Causes of Higher Climate Sensitivity in CMIP6 Models

Mark Zelinka, Tim Myers, Dan McCoy, Stephen Po-Chedley,
Peter Caldwell, Paulo Ceppi, Steve Klein, & Karl Taylor

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Key Points:
- Climate sensitivity is larger on average in CMIP6 than in CMIP5 due mostly to a stronger positive low cloud feedback
- This is due to greater reductions in

Causes of Higher Climate Sensitivity in CMIP6 Models

Mark D. Zelinka[1], Timothy A. Myers[1], Daniel T. McCoy[2], Stephen Po-Chedley[1], Peter M. Caldwell[1], Paulo Ceppi[3], Stephen A. Klein[1], and Karl E. Taylor[1]

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N=27 Nov 2019
N=40 June 2020

Equilibrium Climate Sensitivity

What is it?

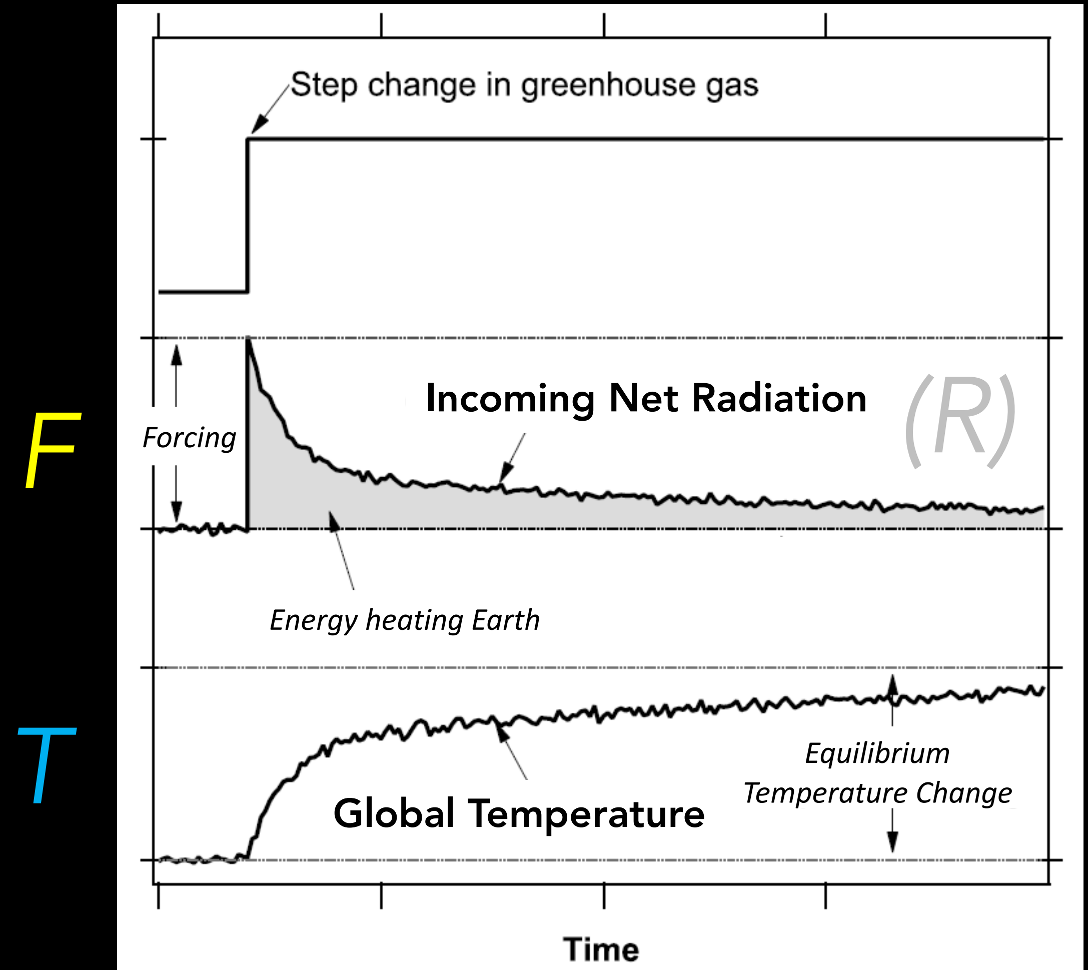
- The equilibrated global surface temperature change in response to a doubling of atmospheric CO_2

Why do I care?

- Highly relevant to future climate warming (Grose et al., 2018)
- Crucial for determining CO_2 stabilization targets to avoid crossing dangerous global temperature thresholds (Rogelj et al., 2014)
- Encapsulates substantial information about the climate system and how it responds to perturbations.

How do we quantify it?

- Paleoclimate
- Instrumental record
- Global climate models



Modified from Murphy et al., *JGR* [2009]

Radiative Forcing

Global Mean T_{sfc} Anomaly

$$R = F + \lambda T$$

TOA Radiation Anomaly

Radiative Feedback

ECS is the equilibrium (*R*=0) response of *T* to the radiative forcing from a doubling of CO_2 (F_{2x}) :

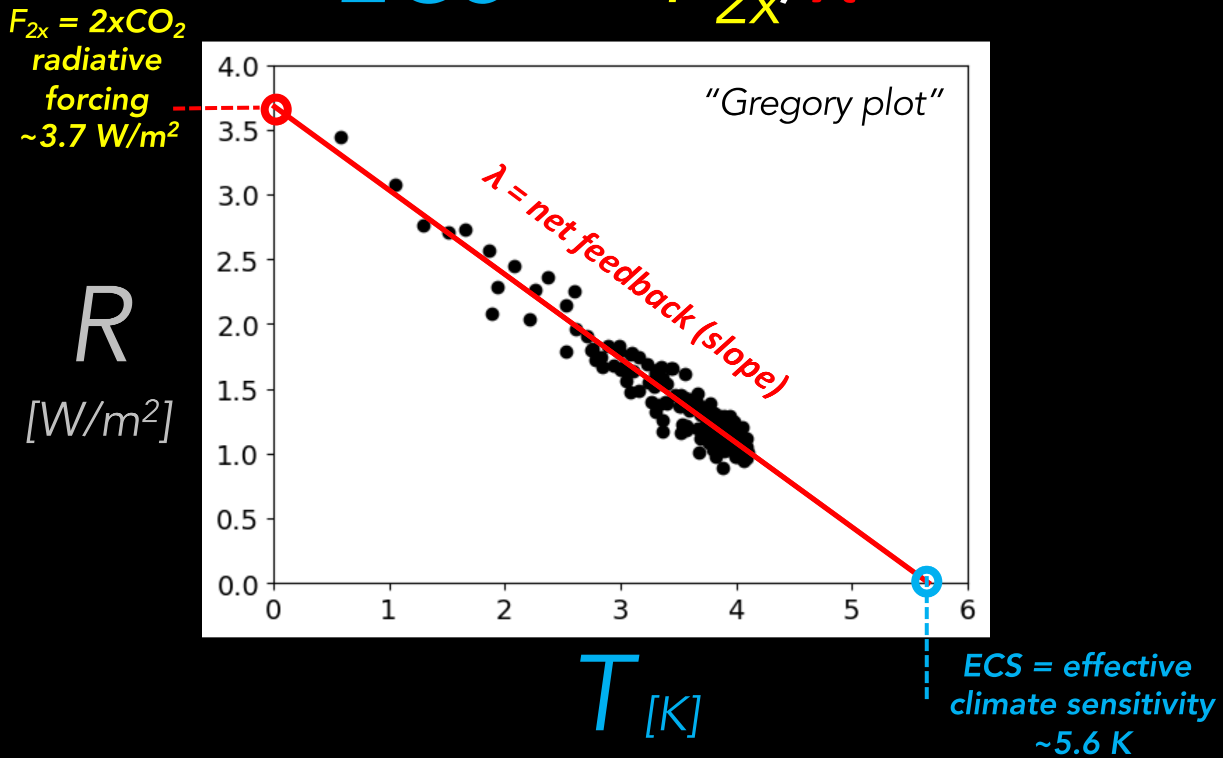
$$ECS = -F_{2x}/\lambda$$

Can diagnose F_{2x}, λ, and *ECS* by scattering *R* against *T* in abrupt CO_2 quadrupling experiments, following *Gregory et al. (2004)*

Forcing, Feedback, Sensitivity

$$R = F + \lambda T$$

$$ECS = -F_{2x}/\lambda$$



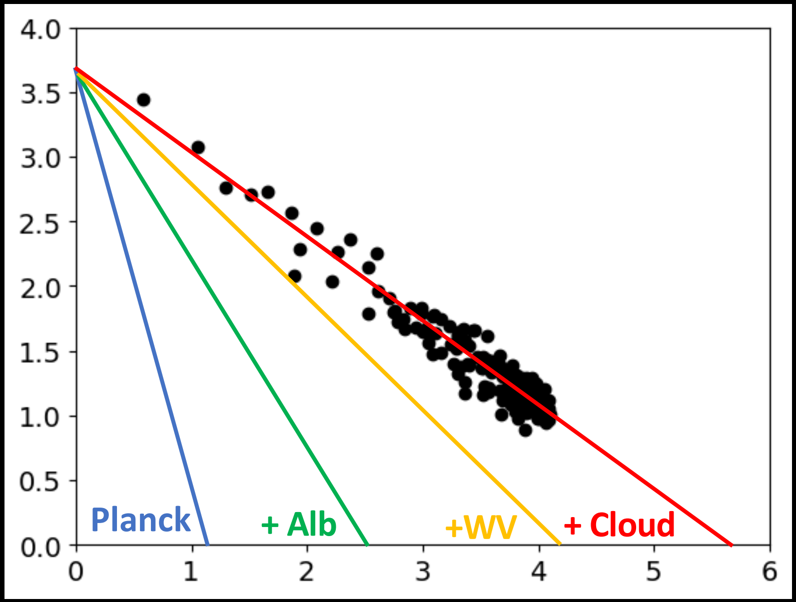
To aid understanding, it is helpful to break **λ** down into components…

Forcing, Feedback, Sensitivity

$$R = F + \lambda T$$

$$ECS = -F_{2x}/\lambda$$

R [W/m²]



T [K]

Planck: A warmer planet emits more LW radiation to space (negative)

Surface Albedo: A warmer planet has less snow and ice; absorbs more SW radiation (positive)

Water Vapor: A warmer atmosphere is more moist (assuming RH unchanged); larger greenhouse effect (positive)

Clouds: ??

Why are we comparing CMIP5 and CMIP6 ECS?

- As models continuously get developed and refined (improved?), it is important to assess whether their climate sensitivities have changed, perhaps giving a more accurate view of Earth's future climate.
- The notion that ECS increased in CMIP6 got a lot of press as early models came into the archive. We wanted to know whether this was actually statistically significant.
- IPCC AR6 needs this information

16 Apr 2019

ECS, Forcings, & Feedbacks Diagnosis

- Data from abrupt CO_2 quadrupling experiments conducted by GCMs as part of the Coupled Model Intercomparison Project phases 5 & 6 (CMIP5/6)
  - Anomalies are with respect to coincident pre-industrial control simulations

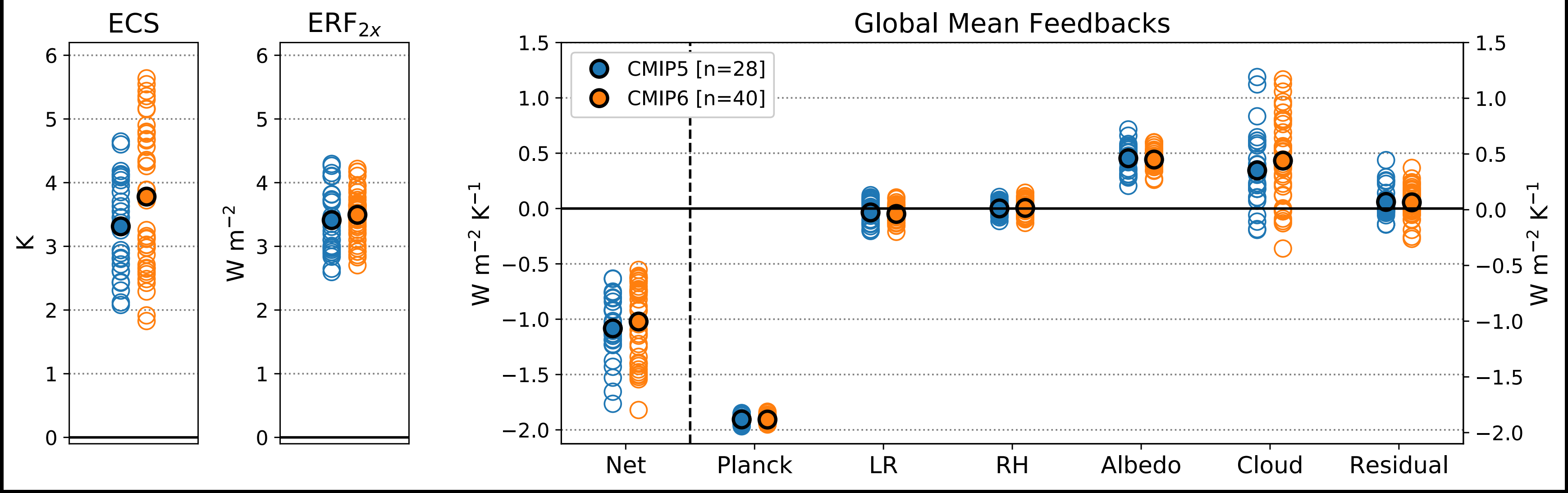
- Regress TOA radiation anomalies on T_{sfc} anomalies from all 150 yrs of the abrupt-4xCO2 simulations [*Gregory et al. 2004*]
  - Regression slope = radiative feedback parameter (**λ**)
  - Y-intercept/2 = 2xCO_2 Effective Radiative Forcing (ERF_{2x})
  - X-intercept/2 = Effective Climate Sensitivity (ECS)

- Decompose **λ** into individual feedback components using radiative kernels
  - Kernels quantify the impact of ΔT, Δq, Δalbedo on TOA radiation
  - All kernels give consistent results; *Huang et al [2017]*'s yield smallest residuals
  - We report constant RH feedbacks [*Held & Shell 2012*]

ECS, Forcings, & Feedbacks
CMIP5 vs CMIP6

Mean ECS: 3.3 → 3.8
ECS>4.5 in 14 models

Current: 40 models from 22 centers
Expected: 102 models from 35 centers



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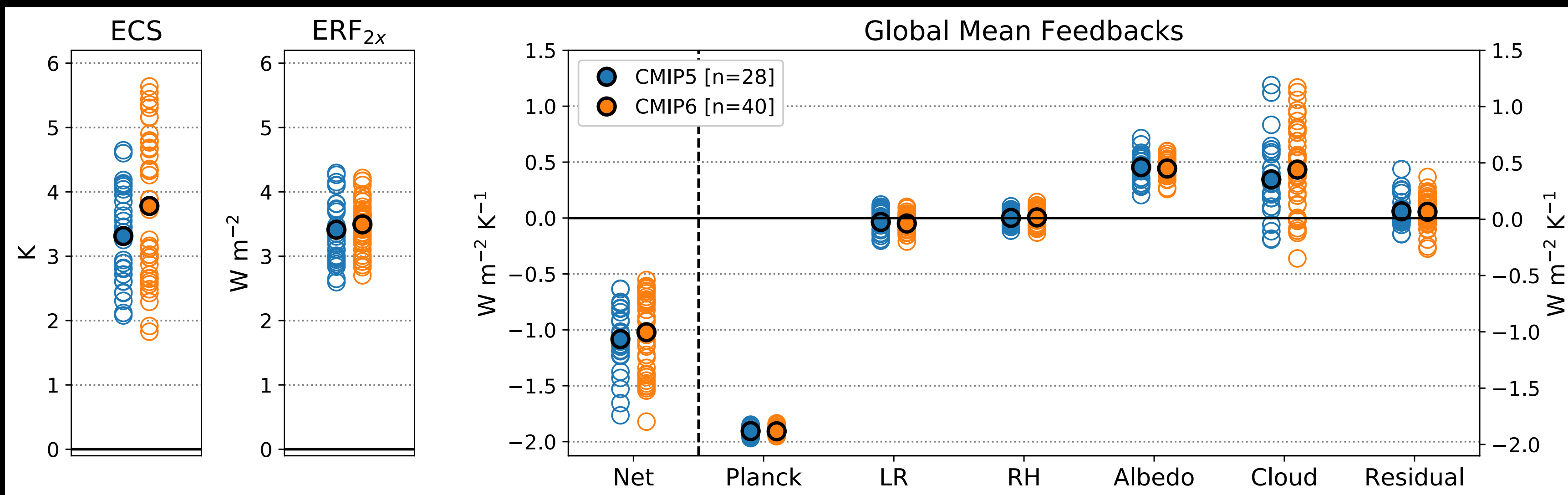
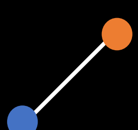
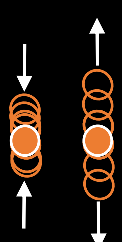




Means are deemed significantly different if the 2-tailed p value of the Welch's t -test for equal means is less than 0.05.



