Process-oriented Model Diagnostics and Observational Constraints on Cloud feedback and Climate Sensitivity

Hui Su[1,2]
With contributions from Mengxi Wu[2], Kathleen A. Schiro[3], Ni Dai[2], Xianan Jiang[2], Longtao Wu[1], Jonathan H. Jiang[1], J. David Neelin[4], Charles Seman[5], Leo Donner[5]

[1]Jet Propulsion Laboratory, California Institute of Technology
[2]Joint Institute for Regional Earth System Science and Engineering, UCLA
[3]Dept. of Environmental Sciences, University of Virginia
[4]Dept. of Atmospheric and Oceanic Sciences, UCLA
[5]Geophysical Fluid Dynamics Laboratory, NOAA

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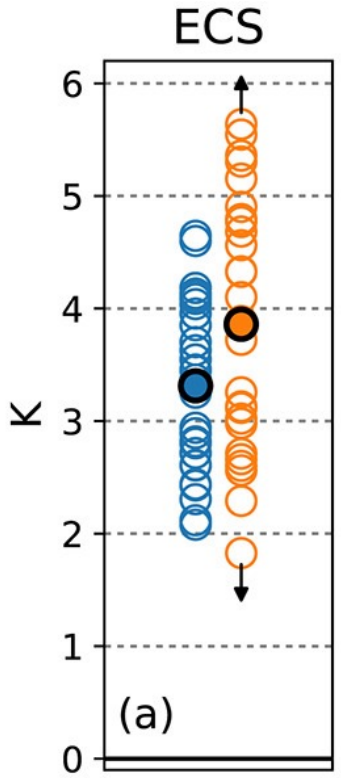
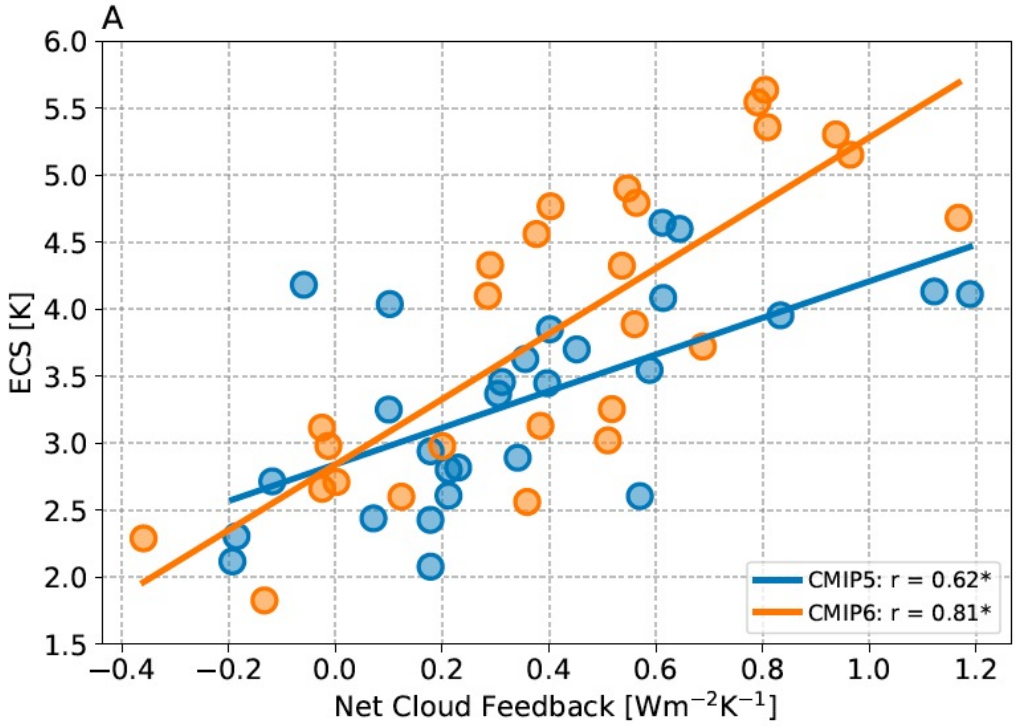
Spread in Equilibrium Climate Sensitivity

