Why are Aerosol-Cloud Interactions and Cloud Feedback Anti-Correlated in Earth System Models?

Xiaohong Liu[1], X. Zhao[1], C. Feng[1], M. Zelinka[2], S. A. Klein[2], Y. Qin[2,3], L. Lin[1,2], Z. Lu[1], M. Zhang[2], K. Zhang[3], P.-L. Ma[3], Y. Shan[4], J. Zhu[5], and R. Saravanan[1]

[1] Texas A&M University. [2] Lawrence Livermore National Laboratory

[3] Pacific Northwest National Laboratory. [4] Argonne National Laboratory

[5] National Center for Atmospheric Research

Global 20th Century Energy Balance

(Kiehl, GRL 2007)

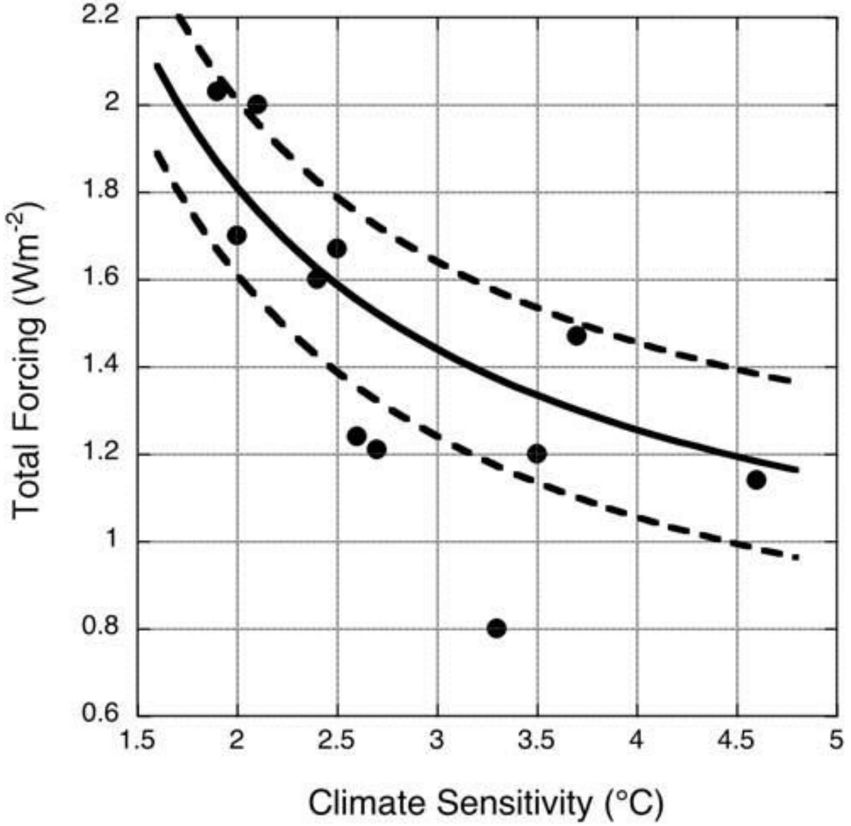
$$\Delta Q = \lambda \Delta T + H$$

$$\lambda \Delta T = \Delta Q_{GG} + \Delta Q_{ADirect} + \Delta Q_{AIndirect} - H$$

↑

0.8 °C (1850 to 2011)

λ ($W\ m^{-2}\ C^{-1}$)	ΔQ_{GG} ($W\ m^{-2}$)	$\Delta Q_{ADirect}$ ($W\ m^{-2}$)	$\Delta Q_{AIndirect}$ ($W\ m^{-2}$)	$-H$ ($W\ m^{-2}$)
2.1±0.3	2.9	-0.5	0	-0.7±0.2
1.5±0.3	2.9	-0.2	-0.8	-0.7±0.2
0.8±0.3	2.9	-0.2	-1.4	-0.7±0.2
0.0±0.3	2.9	-0.2	-2.0	-0.7±0.2



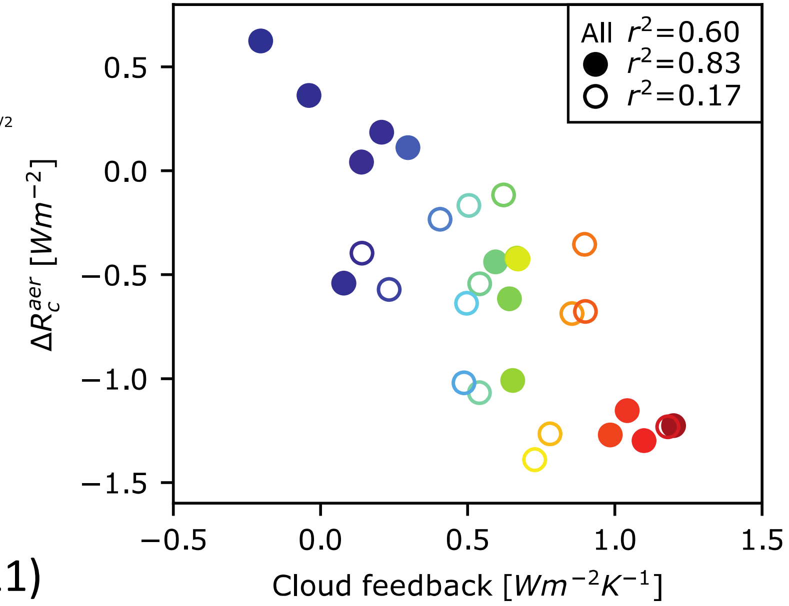
Uncertainty in Climate Modeling

Climate Science 101

Temperature Change = Climate Forcing X Climate Sensitivity

1.1 to 3.3 W m^{-2} (IPCC AR5). Aerosol forcing due to aerosol-cloud interactions (ERF_{ACI}) is the largest source of uncertainty in climate forcing

1.5 to 4.5 ° C with a doubling of CO_2 (a forcing of 3.7 W m^{-2}) (IPCC AR5). Cloud feedbacks are a major source of uncertainty in climate sensitivity



(Wang et al., 2021)

Anti-correlation between ERF_{ACI} and cloud feedback in CMIP6 models. why? by which processes?