Variances are deemed significantly different if the p value of Bartlett's test for equal variances is less than 0.05.

Significance tests done after first averaging data from all models from single modeling centers

ECS, Forcings, & Feedbacks

CMIP5 vs CMIP6

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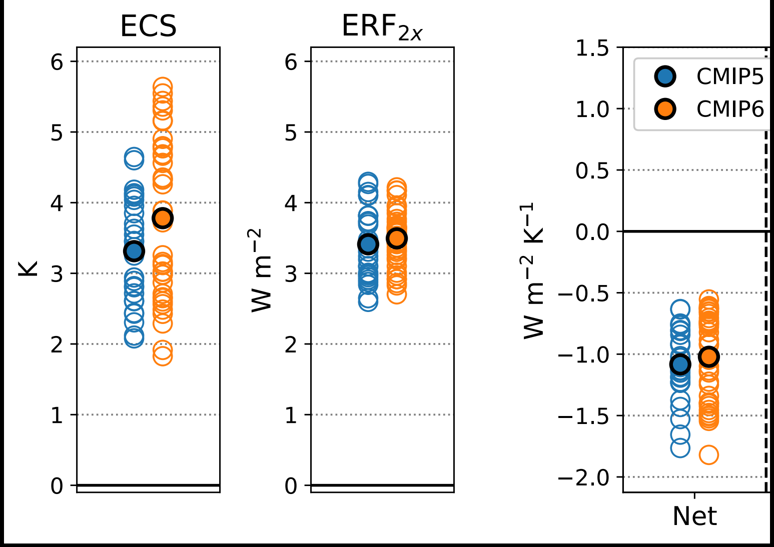


Not Subtle

Subtle

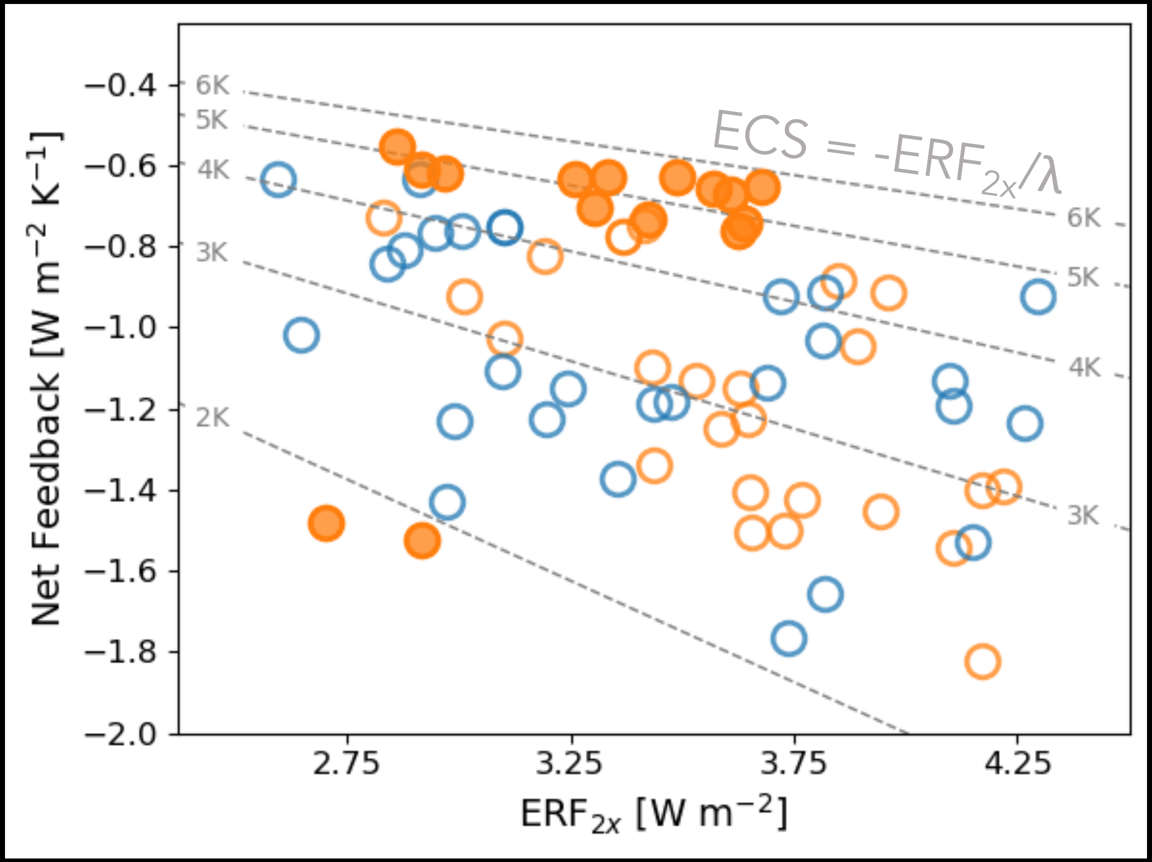
Subtle

Highest & lowest ECS values come from unique forcing-feedback combos

Weak

radiative damping

Strong



See also Andrews et al., *JAMES* (2019)

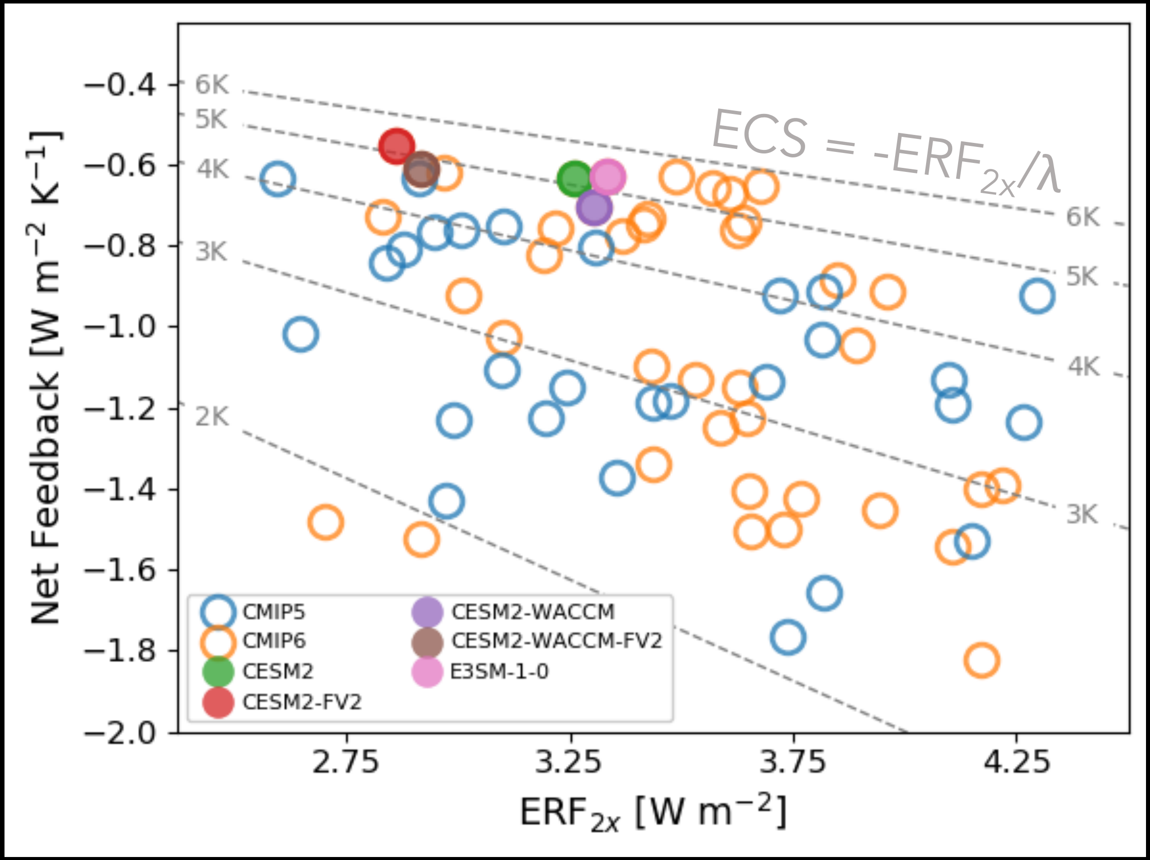
Weak --------- radiative forcing -------- Strong

CESM2 & E3SM are among the models w/highest ECS

Weak

radiative damping

Strong



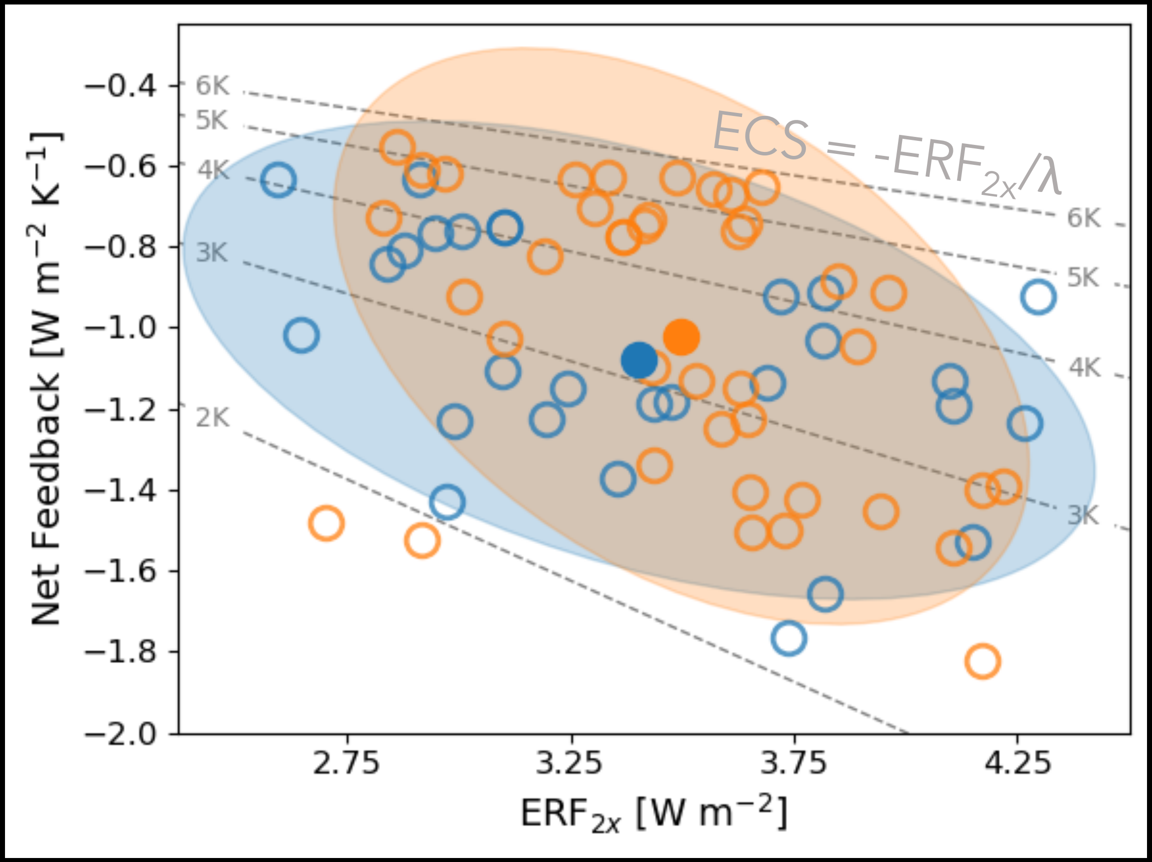
Weak --------- radiative forcing -------- Strong

What is the relative importance of ΔForcing, ΔFeedback, & ΔCovariance in Causing Higher ECS in CMIP6?

Weak

radiative damping

Strong



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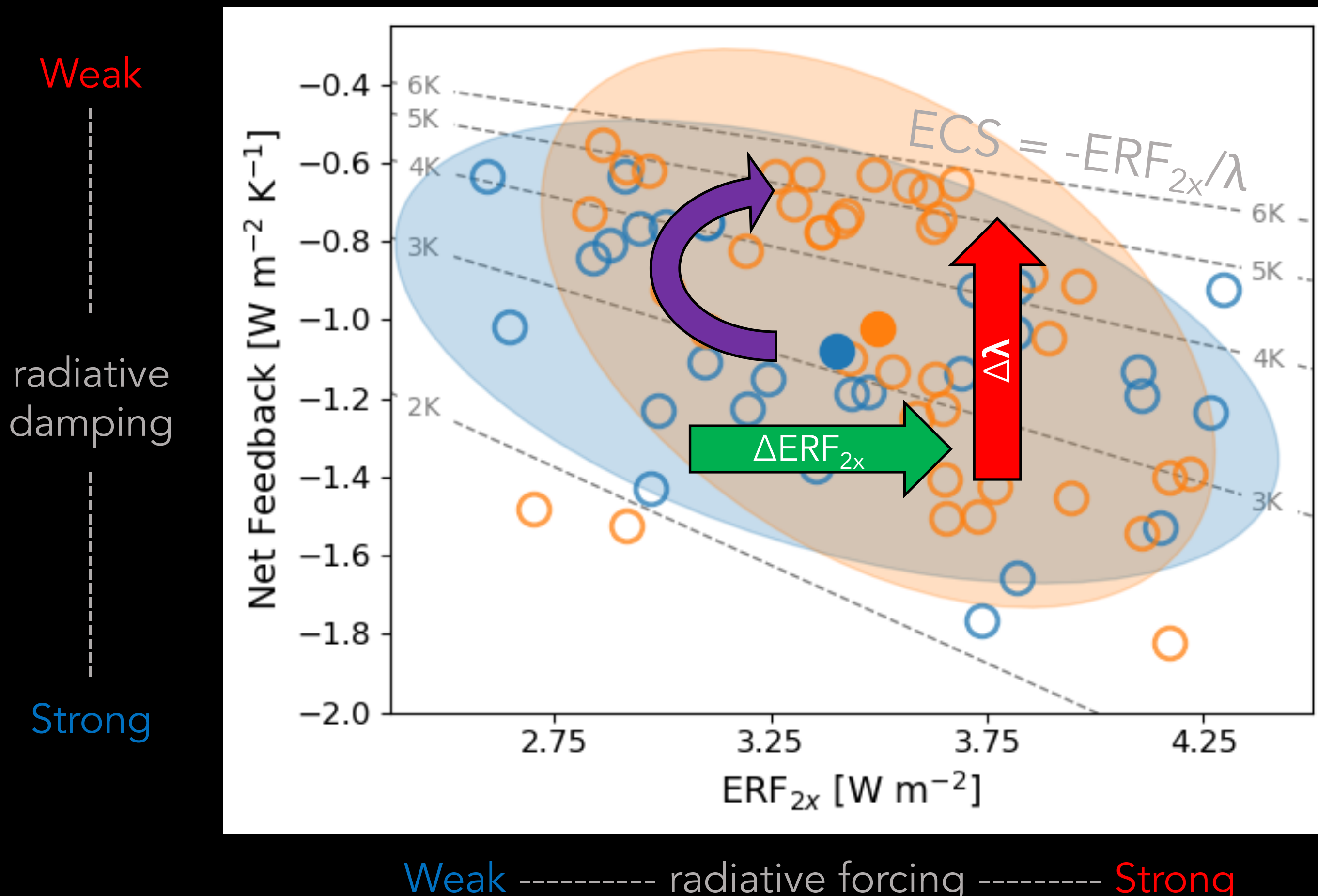
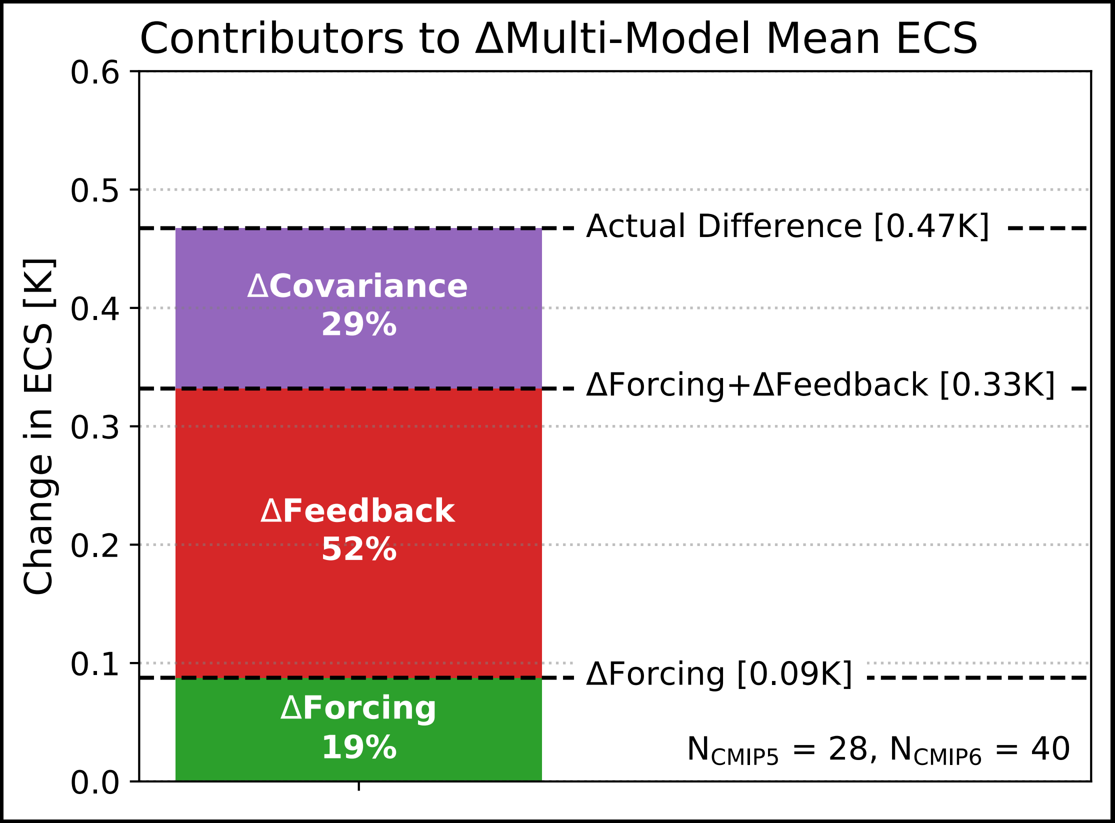


Roles of ΔForcing, ΔFeedback, & ΔCovariance in Causing Higher ECS



Hereafter we focus on the red portion, which is entirely due to more positive cloud feedback.