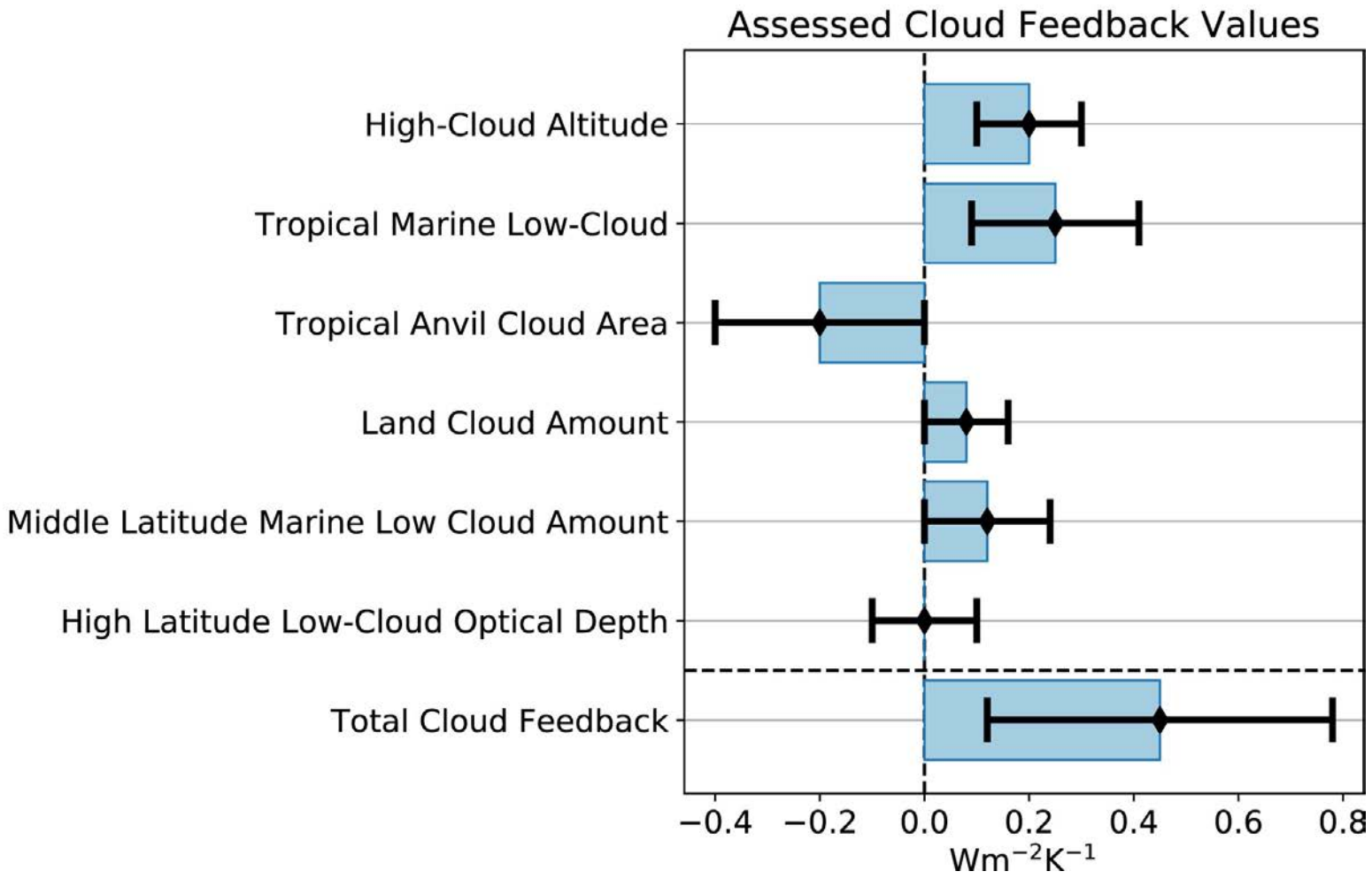
- There is a large spread in equilibrium climate sensitivity (ECS).
- Cloud feedback is a primary contributor to the inter-model spread in ECS.





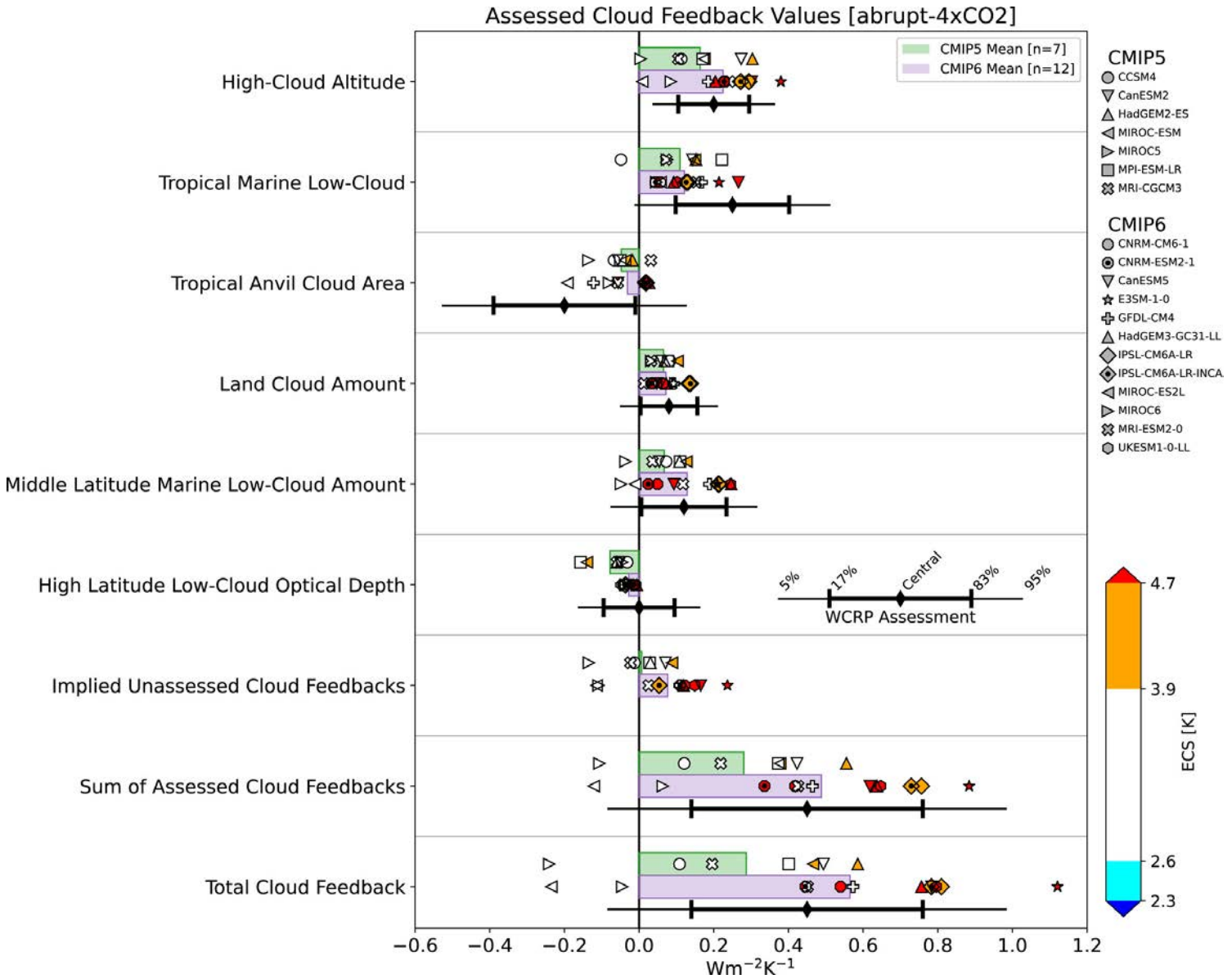
Zelinka et al. (2020, GRL)

