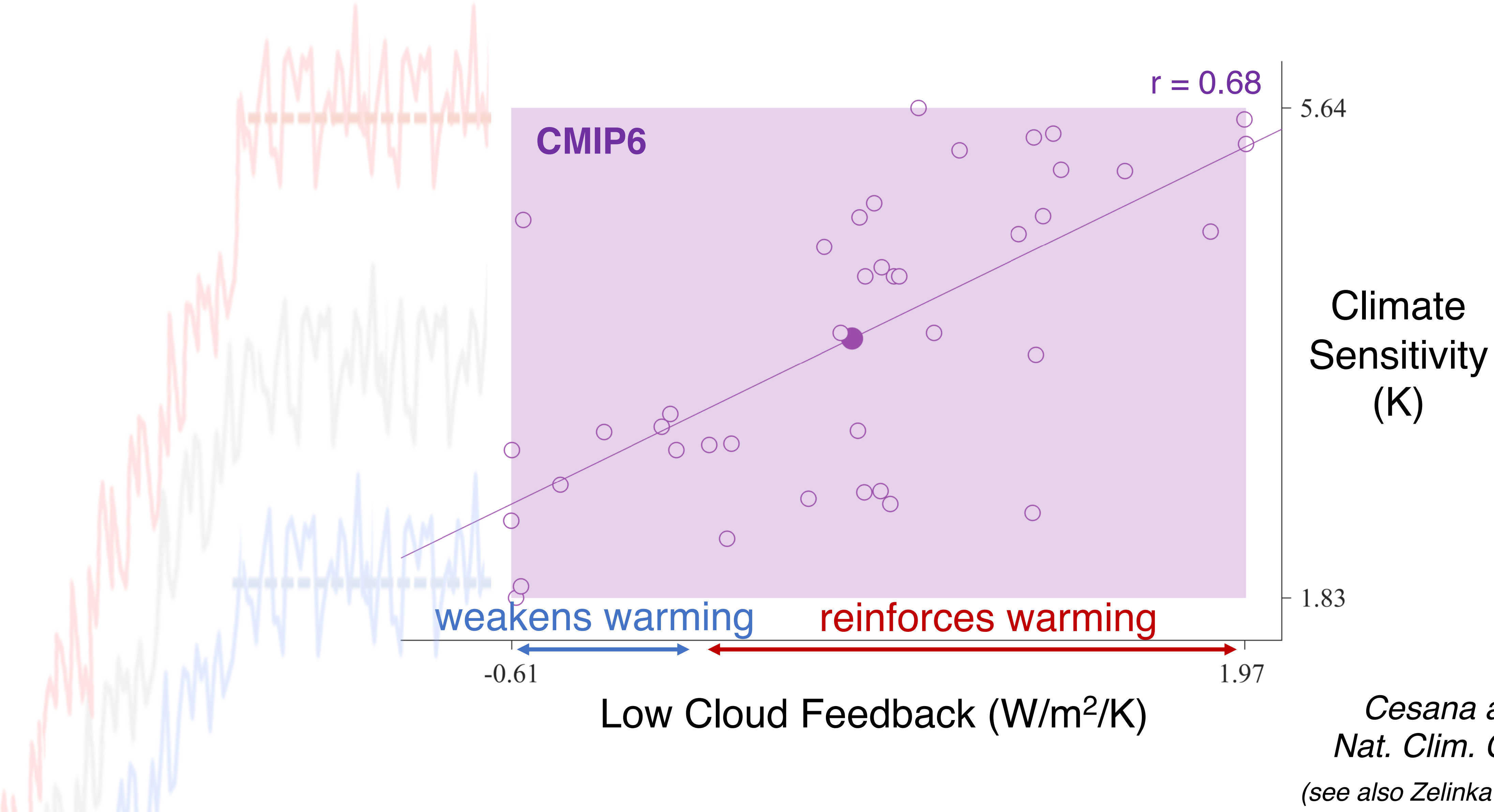


Change of global mean
surface temperature



➔ We focus on the *SW tropical low-cloud feedback*,
referred to as "*cloud feedback*"

SW tropical low-cloud feedback explains a large part of the spread in climate sensitivity

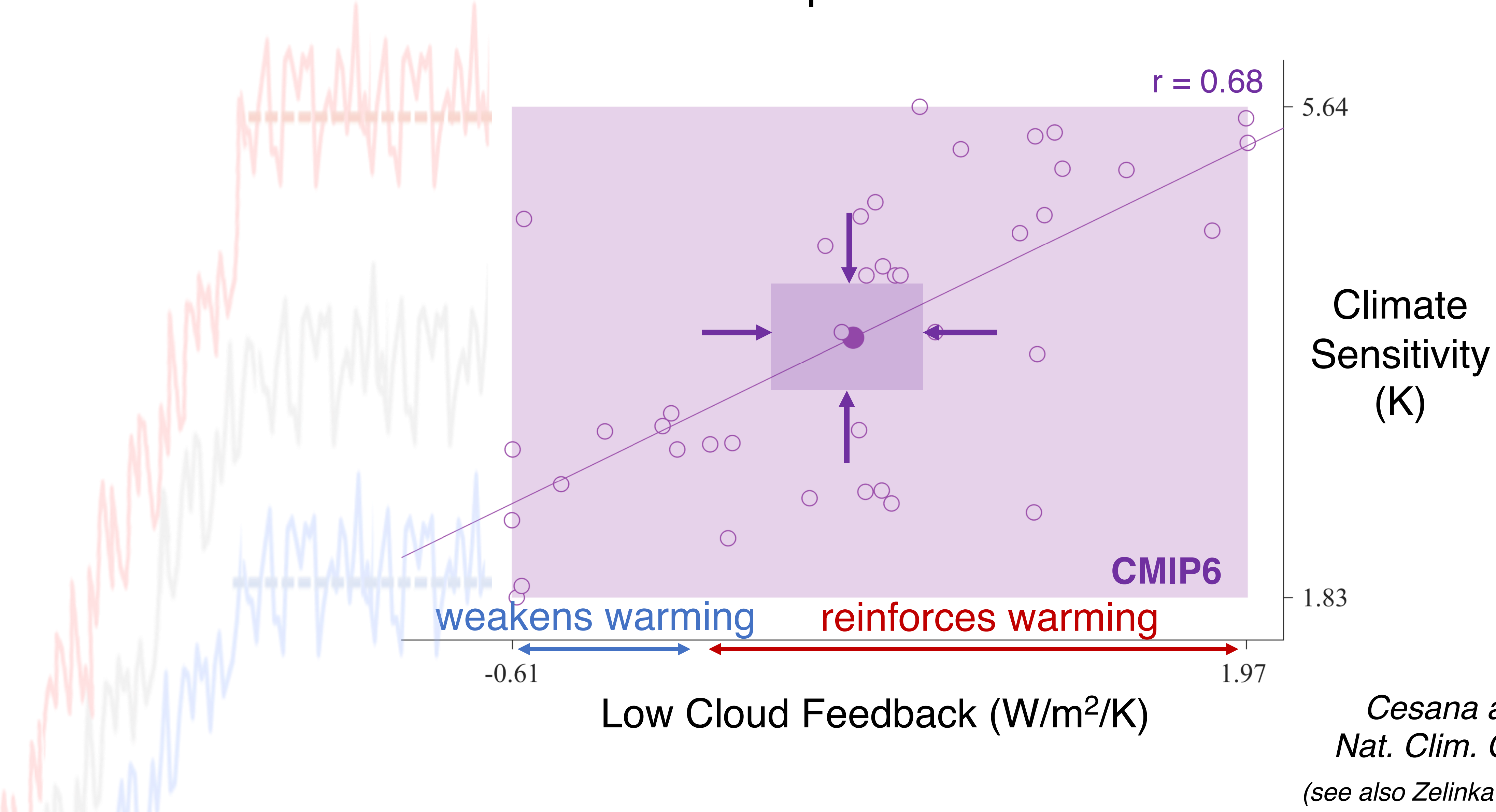


Cesana and Del Genio, Nat. Clim. Change (2021)

(see also Zelinka et al., 2020, 2013)

Objective:

Reducing the uncertainty in low-cloud feedback would reduce its contribution to the spread in ECS



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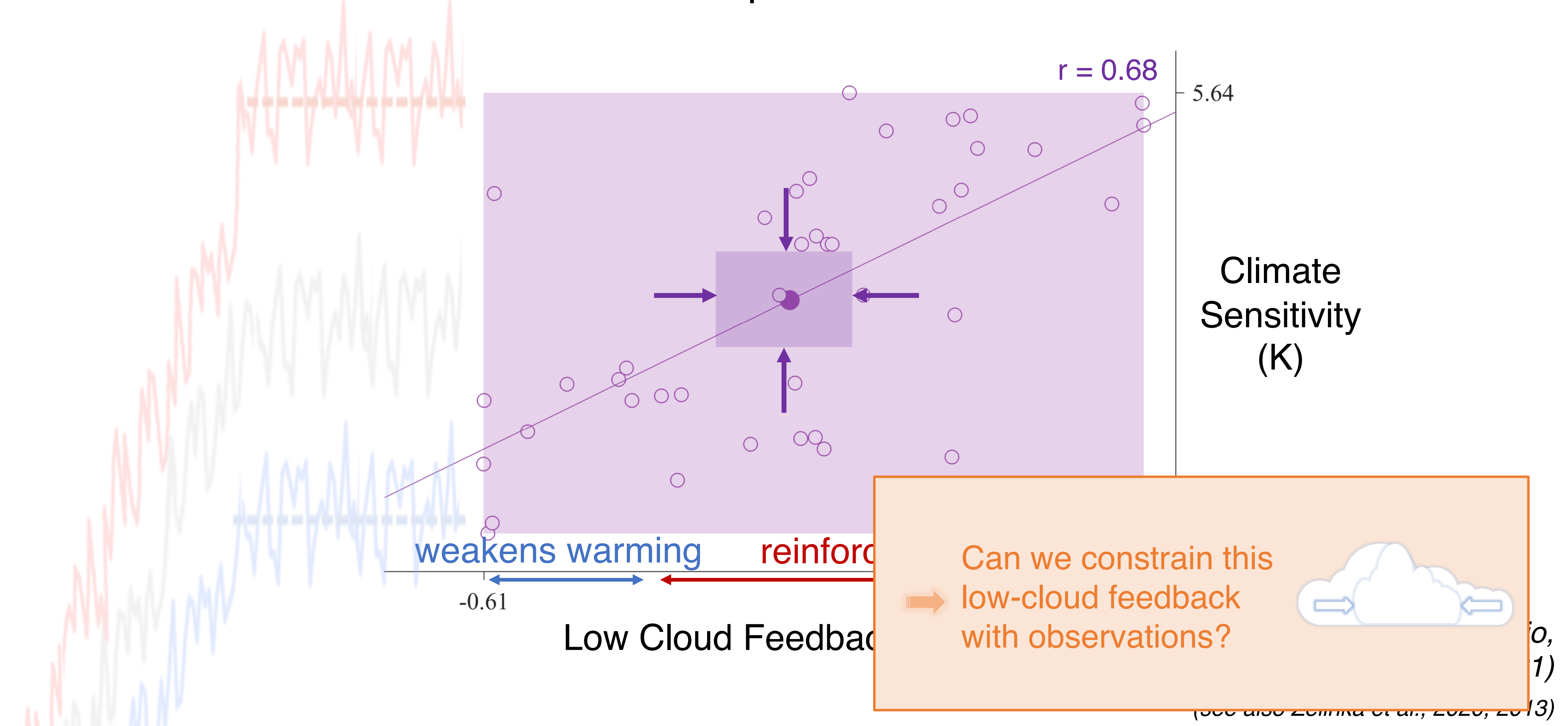