Outline

- Autoconversion of cloud water to rain
  - **Importance for warm clouds**
  - **Representing aerosol 2nd indirect effect in GCMs: $N_d \uparrow$ -> $Q_{Auto} \downarrow$ -> $P_{pre} \downarrow$ -> LWP $\uparrow$**
- Ice microphysical processes
  - **Importance for mixed-phase clouds**

Both these processes are highly uncertain and tuned in GCMs

Outline

- Autoconversion of cloud water to rain
  - **Importance for warm clouds**
  - **Representing aerosol 2nd indirect effect in GCMs: N_d -> Q_{Auto} -> P_{pre} -> LWP**
- Anti-correlation through ice microphysical processes
  - **Importance for mixed-phase clouds**

Both these processes are highly uncertain and tuned in GCMs

Model Experiments

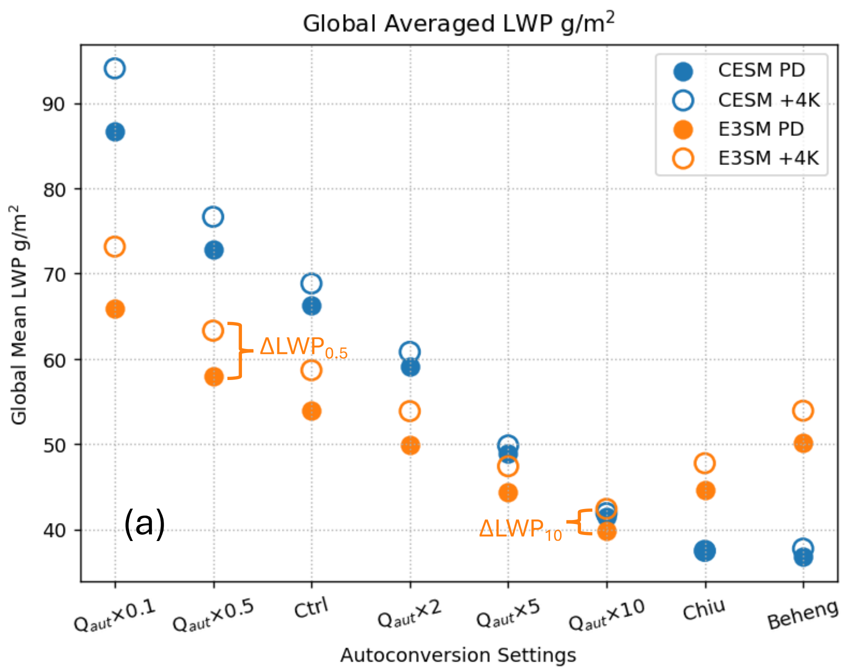
TEXAS A&M UNIVERSITY

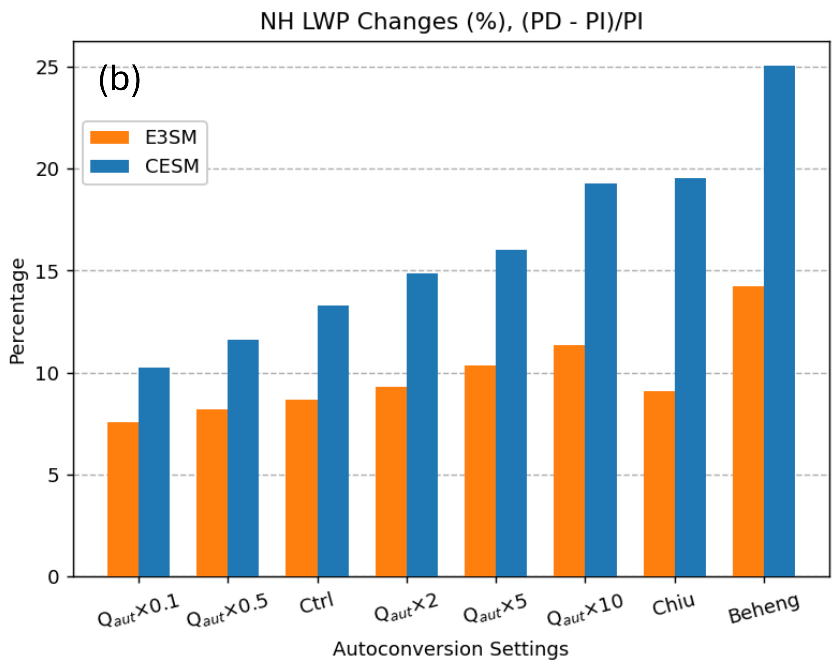
Experiments	Model setup
Ctrl	Simulations with the default settings (Khairoutdinov and Kogan (KK2000))
Q_{aut}×{s}	Same as Ctrl, but the autoconversion rate is scaled by the parameter s, where s can be 0.1, 0.5, 2, 5, and 10.
Beheng	Same as Ctrl, but the autoconversion scheme is replaced by Beheng (1994).
Chiu	Same as Ctrl, but the autoconversion scheme is replaced by Chiu (2021).

Present-day (PD) and pre-industrial (PI) simulations for ERF_{ACI}
PD and PD + 4K sea surface temperature (SST) for cloud feedback
All experiments are run with both E3SMv2 and CESM2

ACI and cloud feedback through autoconversion

Global LWP and ΔLWP between PD & PD+4K under various autoconversion rates.

