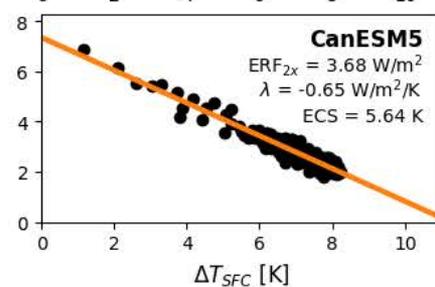
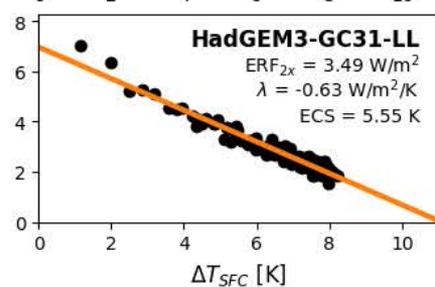
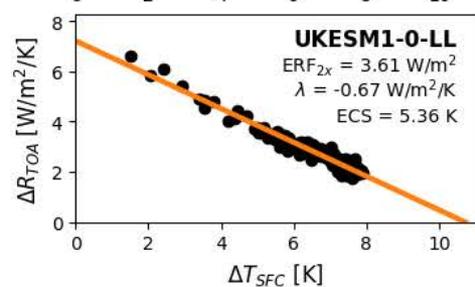
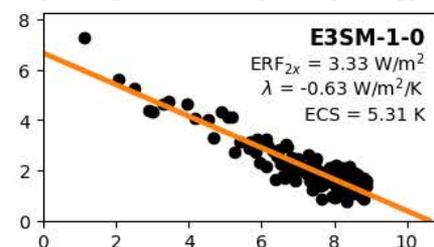
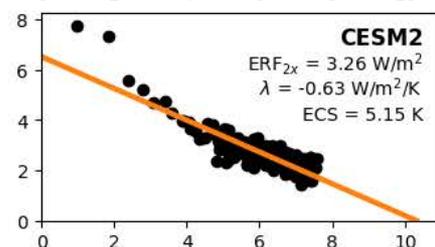
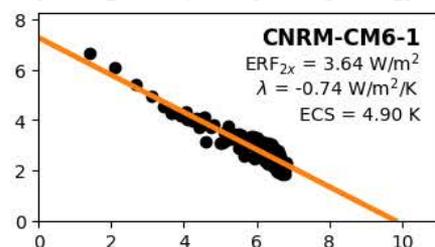
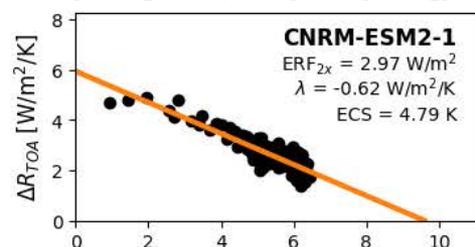
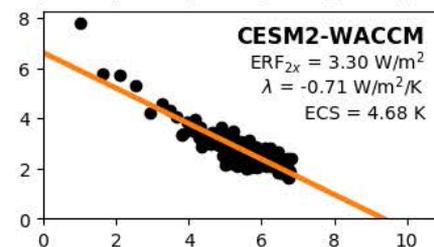
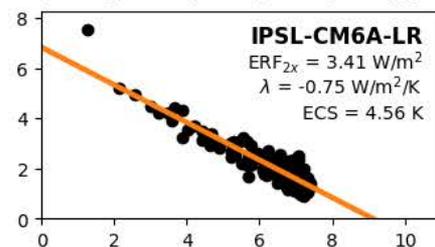
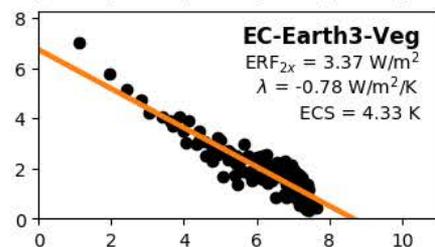
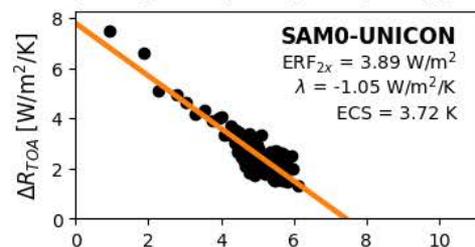
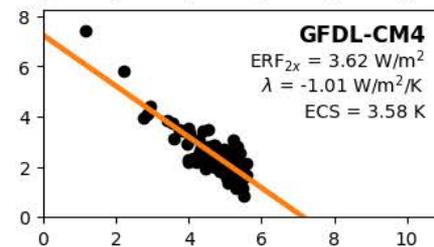
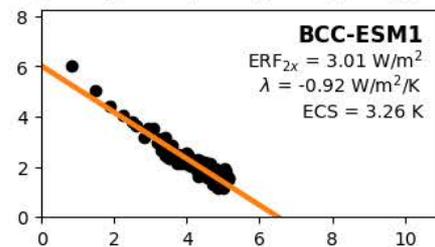
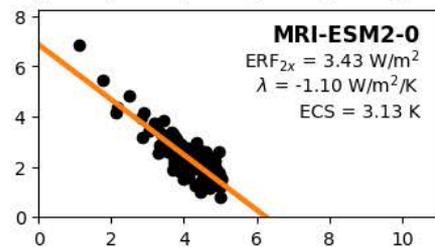
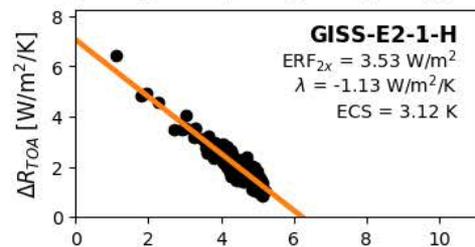
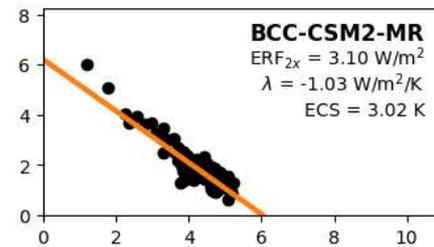
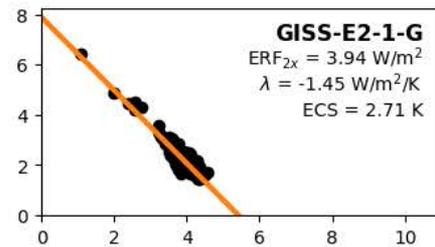
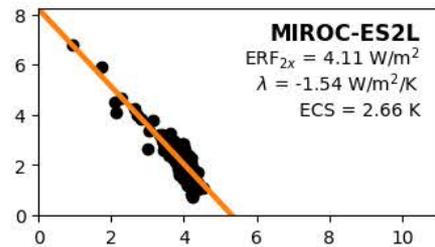
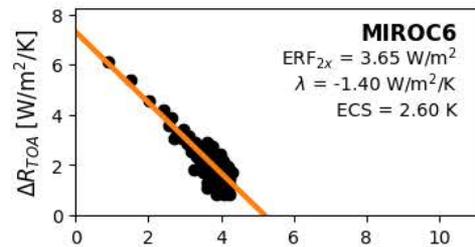


