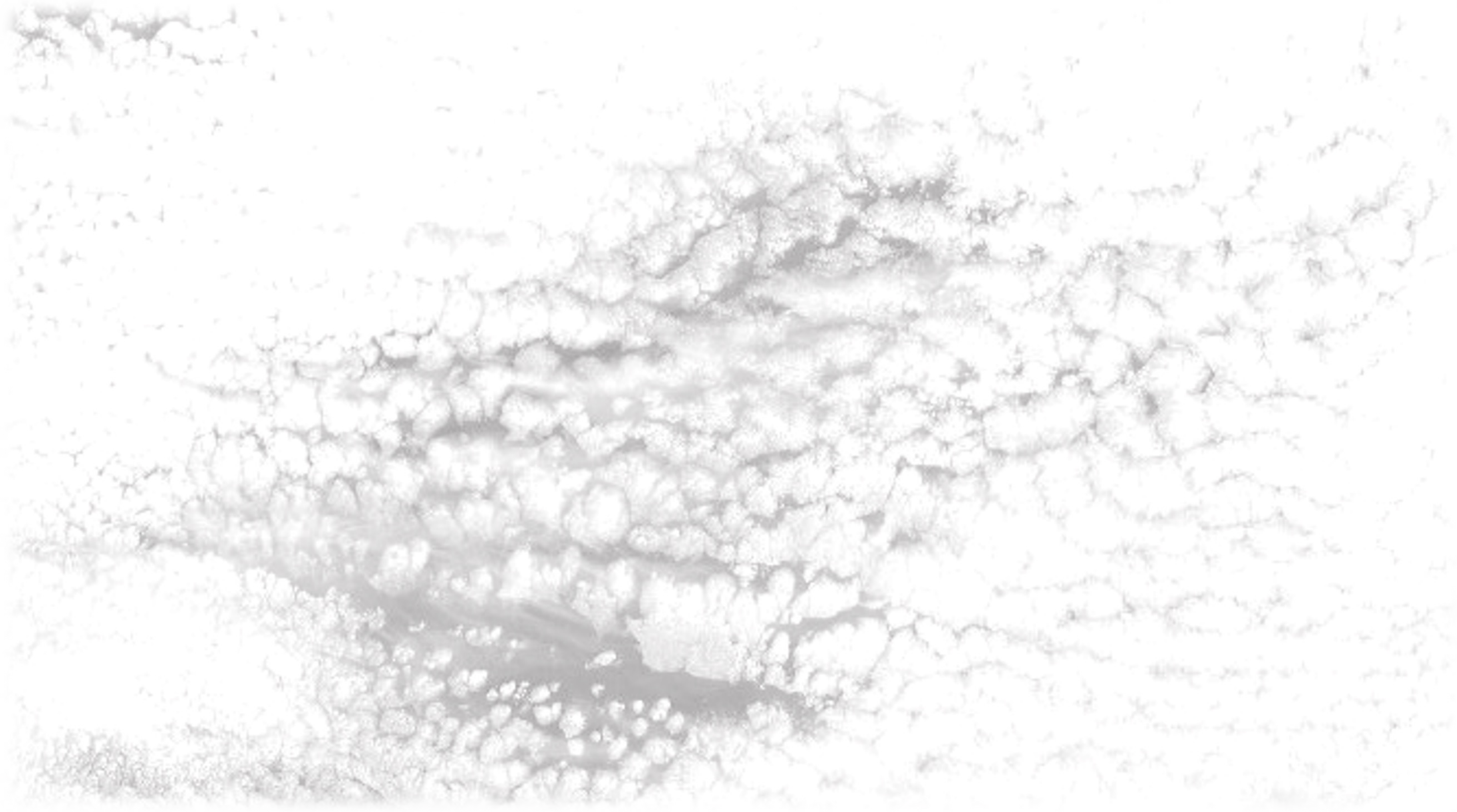
Radiative buffering of extratropical forcing and feedback



Daniel McCoy[1], Ci Song[1], Geethma Werapitiya[1], Andrew Gettelman[2], Trude Eidhammer[3], Gregory Elsaesser[4,5], Isabel McCoy[6,7], Duncan Watson-Parris[8], Casey Wall[9], Chuyan Tan[1,9]

[1]University of Wyoming, [2]PNNL, [3]NCAR, [4]Columbia, [5]NASA-GISS, [6]NOAA, [7]CIRES, [8]UC San Diego, [9]University of Oslo, [10]Hunan Climate Center