Summary so far

- The mean and inter-model spread in ECS has increased markedly in CMIP6.
  - Neither of these changes are statistically significant at 95% confidence
  - ECS > 4.5˚C in 14 of 40 CMIP6 models, including E3SM and all CESM2 variants

- Highest ECS values arise from strong positive feedbacks + moderate forcing.

- Increase in mean ECS in CMIP6 is attributable to…

  …stronger forcing (19%)

  …stronger positive feedbacks (52%), and

  …"steeper" anti-correlation between forcing and feedback (29%)

So why has the [cloud] feedback increased in CMIP6?

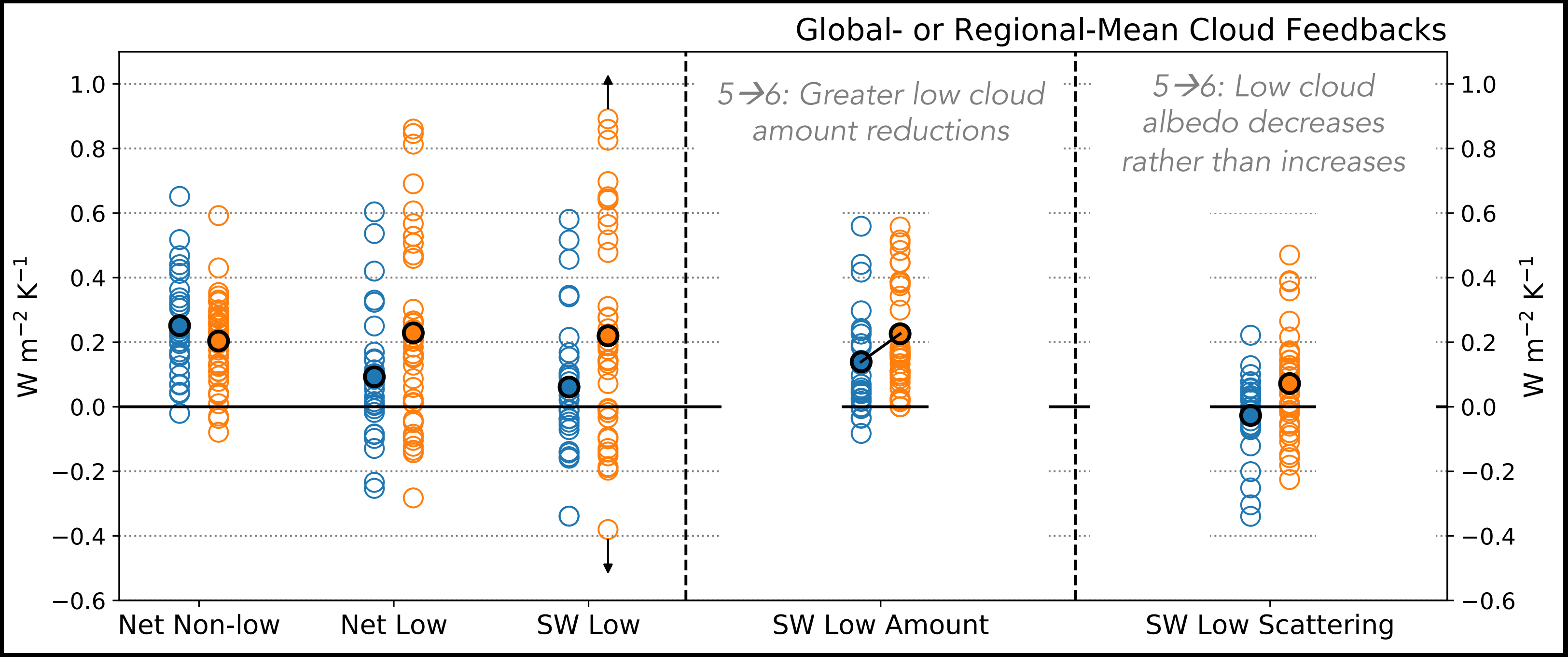
Why has the cloud feedback increased in CMIP6?

We use two methods in concert to detail the cloud feedback:

- *Webb et al (2006)* technique to separate feedback into contributions from low and non-low clouds
- APRP method of *Taylor et al (2007)* to separate SW cloud feedback into contributions from cloud amount & scattering

Cloud Feedbacks

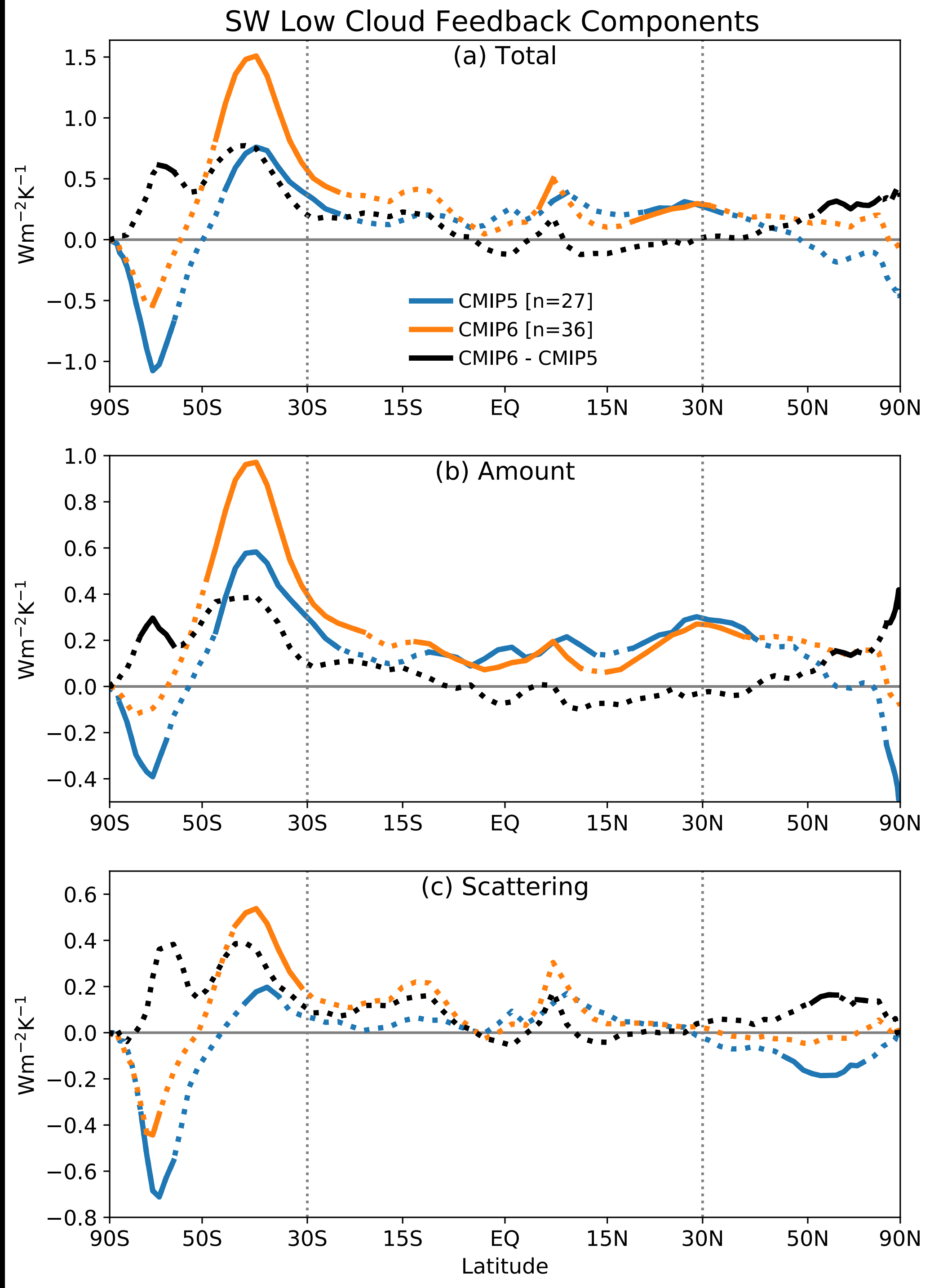
CMIP5 vs CMIP6



Cloud Feedbacks

CMIP5 vs CMIP6

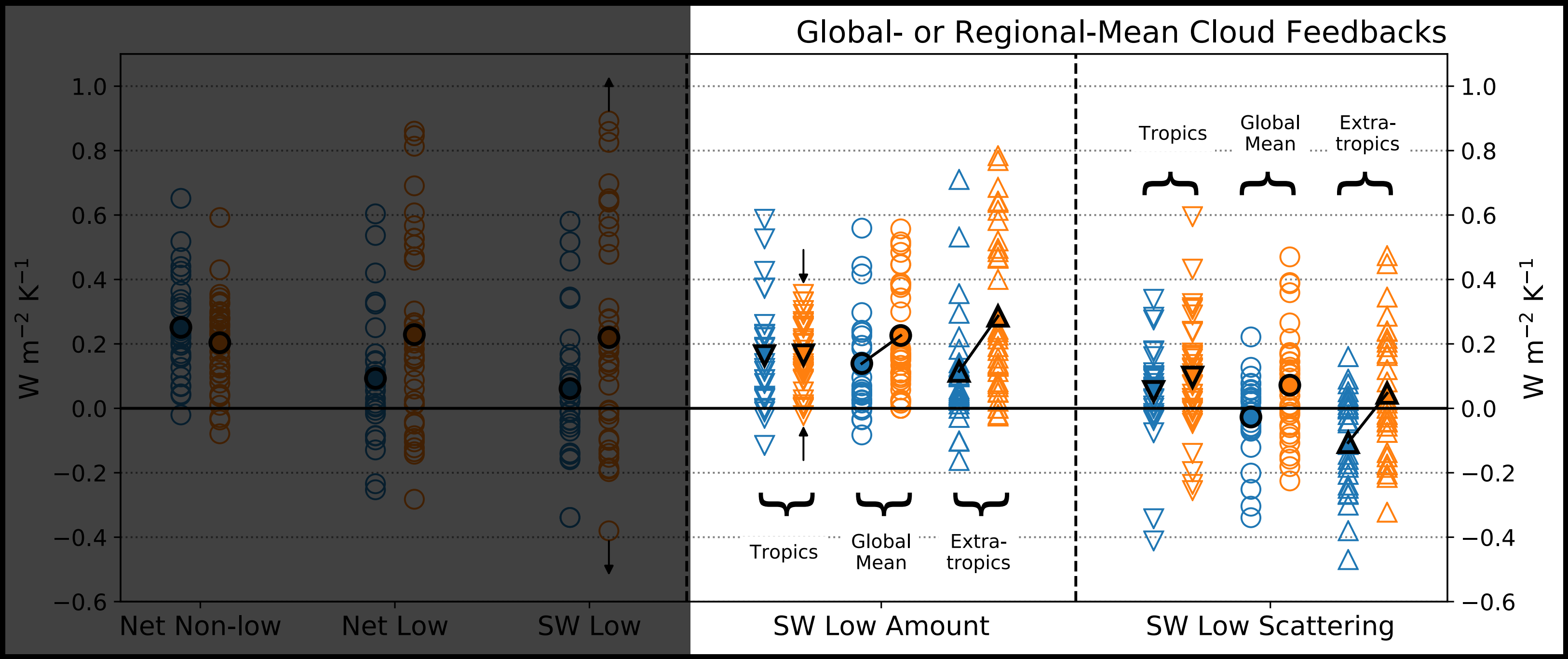
CMIP6 mean SW low cloud amount and scattering feedbacks (and their sum) are substantially more positive at middle-high latitudes



Latitudes where at least 80% of the models agree on the sign of the feedback are plotted with a solid line. Multi-model mean differences are shown in black lines, which are solid where differences are significant.

Cloud Feedbacks

CMIP5 vs CMIP6



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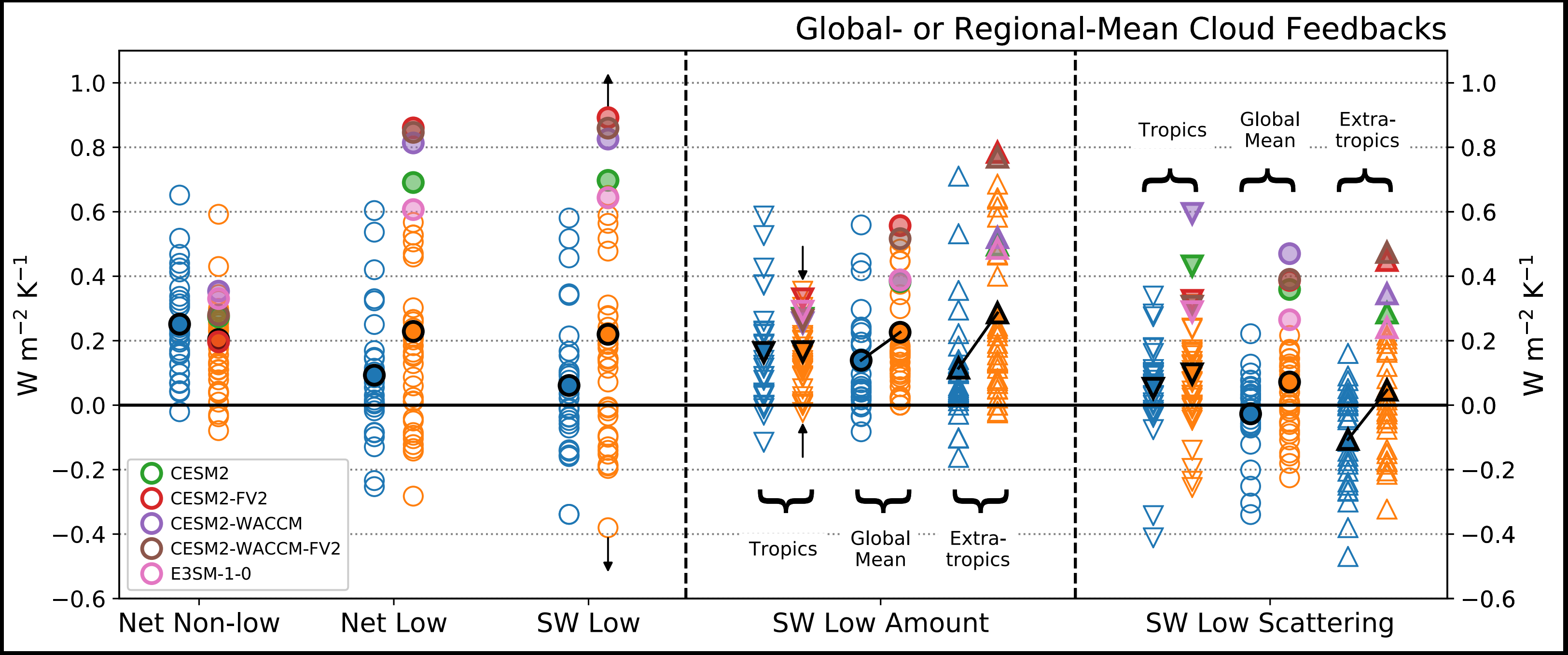
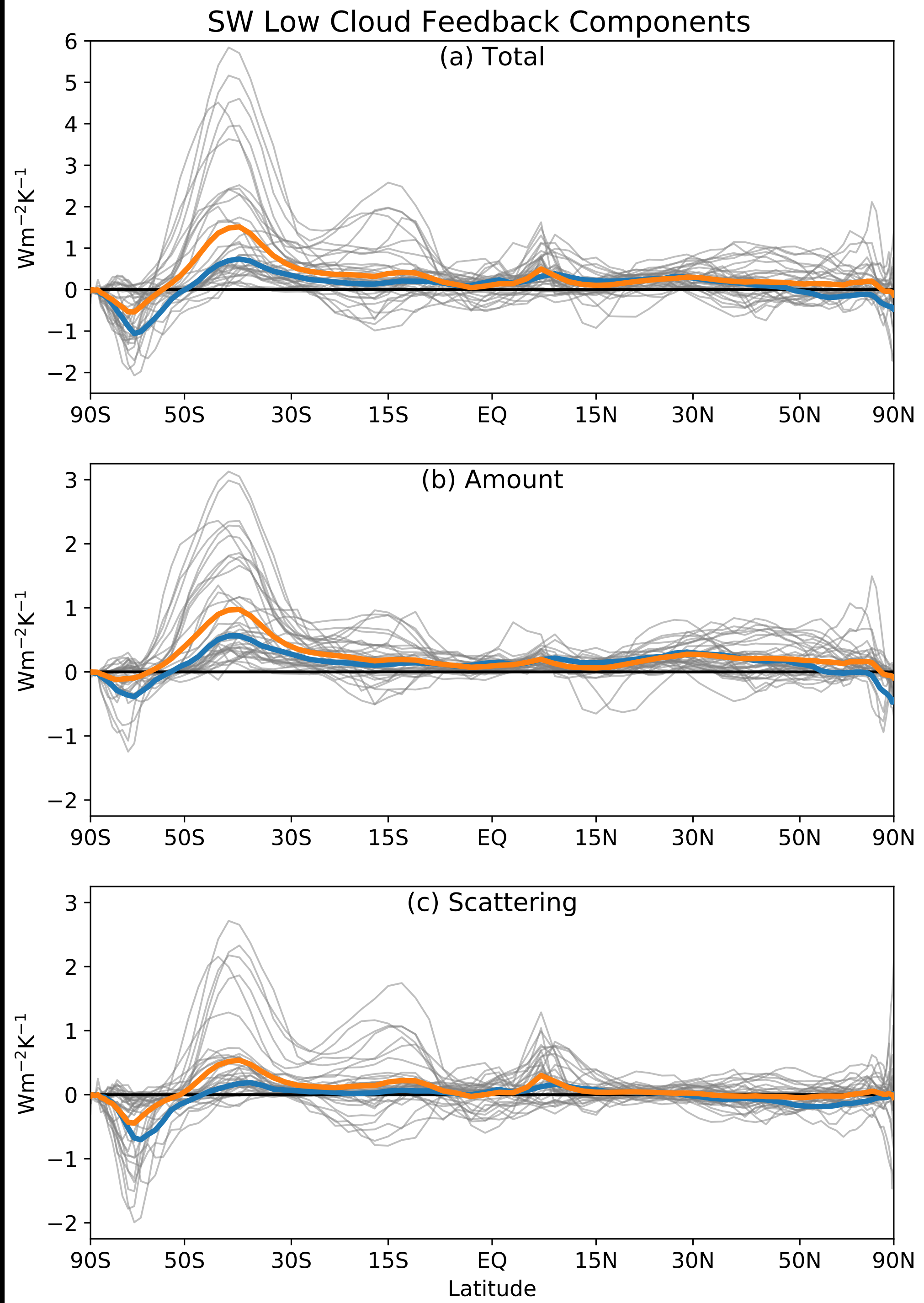