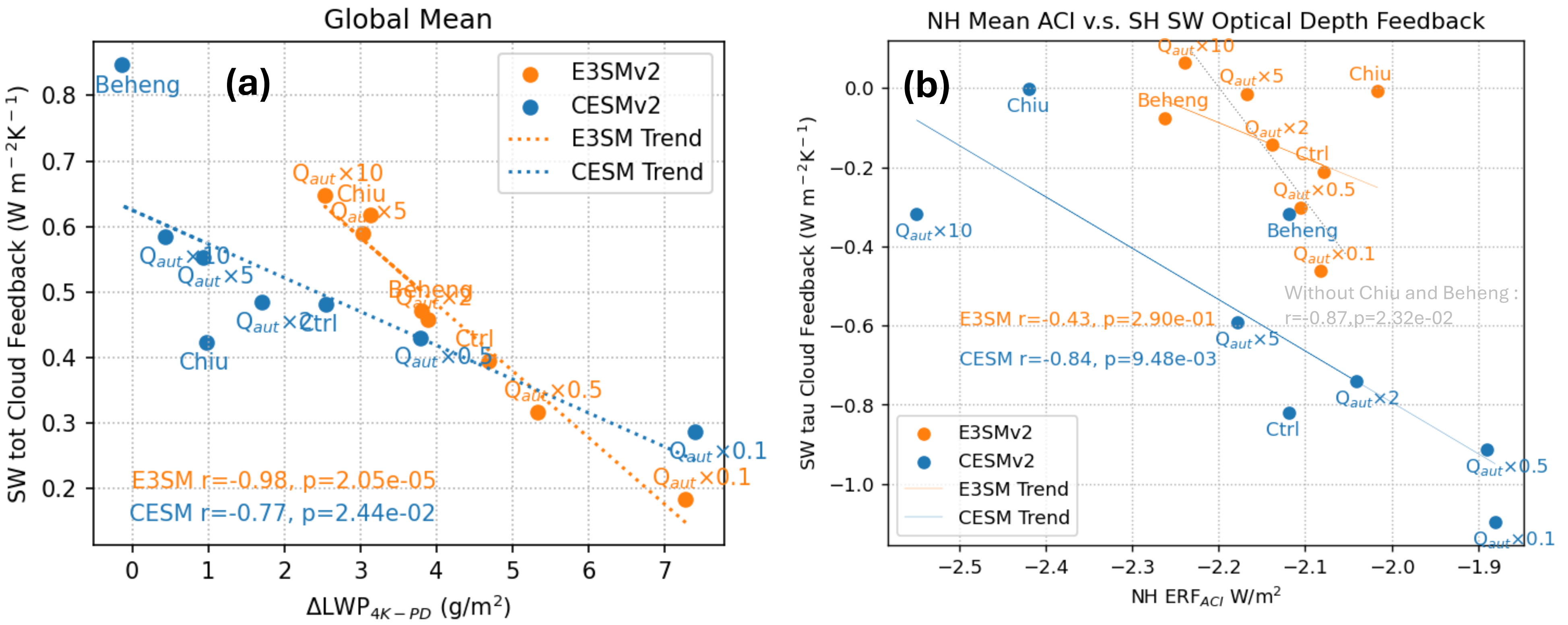




ΔLWP over the Northern Hemisphere between PD & PI under various autoconversion rates.

- **Cases with stronger Q_{auto} tend to exhibit a smaller PD LWP and also less increase in LWP (ΔLWP) with warming**
- **Cases with stronger Q_{auto} tend to show a larger percentage increase in NH LWP change from PI to PD.**

ACI and cloud feedback through autoconversion



(a) SW total cloud feedback decreases with a larger $\Delta LWP_{4K\text{-}PD}$ increase due to warming, because of the enhanced negative cloud optical depth feedback.

(b) Negative correlation between ERF_{ACI} at NH and SW cloud feedback.

Outline

- Autoconversion of cloud water to rain
  - **Importance for warm clouds**
  - **Representing aerosol 2nd indirect effect in GCMs: N_d -> Q_{Auto} -> P_{pre} -> LWP**
- Ice microphysical processes
  - **Importance for mixed-phase clouds**