Forcing, Feedback, and Climate Sensitivity in CMIP6

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

CFMIP Meeting 2019

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$$R = F + \lambda T$$

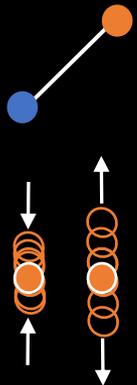
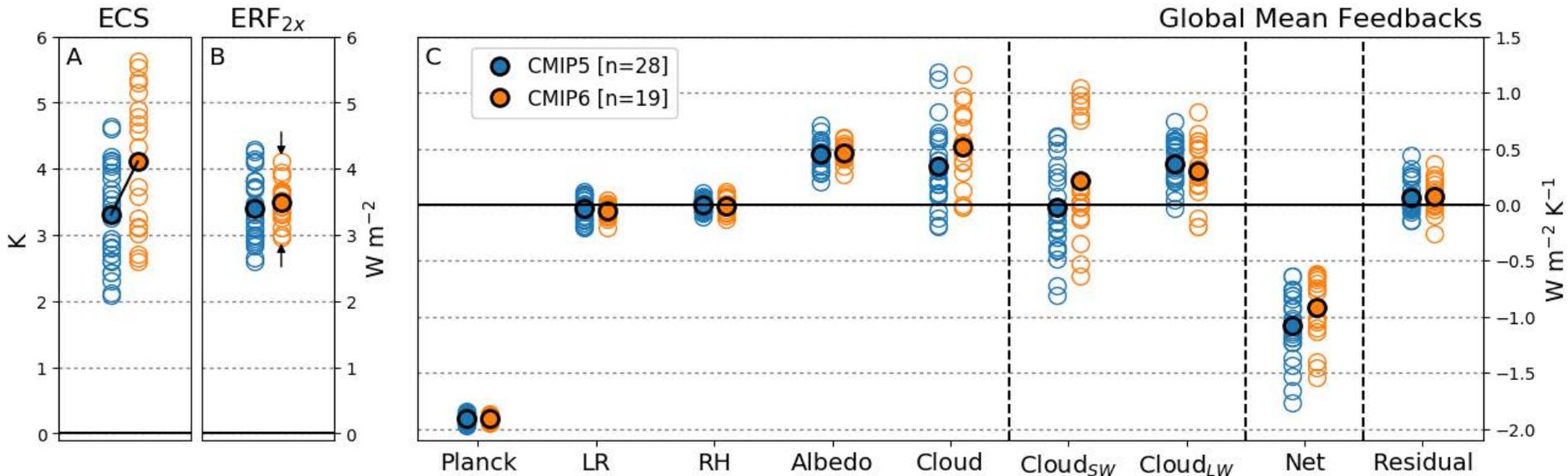
$$ECS = -F_{2x} / \lambda$$

Feedback Diagnosis

- We decompose the radiative feedback parameter (λ) into individual components using *Huang et al. (2017)* radiative kernels
 - Other kernels give consistent results; these ones yield smallest residuals
- We report constant RH feedbacks [*Held & Shell 2012*]