Cloud Feedbacks

CMIP5 vs CMIP6

+Individual CMIP6 models

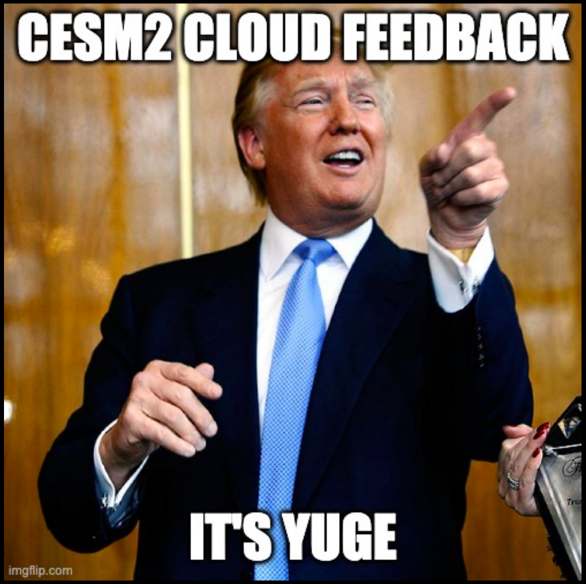


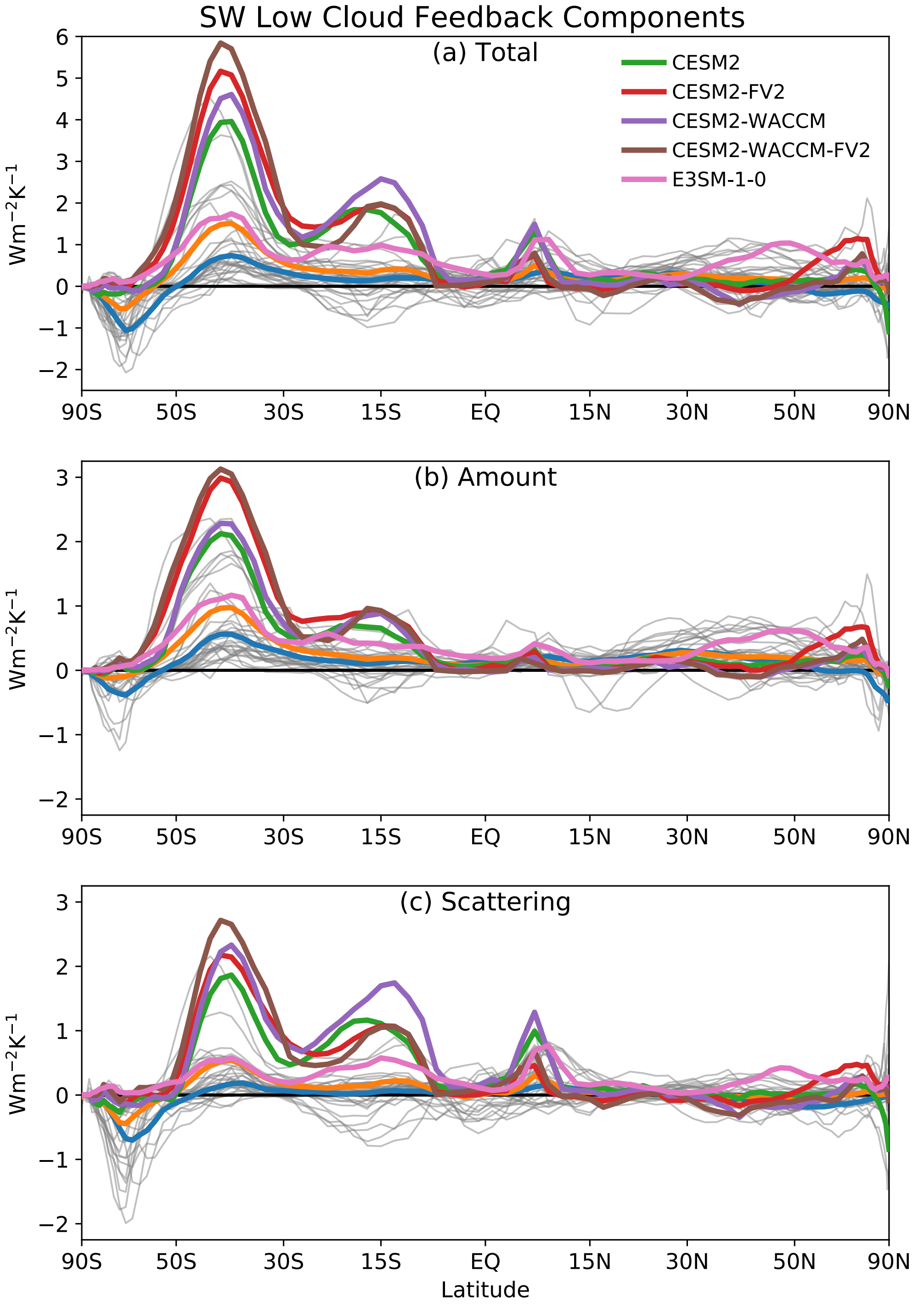
Cloud Feedbacks

CMIP5 vs CMIP6

+Individual CMIP6 models

CESM2* among the models with largest SH low cloud feedbacks, especially in the extratropics





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- Stronger positive feedback in CMIP6 is due to stronger decreases in low cloud coverage and albedo in the extratropics.

So why has the extratropical cloud feedback increased in CMIP6?

Why has the extratropical low cloud scattering feedback increased in CMIP6?

Models with larger positive SW low cloud scattering feedbacks have larger decreases in LWP_{low}

So let's perform cloud controlling factor analysis on LWP_{low} over the SH oceans (30-60˚S)

Cloud-Controlling Factor Analysis

LWP_{low} Sensitivity to CCF (x_i)
[from piControl]

$$\frac{d\mathrm{LWP}_{\mathrm{low}}}{dT_g} = \sum_i \frac{\partial \mathrm{LWP}_{\mathrm{low}}}{\partial x_i} \frac{dx_i}{dT_g}$$

$x_i \in$ *{SST, inversion strength, advection, etc.}*

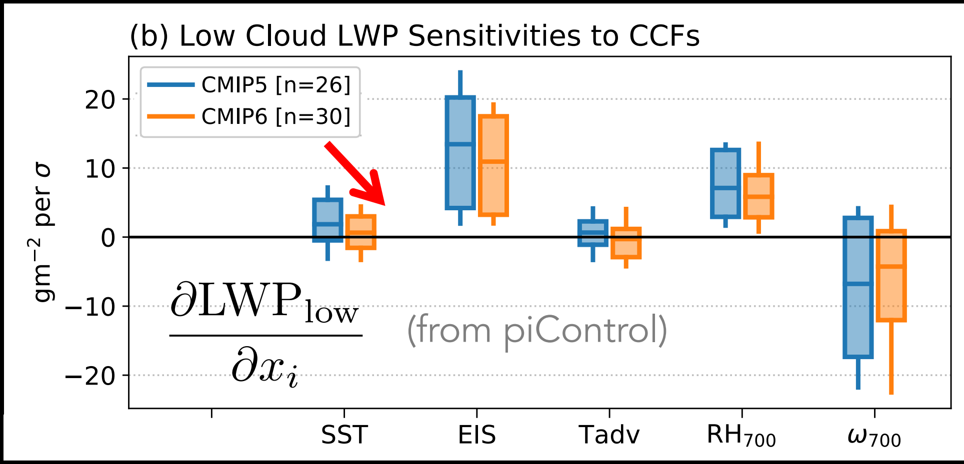
Climate Change in CCF
[from abrupt-4xCO_2]

Low-latitude studies
Qu et al. (2014, 2015)
Zhai et al. (2015)
Zhou et al. (2015)
Myers & Norris (2016)
Brient & Schneider (2016)
McCoy et al. (2017)
And reviewed by Klein et al. (2017)

Extra-tropical studies
Gordon and Klein (2014)
Terai et al. (2016)
Ceppi et al. (2016)
Grise & Medeiros (2016)
Zelinka et al. (2018)
Miyamoto et al. (2018)
Kelleher & Grise (2019)

Why has extratropical low cloud scattering feedback increased in CMIP6?

30-60˚S Ocean-only



In CMIP6, the LWP_{low} increase with SST in the piControl climate is much weaker.

Basically the same story for low cloud cover (& amount feedback)

Why has extratropical low cloud scattering feedback increased in CMIP6?

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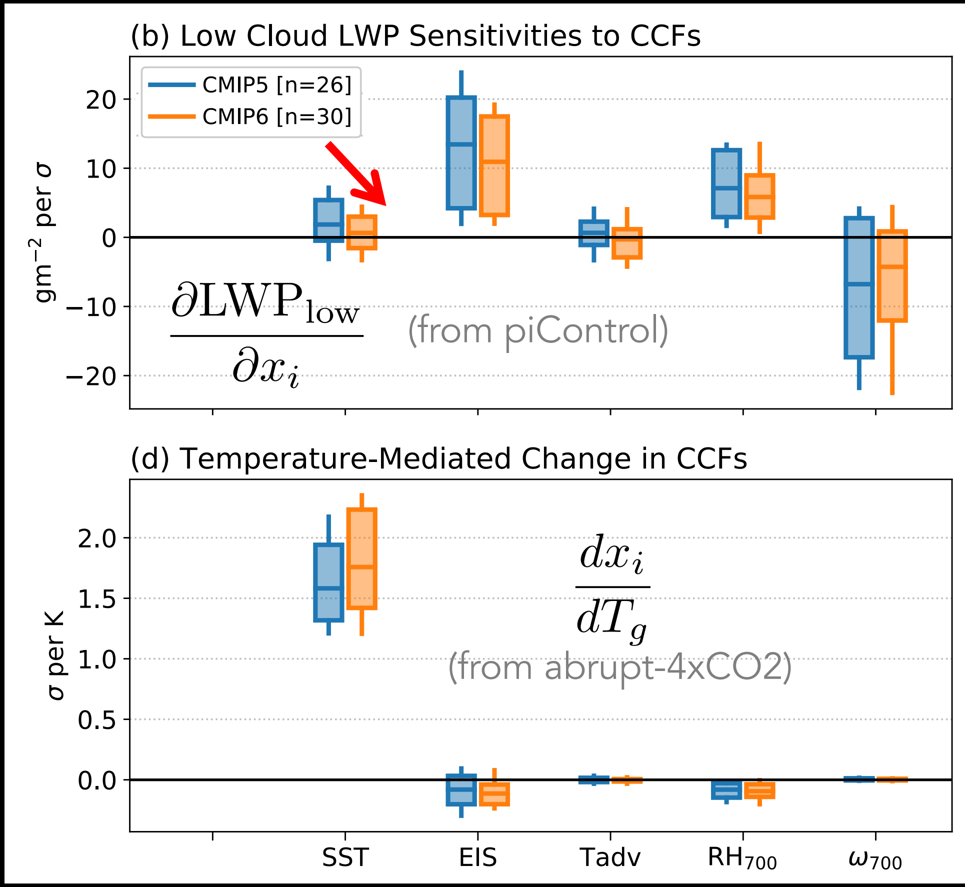
This overwhelms the slightly larger SST increase…



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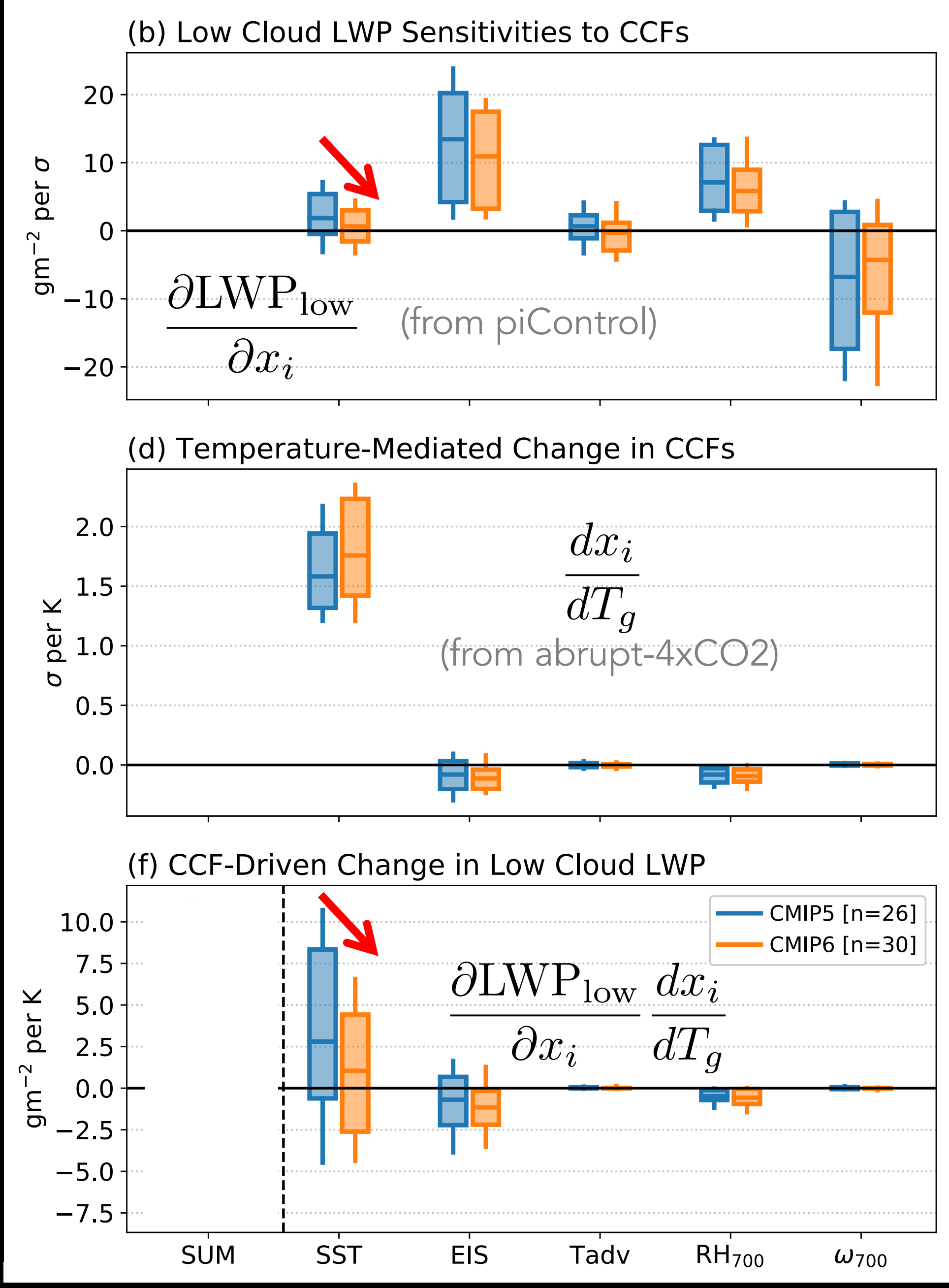

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…causing markedly weaker SST-driven increases in LWP_{low}.