Both these processes are highly uncertain and tuned in GCMs

Model Experiments

TEXAS A&M UNIVERSITY

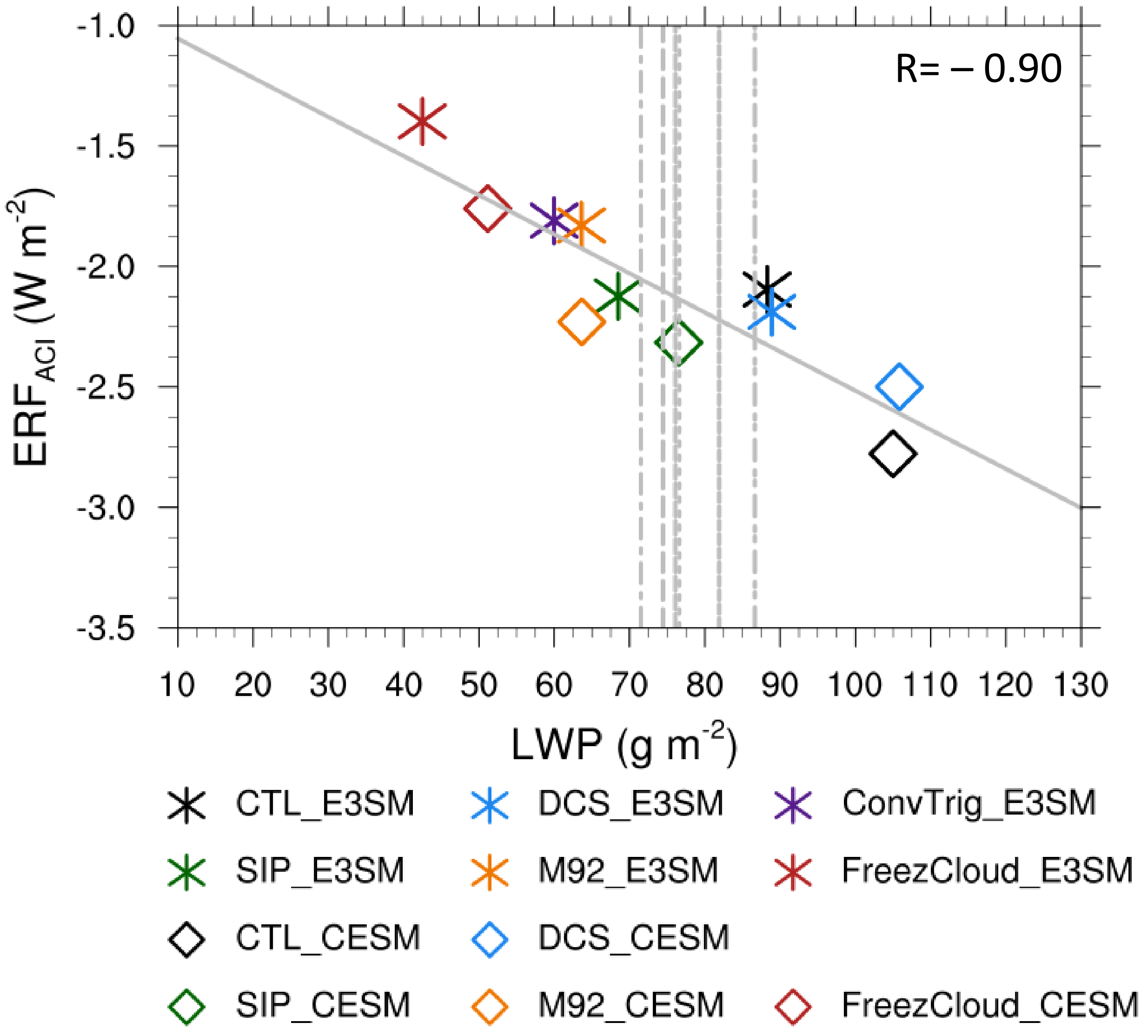
Purpose: modify the cloud phase --- how the ACI changes

Model Experiment	Model Setup
CTL	Default E3SMv2 model
DCS	Same as CTL, but set the threshold on cloud ice and snow autoconversion process from 195 μm to 400 μm.
conv_trigger	Same as CTL, but turn off the new trigger of convection and use the old trigger
SIP	Same as CTL, but add SIP from raindrops freezing breakup and ice-ice collisional breakup
M92	Same as CTL, but use Meyer et al. (1992) scheme for ice nucleation in mixed-phase clouds instead of CNT
Freez_clouds	Same as CTL, but assume all condensation to be ice phase when cloud temperature is smaller than –5℃

Less liquid
More ice

All experiments are run with both E3SMv2 and CESM2

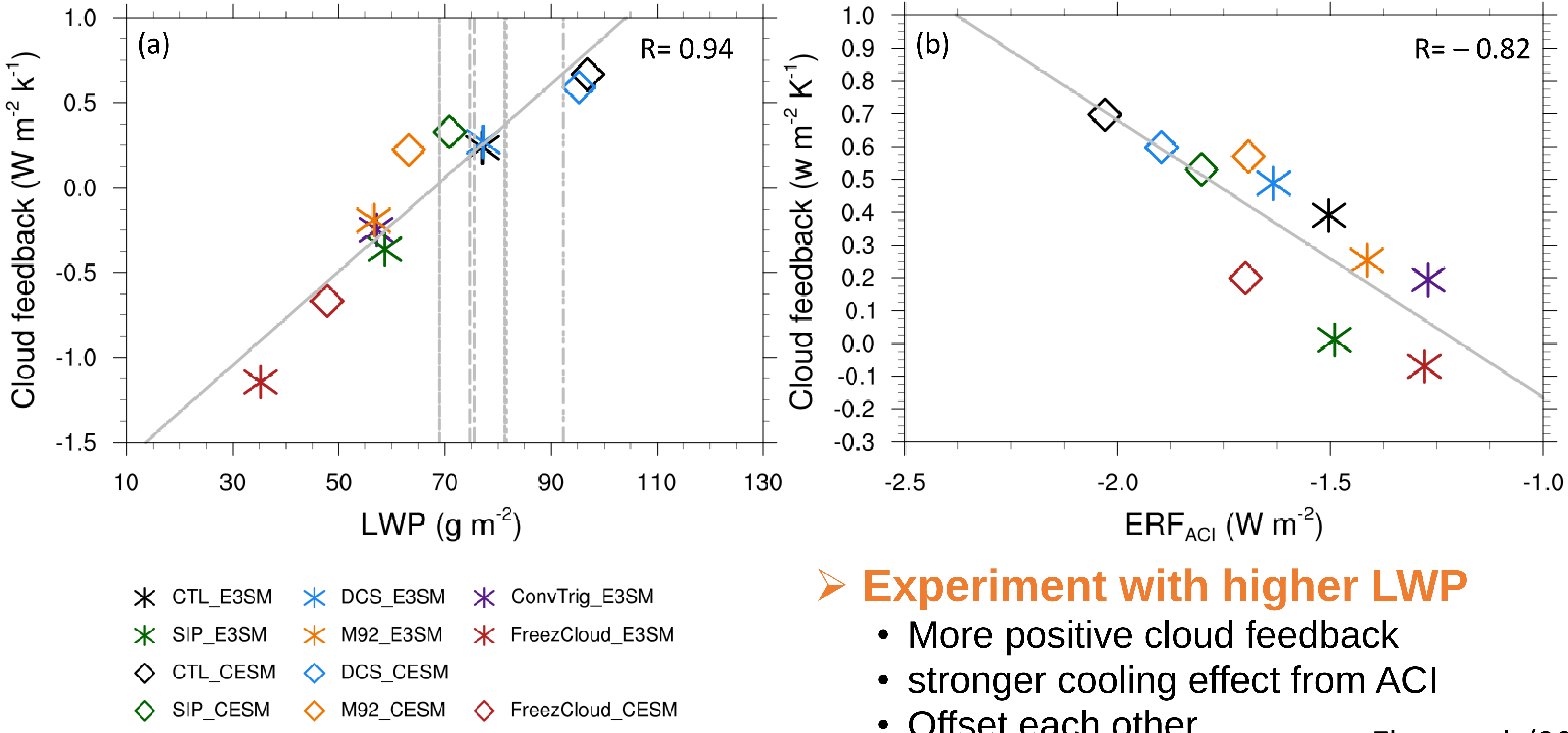
ACI and cloud feedback through ice microphysics