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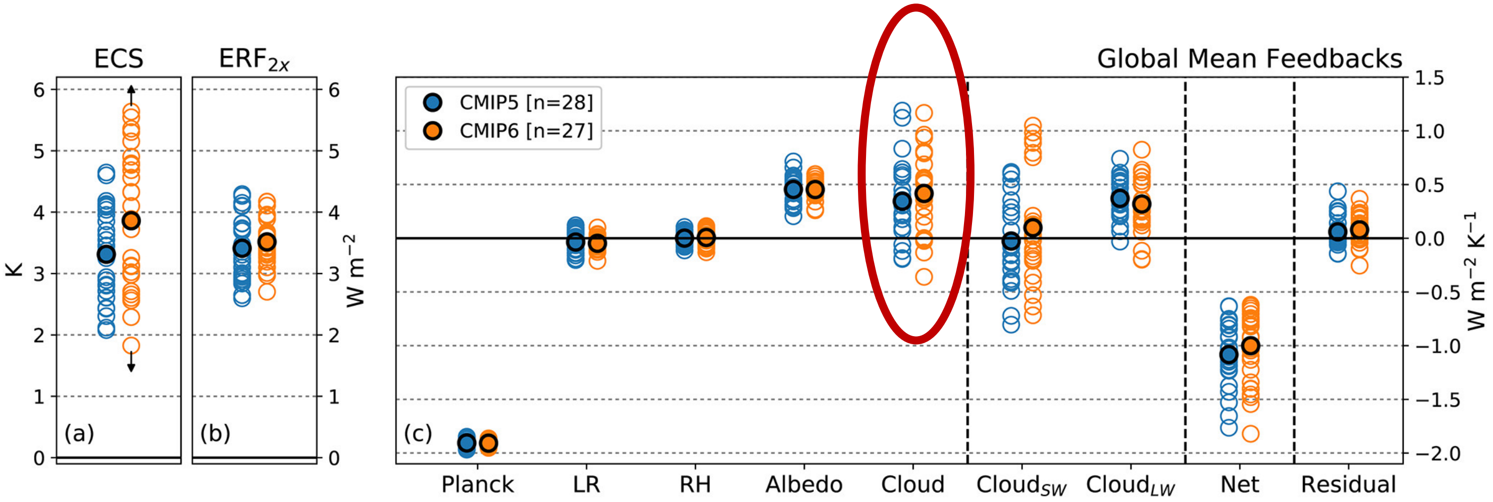
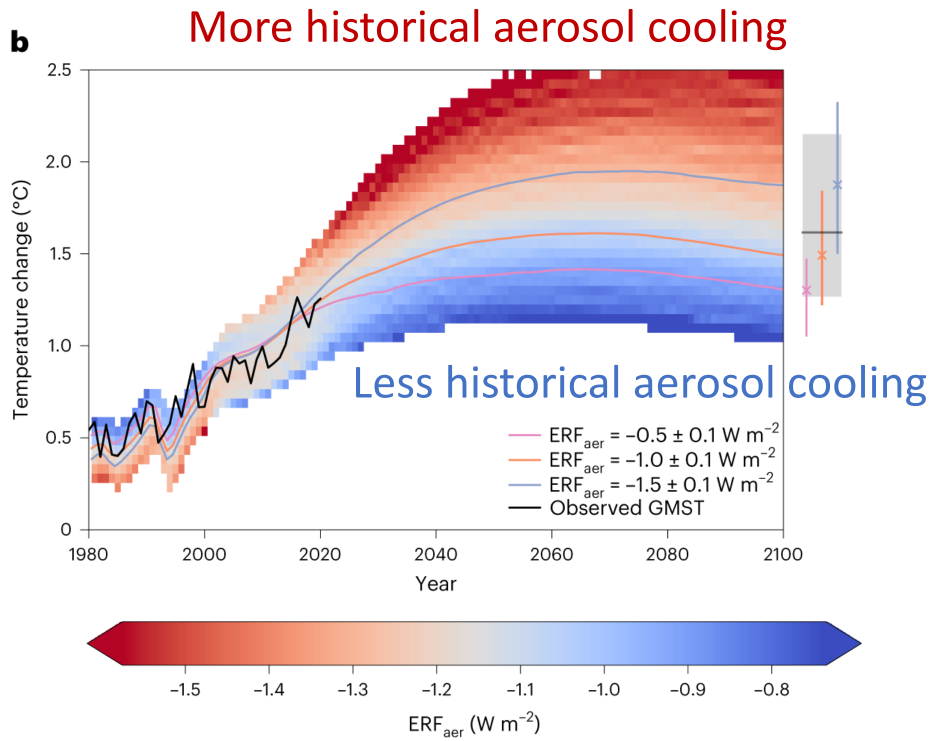
Clouds dominate uncertainty in climate forcing and feedback

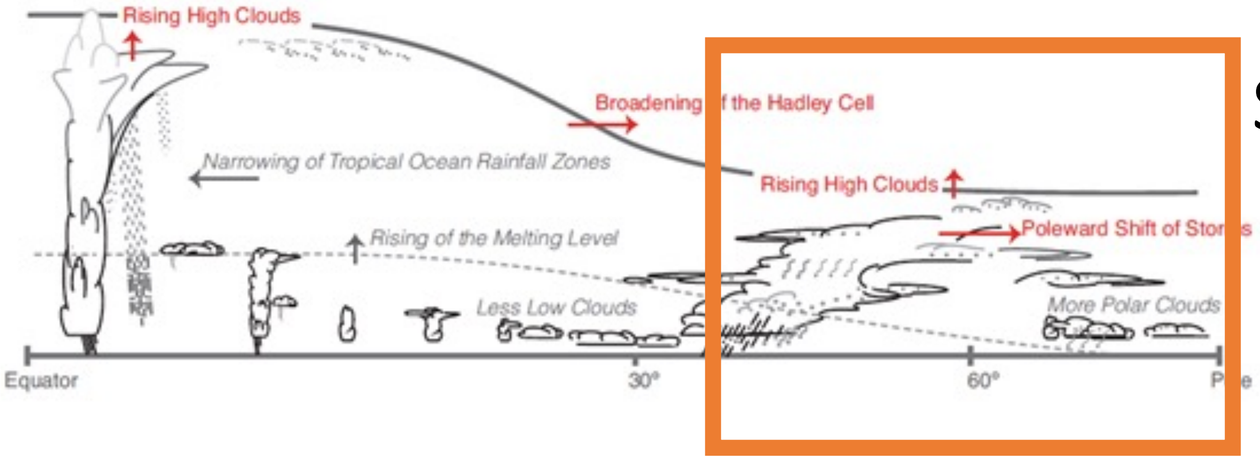


Zelinka, Mark D., Timothy A. Myers, Daniel T. McCoy, Stephen Po-Chedley, Peter M. Caldwell, Paulo Ceppi, Stephen A. Klein, and Karl E. Taylor. "Causes of Higher Climate Sensitivity in CMIP6 Models." *Geophysical Research Letters* n/a, no. n/a (January 3, 2020). https://doi.org/10.1029/2019GL085782.