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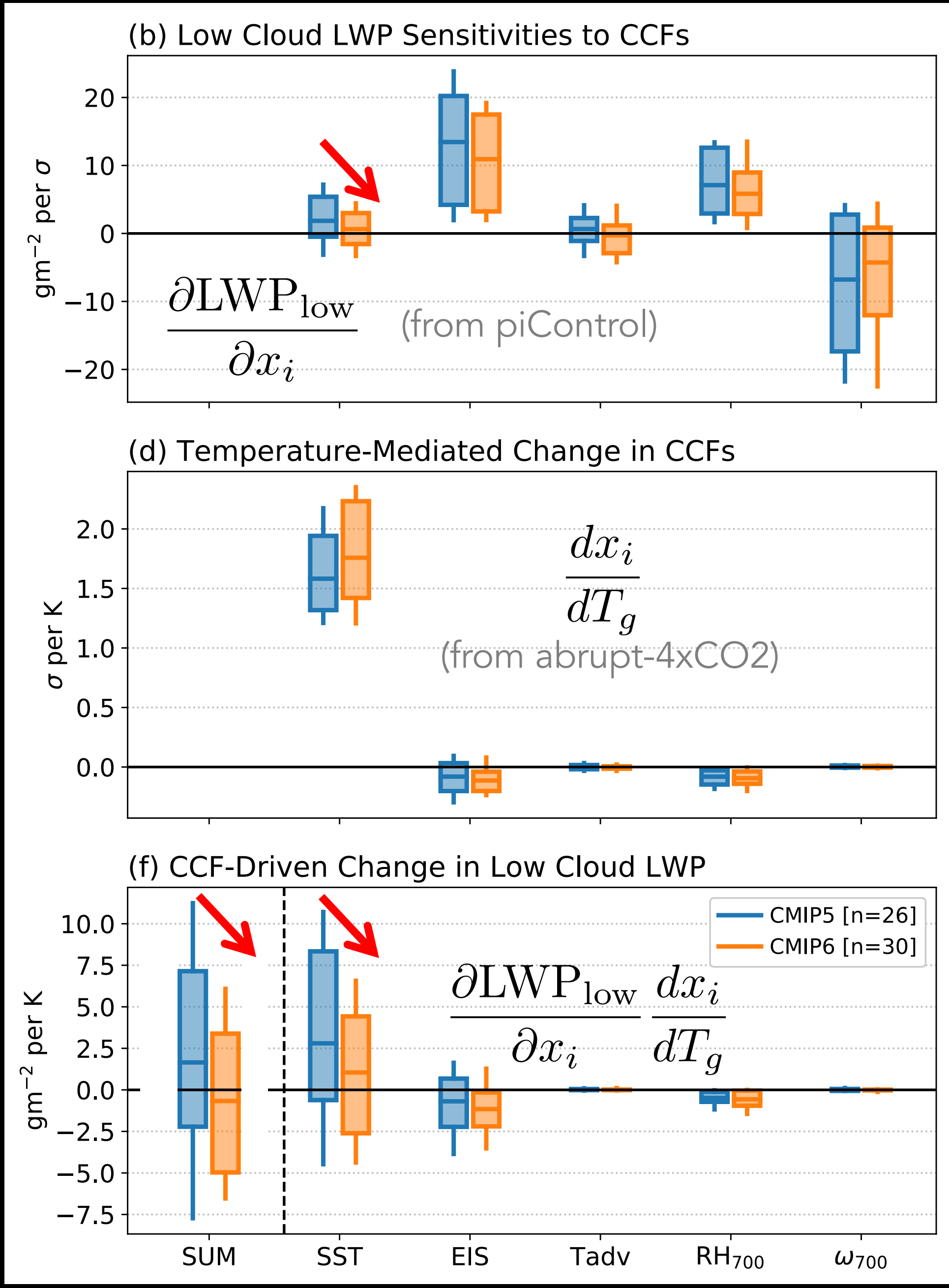
The multi-linear regression model predicts that ΔLWP_{low} changes sign from positive in CMIP5 to negative in CMIP6.



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Why has extratropical low cloud scattering feedback increased in CMIP6?

In CMIP6, the LWP_{low} increase with SST in the piControl climate is much weaker.

This overwhelms the slightly larger SST increase…

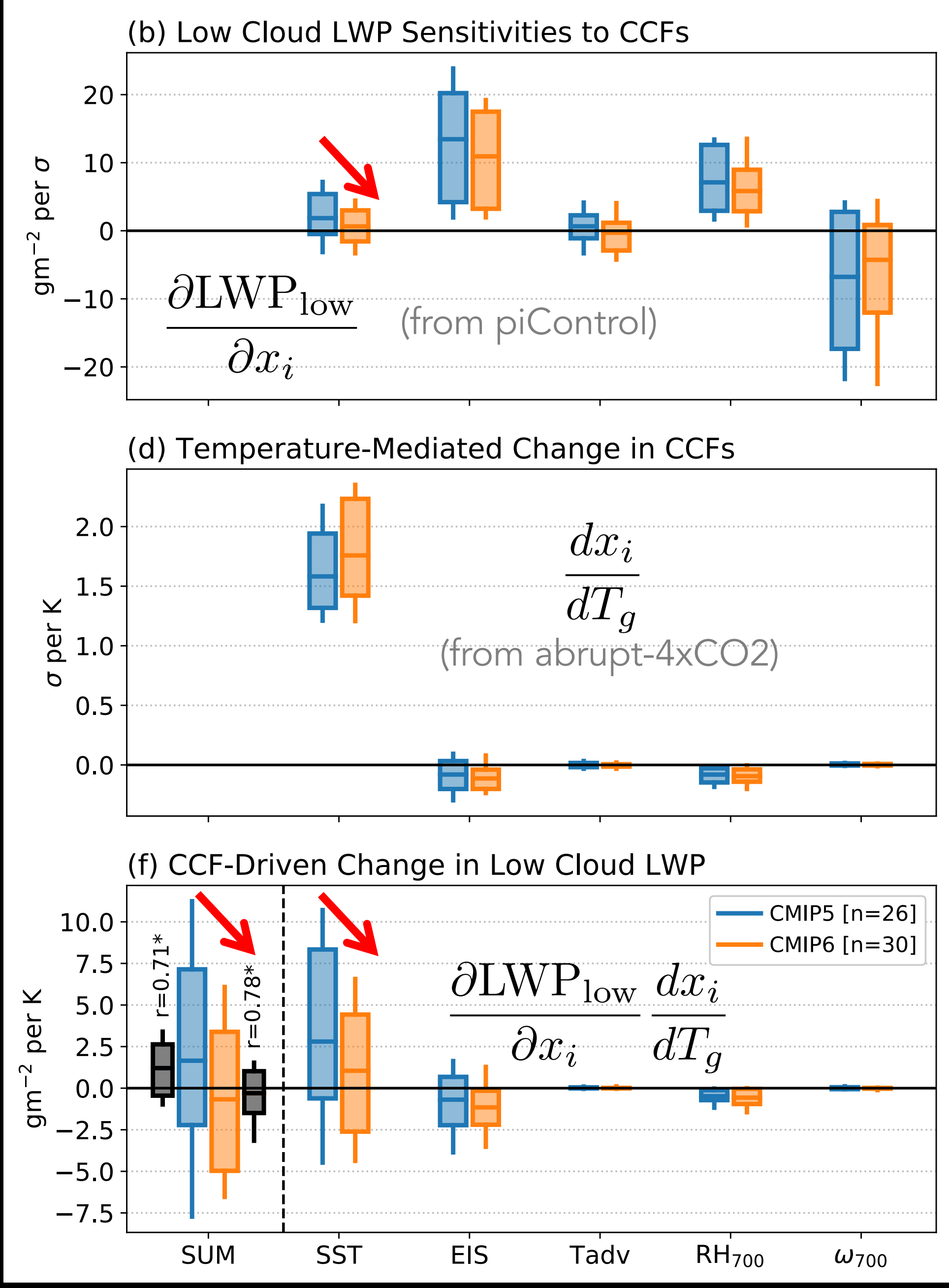
…causing markedly weaker SST-driven increases in LWP_{low}.

The multi-linear regression model correctly predicts that ΔLWP_{low} changes sign from positive in CMIP5 to negative in CMIP6.

It also predicts LWP_{low} changes that are significantly correlated with actual model-produced values.

Basically the same story for low cloud cover (& amount feedback)

30-60˚S Ocean-only



Cloud phase as a potential root cause of increased extratropical cloud feedbacks

Models with larger mean-state liquid condensate fraction (LCF) have been shown to experience weaker LWP increases with warming (*McCoy et al., 2015*).

CAM5 modified to produce higher mean-state LCF have more positive extratropical scattering (*Tan et al. 2016*) and amount (*Frey and Kay, 2017*) feedbacks.

Increased mean-state LCF is implicated in causing increased cloud feedback in HadGEM2 (*Bodas-Salcedo et al., 2019*) and CESM2 (*Gettelman et al., 2019*).

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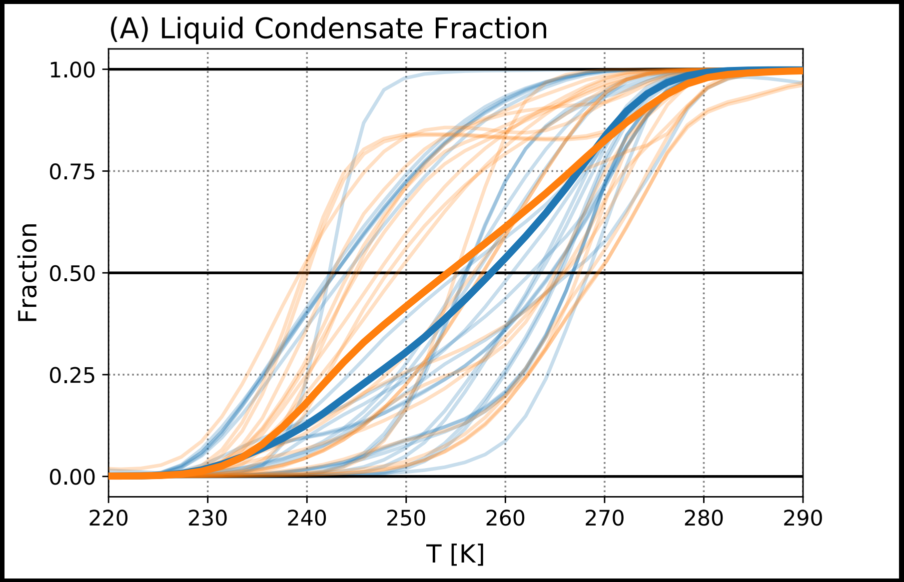
CMIP6 models have higher LCF on average.



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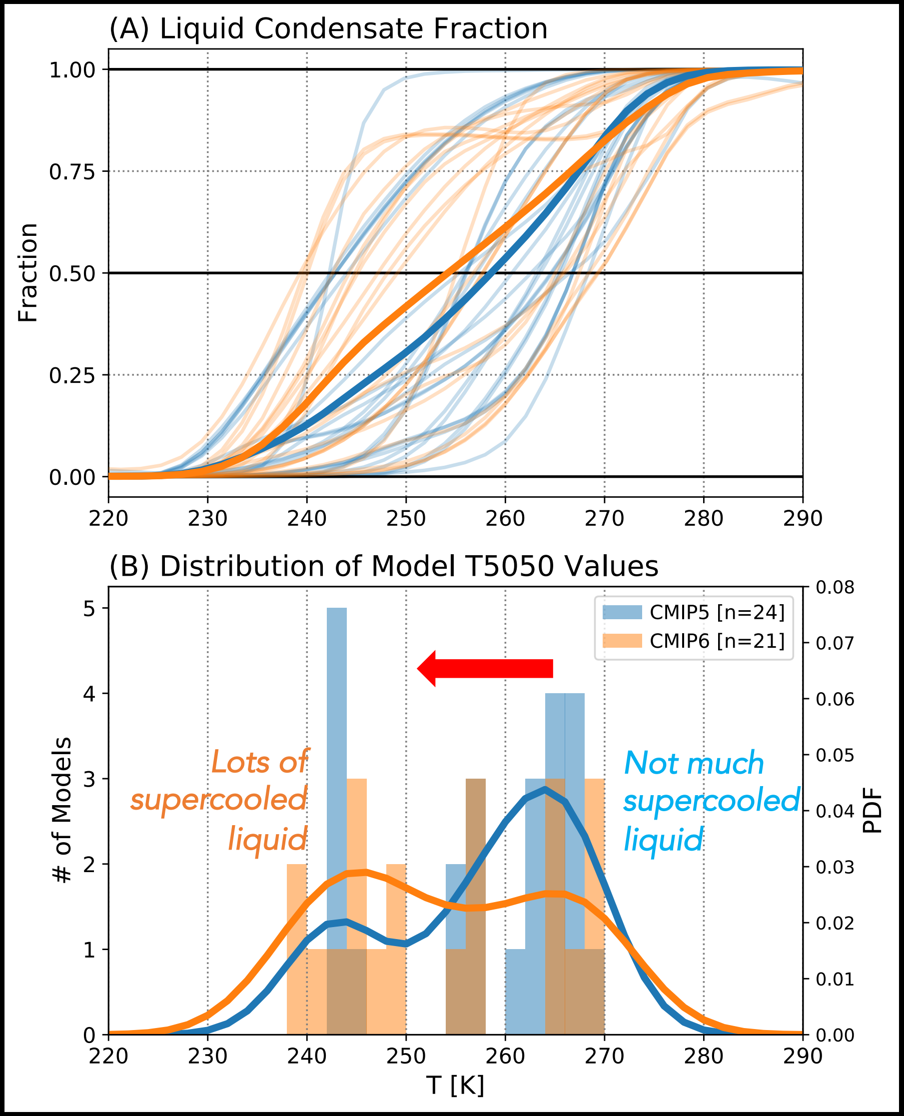