ECS, Forcings, & Feedbacks

CMIP5 vs CMIP6

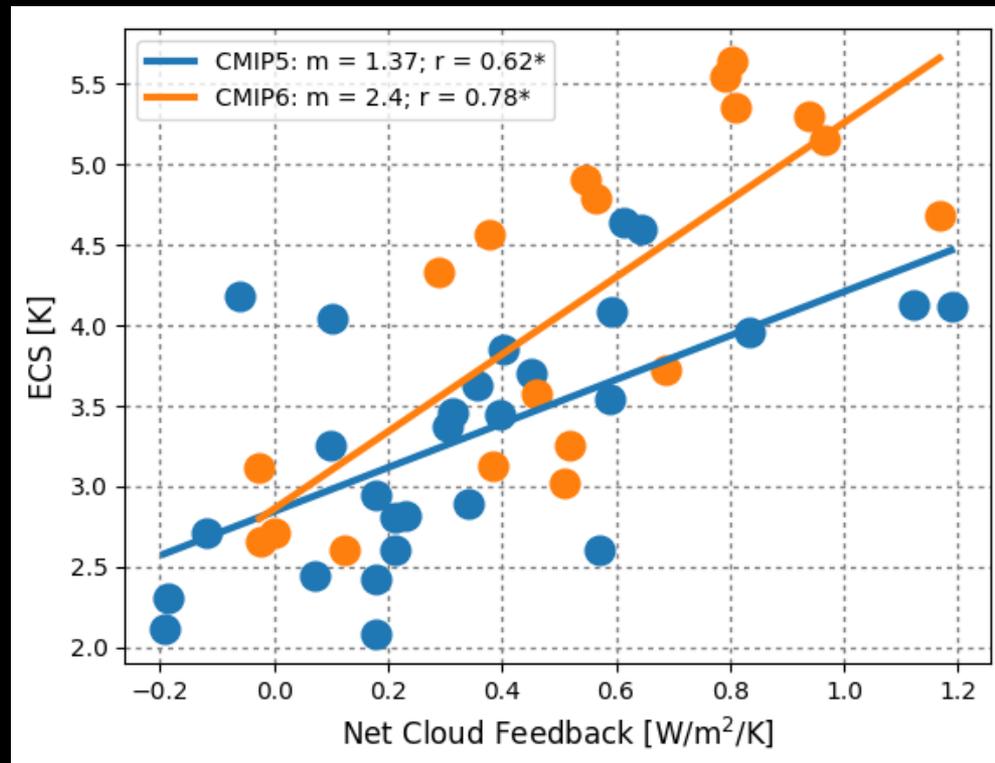


Means are deemed significantly different if the 2-tailed p value of the Welch's t -test for equal means is less than 0.05.

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

Same as the old boss



As with previous generations of models*, the cloud feedback exhibits the largest inter-model spread of all feedbacks and is highly correlated with ECS, with a stronger correlation in CMIP6

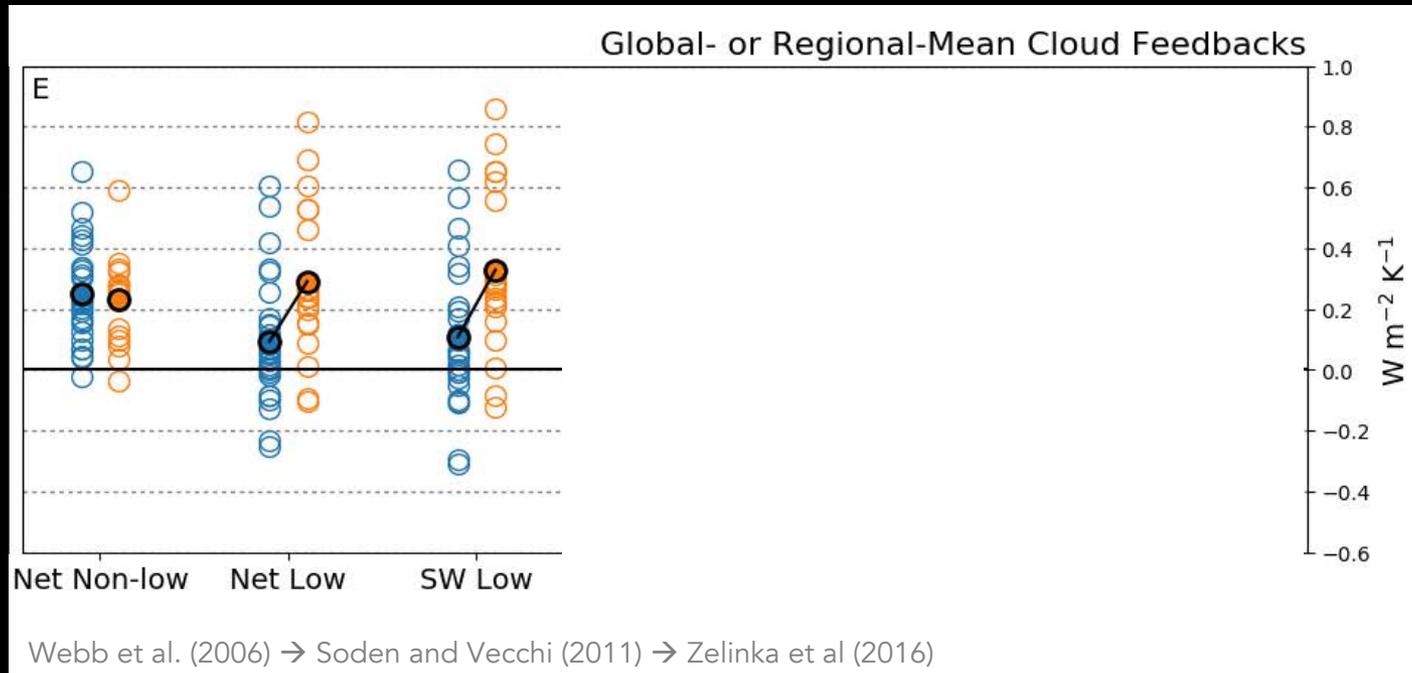
*Cess et al. (1989, 1990); Soden & Held (2006); Dufresne & Bony (2008); Webb et al. (2013)

Why has the cloud feedback increased in CMIP6?