Components of Cloud Feedback



Sherwood et al (2020, Review of Geophysics)

CMIP5/CMIP6 Cloud Feedbacks Against Expert Assessment



- The models with the smallest feedback errors relative to the expert assessment have moderate total cloud feedbacks (0.4–0.6 W m^{-2} K^{-1}) and ECS (3–4 K)
- The models with the largest errors have total cloud feedback and ECS values that are too large or too small
- Models with large positive total cloud feedbacks have several systematically high-biased feedback components
- A better simulation of mean-state cloud properties is associated with stronger but not necessarily better cloud feedbacks
- Several components of cloud feedback are correlated

Zelinka et al. (2022, JGR)

How can we constrain cloud feedback and climate sensitivity?

Process-oriented model diagnostics

- Analysis of cloud-controlling factors (CCF) using PPEs
- Pathways that link high cloud and low cloud feedbacks
- Seasonal cycle of low cloud fraction

Observational constraints

- Caveats of emergent constraints of ECS

NCAR CAM5 PPEs

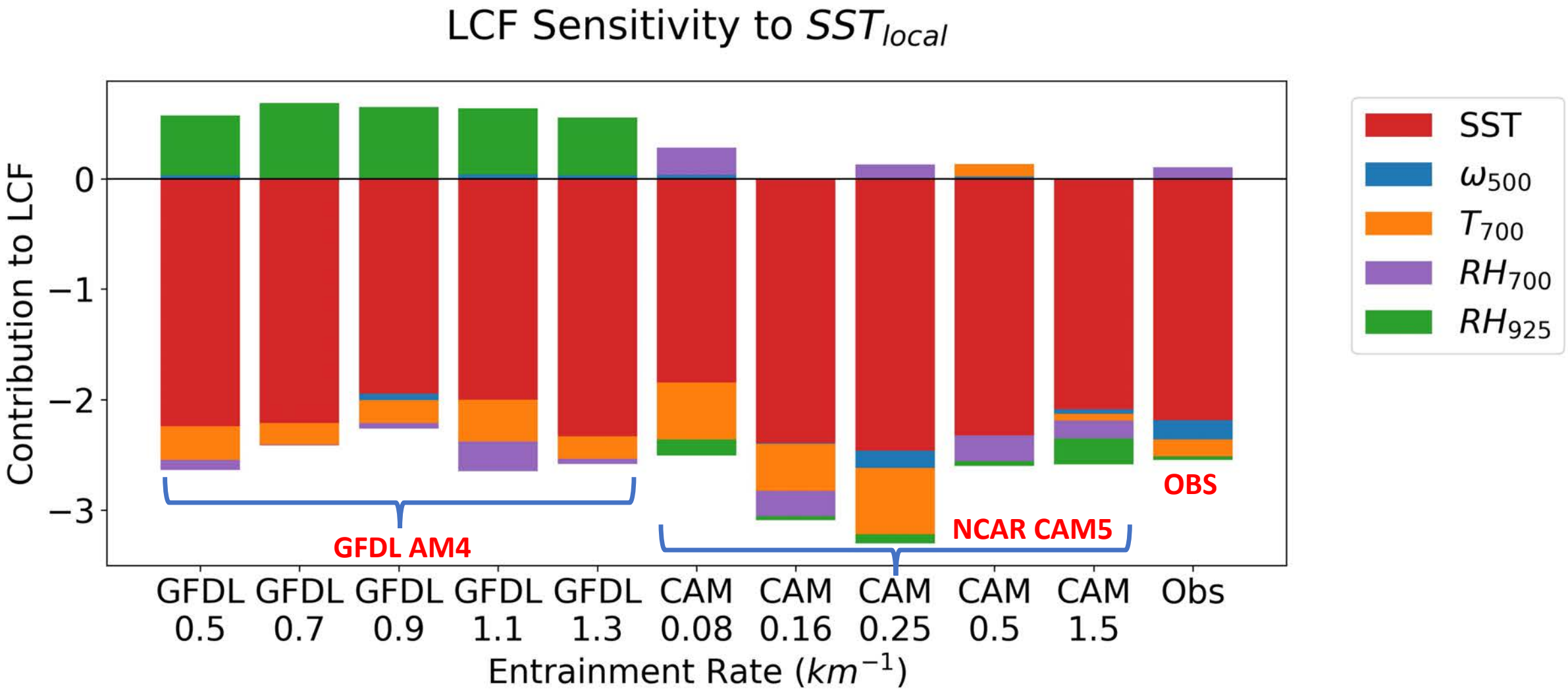
- Prescribed sea surface temperature (1995 – 2005)
- Entrainment rate specified from 0.08 km^{-1} to 1.5 km^{-1}
  (Bernstein and Neelin 2016; Langenbrunner and Neelin 2017; Schiro et al. 2019)