$$\frac{d\mathrm{CRE}}{dT} = ?$$

➡ Estimating the cloud feedback from observations is challenging because the satellite record is too short

The cloud feedback is linearly correlated with the change in low cloud cover (in subsidence regime)

$$\frac{d\mathrm{CRE}}{dT} = a\,\frac{d\mathrm{LCC}}{dT}$$

Sensitivity of CRE to low clouds (~ -1 W/m^2/%)

Change of low clouds in response to warming

LCC: low cloud cover

T: global mean surface temperature

The change of low clouds results from changes in low-cloud predictors (x) multiplied by the sensitivity of low-clouds to their predictors

$$\frac{d\mathrm{CRE}}{dT} = a\,\frac{d\mathrm{LCC}}{dT}$$

$$\frac{d\mathrm{LCC}}{dT} = \sum_i \frac{\partial \mathrm{LCC}}{\partial x_i}\,\frac{d\mathrm{x_i}}{dT}$$

x_i: low-cloud predictors
(aka controlling factors)

Sensitivity of low clouds to predictors

Change of low-cloud predictors in response to warming

e.g. Qu et al. (2015)

The SST and the inversion strength control the future change of low clouds

$$\frac{d\mathrm{CRE}}{dT} = a\,\frac{d\mathrm{LCC}}{dT}$$

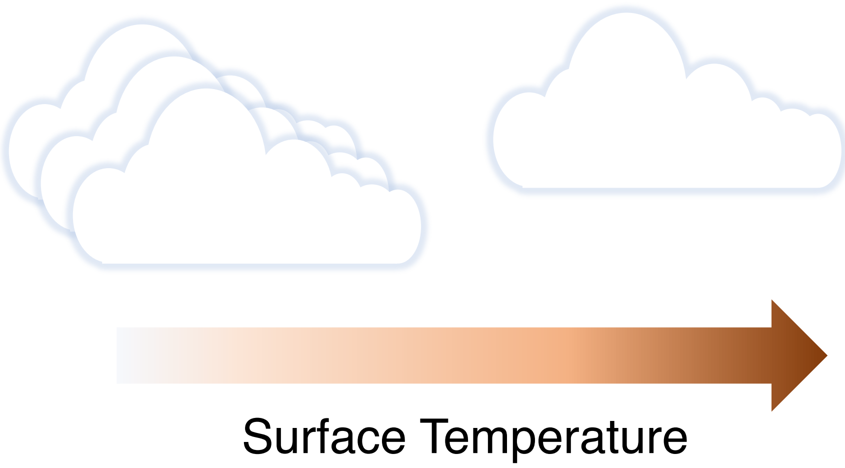
$$\frac{dLCC}{dT} = \left(\frac{\partial LCC}{\partial SST}\,\frac{dSST}{dT} + \frac{\partial LCC}{\partial EIS}\,\frac{dEIS}{dT}\right)$$

x: SST and EIS

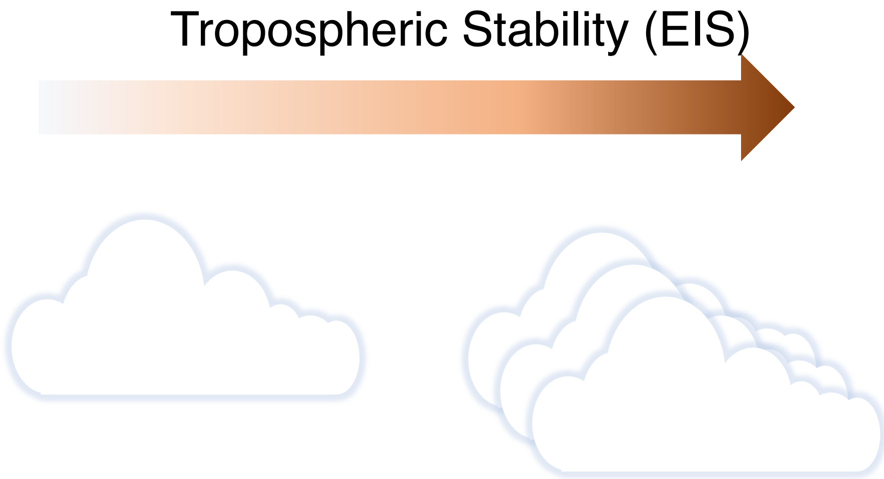
Sea surface temperature

Inversion strength

High SSTs reduces the low cloud cover while high stability (EIS) increases it



Higher SSTs promote mixing
with the drier free troposphere
➔ **Cloud decrease**



High stability reduces mixing
with the drier free troposphere
➔ **Cloud increase**

Cloud feedback can be inferred from (low cloud) observations

$$\frac{dCRE}{dT} = a\frac{dLCC}{dT}$$

$$\frac{dLCC}{dT} = \sum_i \frac{\partial LCC}{\partial x_i}\frac{dx_i}{dT}$$

$$\frac{dLCC}{dT} = \left(\frac{\partial LCC}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC}{\partial EIS}\frac{dEIS}{dT}\right)$$

$$\frac{dCRE}{dT} = a\left(\frac{\partial LCC}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC}{\partial EIS}\frac{dEIS}{dT}\right)$$

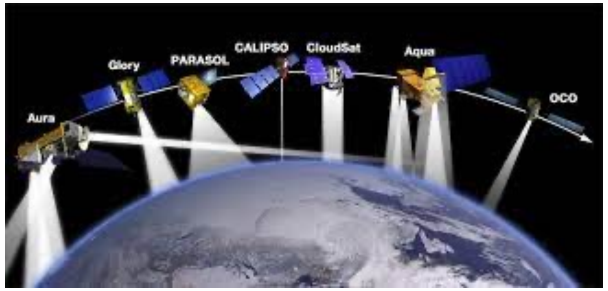
Inferred Feedback

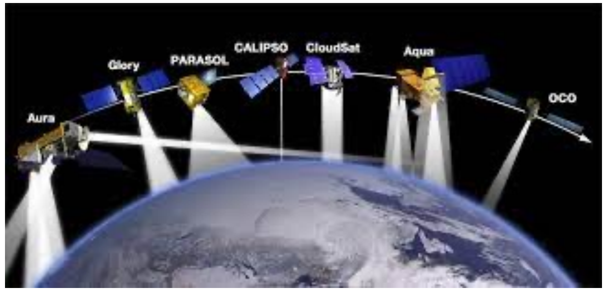
Cloud feedback can be inferred from (low cloud) observations

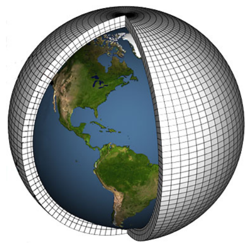
$$\frac{d\mathrm{CRE}}{dT} = a\left(\frac{\partial\mathrm{LCC}}{\partial SST}\frac{d\mathrm{SST}}{dT} + \frac{\partial\mathrm{LCC}}{\partial EIS}\frac{d\mathrm{EIS}}{dT}\right)$$