- ISCCP simulator output is limited, so we rely on two alternative methods to detail the cloud feedback:
 - *Webb et al (2006)* to separate feedback into contributions from **clouds at different heights**
 - Inspired by *Soden and Vecchi (2011)* we aggregate Webb's 8 categories into a smaller subset (low and non-low)
 - APRP method of *Taylor et al (2007)* to separate SW cloud feedback into contributions from **cloud amount & scattering**

Cloud Feedbacks

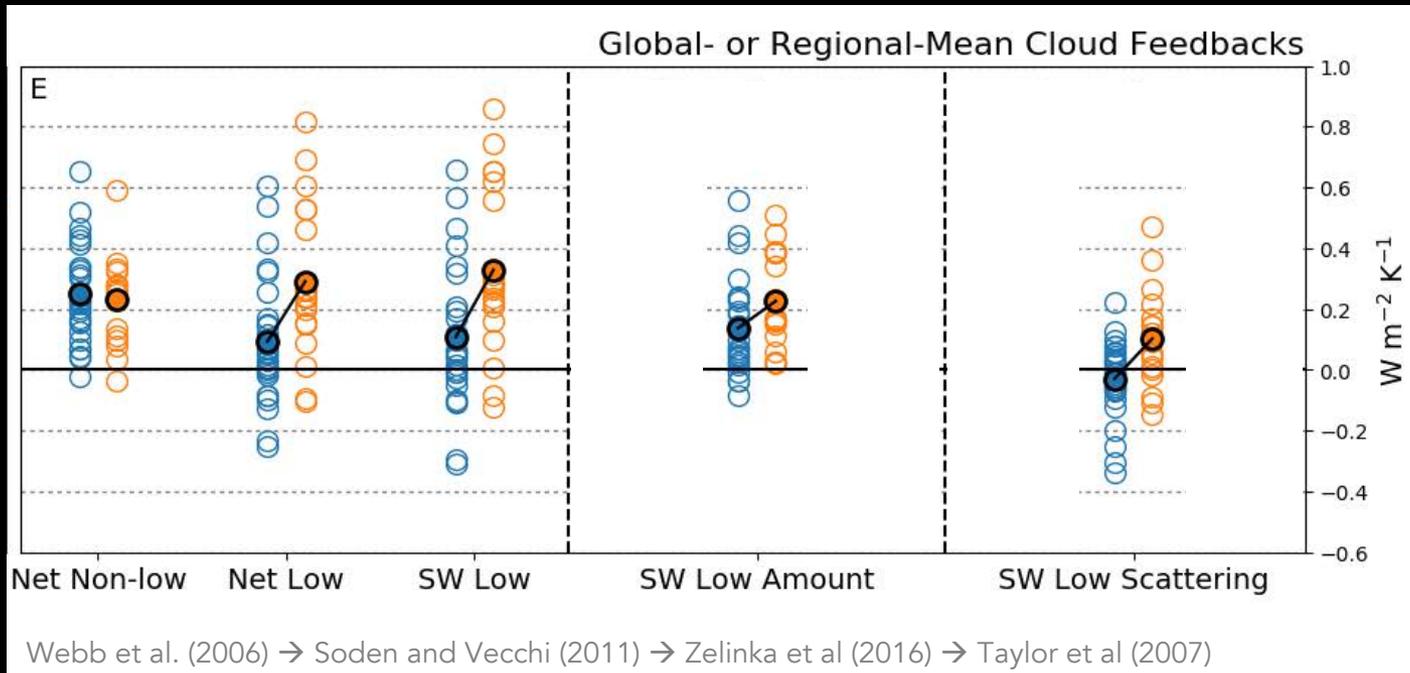
CMIP5 vs CMIP6



- Net non-low cloud feedback is positive in all but one GCM; mean is essentially unchanged
- Net/SW low cloud feedback is shifted upwards, with a significantly larger mean
- SW low cloud feedback is highly correlated with ECS in both collections