GFDL AM4 PPEs

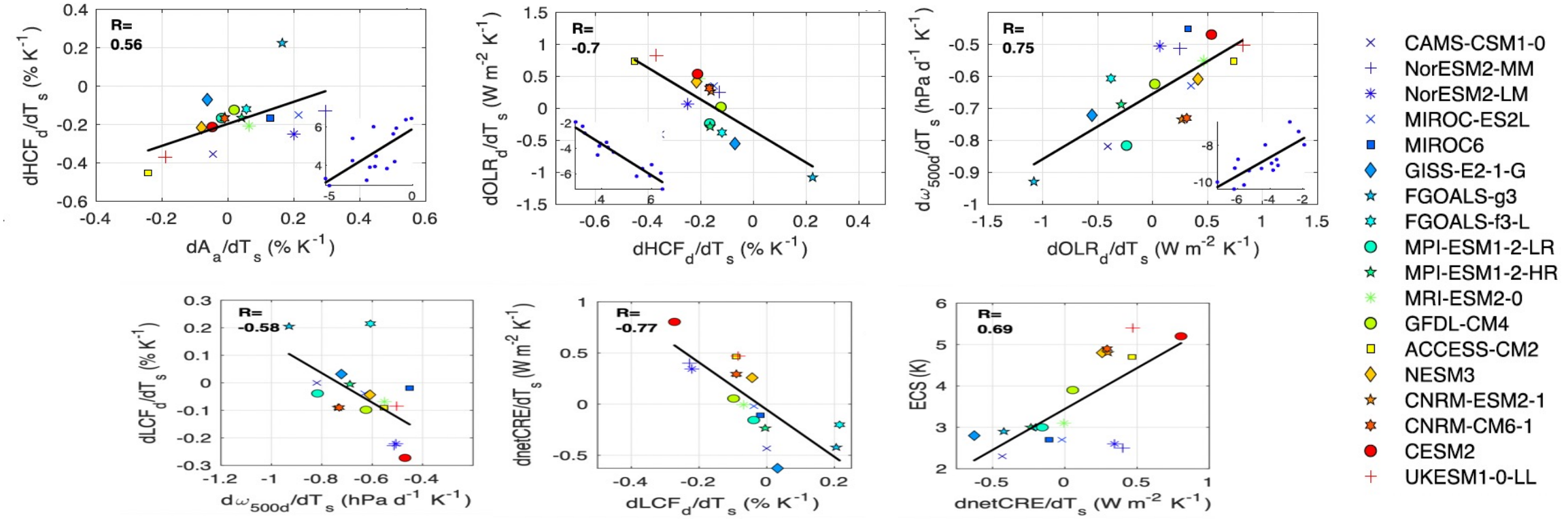
- Prescribed sea surface temperature (2001 – 2014)
- Entrainment rate in deep convection depends on column relative humidity ζ
  - $\varepsilon_d = \varepsilon_1 + \frac{\zeta - \zeta_0}{1 - \zeta_0}(\varepsilon_2 - \varepsilon_1)$
  - The constant ε_1 varied from 0.5 km^{-1} to 1.3 km^{-1}

Multivariate Regression Analysis of Low Cloud Fraction Response

$$\frac{dLCF}{dSST} = \frac{\partial LCF}{\partial SST} + \frac{\partial LCF}{\partial \omega_{500}}\frac{d\omega_{500}}{dSST} + \frac{\partial LCF}{\partial EIS}\frac{dEIS}{dSST} + \frac{\partial LCF}{\partial q_{diff}}\frac{dq_{diff}}{dSST}$$



Linkage between Tropical High Cloud Fraction Feedback and Descent Region Low Cloud Fraction Feedback