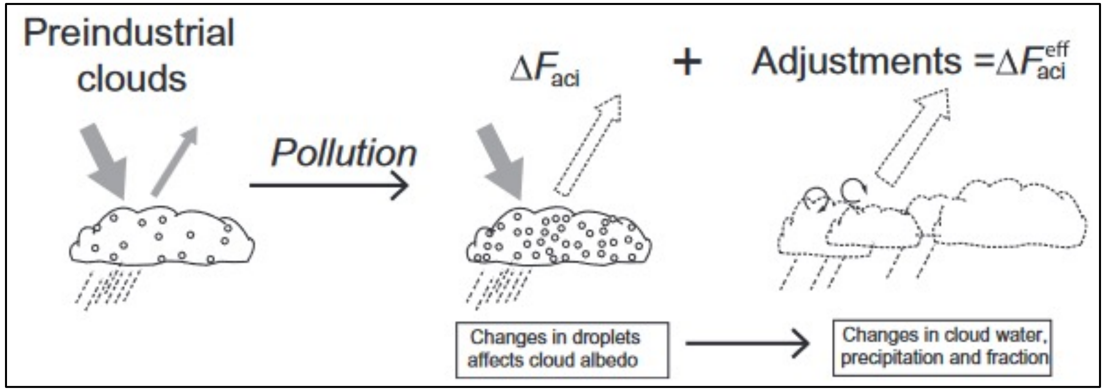
Watson-Parris, D., and C. J. Smith, 2022: Large uncertainty in future warming due to aerosol forcing. *Nature Climate Change*, https://doi.org/10.1038/s41558-022-01516-0.

Motivation



SW Cloud feedback on warming

IPCC AR5 report (Chapter 7, Fig. 11)



Historical forcing from aerosol-cloud interactions (aci)

Effective radiative forcing from aci (ERFaci)

Carslaw, Ken S. “Chapter 2 - Aerosol in the Climate System.” In *Aerosols and Climate*, edited by Ken S. Carslaw, 9–52. Elsevier, 2022. https://doi.org/10.1016/B978-0-12-819766-0.00008-0.

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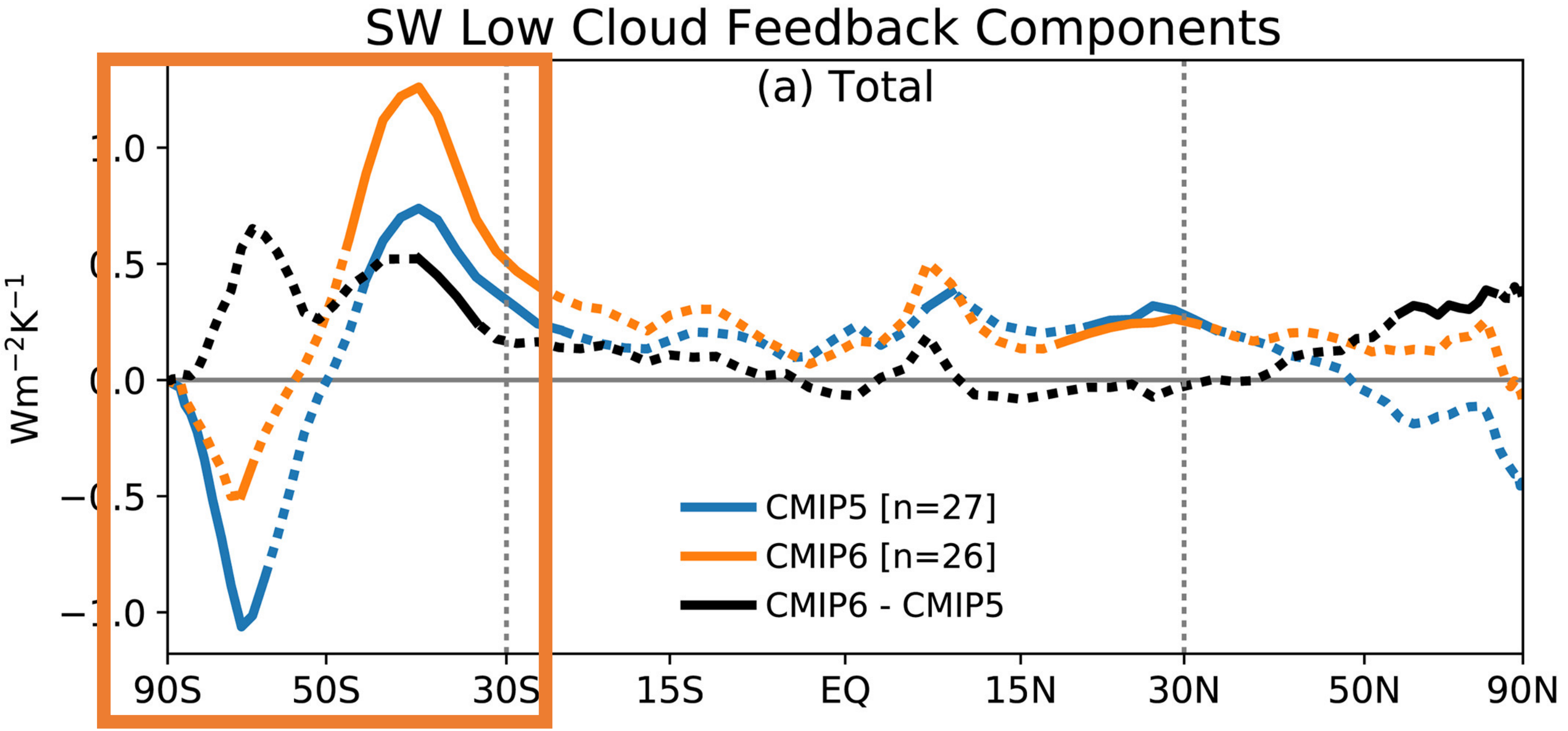
Substantial uncertainty relate to extratropical clouds