Cloud Feedbacks

CMIP5 vs CMIP6

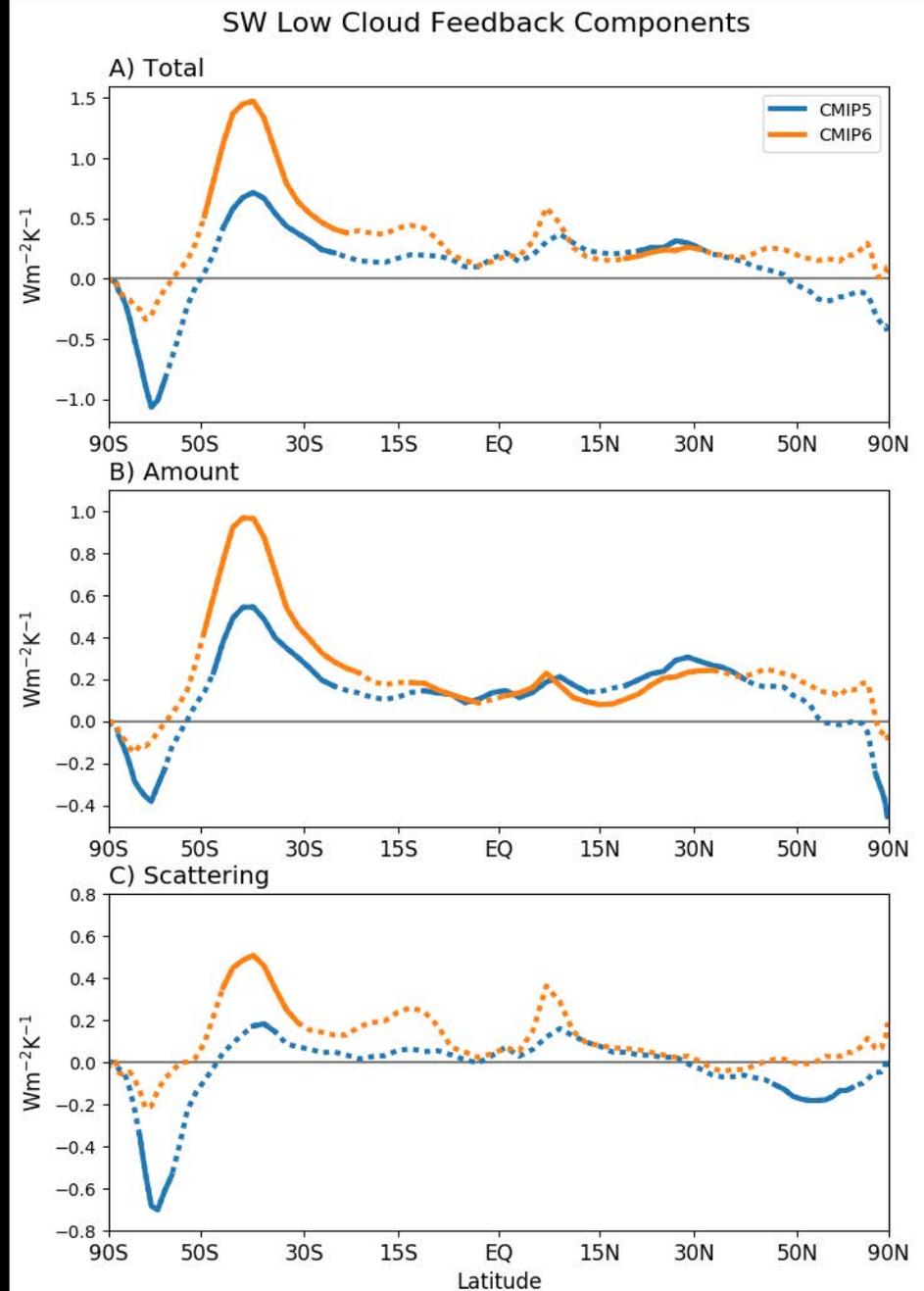


- Net non-low cloud feedback is positive in all but one GCM; mean is essentially unchanged
- Net/SW low cloud feedback is shifted upwards, with a significantly larger mean
- SW low cloud feedback is highly correlated with ECS in both collections
- Both amount and scattering components contribute roughly equally to the increase in multi-model mean SW low cloud feedback.

Cloud Feedbacks

CMIP5 vs CMIP6

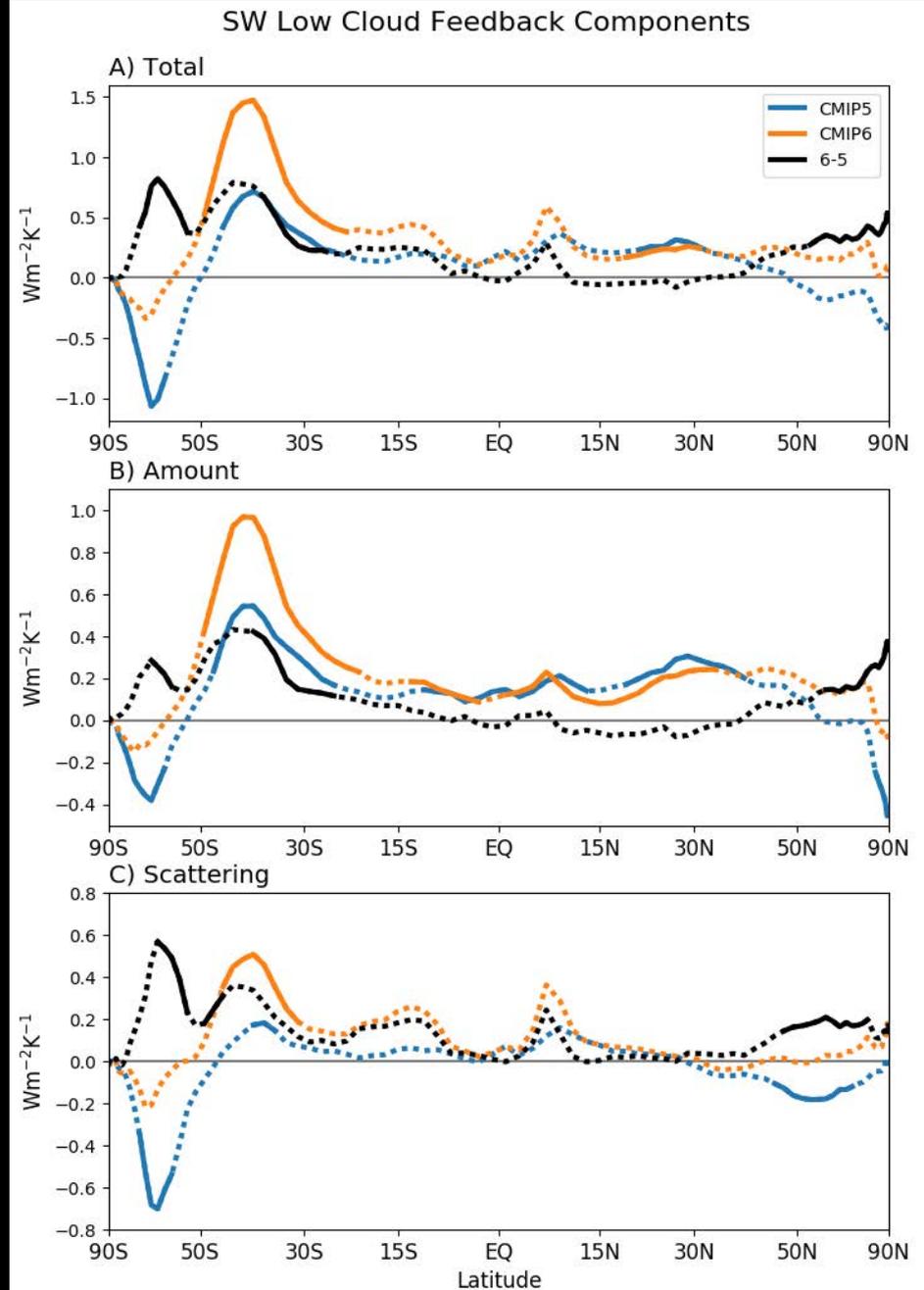
CMIP6 mean SW low cloud amount and scattering feedbacks (and their sum) are significantly more positive at middle-high latitudes