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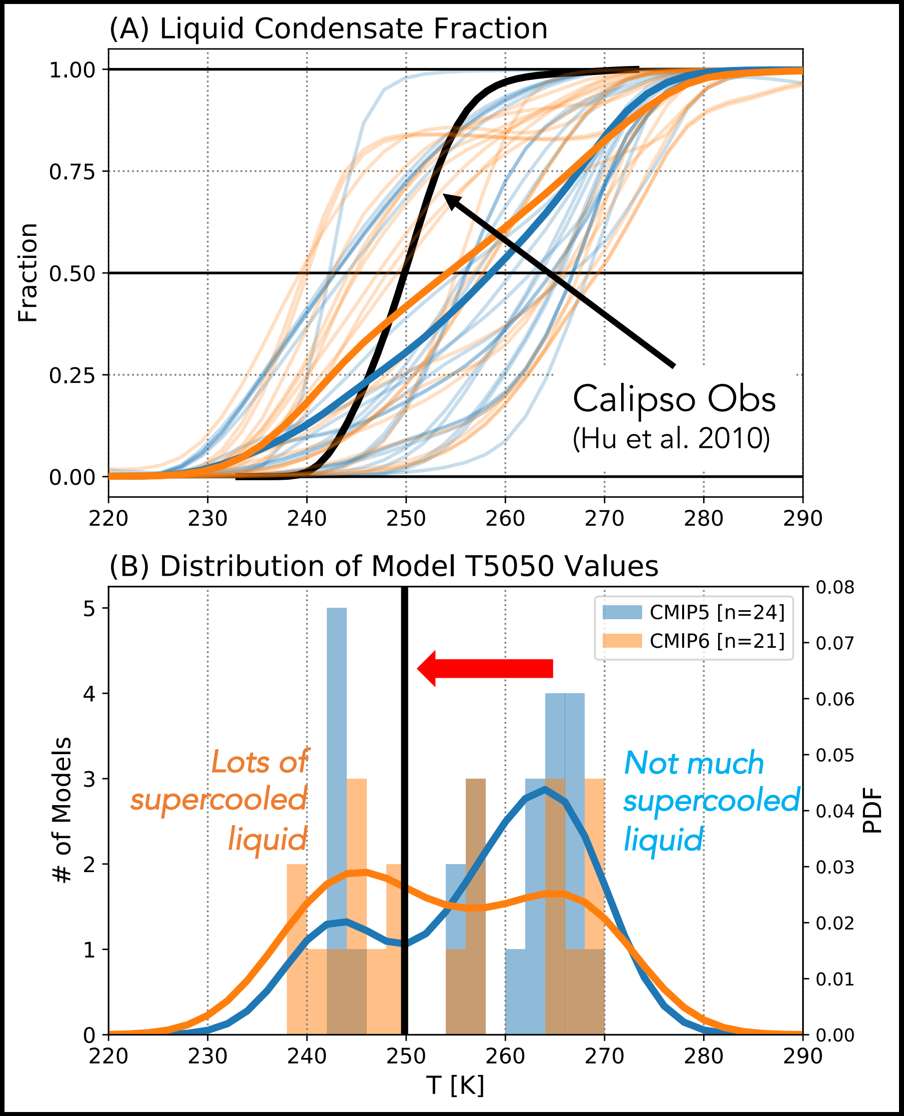
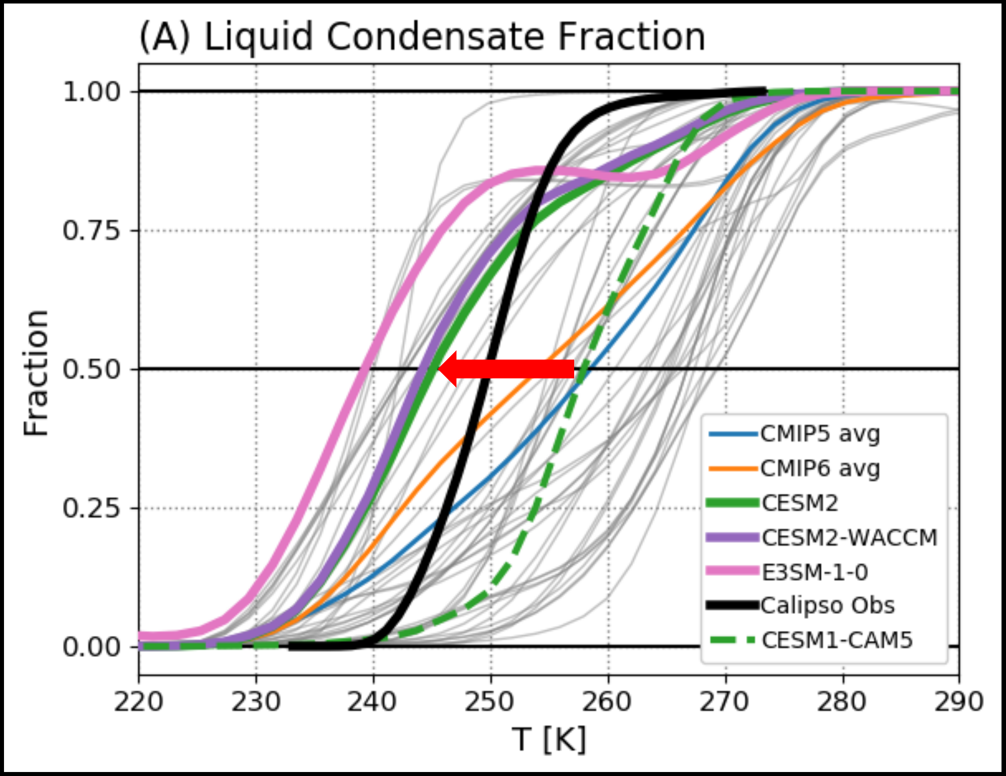
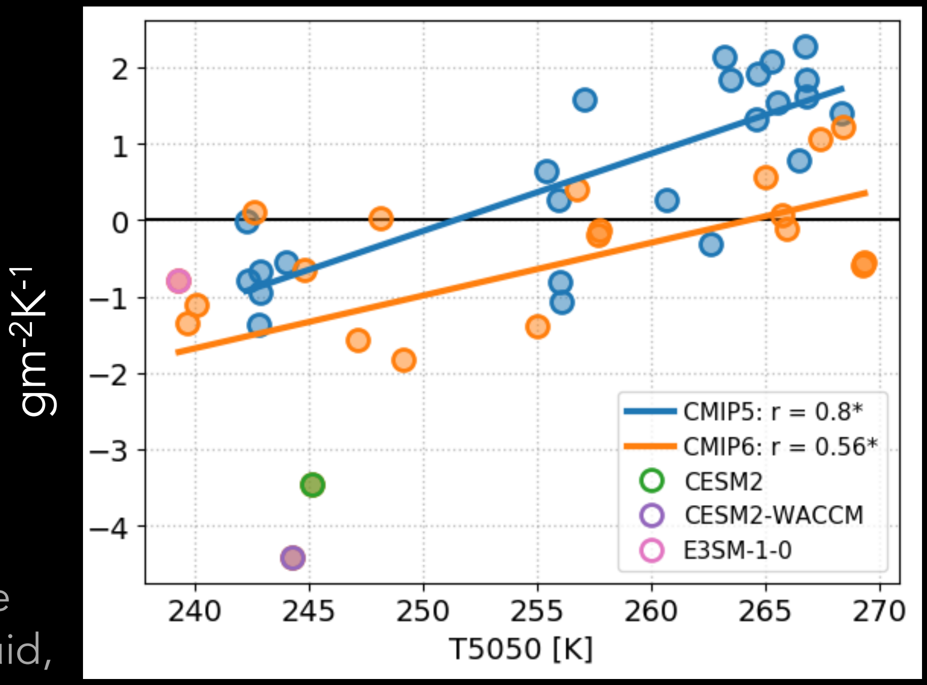


CESM2 & E3SM among the supercool kids …may have overshot



Cloud phase as a potential root cause of increased extratropical cloud feedbacks

ΔLWP_{low} [30-60˚S]



Less mean-state supercooled liquid, larger increase in LWP with warming

More mean-state supercooled liquid, larger decrease in LWP with warming

Conclusions

- The mean and inter-model spread in ECS has increased markedly in CMIP6.
  - Neither of these changes are statistically significant at 95% confidence
  - ECS > 4.5˚C in 14 of 40 CMIP6 models, including E3SM and all CESM2 variants

- Highest ECS values arise from strong positive feedbacks + moderate forcing.

- Increase in mean ECS in CMIP6 is attributable to…

  …stronger forcing (19%)

  …stronger positive feedbacks (52%), and

  …"steeper" anti-correlation between forcing and feedback (29%)

- Stronger positive feedback in CMIP6 is due to stronger decreases in low cloud coverage and albedo in the extratropics.
  - Both of these changes are tied to models' physical representation of clouds, with CMIP6 models showing weaker increases in extratropical low cloud cover and water content with SST.
  - Could be related to increased mean-state supercooled liquid fraction in CMIP6.
  - E3SM and CESM2: lots of supercooled liquid & big extratropical cloud feedbacks

Implications

✓ Global non-low cloud feedbacks are uniformly positive.
✓ Tropical low cloud feedbacks are uniformly positive.
✓ Extratropical low cloud scattering feedback has shifted to more positive values, possibly related to improved cloud phase.

All of these are qualitatively consistent with GCMs achieving a better match with theory, observations, and/or high-res modeling.
So is ECS higher than we previously thought?

Implications

- ✓ Global non-low cloud feedbacks are uniformly positive.
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All of these are qualitatively consistent with GCMs achieving a better match with theory, observations, and/or high-res modeling.
So is ECS higher than we previously thought?

Not necessarily.

1) We need to determine whether models' individual cloud feedbacks *quantitatively* agree with other constraints.
2) Moreover, any model-based inference that ECS is high needs to be evaluated alongside independent evidence [paleo, historical record].

https://github.com/mzelinka/cmip56_forcing_feedback_ecs
or just google "Mark Zelinka github"

mzelinka / **cmip56_forcing_feedback_ecs**

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Tables of ECS, Effective Radiative Forcing, and Radiative Feedbacks from Zelinka et al., GRL (2020).

Edit

Manage topics

19 commits | **1** branch | **0** packages | **0** releases | **1** contributor

Branch: master | New pull request | Create new file | Upload files | Find file | Clone or download

mzelinka updated json file — Latest commit 295311f 13 hours ago

CMIP5_ECS_ERF_fbks.txt	updated files to include multiple variants	19 hours ago
CMIP6_ECS_ERF_fbks.txt	updated files to include multiple variants	19 hours ago
CMIP6_ECS_ERF_fbks_nonflag.txt	updated files to include multiple variants	19 hours ago
README.md	added json tutorial to readme	17 hours ago
cmip56_forcing_feedback_ecs.json	updated json file	13 hours ago
gregory_plots_all_models_v2.pdf	Add files via upload	23 days ago

README.md

Summary

Two tables and a JSON file are provided containing effective climate sensitivity, effective 2xCO_2 radiative forcing, and radiative feedbacks for all CMIP5 and CMIP6 models that have published output from abrupt CO_2 quadrupling experiments. Also provided is a figure showing Gregory plots for the CMIP6 models. Methdology is described in Zelinka et al. (2020), but the CMIP6 results are regularly updated as new models are published.

Table Contents

For each model, the following global mean values are provided:

Abbreviation	Description	Units
ECS	effective climate sensitivity	K
ERF2x	2xCO_2 effective radiative forcing	Wm^{-2}

Conclusions

- Average ECS has increased by 0.5˚C in CMIP6; values > 4.5˚C in 14 of 40 models.
  - Neither the increase in multi-model mean, nor the increase in inter-model spread is statistically significant at 95% confidence

- Highest ECS values arise from weak radiative damping + moderately strong forcing.

- Increase in mean ECS in CMIP6 is attributable to…

  …stronger forcing (19%)

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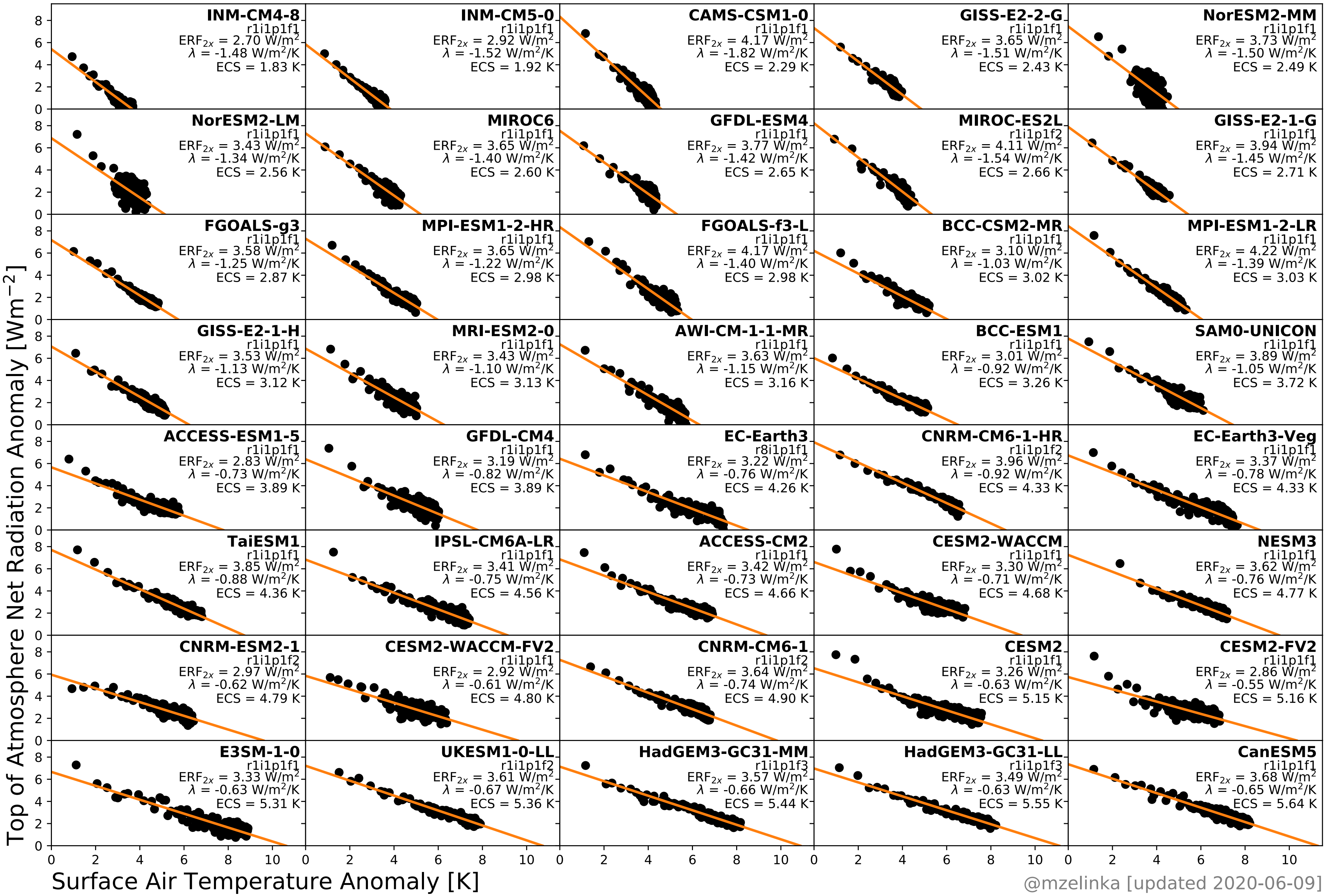
  …"steeper" anti-correlation between forcing and feedback (29%)

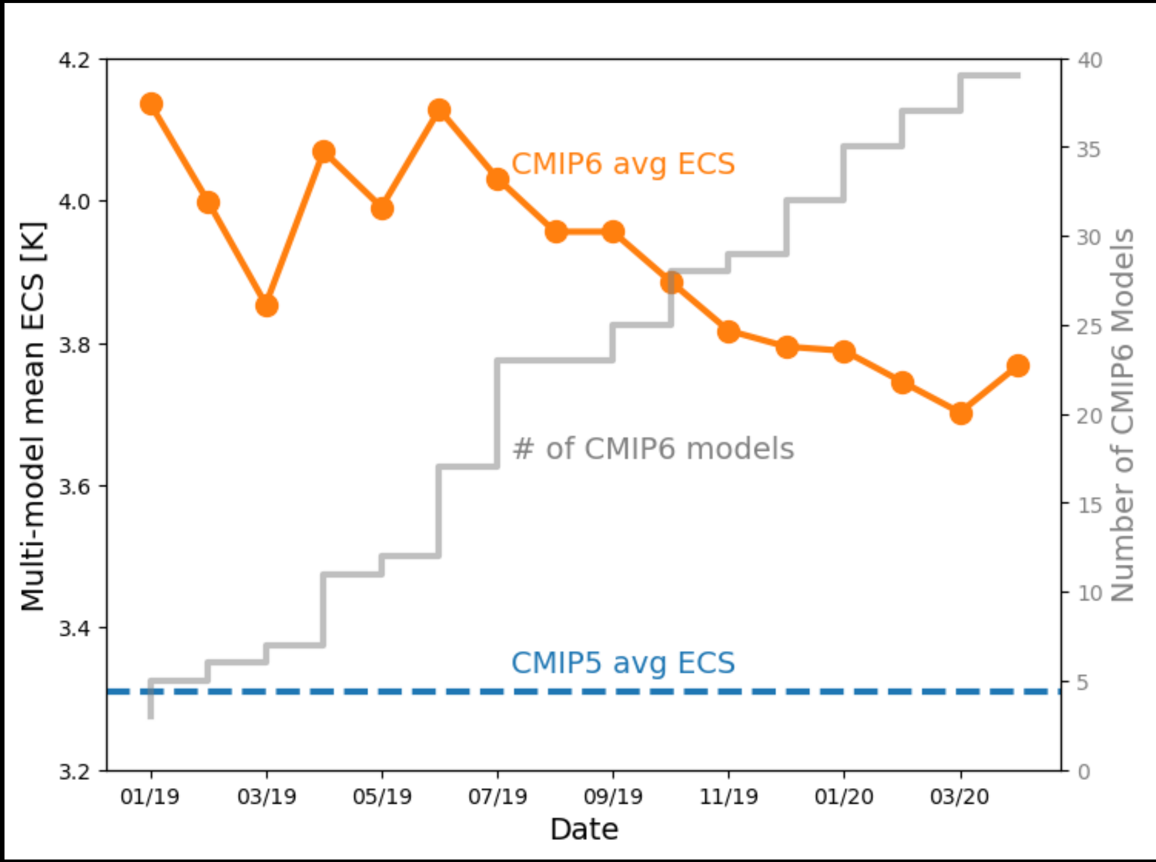
- Stronger positive feedback in CMIP6 is due to stronger decreases in low cloud coverage and albedo in the extratropics.
  - Both of these changes are tied to models' physical representation of clouds, with CMIP6 models showing weaker increases in extratropical low cloud cover and water content with SST.
  - Could be related to increased mean-state supercooled liquid fraction in CMIP6.