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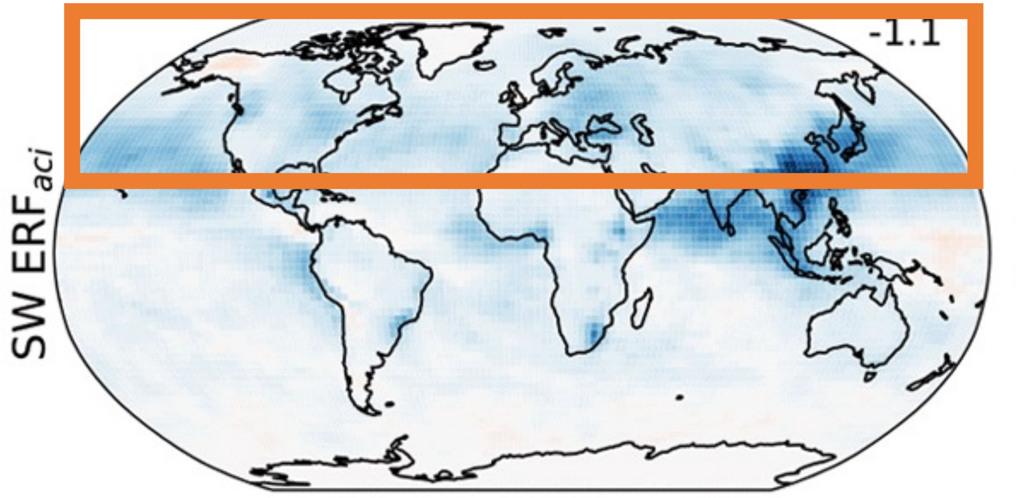
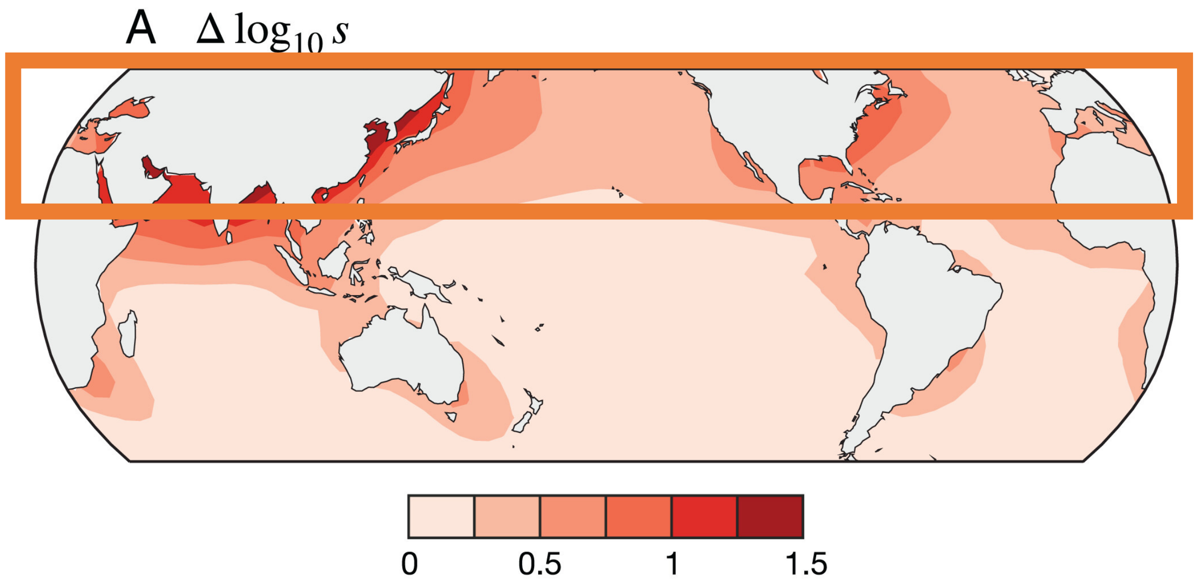
Substantial uncertainty relate to extratropical clouds