- **ERF_{ACI} decreases (i.e., more negative) with increasing PD LWP**

Zhao et al. (2024)

ACI and cloud feedback through ice microphysics

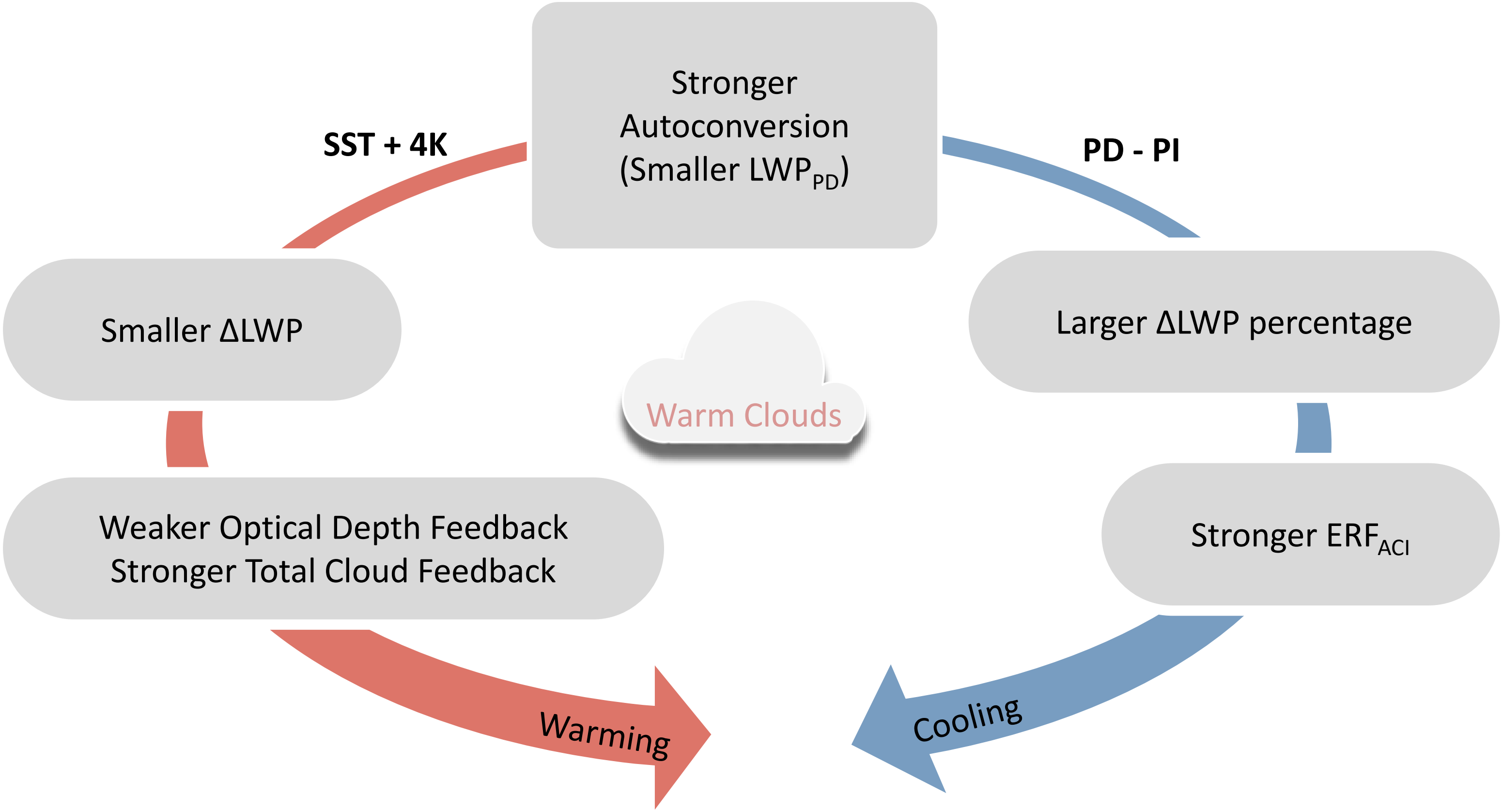


➢ **Experiment with higher LWP**

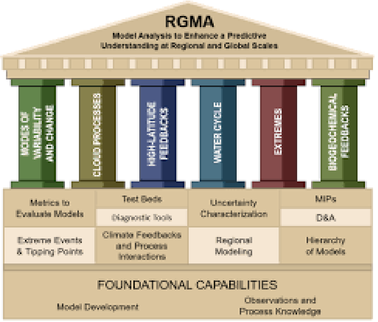
- More positive cloud feedback
- stronger cooling effect from ACI
- Offset each other

Zhao et al. (2024)