Cloud Feedbacks

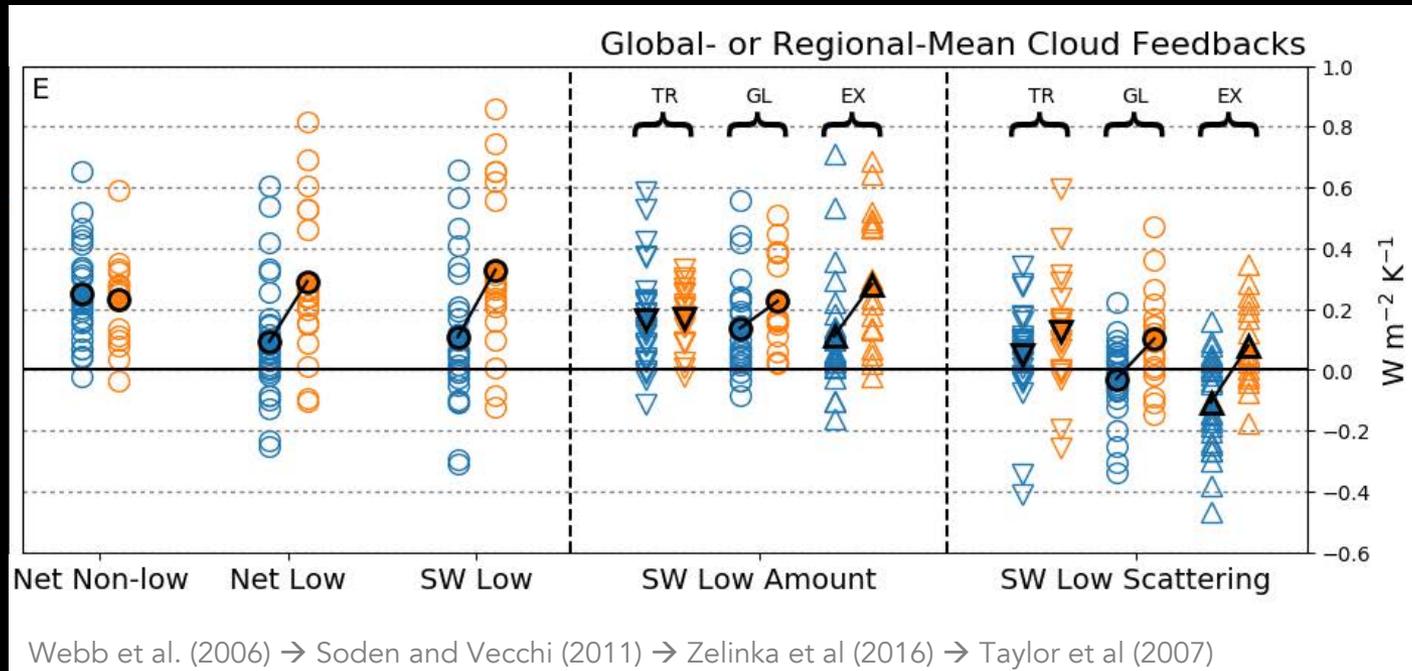
CMIP5 vs CMIP6

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



Cloud Feedbacks

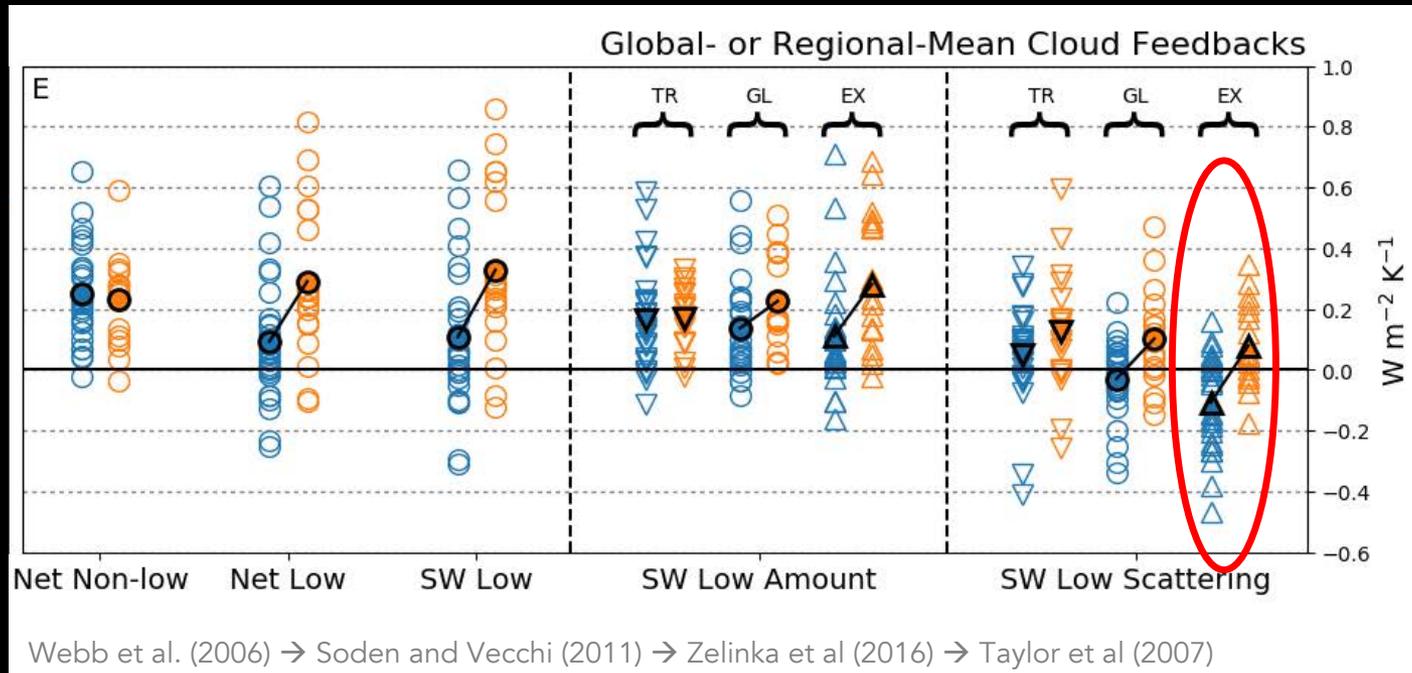
CMIP5 vs CMIP6



- Increase in SW low cloud feedbacks more dramatic & statistically significant in the extratropics.
- MMM extratropical SW low cloud scattering feedback changes from negative to positive
- MMM low cloud amount feedback is actually larger in the extratropics than in the tropics

Cloud Feedbacks

CMIP5 vs CMIP6



- Increase in SW low cloud feedbacks more dramatic & statistically significant in the extratropics.