Cloud sensitivity to predictors

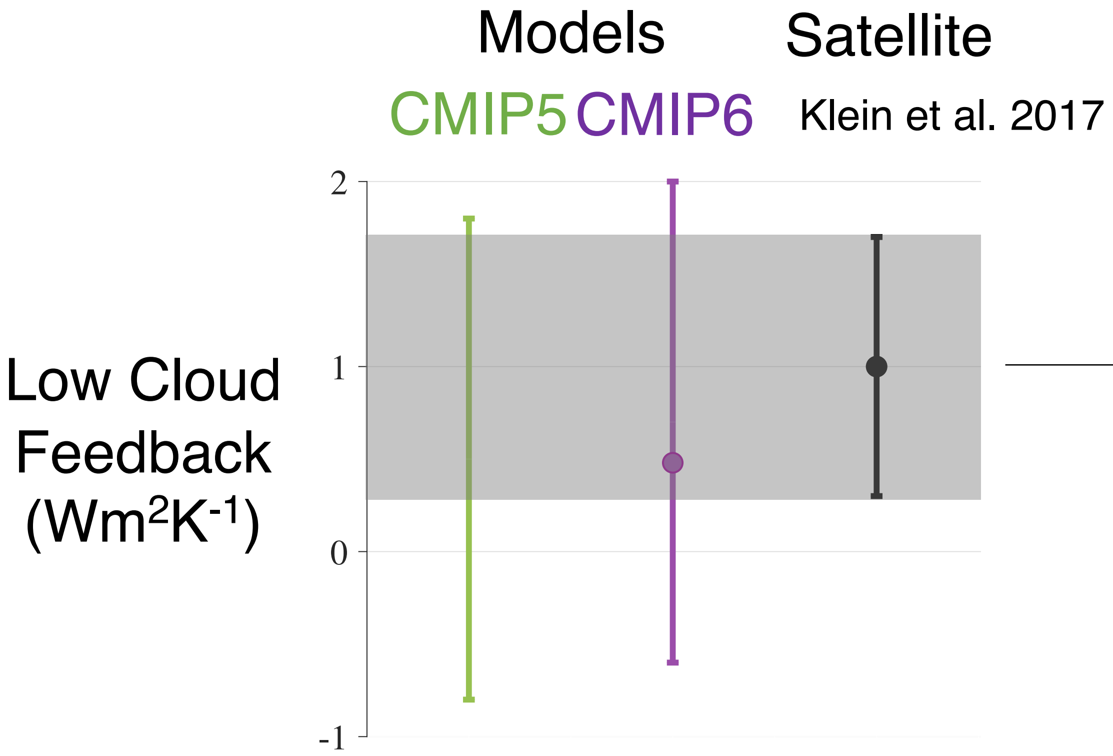
Predictor changes



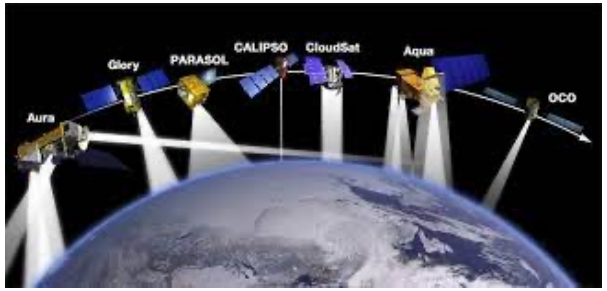




This method provides some good observational constraint on climate models but the uncertainty is still quite high



$$\frac{d\mathrm{CRE}}{dT} = a\left(\frac{\partial \mathrm{LCC}}{\partial SST}\frac{dSST}{dT} + \frac{\partial \mathrm{LCC}}{\partial EIS}\frac{dEIS}{dT}\right)$$



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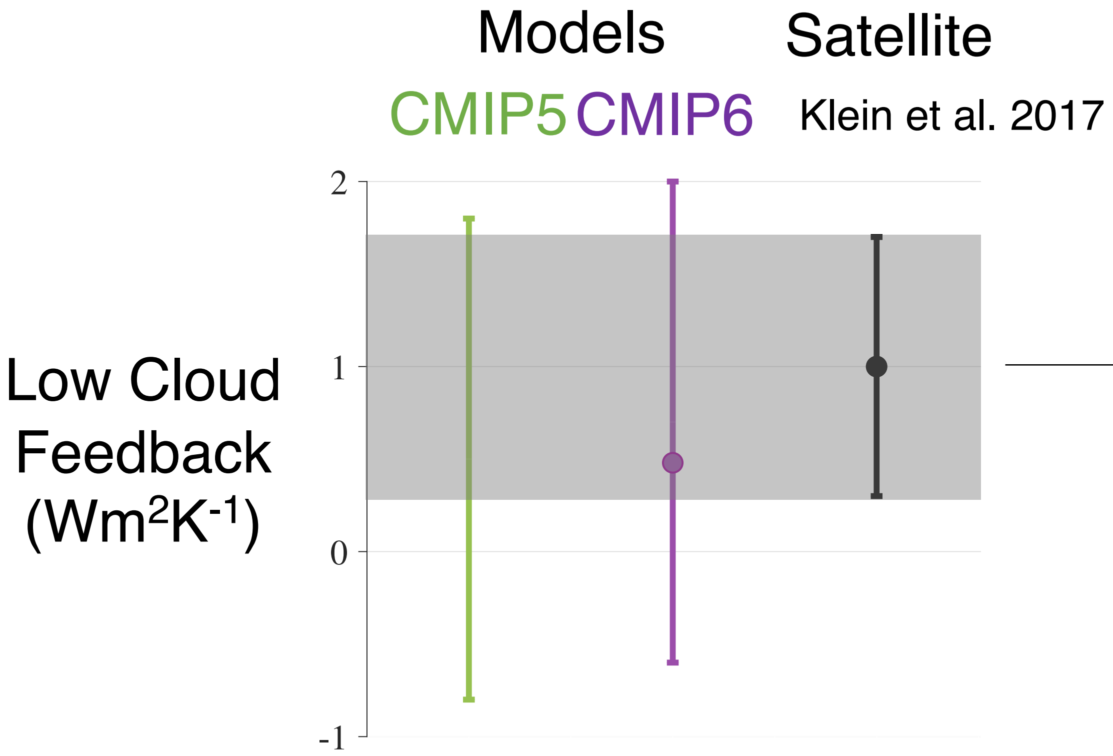


$$\frac{d\mathrm{CRE}}{dT} = a\left(\frac{\partial \mathrm{LCC}}{\partial SST}\frac{d\mathrm{SST}}{dT} + \frac{\partial \mathrm{LCC}}{\partial EIS}\frac{d\mathrm{EIS}}{dT}\right)$$

➡ 2 shortcomings need to be addressed in this method

1. The contribution of Sc and Cu must be accounted for separately

$$\frac{dCRE_{Sc}}{dSST} \neq \frac{dCRE_{Cu}}{dSST}$$

Bretherton et al. (2015); Cesana et al., (2019)

$$\frac{dCRE}{dT} = \frac{dCRE_{Sc}}{dLCC_{Sc}}\left(\frac{\partial LCC_{Sc}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Sc}}{\partial EIS}\frac{dEIS}{dT}\right) + \frac{dCRE_{Cu}}{dLCC_{Cu}}\left(\frac{\partial LCC_{Cu}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Cu}}{\partial EIS}\frac{dEIS}{dT}\right)$$

2. Each cloud-type feedback depends on the relative presence of the cloud type

If no Sc or Cu then $\frac{dCRE_{Sc\ or\ Cu}}{dT} \approx 0$

presence ratio

$$\frac{dCRE}{dT} = \frac{dCRE_{Sc}}{dLCC_{Sc}}\left(\frac{\partial LCC_{Sc}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Sc}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Sc}}{LCC}$$

$$+\frac{dCRE_{Cu}}{dLCC_{Cu}}\left(\frac{\partial LCC_{Cu}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Cu}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Cu}}{LCC}$$

Can we determine each term of the equation using observations?

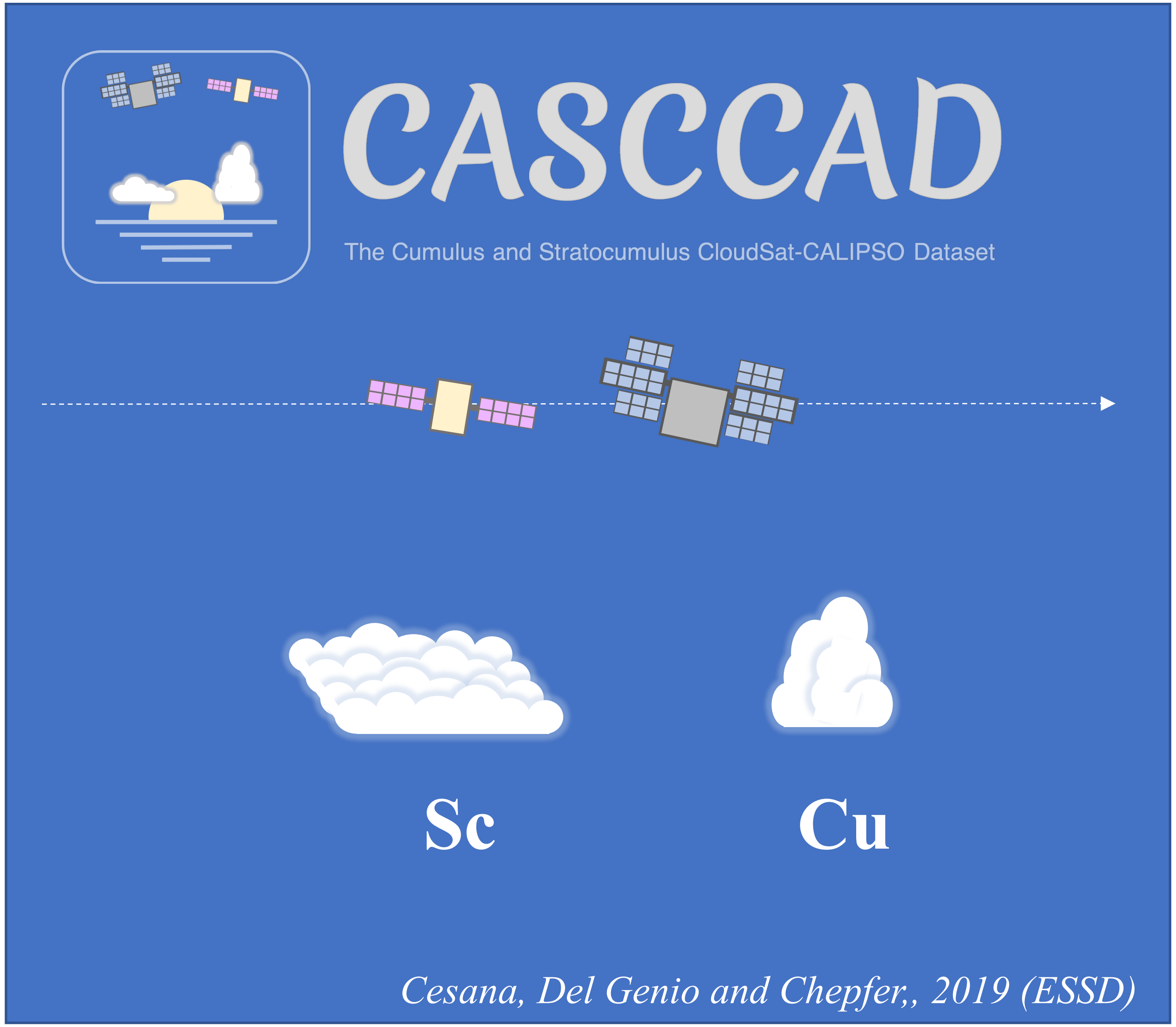
$$\frac{dCRE}{dT} = \frac{dCRE_{Sc}}{dLCC_{Sc}}\left(\frac{\partial LCC_{Sc}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Sc}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Sc}}{LCC}$$

$$+ \frac{dCRE_{Cu}}{dLCC_{Cu}}\left(\frac{\partial LCC_{Cu}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Cu}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Cu}}{LCC}$$