Summary

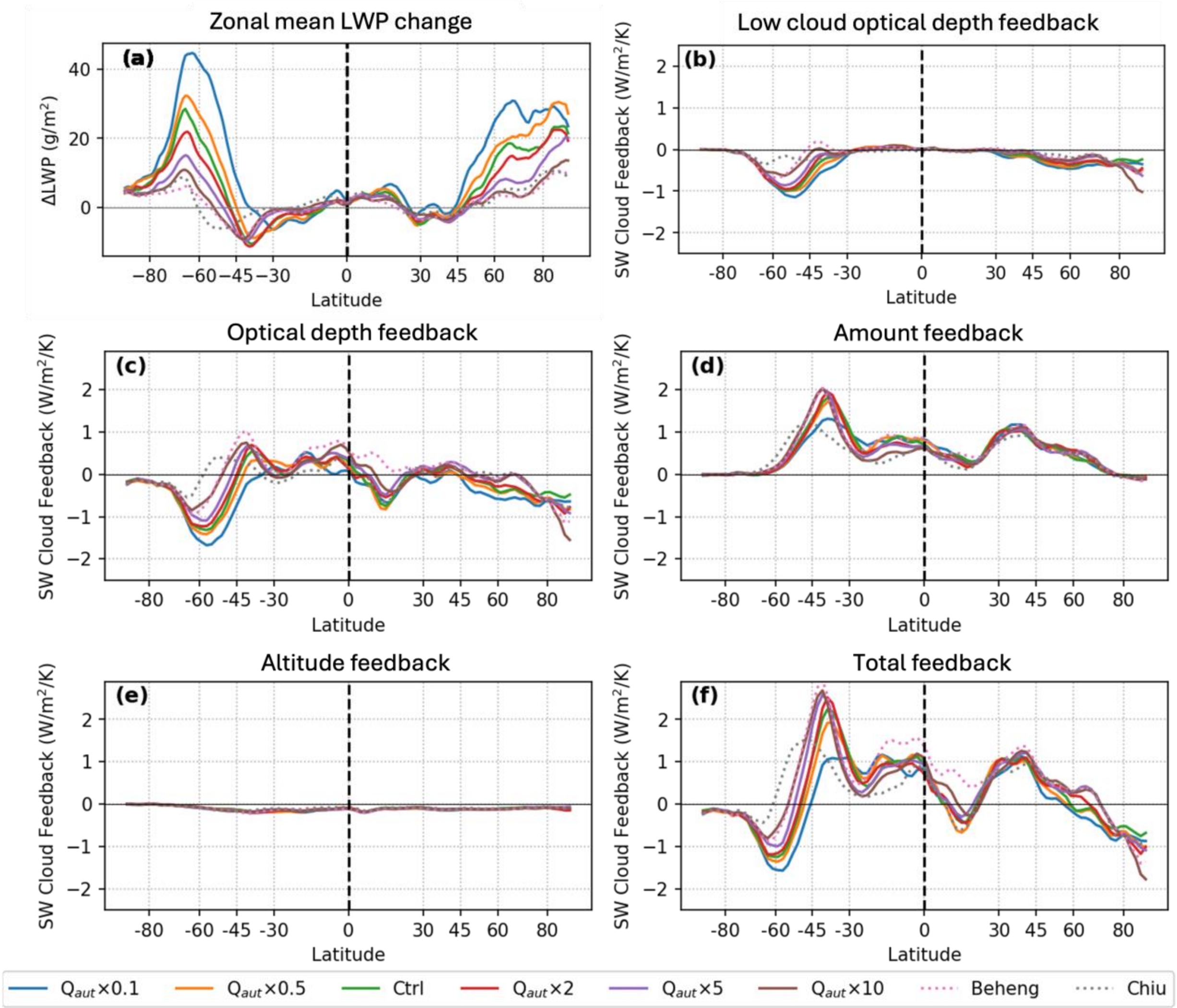


Schematic of correlation between cloud feedback and ERF_{ACI} mediated by cloud liquid water path



Thanks!