- MMM extratropical SW low cloud scattering feedback changes from negative to positive
- MMM low cloud amount feedback is actually larger in the extratropics than in the tropics

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

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

So let's perform cloud controlling factor analysis on LWP_{low} following the approach of *Myers and Norris (2016)*, but extended to the SH oceans (30-60°S)

Why has extratropical low cloud scattering feedback increased in CMIP6?

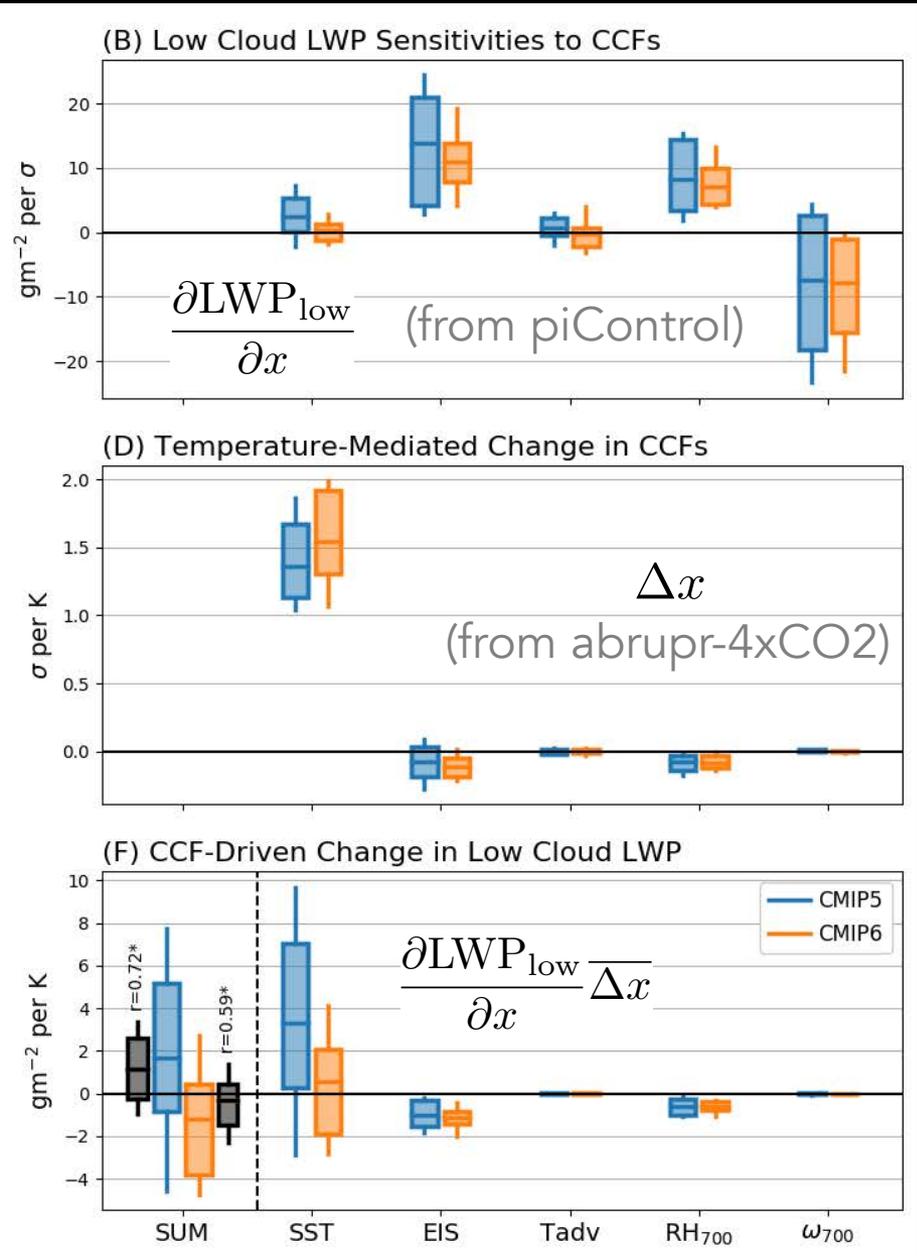
In CMIP6, the LWP_{low} increase with SST in the piControl climate is much weaker.