➡ Need Cu – Sc observations

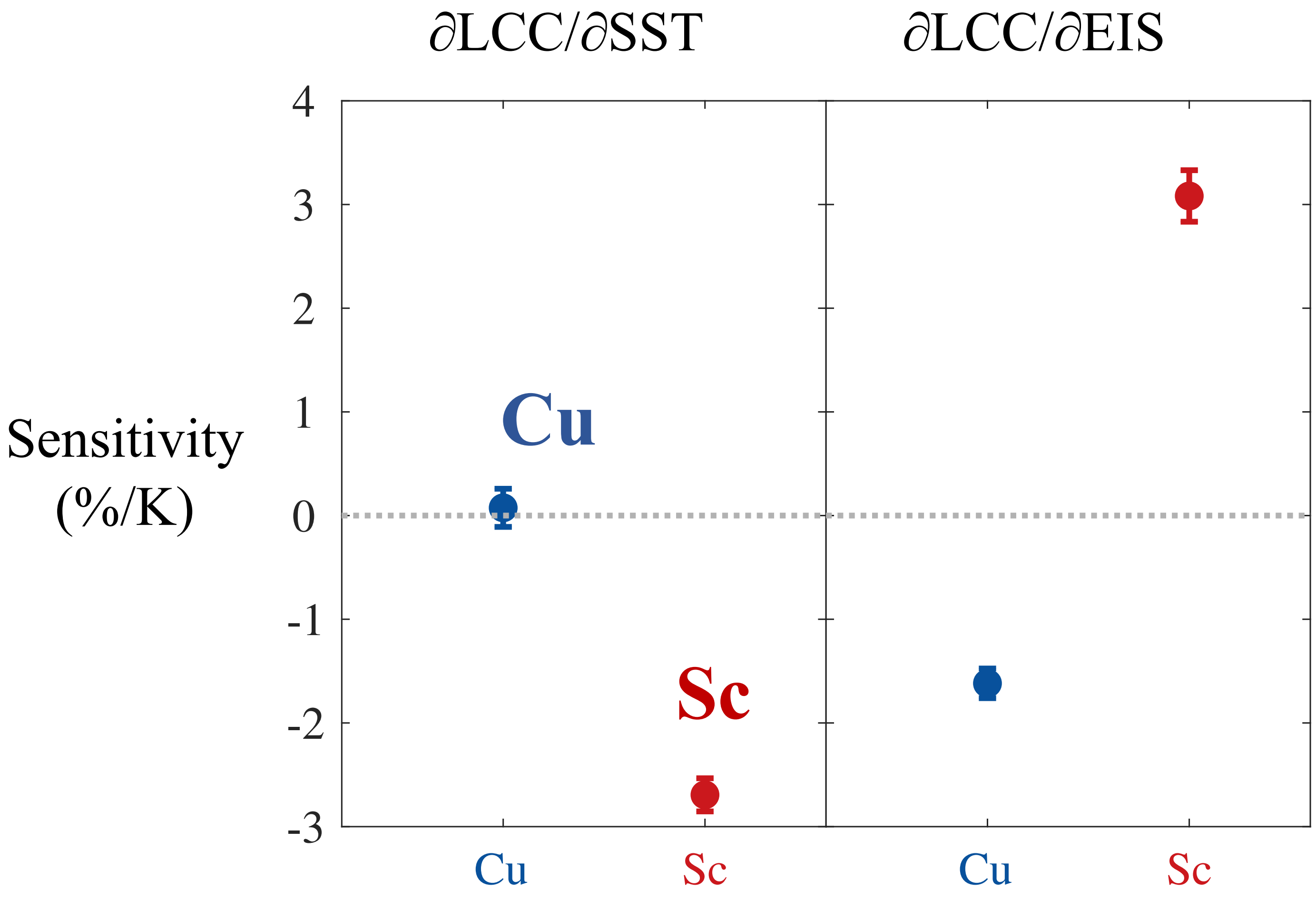
The Cumulus and Stratocumulus CloudSat-CALIPSO Dataset

- Detects Sc, Cu and transitioning clouds at orbital level
- Method based on morphology
- More than 10 years of data



Shortcoming 1: Different sensitivities of Sc and Cu

We demonstrate that Sc clouds are more sensitive than Cu to predictors



$$\frac{\partial LCCSc}{\partial x} \neq \frac{\partial LCCCu}{\partial x}$$

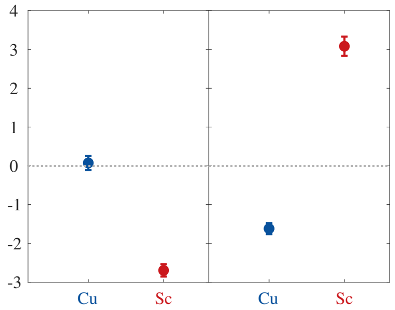
Cesana and Del Genio, Nat. Clim. Change (2021)

We determine each of the terms using observations

$$\frac{dCRE}{dT} = \frac{dCRE_{Sc}}{dLCC_{Sc}}\left(\frac{\partial LCC_{Sc}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Sc}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Sc}}{LCC}$$

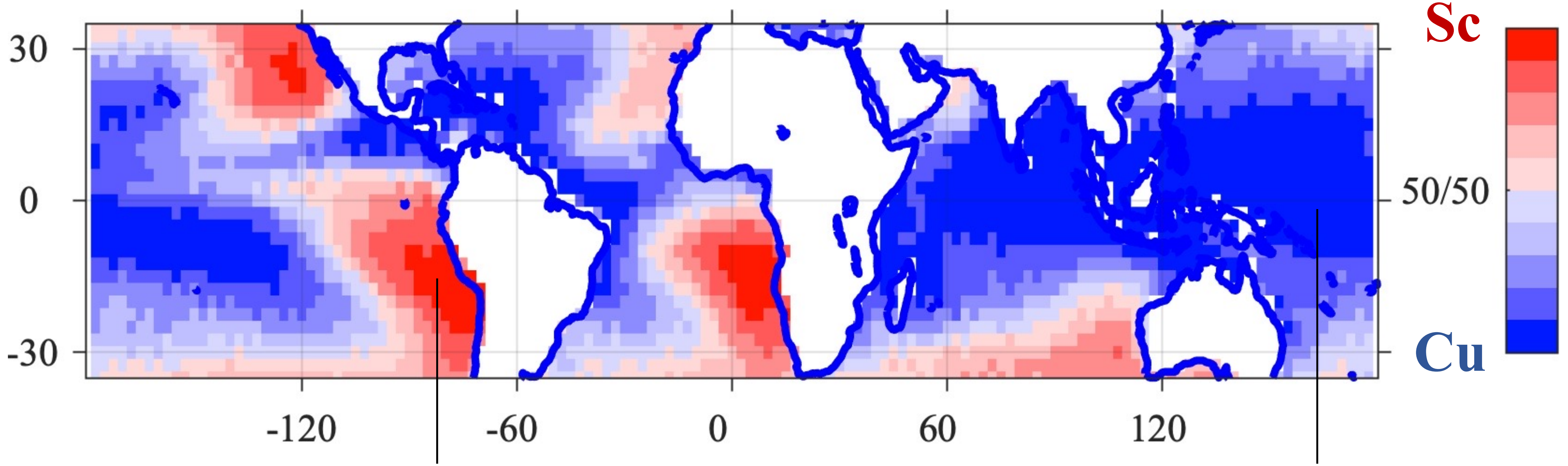
$$+ \frac{dCRE_{Cu}}{dLCC_{Cu}}\left(\frac{\partial LCC_{Cu}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Cu}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Cu}}{LCC}$$

Sensitivity of Sc and Cu to SST and EIS



Shortcoming 2: Different relative presence of Sc and Cu

We demonstrate that Sc and Cu clouds are spatially well separated



$\frac{LCC_{Cu}}{LCC} = 0$ ➔ No Cu feedback expected

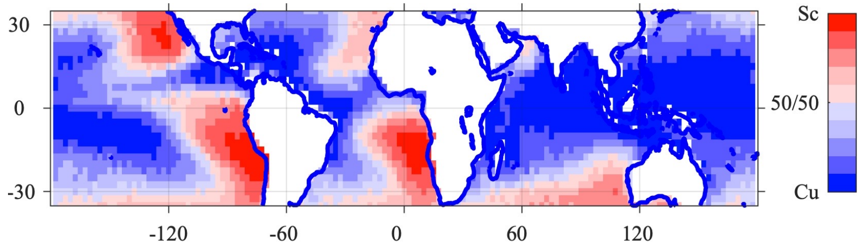
$\frac{LCC_{Sc}}{LCC} = 0$ ➔ No Sc feedback expected

We determine each of the terms using observations

$$\frac{dCRE}{dT} = \frac{dCRE_{Sc}}{dLCC_{Sc}}\left(\frac{\partial LCC_{Sc}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Sc}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Sc}}{LCC}$$

$$+ \frac{dCRE_{Cu}}{dLCC_{Cu}}\left(\frac{\partial LCC_{Cu}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Cu}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Cu}}{LCC}$$

Presence ratio for each cloud type



We determine each of the terms using observations and reanalysis

$$\frac{dCRE}{dT} = \frac{dCRE_{Sc}}{dLCC_{Sc}}\left(\frac{\partial LCC_{Sc}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Sc}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Sc}}{LCC}$$

$$+ \frac{dCRE_{Cu}}{dLCC_{Cu}}\left(\frac{\partial LCC_{Cu}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Cu}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Cu}}{LCC}$$