ERFaci across 10 ESMs in CMIP6



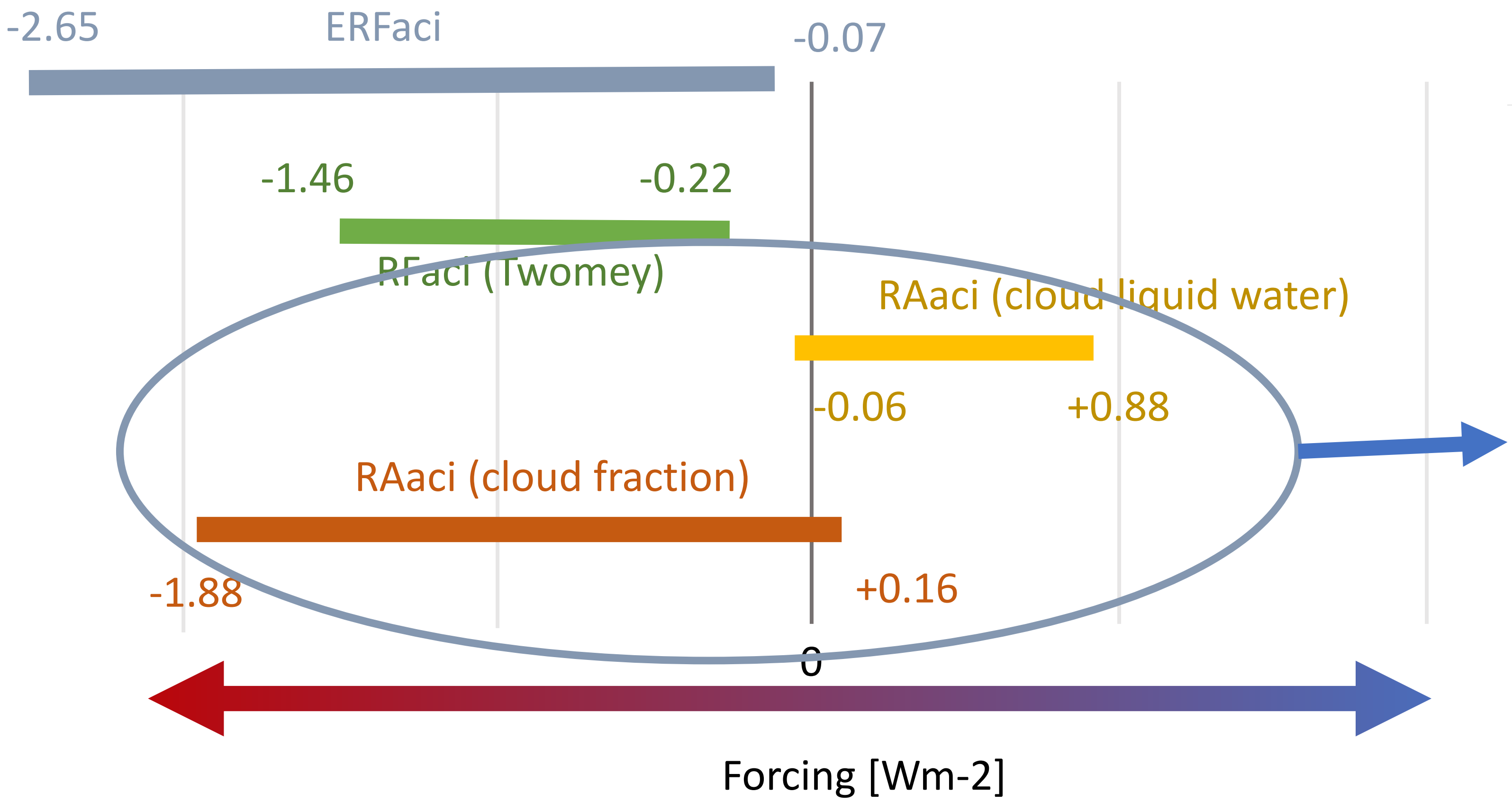
Zelinka, M. D., C. J. Smith, Y. Qin, and K. E. Taylor. "Aerosol Effective Radiative Forcings in CMIP Models." *EGUsphere* 2023 (April 25, 2023): 1–24. https://doi.org/10.5194/egusphere-2023-689.

Change in sulfate in 20 CMIP6 ESMs between PI and PD



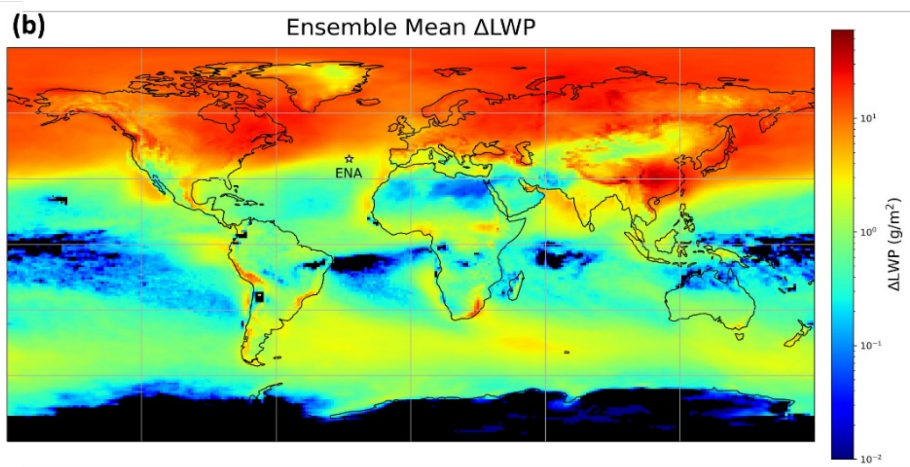
Wall, Casey J., Joel R. Norris, Anna Possner, Daniel T. McCoy, Isabel L. McCoy, and Nicholas J. Lutsko. "Assessing Effective Radiative Forcing from Aerosol–Cloud Interactions over the Global Ocean." *Proceedings of the National Academy of Sciences* 119, no. 46 (November 15, 2022): e2210481119. https://doi.org/10.1073/pnas.2210481119.