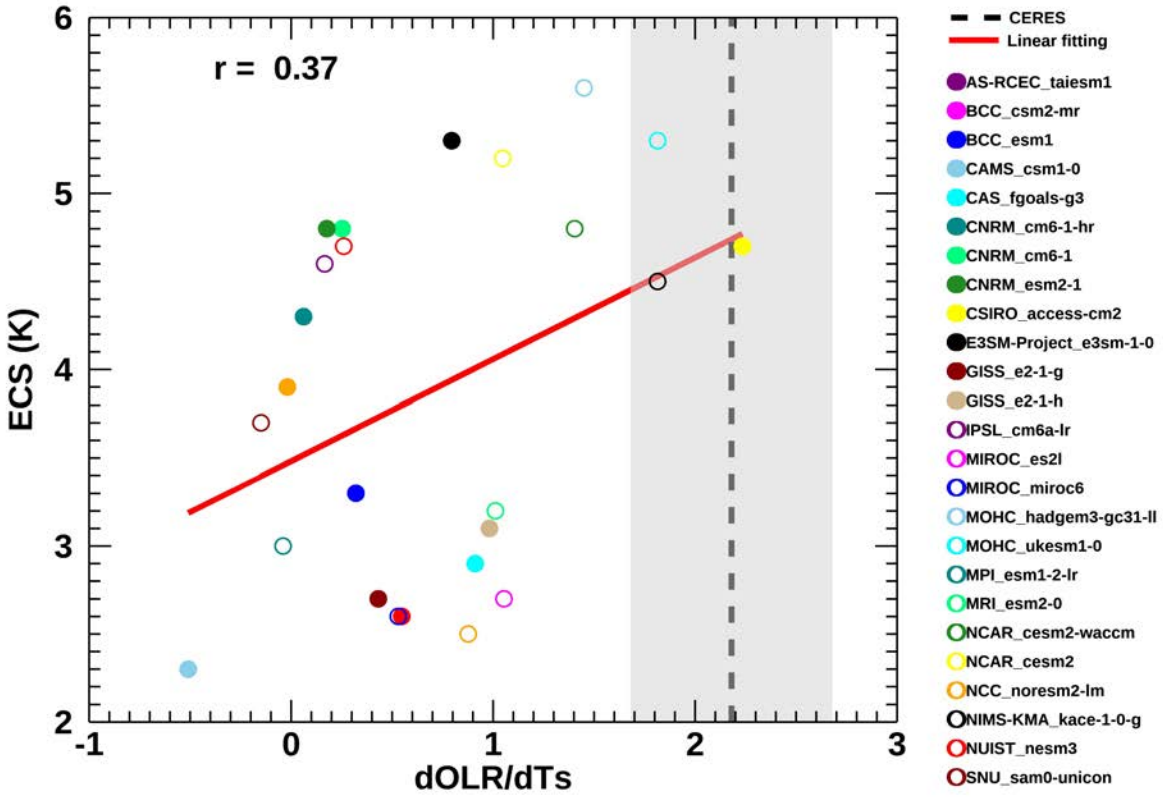


Tightening of tropical ascent → Narrowing of ITCZ → Decrease of tropical high clouds → Expansion of dry and clear area → Enhanced atmospheric longwave cooling → Less weakening of large-scale subsidence rate → Greater reduction of low cloud fraction → Stronger shortwave cloud feedback → Higher Climate Sensitivity

The Radiation-Subsidence Pathway

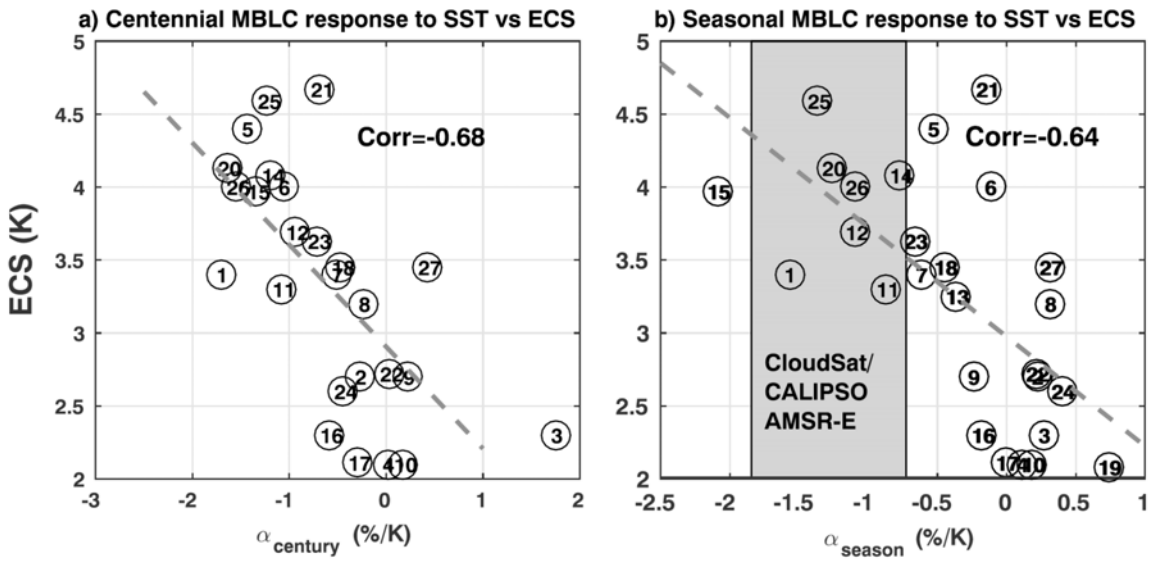
Schiro et al. (2021, in review)