Change of SST and EIS in response to warming

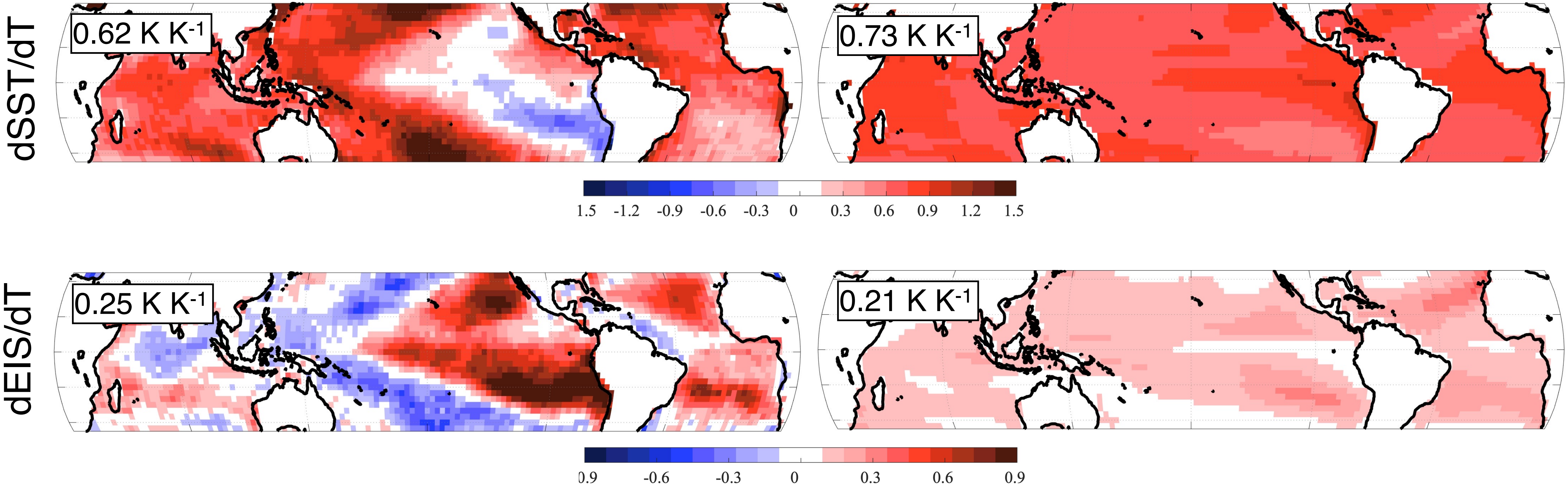
→ Can be determined from:

- historical trends using the past few decades
- simulated future warming from CMIP6 models

Observed historical trends are different from simulated future changes *(yet all positive)*

Observed historical trend (1979-2018)

Simulated future change (4xCO2 - piC)



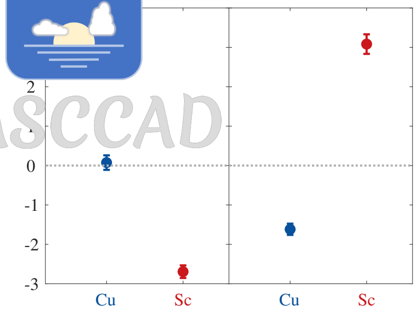
→ <u>Consider two scenarios</u>

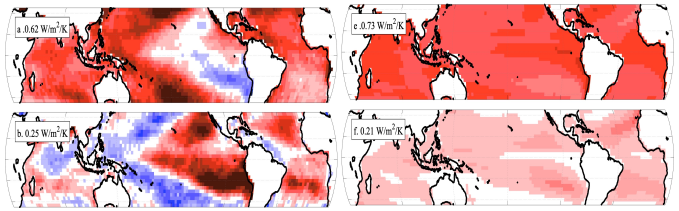
We have determined each of the terms using observations and reanalysis

$$\frac{dCRE}{dT} = \frac{dCRE_{Sc}}{dLCC_{Sc}}\left(\frac{\partial LCC_{Sc}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Sc}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Sc}}{LCC}$$

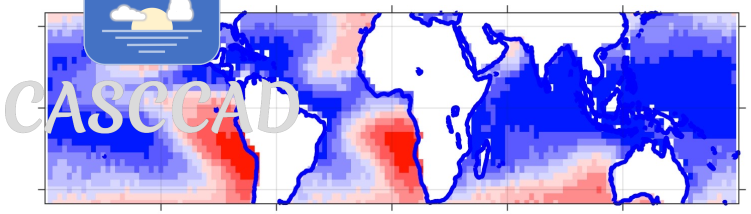
$$+ \frac{dCRE_{Cu}}{dLCC_{Cu}}\left(\frac{\partial LCC_{Cu}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Cu}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Cu}}{LCC}$$

CASCCAD
+ CERES





Observations/Reanalyses or CMIP models



We have determined each of the terms using observations and reanalysis

$$\frac{dCRE}{dT} = \frac{dCRE_{Sc}}{dLCC_{Sc}}\left(\frac{\partial LCC_{Sc}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Sc}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Sc}}{LCC}$$

$$+ \frac{dCRE_{Cu}}{dLCC_{Cu}}\left(\frac{\partial LCC_{Cu}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Cu}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Cu}}{LCC}$$

CASCCAD
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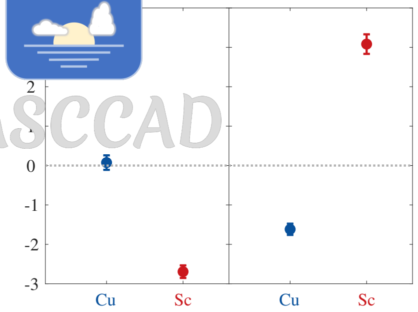
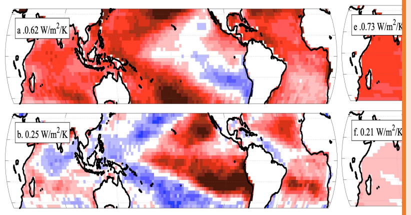
CASCCAD





Observations/R

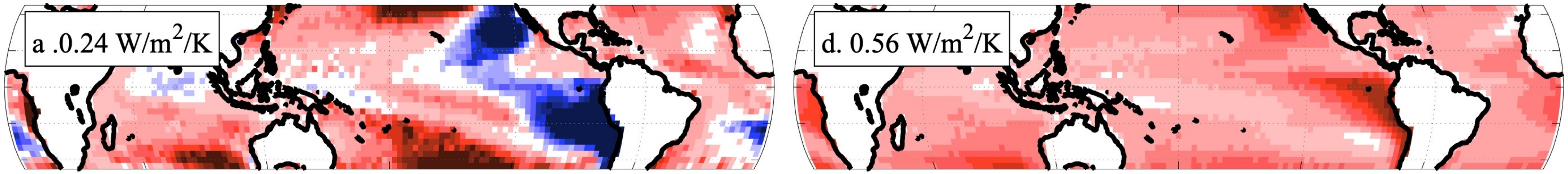
or CMIP m

We can now infer an estimate of the low cloud feedback using observations

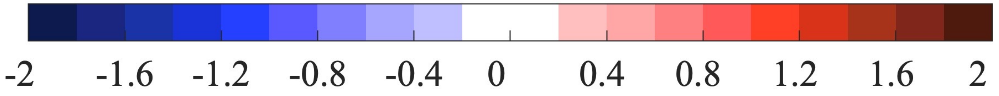
The inferred feedback is 2.3 times smaller using the historical scenario…

dSST/dT
dEIS/dT
from observed historical trend
from simulated future change

Total

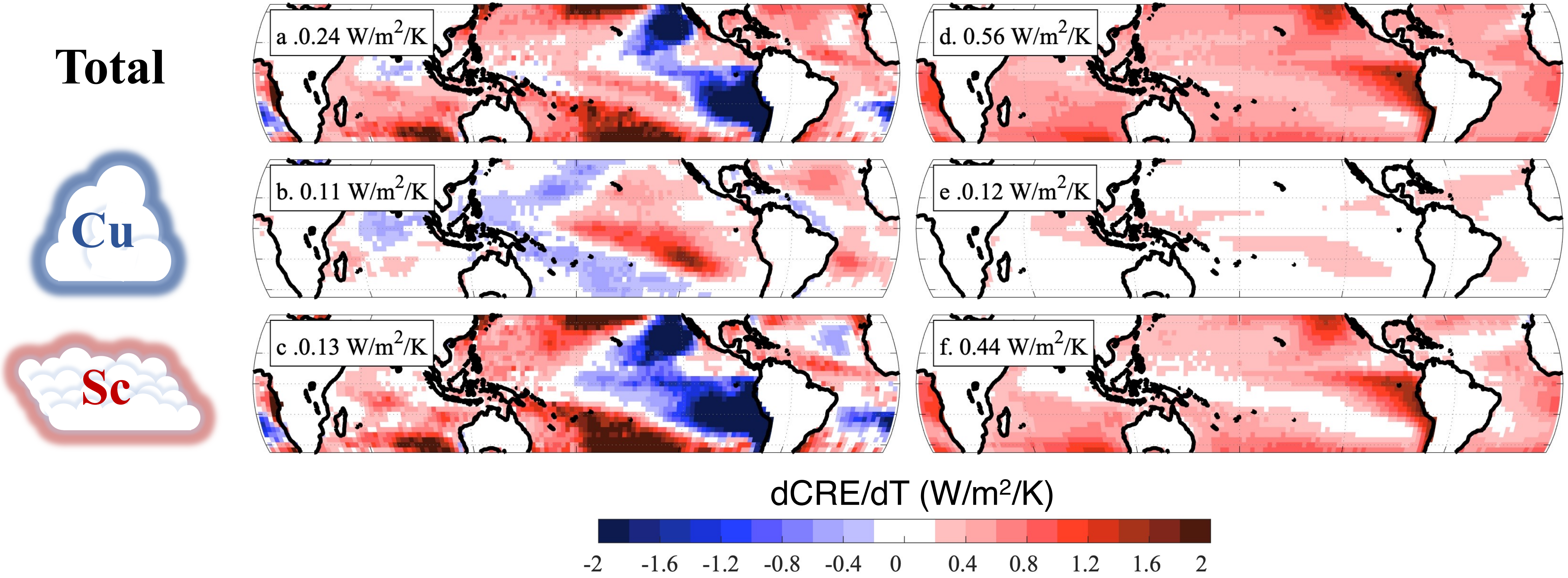


dCRE/dT (W/m²/K)



The inferred feedback is 2.3 times smaller using the historical scenario… and comes from Sc clouds