ACI and cloud feedback through autoconversion

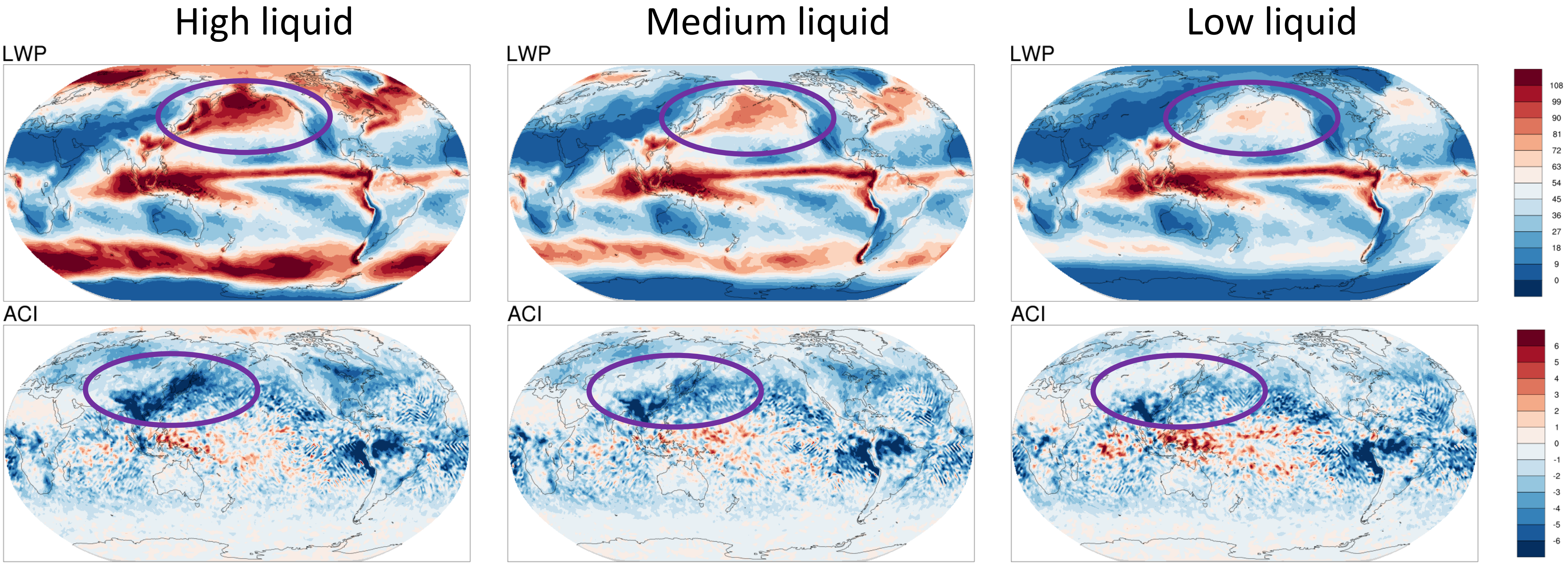


(a) LWP change
(b) SW low cloud optical depth feedback
(c) SW optical depth feedback
(d) SW amount feedback
(e) SW altitude feedback
(f) SW total cloud feedback from CESM2

Simulations from E3SMv2 show similar results.

Perturbed Q_{auto} results in a change in ΔLWP from global warming (a), particularly over the mid to high latitudes. Such change in cloud LWP leads to changes in cloud feedback, particularly in the shortwave (SW) component (f).

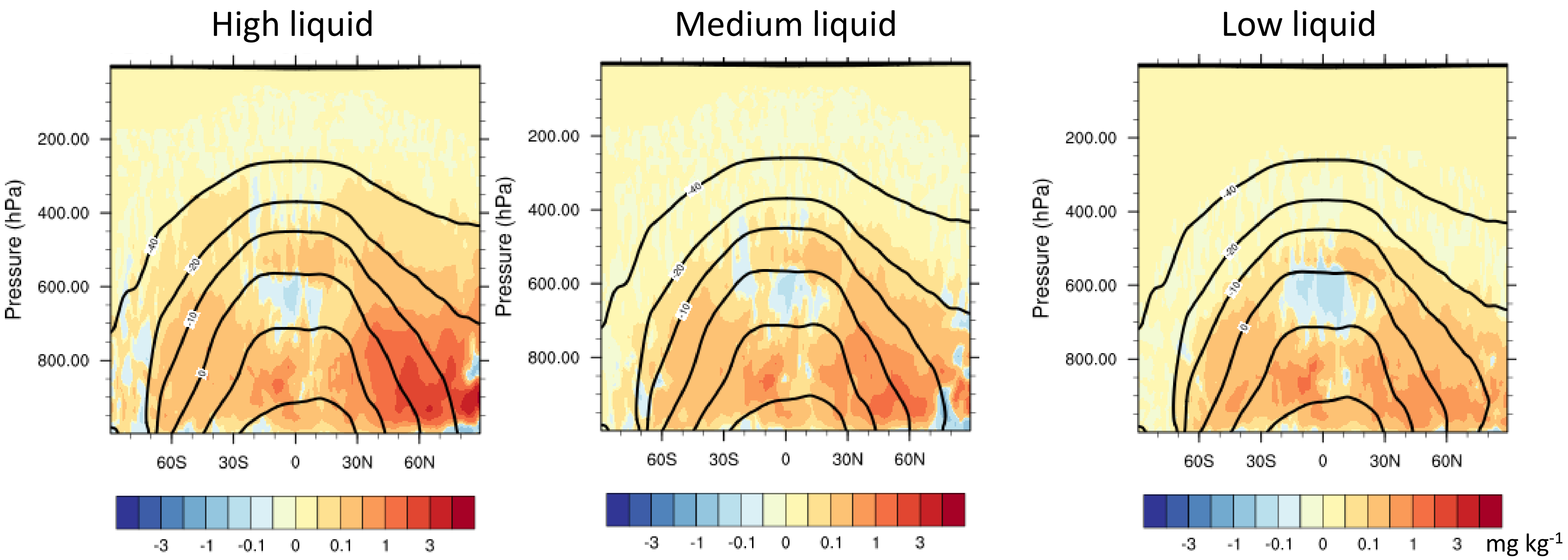
LWP and ERF_{ACI} over NH



With smaller LWP, the clouds are less susceptible to aerosol perturbations.