Substantial uncertainty relate to extratropical clouds



(95% ranges from Bellouin et al. 2019)

CAM6 ΔLWP between PI and PD in a perturbed parameter ensemble



Causally-aware constraints on aerosol-cloud adjustments from surface observations
Mikkelsen et al. 2024 (ACP, in prep)

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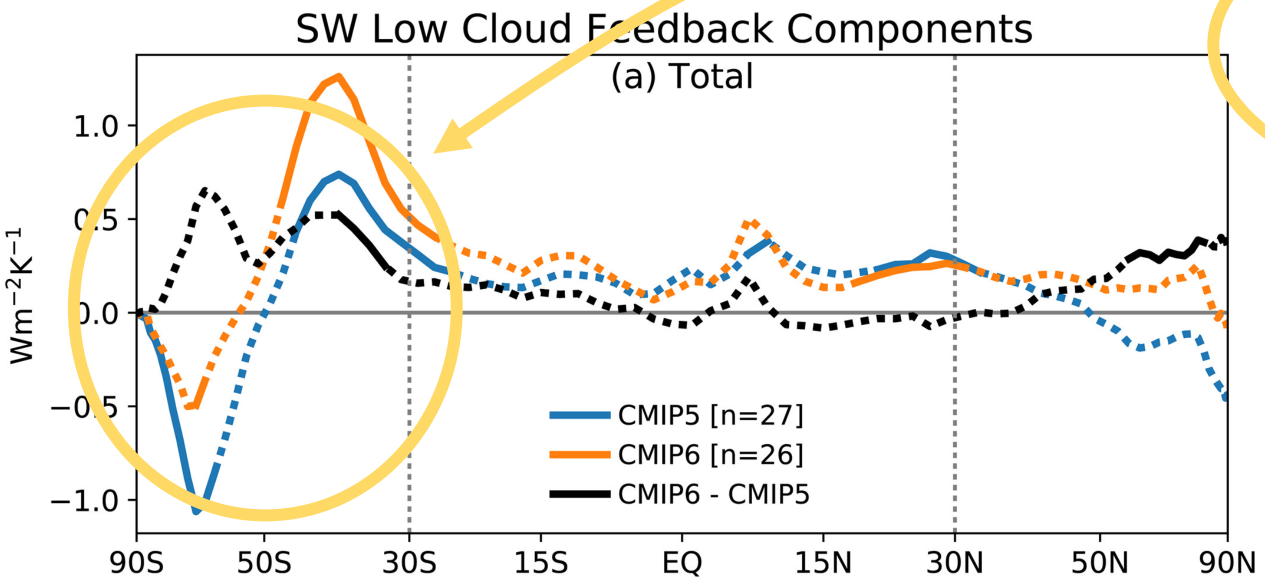
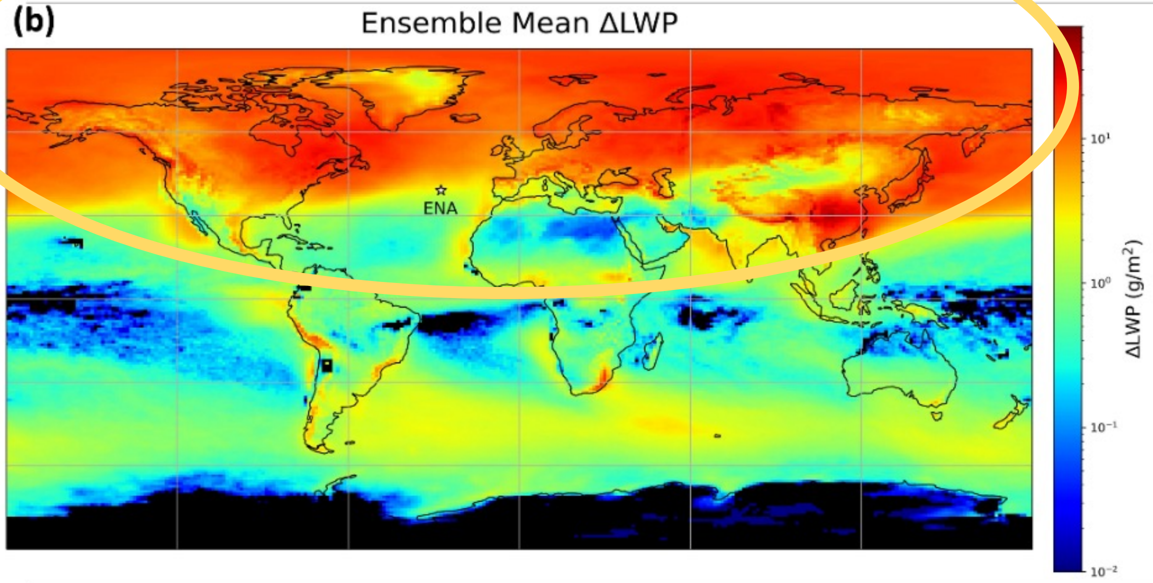
Commonality among extratropical cloud processes?