Emergent Constraint Based on the Radiation-Subsidence Pathway



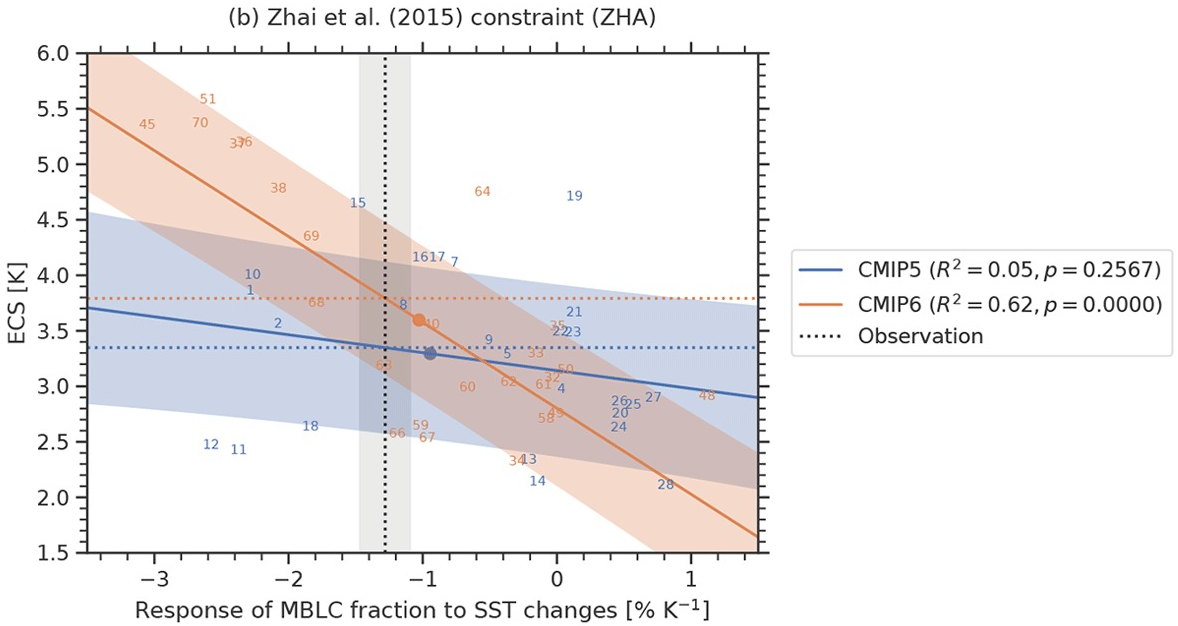
- Based on observed outgoing longwave radiation sensitivity to interannual surface warming, the ECS values greater than 4.5 K are more consistent with the observations.

Seasonal Cycle of Low Cloud Fraction



Marine Boundary Layer Cloud Fraction:
below 700 hPa, 20-40N/S; $\omega_{500} > 0$

Zhai et al. (2015, GRL)