$\frac{dSST/dT}{dEIS/dT}$ from observed historical trend | from simulated future change

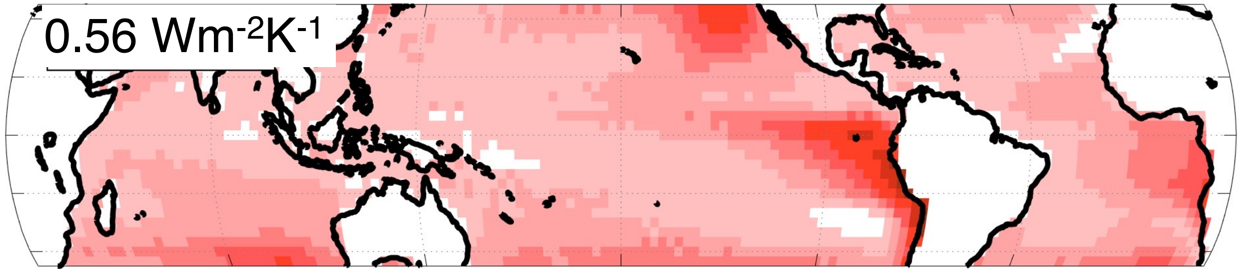


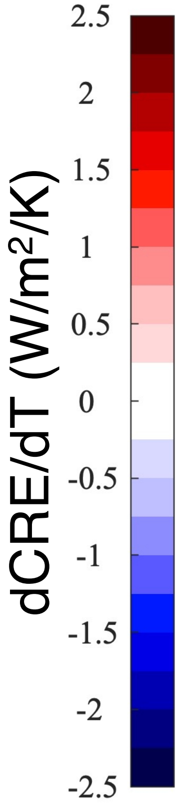
How does the future-scenario inferred feedback compare with the low- and high-ECS CMIP6 feedbacks?

Observationally

Inferred feedback

(using dSST/dT & dEIS/dT from simulated future change)





$$\frac{dCRE}{dT} = \frac{dCRE_{Sc}}{dLCC_{Sc}}\left(\frac{\partial LCC_{Sc}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Sc}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Sc}}{LCC} + \frac{dCRE_{Cu}}{dLCC_{Cu}}\left(\frac{\partial LCC_{Cu}}{\partial SST}\frac{dSST}{dT} + \frac{\partial LCC_{Cu}}{\partial EIS}\frac{dEIS}{dT}\right)\frac{LCC_{Cu}}{LCC}$$

CASCCAD

Both high and low-ECS models simulate unrealistic cloud feedbacks

Observationally Inferred feedback

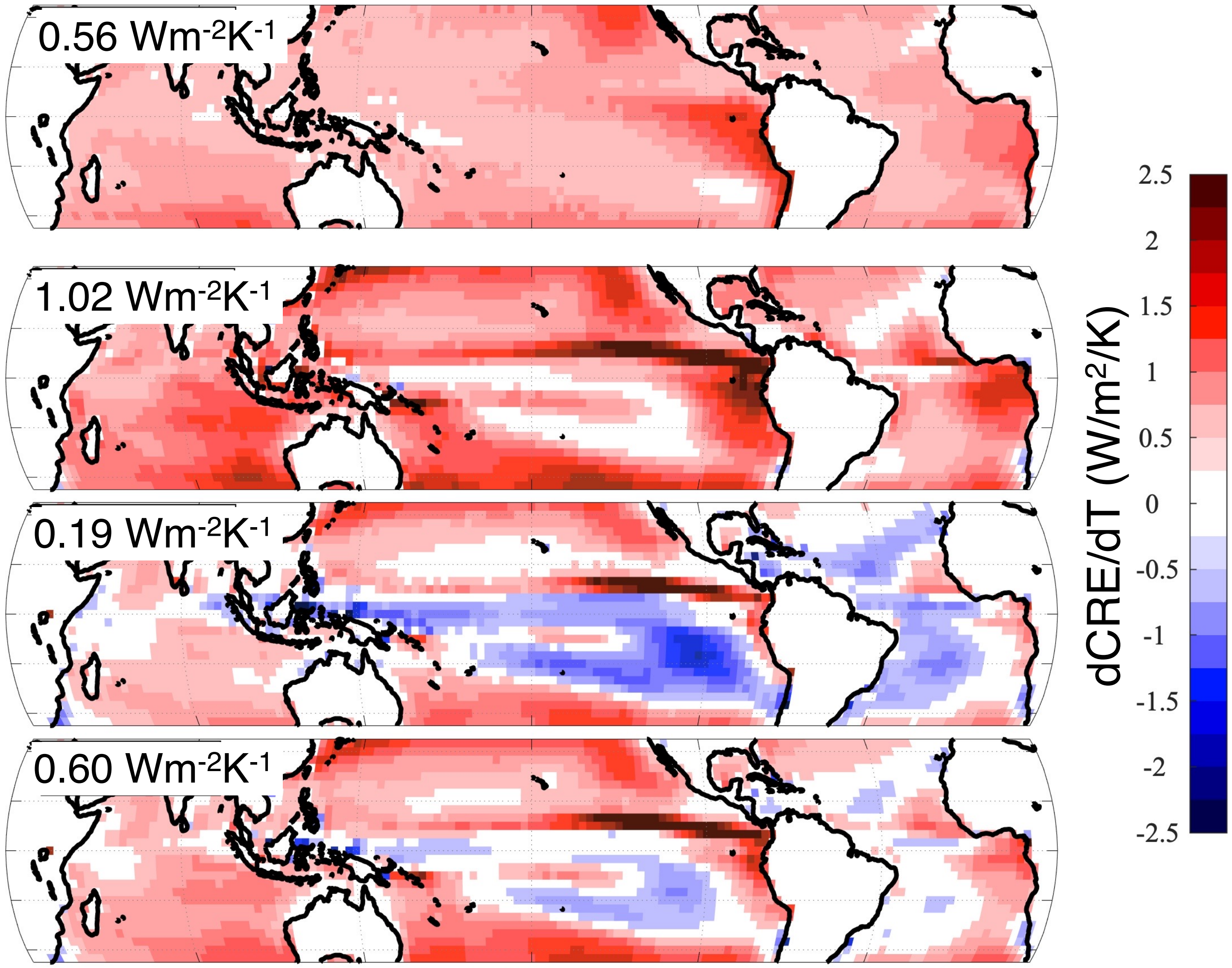
(using dSST/dT & dEIS/dT from simulated future change)

Actual simulated CMIP6 feedback

High-ECS

Low-ECS

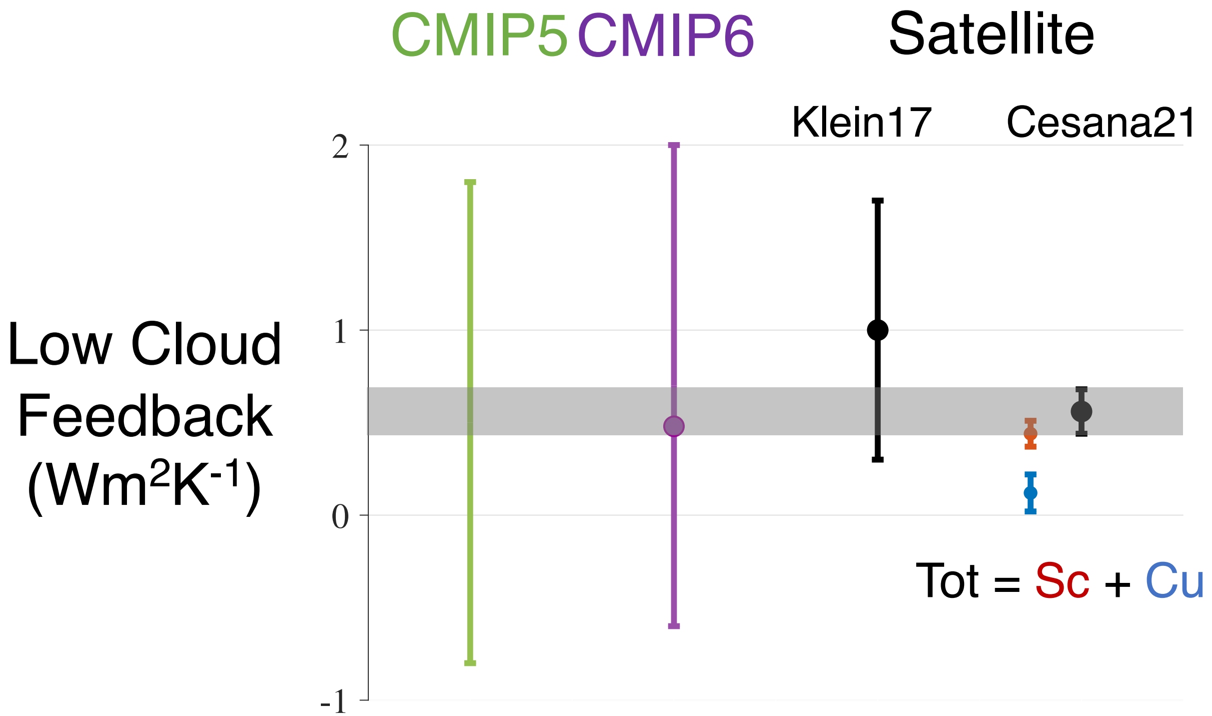
All models



Compared to previous literature

By separating Sc and Cu contributions, we can:
- Infer a direct constraint on Sc and Cu feedbacks
- Reduce overall uncertainty in low-cloud feedbacks

The Cumulus and Stratocumulus CloudSat-CALIPSO Dataset



Cesana and Del Genio, Nat. Clim. Change (2021)