Extras

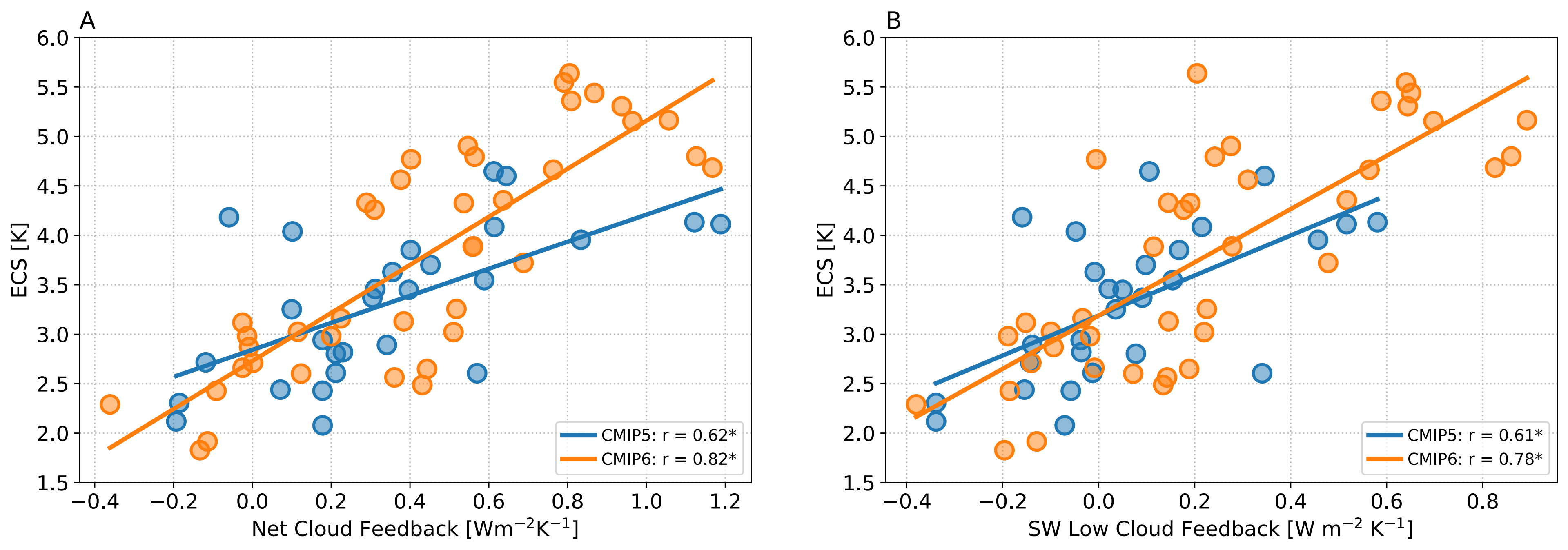


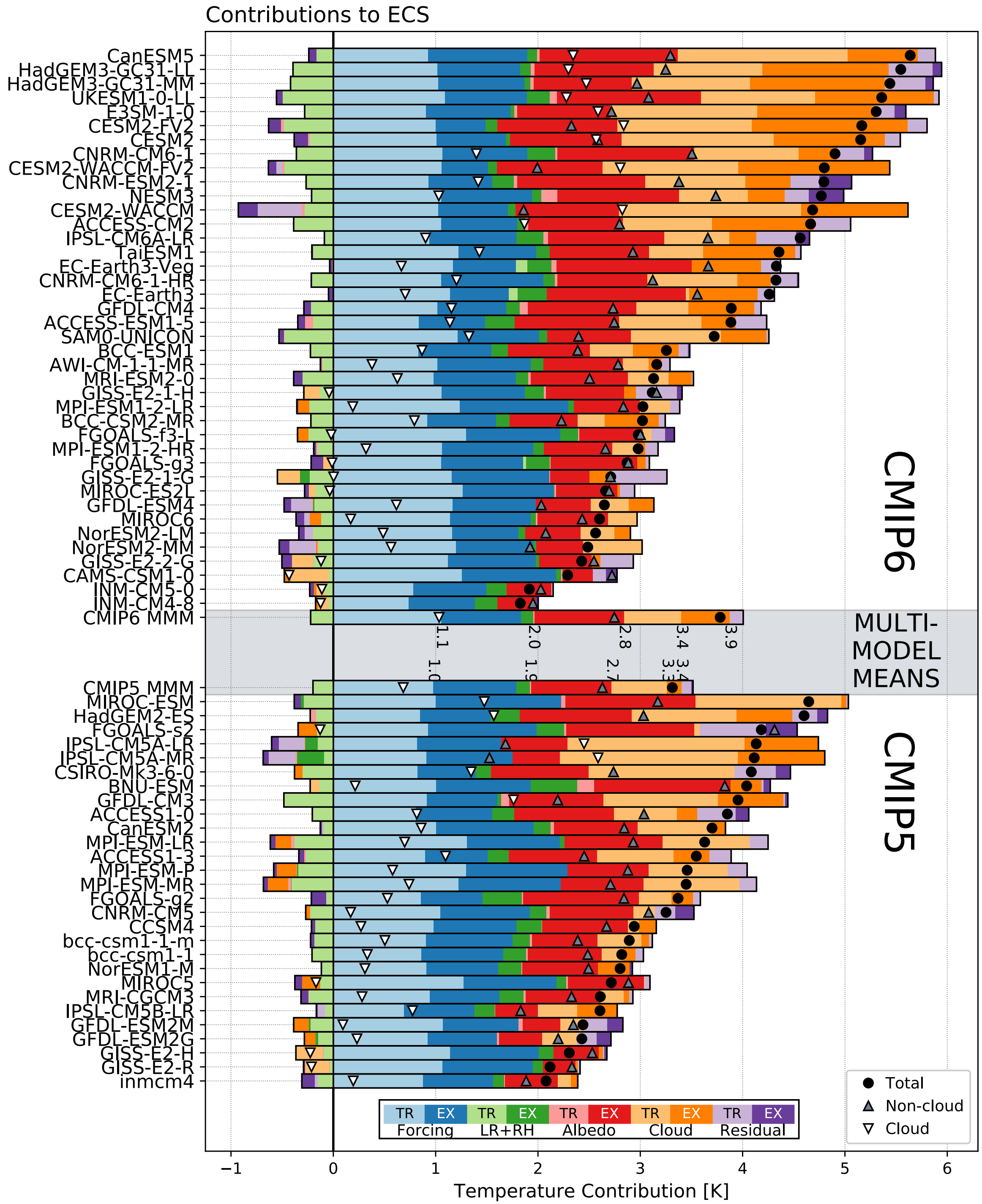
Note, these are for 4xCO2, so ECS and F are ½ of the intercepts

Evolution of CMIP6 mean ECS

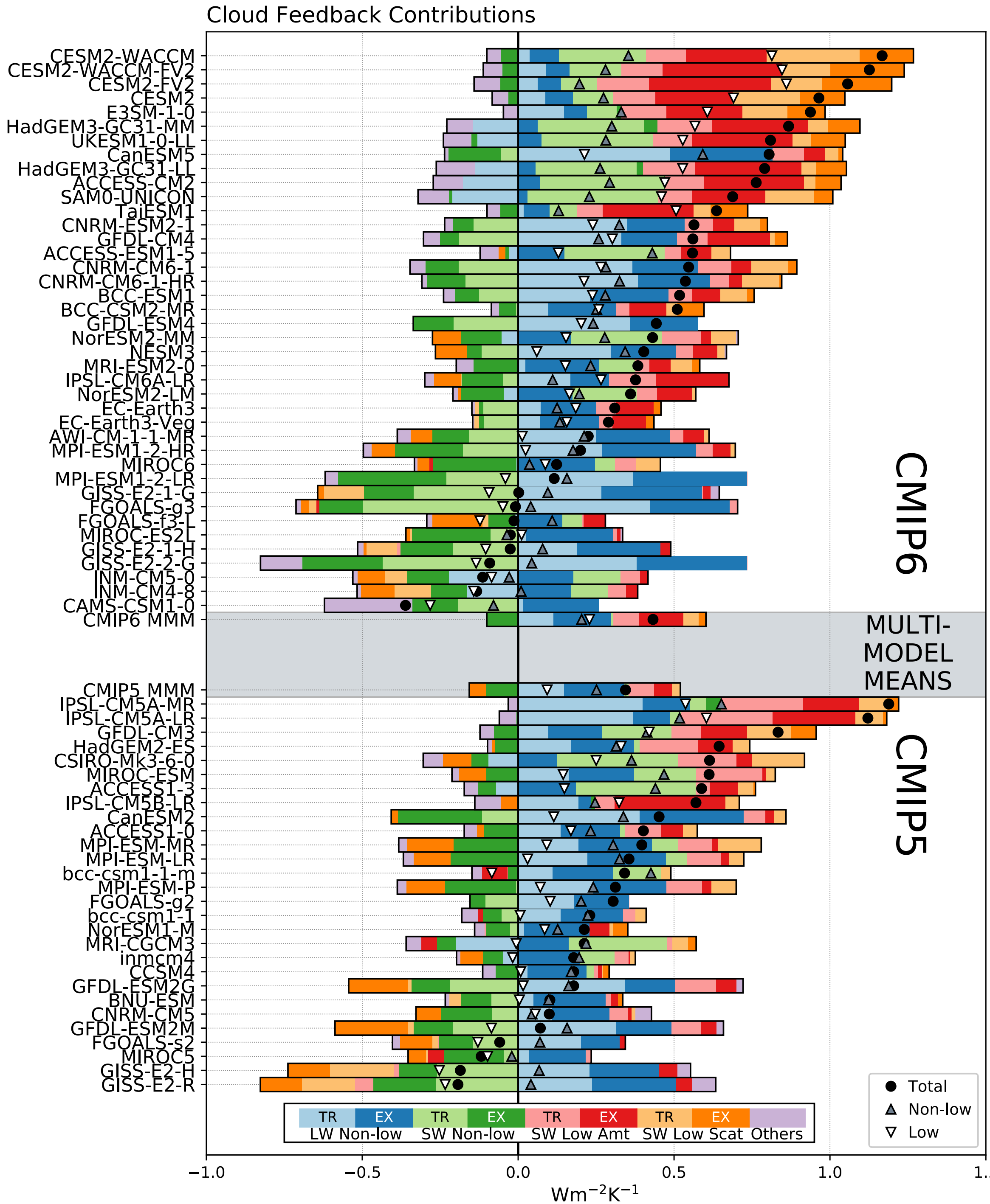


Dates are *roughly* when enough complete data were present @PCMDI for a model to be included in my analysis

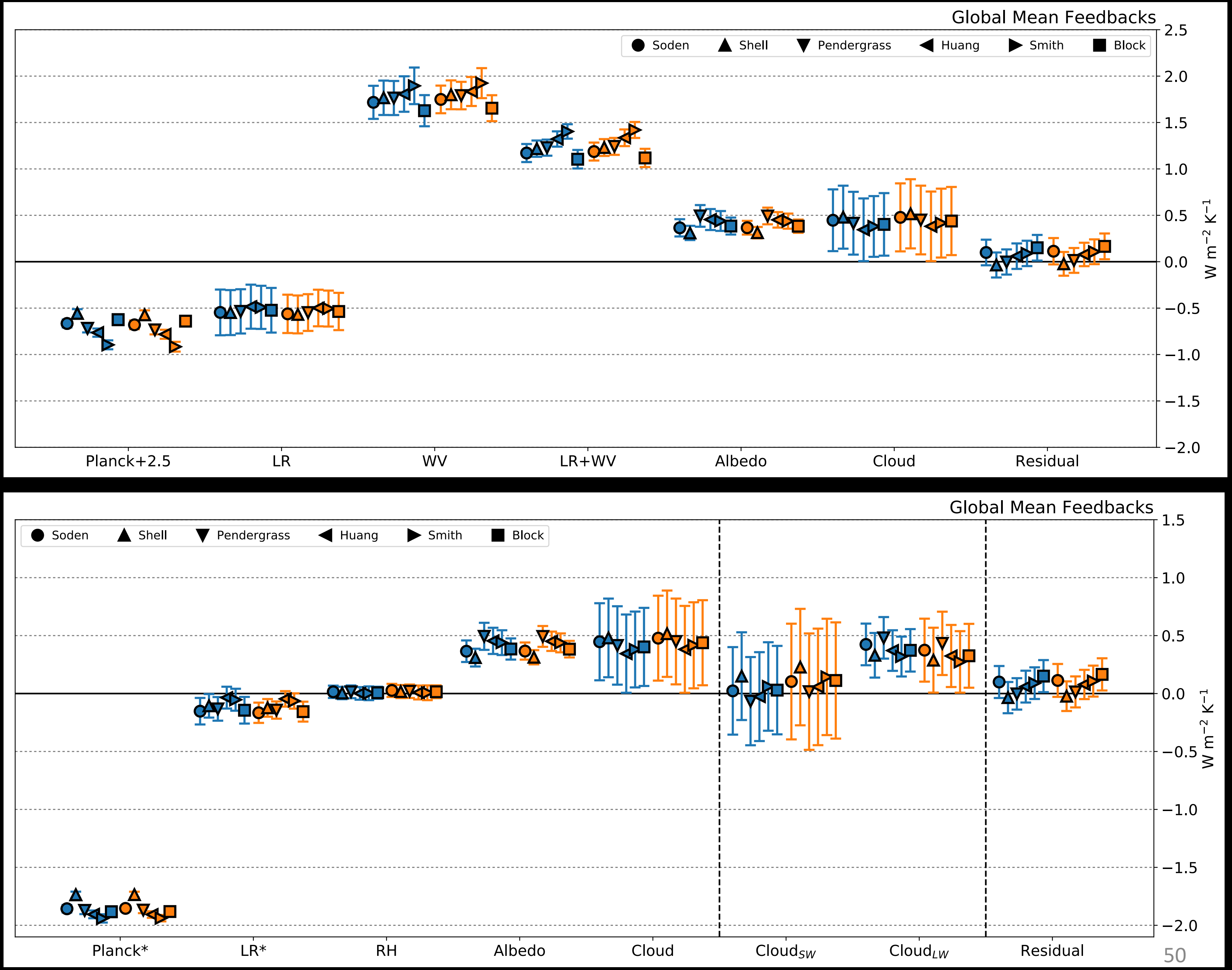

A
ECS [K]
Net Cloud Feedback [Wm^{-2}K^{-1}]
CMIP5: r = 0.62*
CMIP6: r = 0.82*
B
ECS [K]
SW Low Cloud Feedback [W m^{-2} K^{-1}]
CMIP5: r = 0.61*
CMIP6: r = 0.78*



Contributions to ECS
CanESM5
HadGEM3-GC31-LL
HadGEM3-GC31-MM
UKESM1-0-LL
E3SM-1-0
CESM2-FV2
CESM2
CNRM-CM6-1
CESM2-WACCM-FV2
CNRM-ESM2-1
NESM3
CESM2-WACCM
ACCESS-CM2
IPSL-CM6A-LR
TaiESM1
EC-Earth3-Veg
CNRM-CM6-1-HR
EC-Earth3
GFDL-CM4
ACCESS-ESM1-5
SAM0-UNICON
BCC-ESM1
AWI-CM-1-1-MR
MRI-ESM2-0
GISS-E2-1-H
MPI-ESM1-2-LR
BCC-CSM2-MR
FGOALS-f3-L
MPI-ESM1-2-HR
FGOALS-g3
GISS-E2-1-G
MIROC-ES2L
GFDL-ESM4
MIROC6
NorESM2-LM
NorESM2-MM
GISS-E2-2-G
CAMS-CSM1-0
INM-CM5-0
INM-CM4-8
CMIP6 MMM
CMIP5 MMM
MIROC-ESM
HadGEM2-ES
FGOALS-s2
IPSL-CM5A-LR
IPSL-CM5A-MR
CSIRO-Mk3-6-0
BNU-ESM
GFDL-CM3
ACCESS1-0
CanESM2
MPI-ESM-LR
ACCESS1-3
MPI-ESM-P
MPI-ESM-MR
FGOALS-g2
CNRM-CM5
CCSM4
bcc-csm1-1-m
bcc-csm1-1
NorESM1-M
MIROC5
MRI-CGCM3
IPSL-CM5B-LR
GFDL-ESM2M
GFDL-ESM2G
GISS-E2-H
GISS-E2-R
inmcm4
CMIP6
MULTI-MODEL MEANS
CMIP5
1.1 2.0 2.8 3.4 3.9
1.0 1.9 2.7 3.3 3.4
TR EX TR EX TR EX TR EX TR EX
Forcing LR+RH Albedo Cloud Residual
Total
Non-cloud
Cloud
−1 0 1 2 3 4 5 6
Temperature Contribution [K]