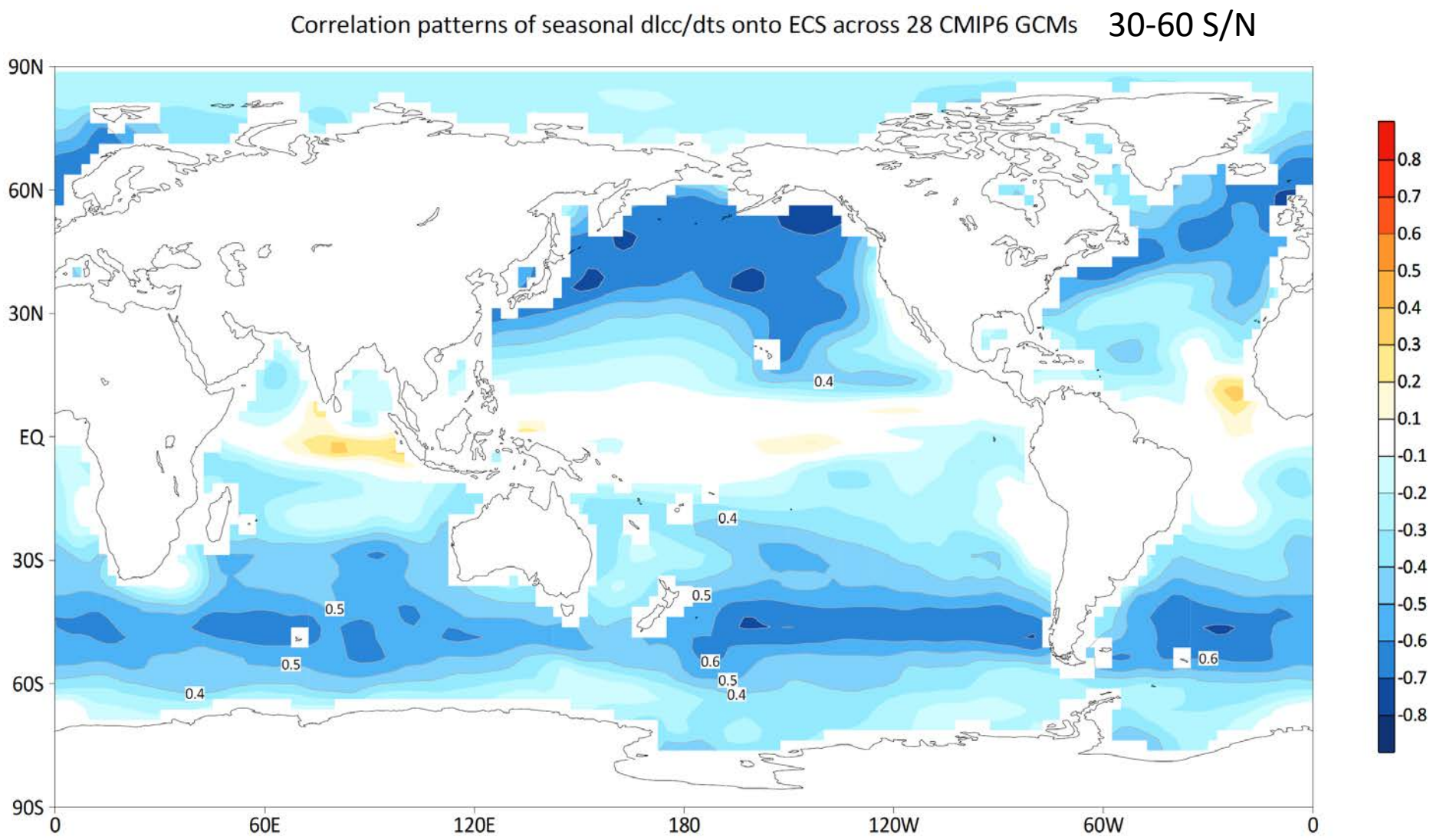


- Except for the ZHAI metric, most emergent relationships are weaker in CMIP6 compared to CMIP5.

=> ECS (66% likelihood) 3.48 to 4.32 K

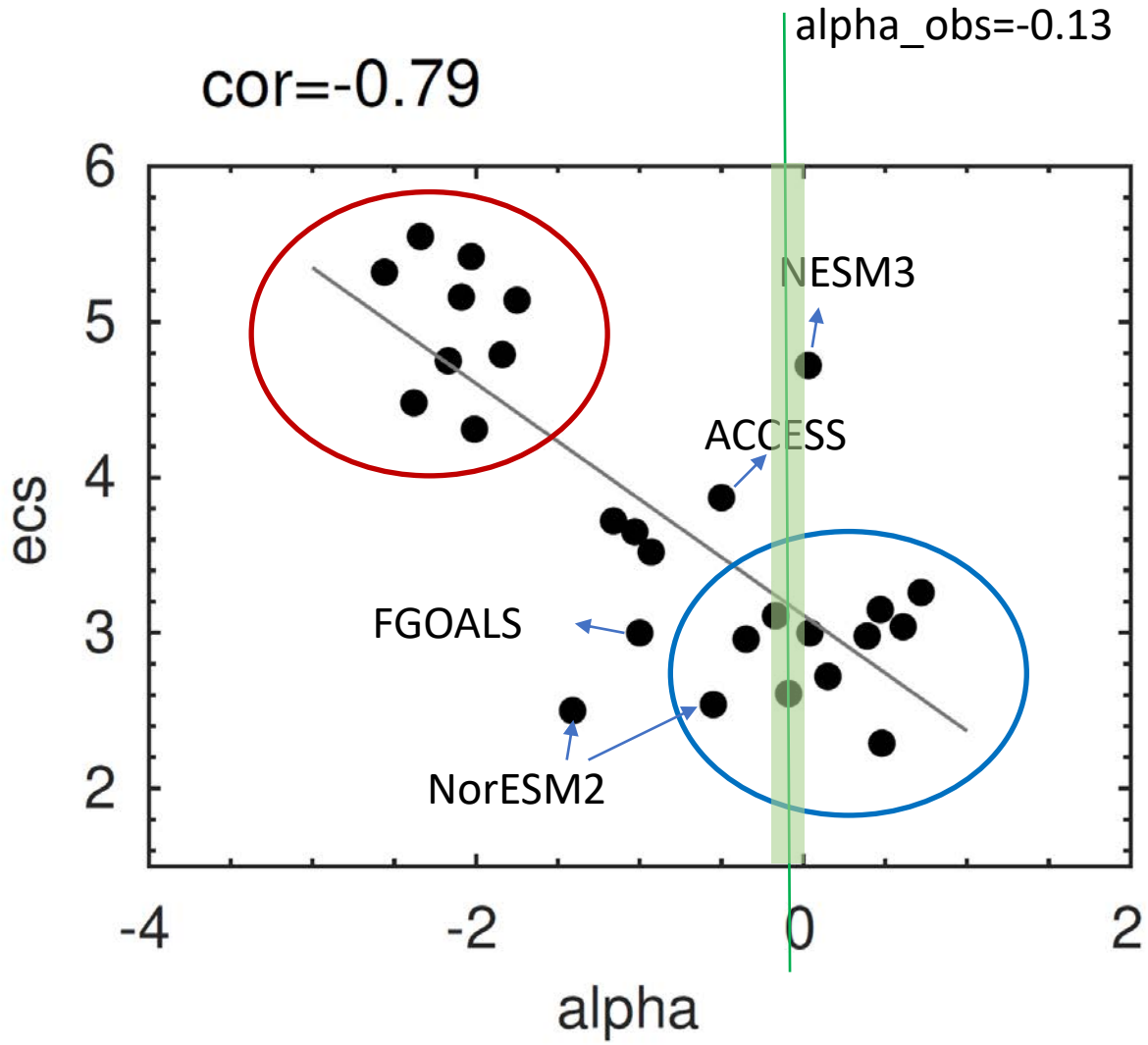
Schlund et al. (2021, Earth System Dynamics)