LWP and ERF_{ACI}

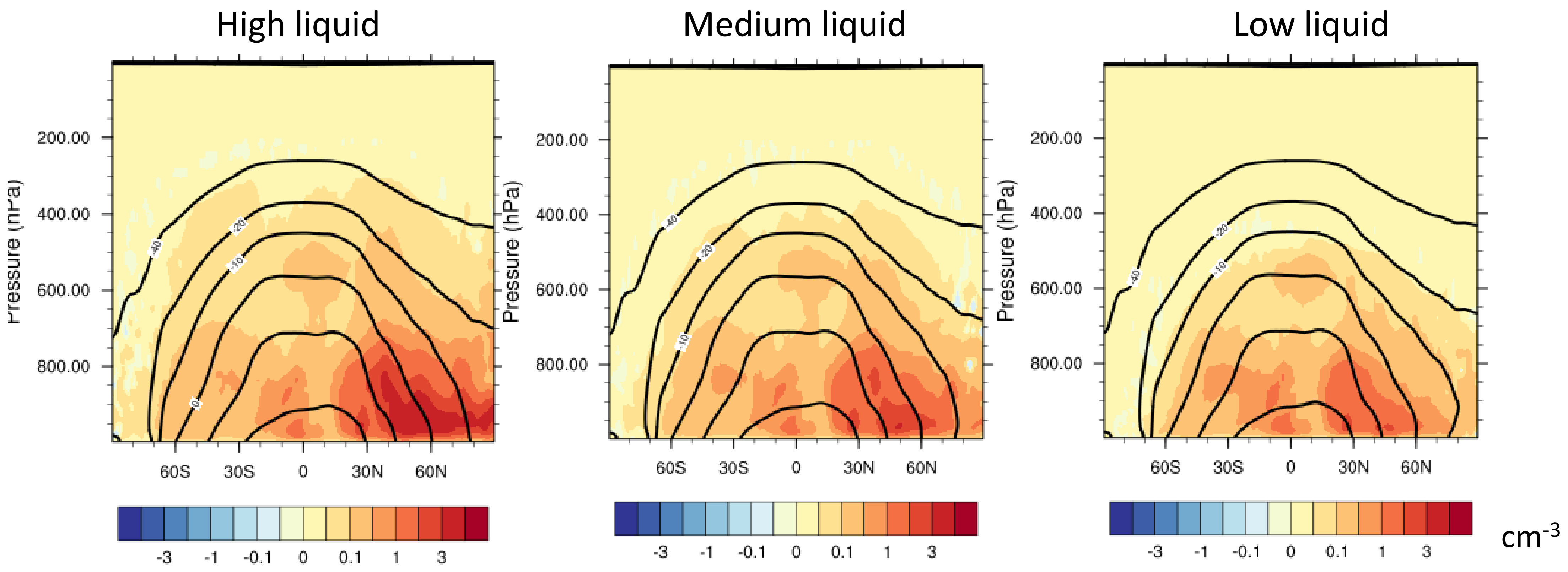
ΔLWC from PD-PI



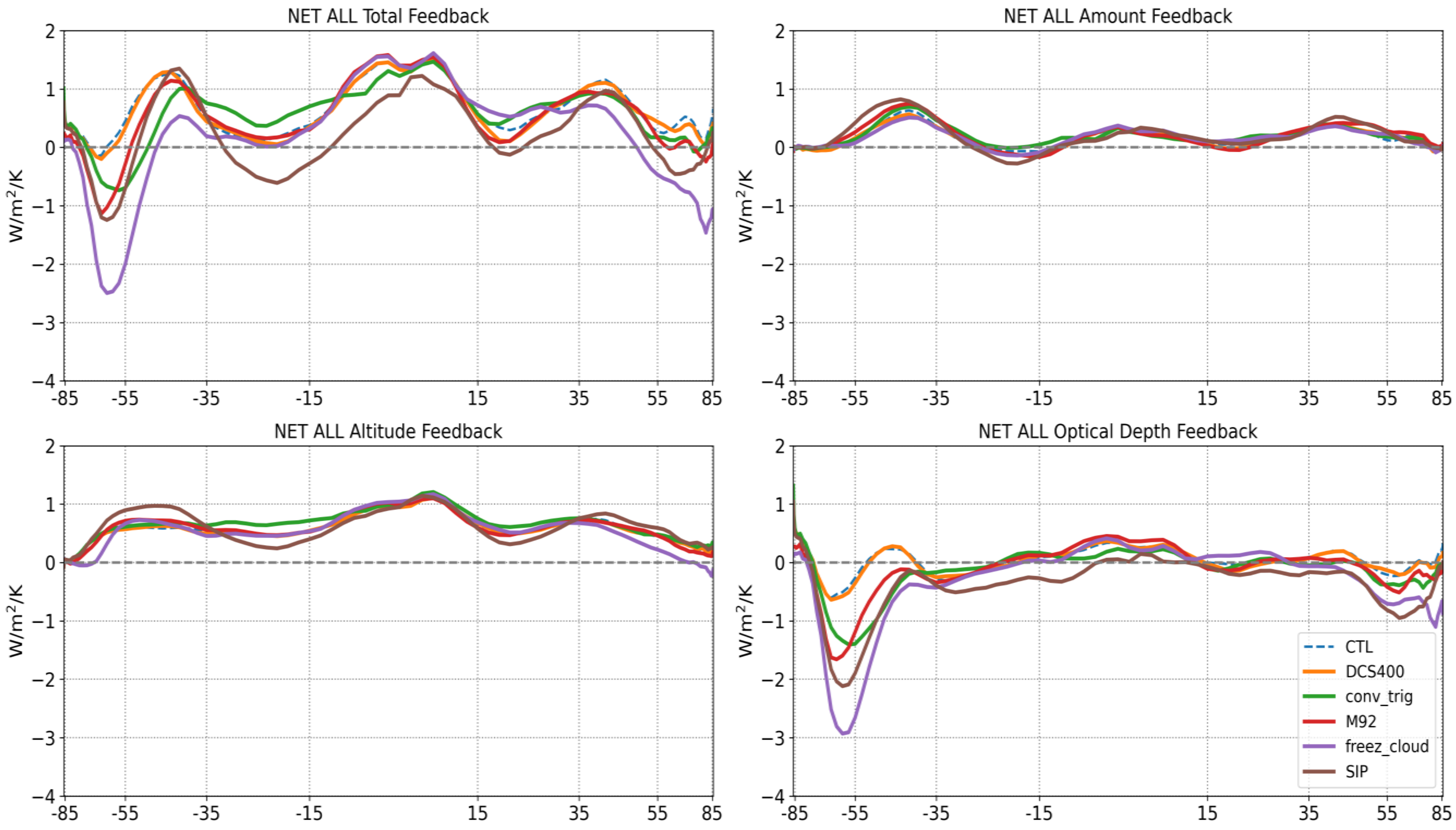
- Low liquid experiments: strong glaciation of cloud
  - which freezes available liquid water in the cloud
- Also freezes cloud water enhanced by anthropogenic aerosols

LWP and ERF_{ACI}

ΔCDNC from PD-PI



Cloud feedback



Less LWP, more ice

When warming, more ice melting to liquid → cloud optical depth increase →stronger negative feedback