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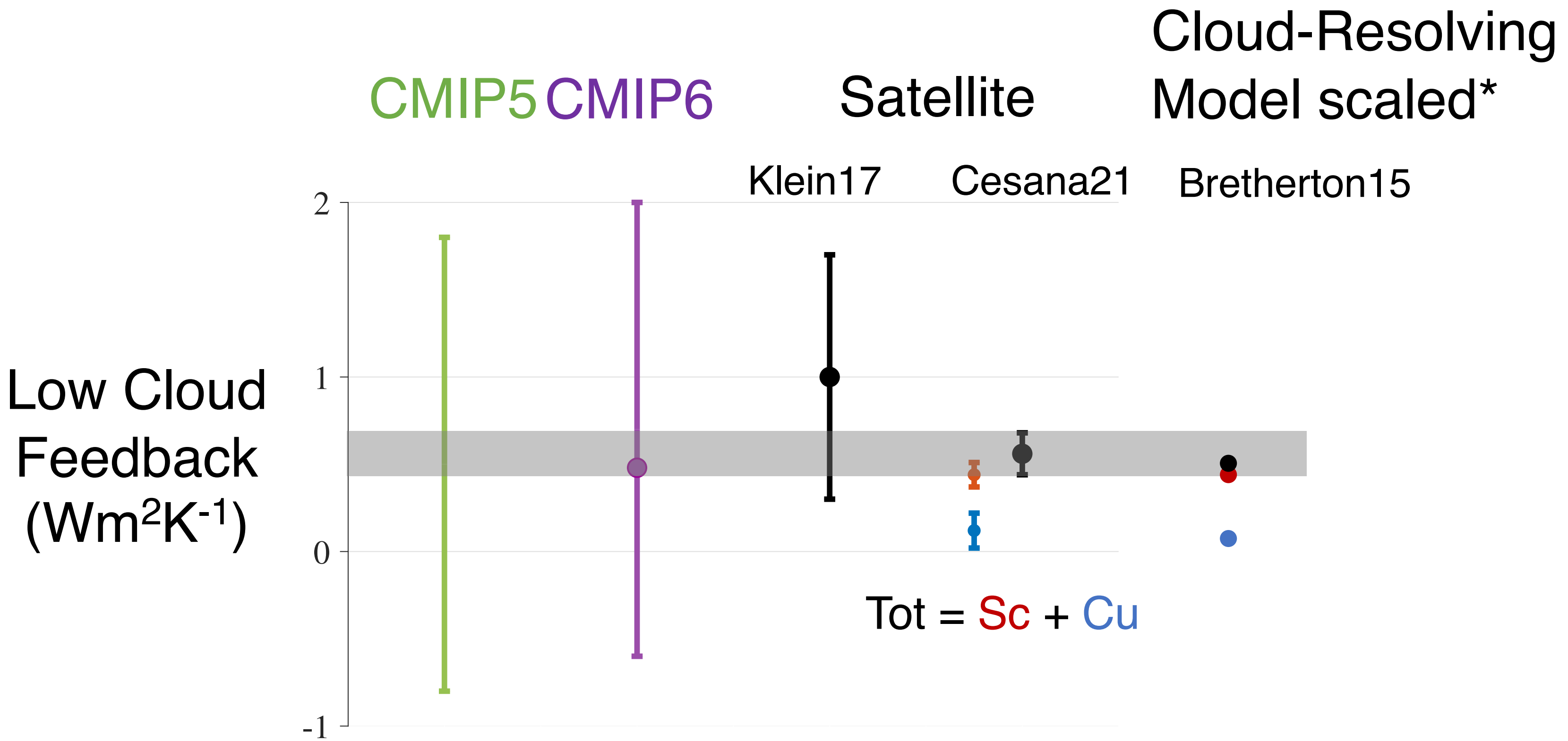
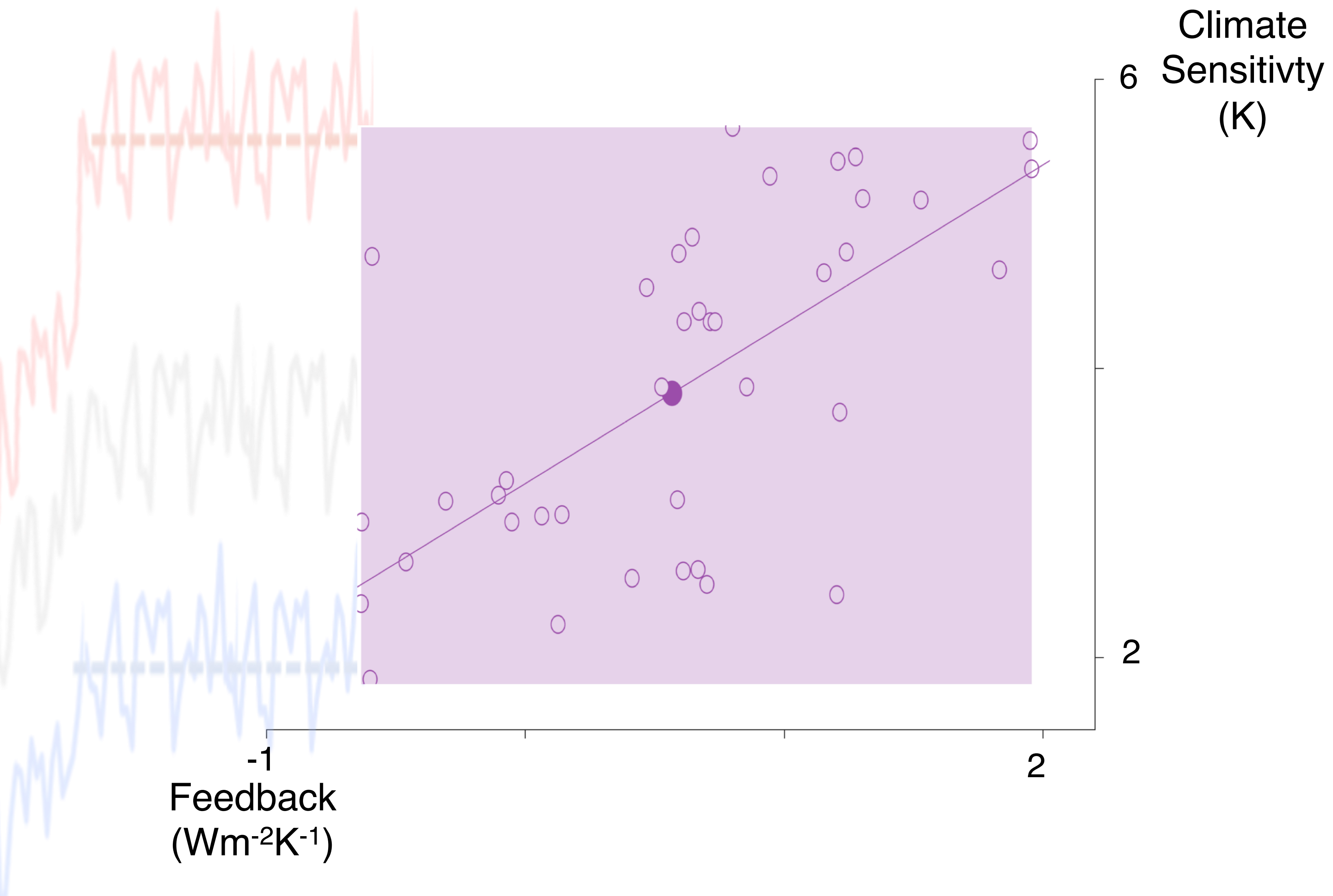
- Reduce overall uncertainty in low-cloud feedbacks

CASCCAD
The Cumulus and Stratocumulus CloudSat-CALIPSO Dataset



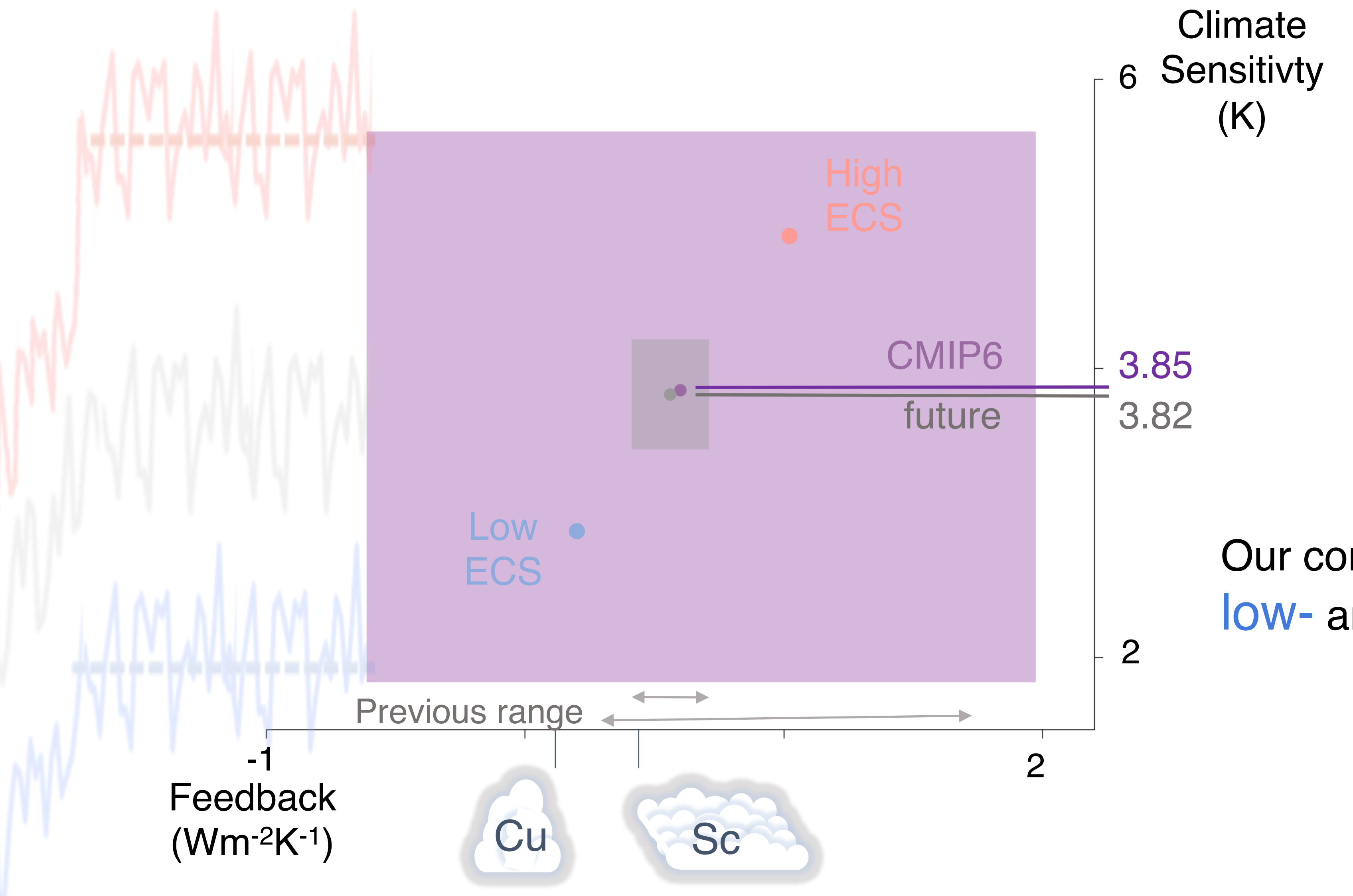
*Multiplied by CASCCAD Sc Cu cloud fractions