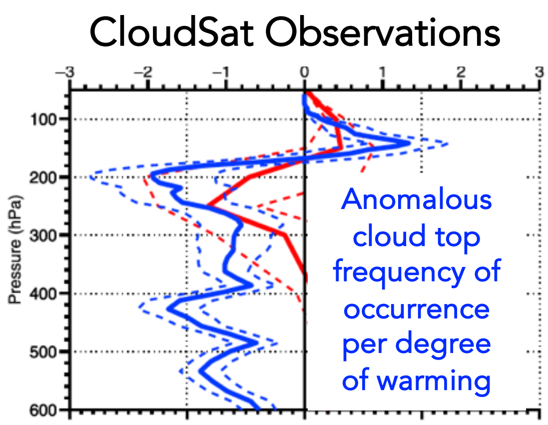
Cloud Feedback Contributions
CESM2-WACCM
CESM2-WACCM-FV2
CESM2-FV2
CESM2
E3SM-1-0
HadGEM3-GC31-MM
UKESM1-0-LL
CanESM5
HadGEM3-GC31-LL
ACCESS-CM2
SAM0-UNICON
TaiESM1
CNRM-ESM2-1
GFDL-CM4
ACCESS-ESM1-5
CNRM-CM6-1
CNRM-CM6-1-HR
BCC-ESM1
BCC-CSM2-MR
GFDL-ESM4
NorESM2-MM
NESM3
MRI-ESM2-0
IPSL-CM6A-LR
NorESM2-LM
EC-Earth3
EC-Earth3-Veg
AWI-CM-1-1-MR
MPI-ESM1-2-HR
MIROC6
MPI-ESM1-2-LR
GISS-E2-1-G
FGOALS-g3
FGOALS-f3-L
MIROC-ES2L
GISS-E2-1-H
GISS-E2-2-G
INM-CM5-0
INM-CM4-8
CAMS-CSM1-0
CMIP6 MMM
CMIP6
MULTI-MODEL MEANS
CMIP5 MMM
IPSL-CM5A-MR
IPSL-CM5A-LR
GFDL-CM3
HadGEM2-ES
CSIRO-Mk3-6-0
MIROC-ESM
ACCESS1-3
IPSL-CM5B-LR
CanESM2
ACCESS1-0
MPI-ESM-MR
MPI-ESM-LR
bcc-csm1-1-m
MPI-ESM-P
FGOALS-g2
bcc-csm1-1
NorESM1-M
MRI-CGCM3
inmcm4
CCSM4
GFDL-ESM2G
BNU-ESM
CNRM-CM5
GFDL-ESM2M
FGOALS-s2
MIROC5
GISS-E2-H
GISS-E2-R
CMIP5
Total
Non-low
Low
TR EX TR EX TR EX TR EX
LW Non-low SW Non-low SW Low Amt SW Low Scat Others
−1.0 −0.5 0.0 0.5 1.0 1.5
$Wm^{-2}K^{-1}$



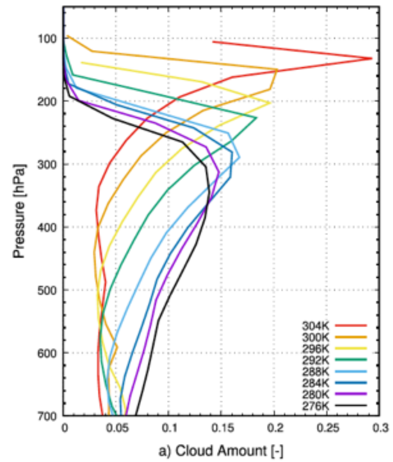
Global Mean Feedbacks
Soden
Shell
Pendergrass
Huang
Smith
Block
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
W m^{-2} K^{-1}
Planck+2.5
LR
WV
LR+WV
Albedo
Cloud
Residual
Global Mean Feedbacks
Soden
Shell
Pendergrass
Huang
Smith
Block
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
W m^{-2} K^{-1}
Planck*
LR*
RH
Albedo
Cloud
Cloud$_{SW}$
Cloud$_{LW}$
Residual

High confidence in <u>positive</u> feedback from high clouds rising w/warming.

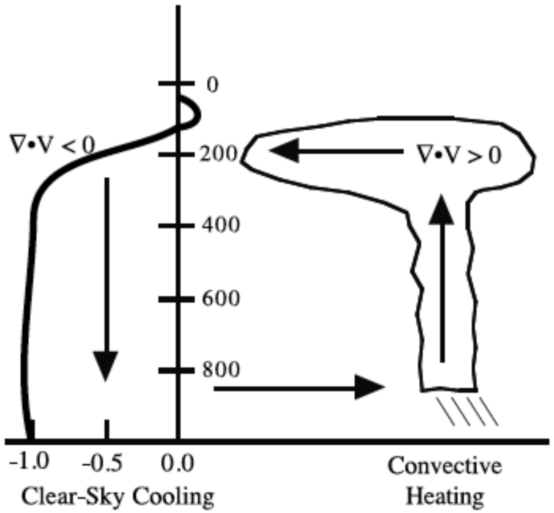
- <u>Observational</u> support from tropical inter-annual variability
- <u>Fine-scale model</u> support from simulations of tropical radiative convective equilibrium
- <u>Theory</u>: High cloud tops rise as a consequence of radiative-convective equilibrium, as articulated in the fixed anvil temperature (FAT) hypothesis [Hartmann & Larson, 2002].



Zelinka & Hartmann, *JGR* [2011]

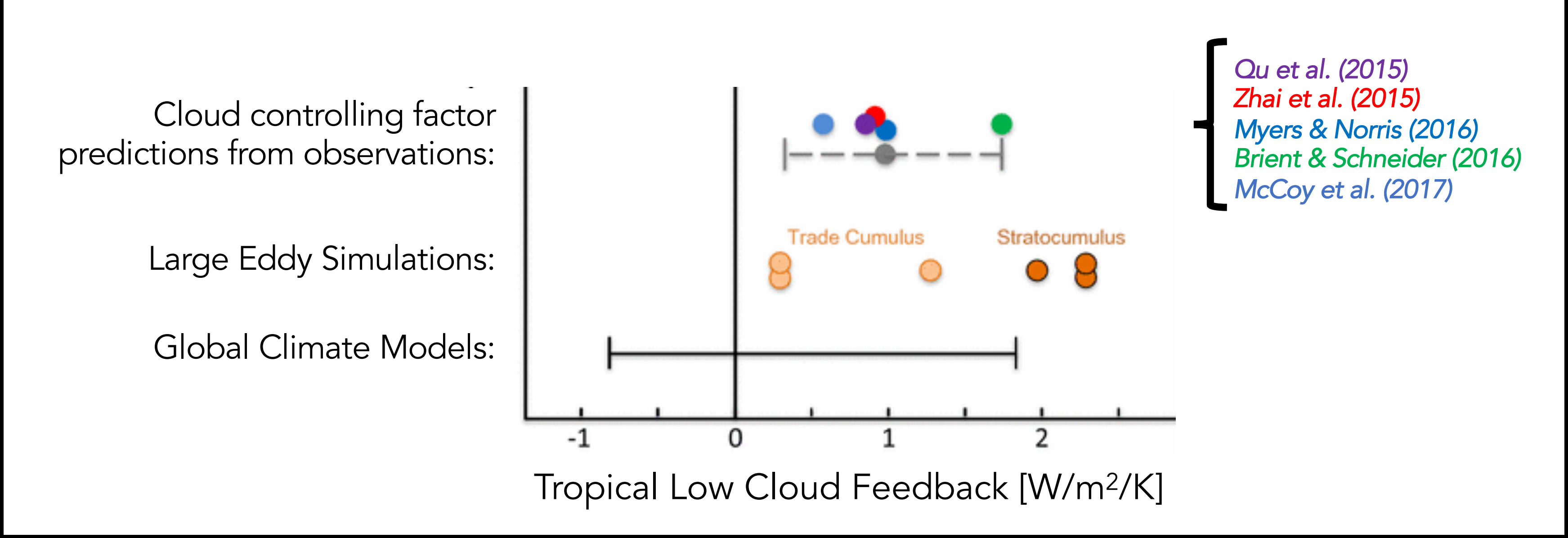


Ohno & Satoh, *JAMES* [2018]



Hartmann & Larson, *GRL* [2002]

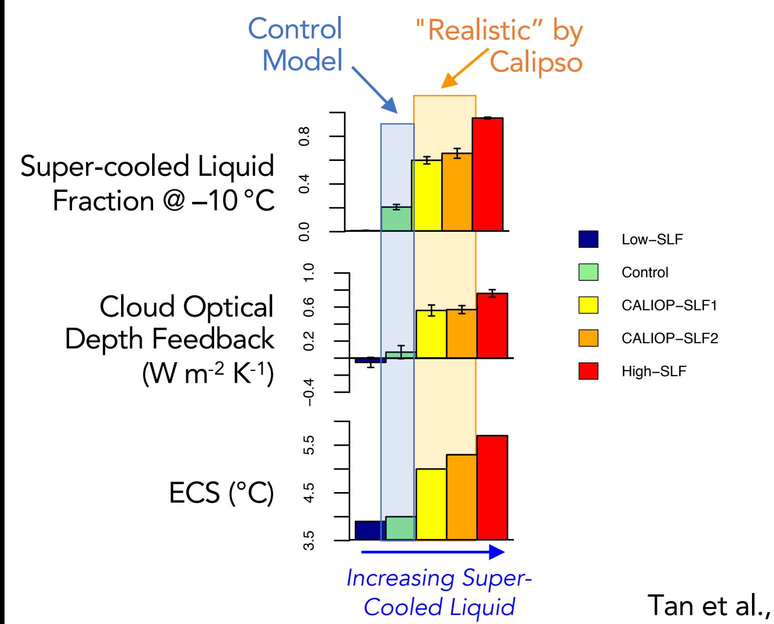
Observations and high-resolution modeling agree that tropical low cloud feedbacks should be **positive**.



Modified from Klein et al., *Surv. Geophys.* [2017]

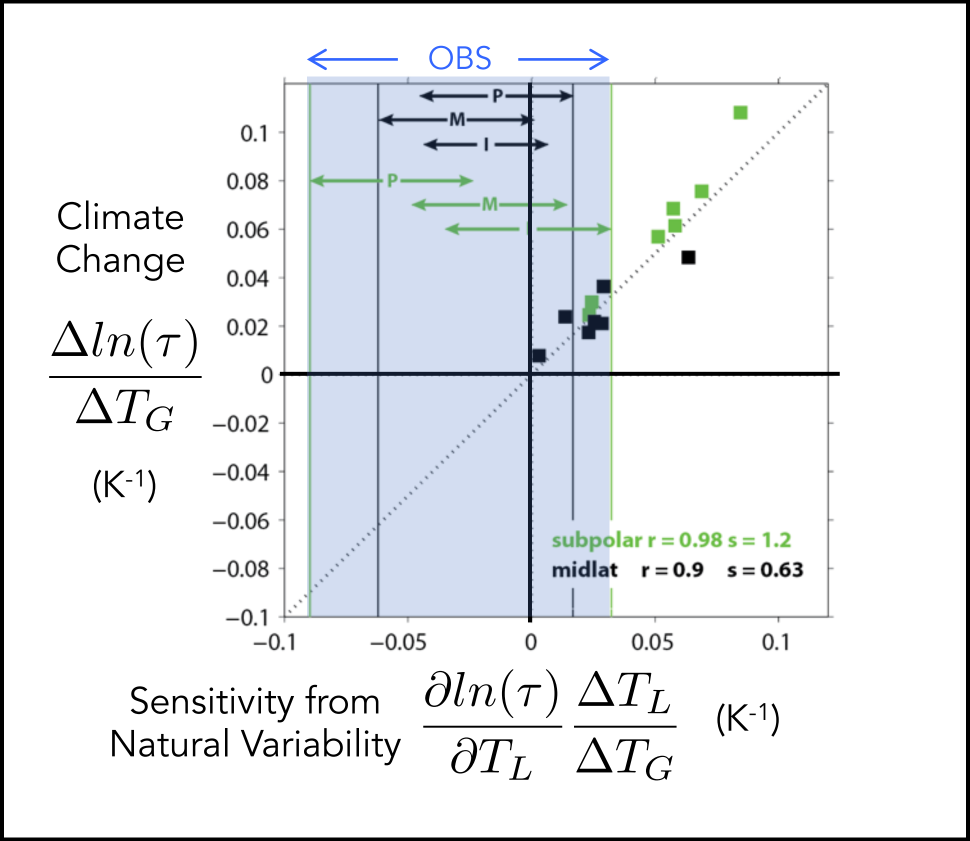
Models lack sufficient super-cooled liquid. Eliminating this bias increases ECS.

- Observational analyses indicate that models exaggerate extratropical clouds brightening with warming
- Part of this is likely related to a too-strong 'phase feedback' from ice transitioning to liquid
- Increasing the present-day amount of super-cooled liquid in accord with Calipso observations increases climate sensitivity markedly in CAM5 (*Tan et al. 2016; Frey & Kay 2017*)
- Multi-model analysis supports this view (*McCoy et al. 2016*)



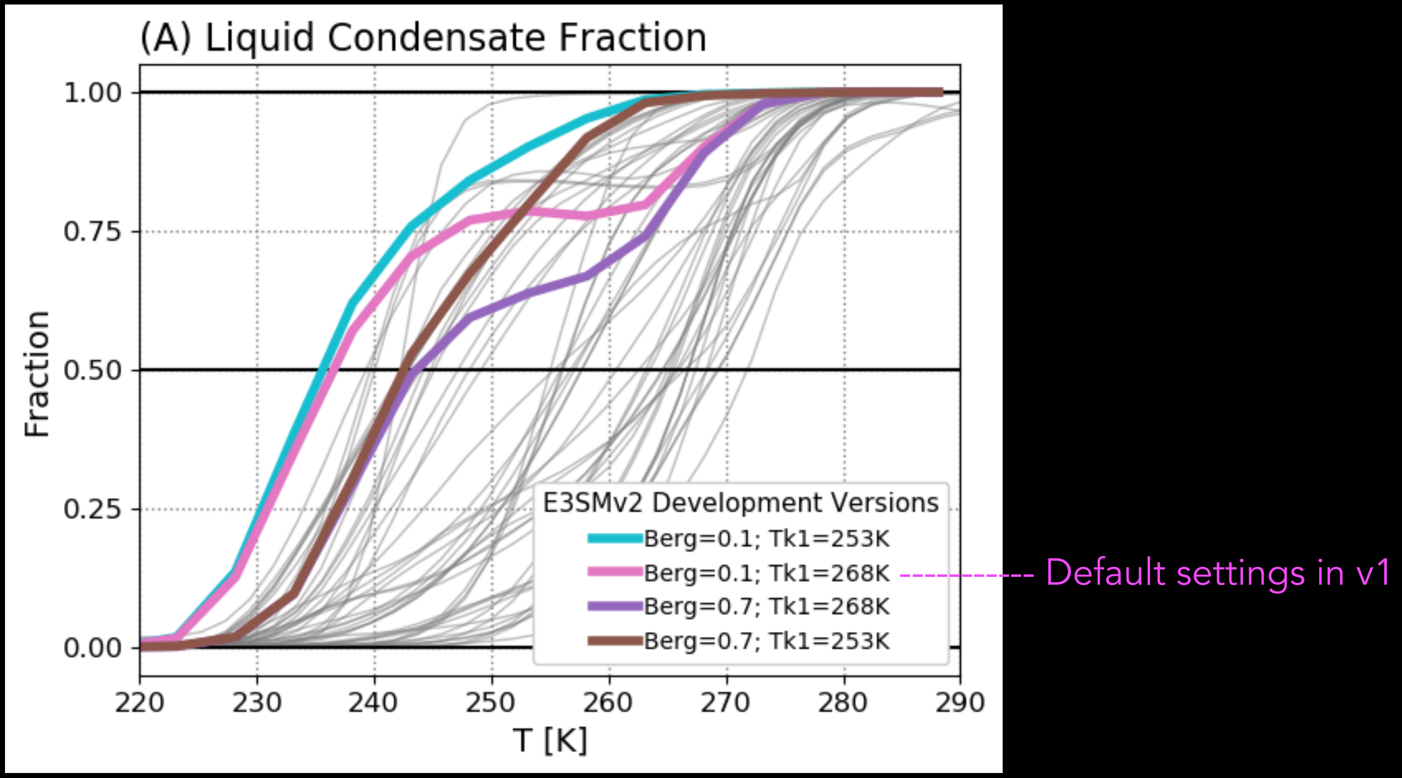
Tan et al., *Science* [2016]

Cloud-Controlling Factor Analysis: An example w/ cloud optical depth



Terai et al., *JGR* [2016]
Gordon & Klein, *JGR* [2014]

Punchline: *current-climate sensitivities are highly relevant for long-term response …so observations of the former can help constrain the latter.*



Simulations by Xue Zheng (LLNL)
loosely following *Kay et al (2016)*