CAM6 ΔLWP between PI and PD in a perturbed parameter ensemble





Causally-aware constraints on aerosol-cloud adjustments from surface observations
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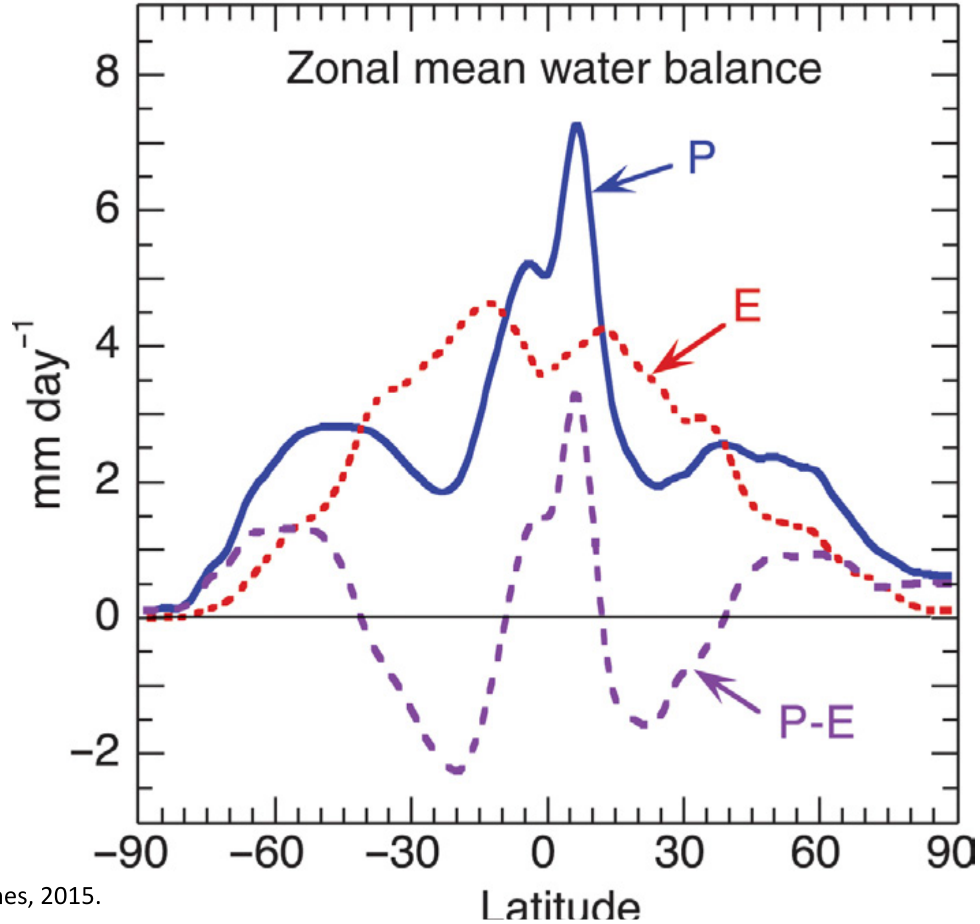
Extratropics are a region of net moisture convergence



Hartmann, Dennis L. *Global Physical Climatology*. Vol. 103. Newnes, 2015.

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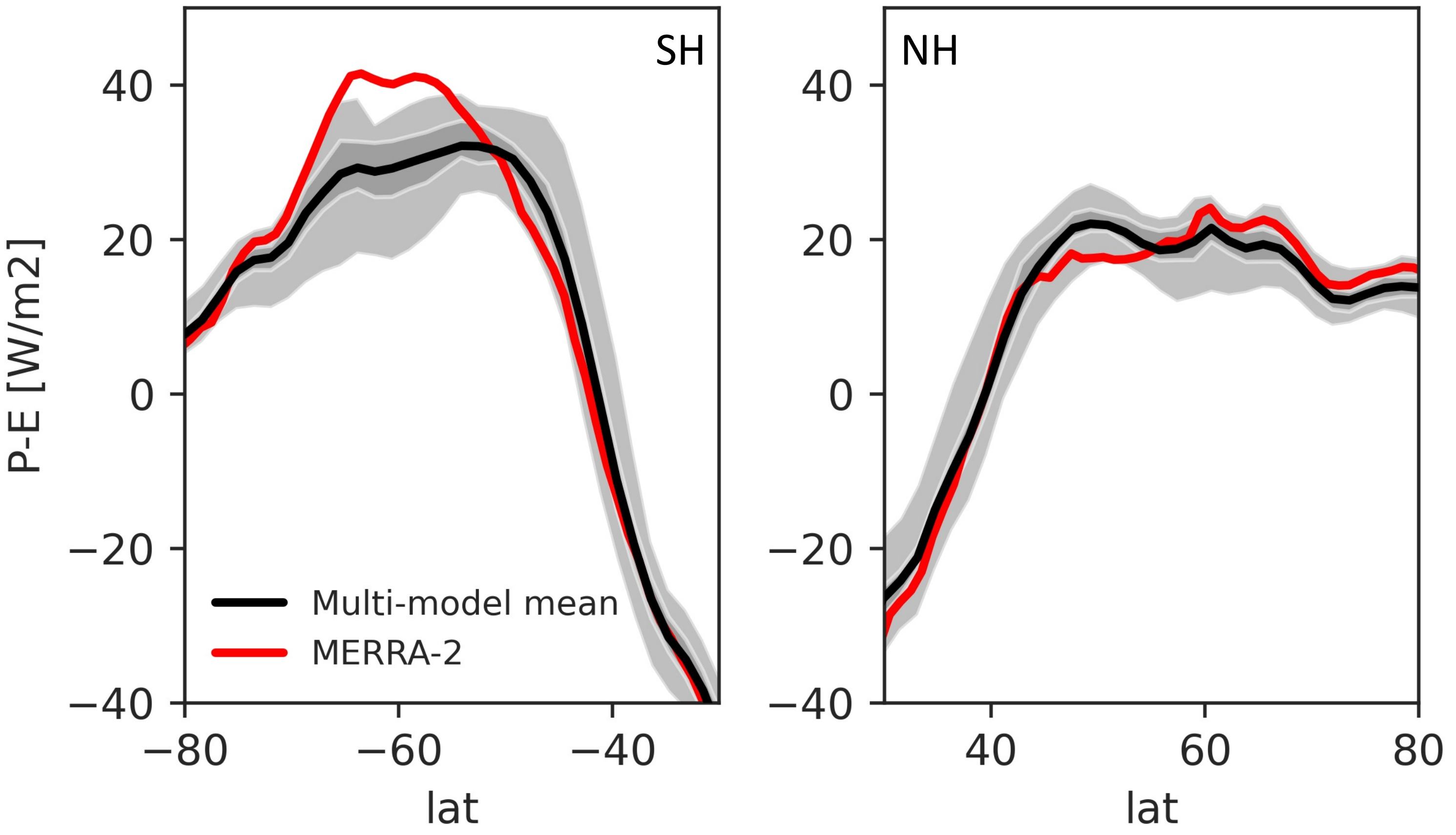
Extratropical moisture convergence (CMIP5+CMIP6)