This overwhelms the slightly larger increase in SST...

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

The multi-linear regression model predicts LWP_{low} changes that are significantly correlated with actual model-produced values. It also correctly predicts that ΔLWP_{low} changes sign from positive in CMIP5 to negative in CMIP6.

30-60S Oceans



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

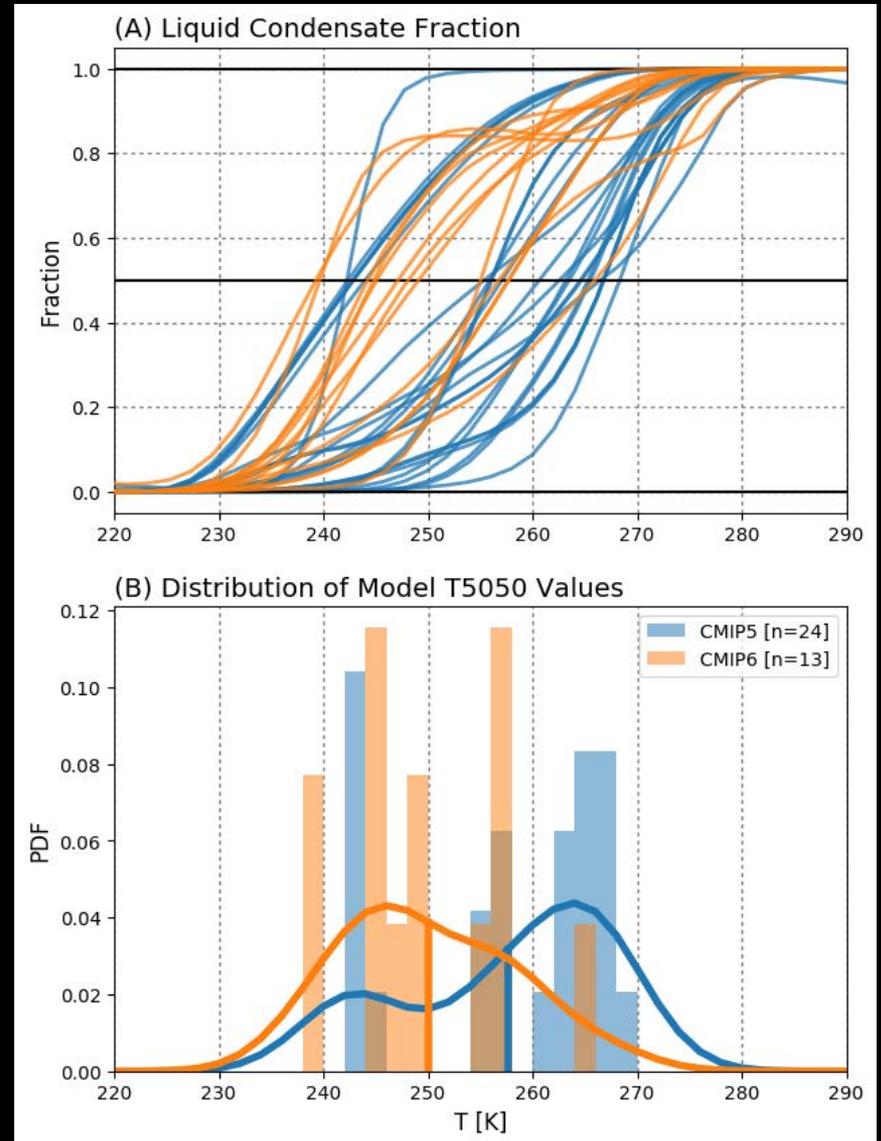
Cloud phase as a potential root cause of increased extratropical cloud feedbacks

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

This could also allow them to have stronger cloud fraction reductions with warming.

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

CMIP6 models have higher LCF on average.



Conclusions

ECS has increased significantly in the latest generation of GCMs, with values exceeding 4.5°C in 9/19 models.

This increase is due to stronger positive cloud feedbacks from decreasing extratropical low cloud coverage and albedo.

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.

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 increases in mean-state LCF.

All of these are qualitatively consistent with GCMs achieving a better match with theory, observations, and/or high-res modeling.

Does this scare you?

Implications

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- ✓ Tropical 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.

Does this scare you?

It is necessary to determine whether models' individual cloud feedbacks *quantitatively* agree with expert judgement [Steve's talk]

Regardless, any model-based inference that ECS is high needs to be evaluated alongside independent evidence [WCRP ECS Assessment].