Extratropical Low Cloud Seasonal Cycle



Emergent Constraint Based on Extratropical Low Cloud Seasonal Cycle

CESM2(4)
E3SM
HadGEM3(2)
KACE
TaiESM1



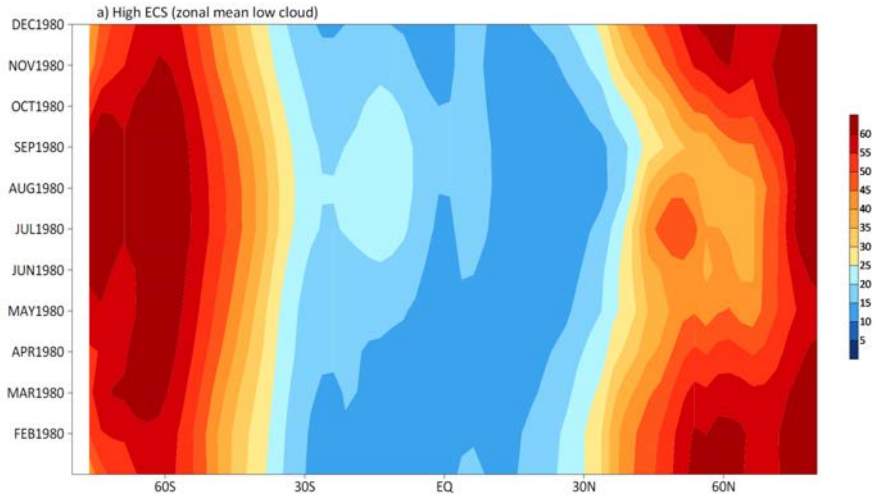
dLCF/dSST over 30-60 S/N

- Low ECS models are closer to the observations.

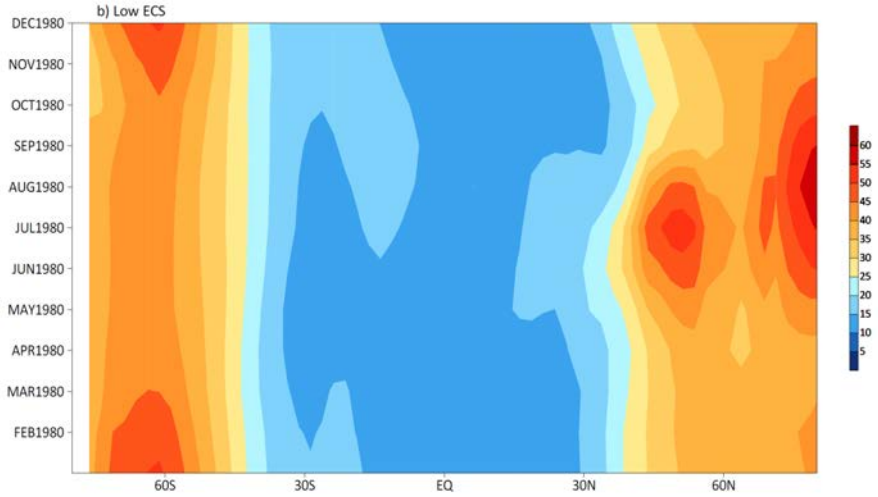
BCC-CSM2 (2)
CAMS-CSM1
GISS-E2(2)
MPI-ESM1(3)
MRI-ESM2

Seasonal Cycle of Zonal-mean Extratropical Low Cloud Fraction

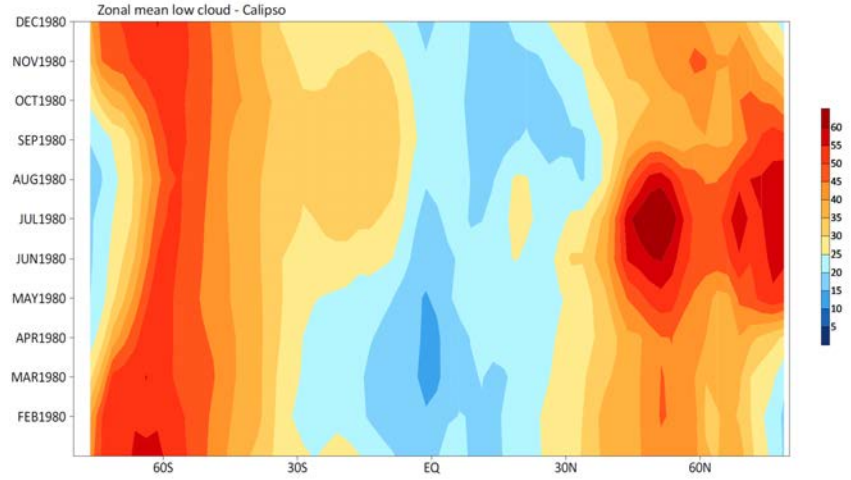
High ECS



Low ECS



CALIPSO



- Low ECS models are closer to the observations.

Summary

- The differences in cloud sensitivity to cloud-controlling factors caused by entrainment rate perturbation in one model are smaller than the structural differences between the models.
- Tropical high cloud fraction change is linked to the subtropical low cloud fraction feedback through the radiation-subsidence pathway.
- Seasonal cycle of low cloud fraction is strongly correlated with ECS, but the model performance over the subtropical descent region and midlatitude storm tracks are different.
- Emergent constraints based on different processes can yield conflicting results.
- It is necessary to synthesize all available observational data and process-oriented model diagnostics for a comprehensive assessment of cloud feedback and climate sensitivity.