What are the implications for the climate sensitivity



Our observational constraint

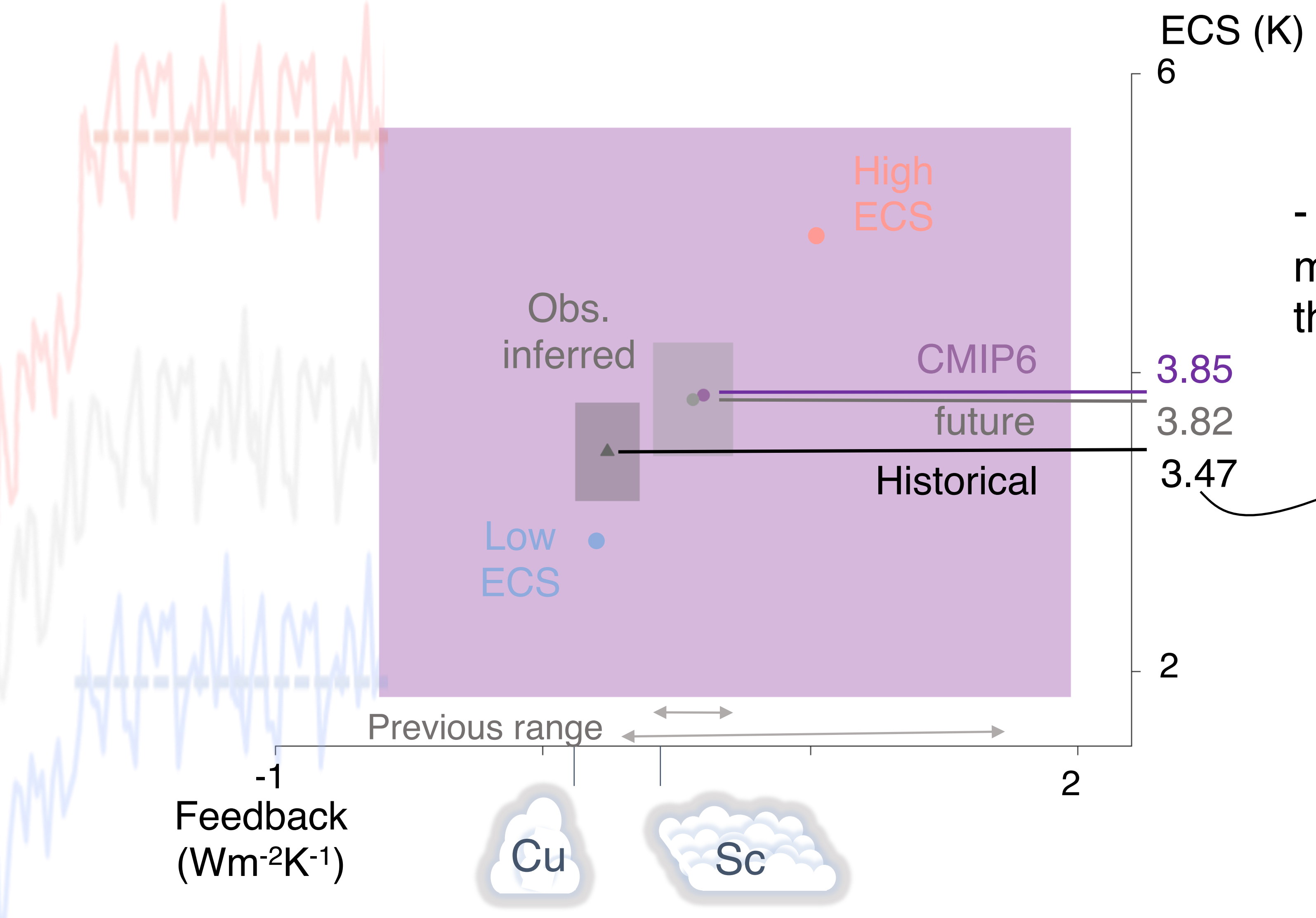
- Substantially reduces the uncertainty on low-cloud feedback



Our constraint suggests that both low- and high-ECS models seem unlikely

Our observational constraint

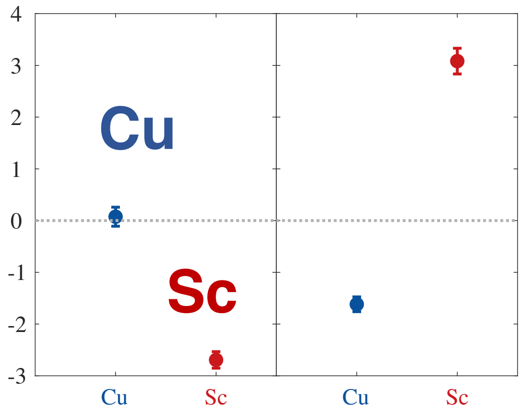
- Substantially reduces the uncertainty on low-cloud feedback
- Suggests a moderate ECS if historical trends persist



- Historical SST-EIS trends suggest more moderate ECS (3.47 ± 0.33 K) than most CMIP6 models (22/40)

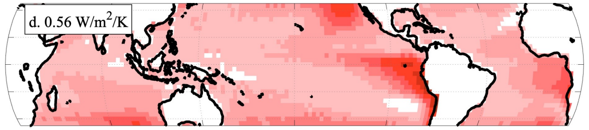
Take-away messages

1. Most of the low-cloud sensitivity to cloud predictors is driven by **Sc**

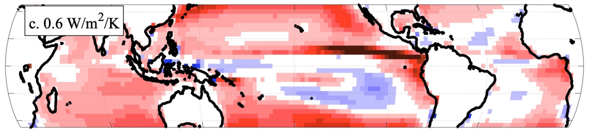


2. Unrealistic simulated feedbacks particularly in Cu regions

Obs Inferred

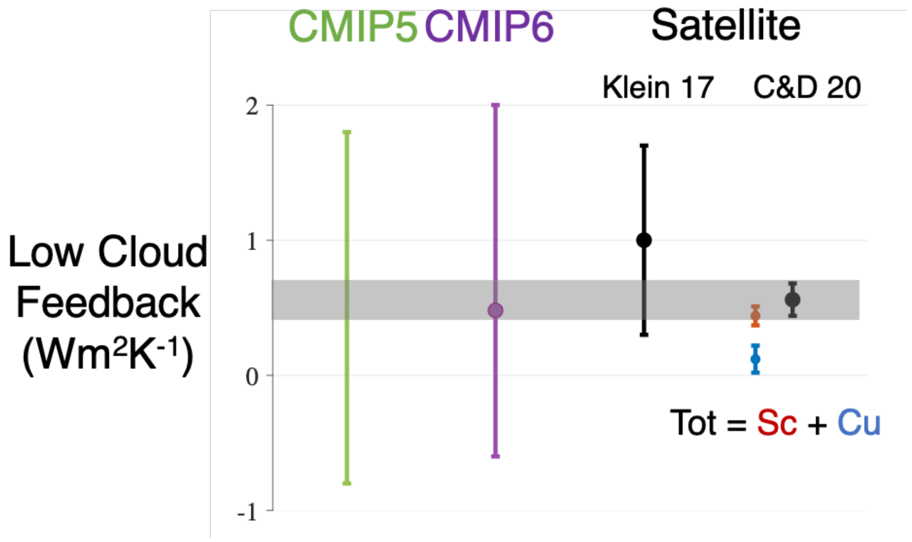


Actual GCM

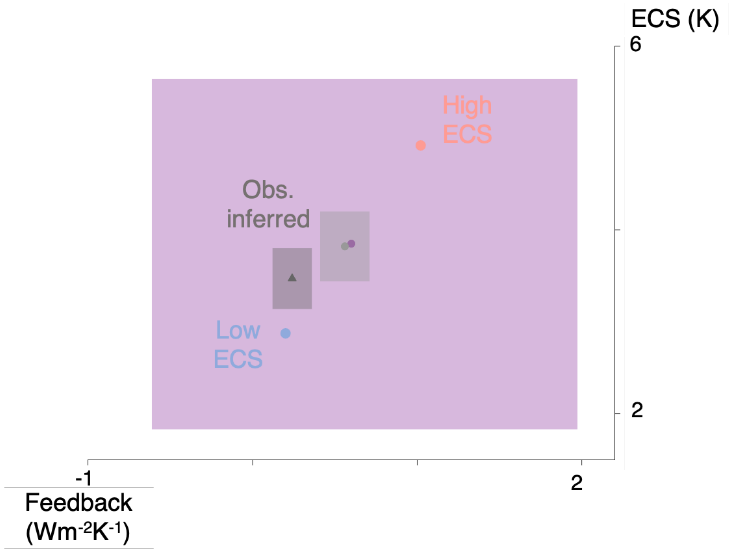


Take-away messages

3. Our method provides:
- Constraint on Sc and Cu feedbacks
- Smaller uncertainty on feedback



4. Historical SST-EIS trends suggest more moderate ECS (3.47 ± 0.33 K) than most CMIP6 models (22/40)



Cesana, G. and Del Genio, A. D., (2021), Observational constraint on cloud feedbacks suggests moderate climate sensitivity, Nat. Clim. Change, 11, no. 3, 213-218, doi:10.1038/s41558-020-00970-y.

Acknowledgments
NASA CALIPSO-CloudSat ROSES 2015 and 2018: NNH15ZDA001N and NNH18ZDA001N