McCoy, Daniel T., Michelle E. Frazer, Johannes Mülmenstädt, Ivy Tan, Christopher R. Terai, and Mark D. Zelinka. "Extratropical Cloud Feedbacks." In *Clouds and Their Climatic Impacts*, 133–57. Geophysical Monograph Series, 2023. https://doi.org/10.1002/9781119700357.ch6.

In this talk:

Ci Song

Buffering of aerosol-cloud adjustments by coupling between radiative susceptibility and precipitation efficiency
Song et al. 2024 (GRL, in press)

Geethma Werapitiya

Climate Model Extratropical Cloud Feedback Constrained by Cloud Sources and Sinks in Cyclones
Werapitiya et al. 2024 (JCLI, in prep)

"Aerosol-cloud adjustment forcing is buffered by competition between radiative susceptibility and precipitation efficiency across ESMs."

"Extratropical SW cloud feedback is driven in by moisture convergence, but buffered by radiative susceptibility through precipitation efficiency."

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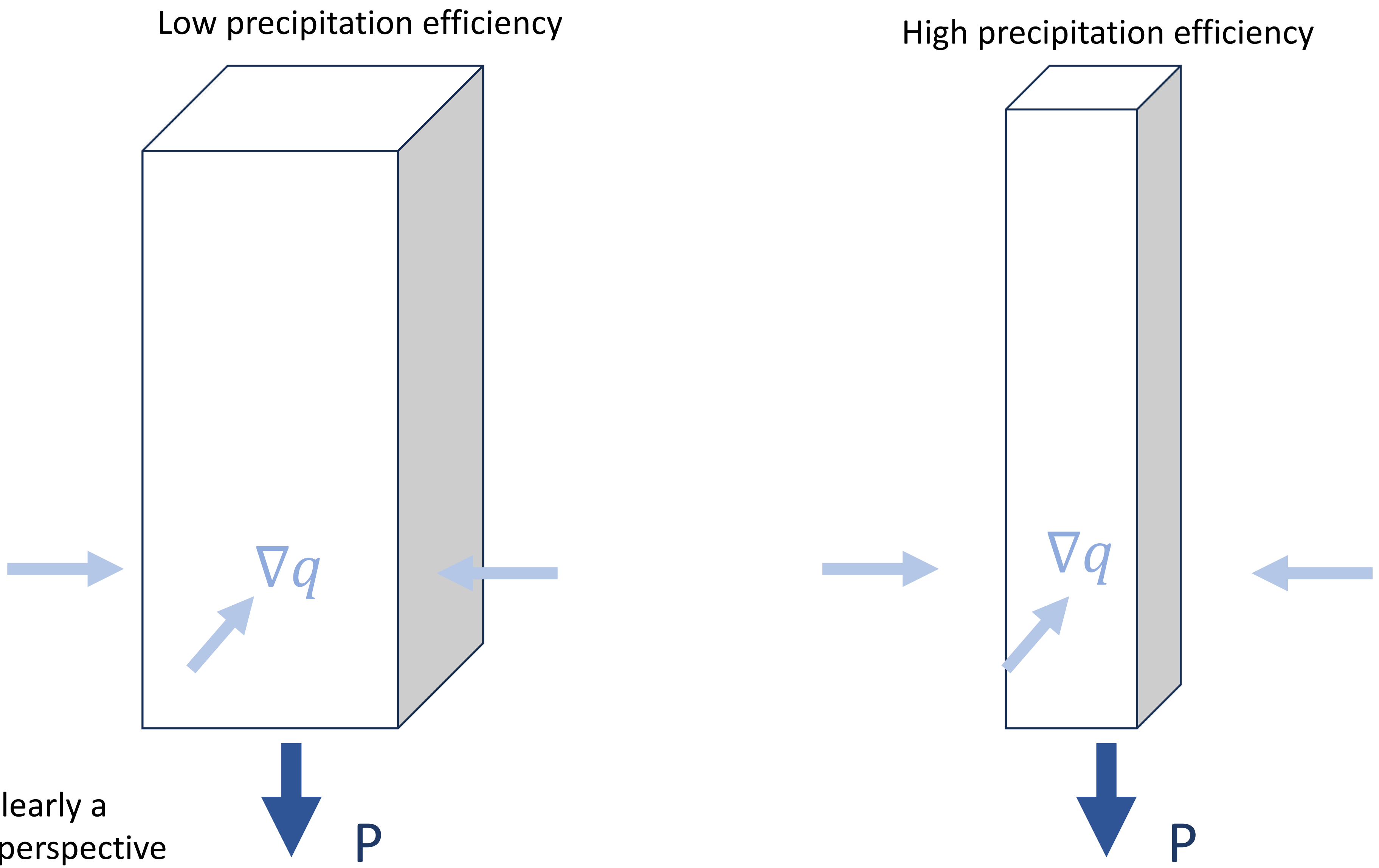
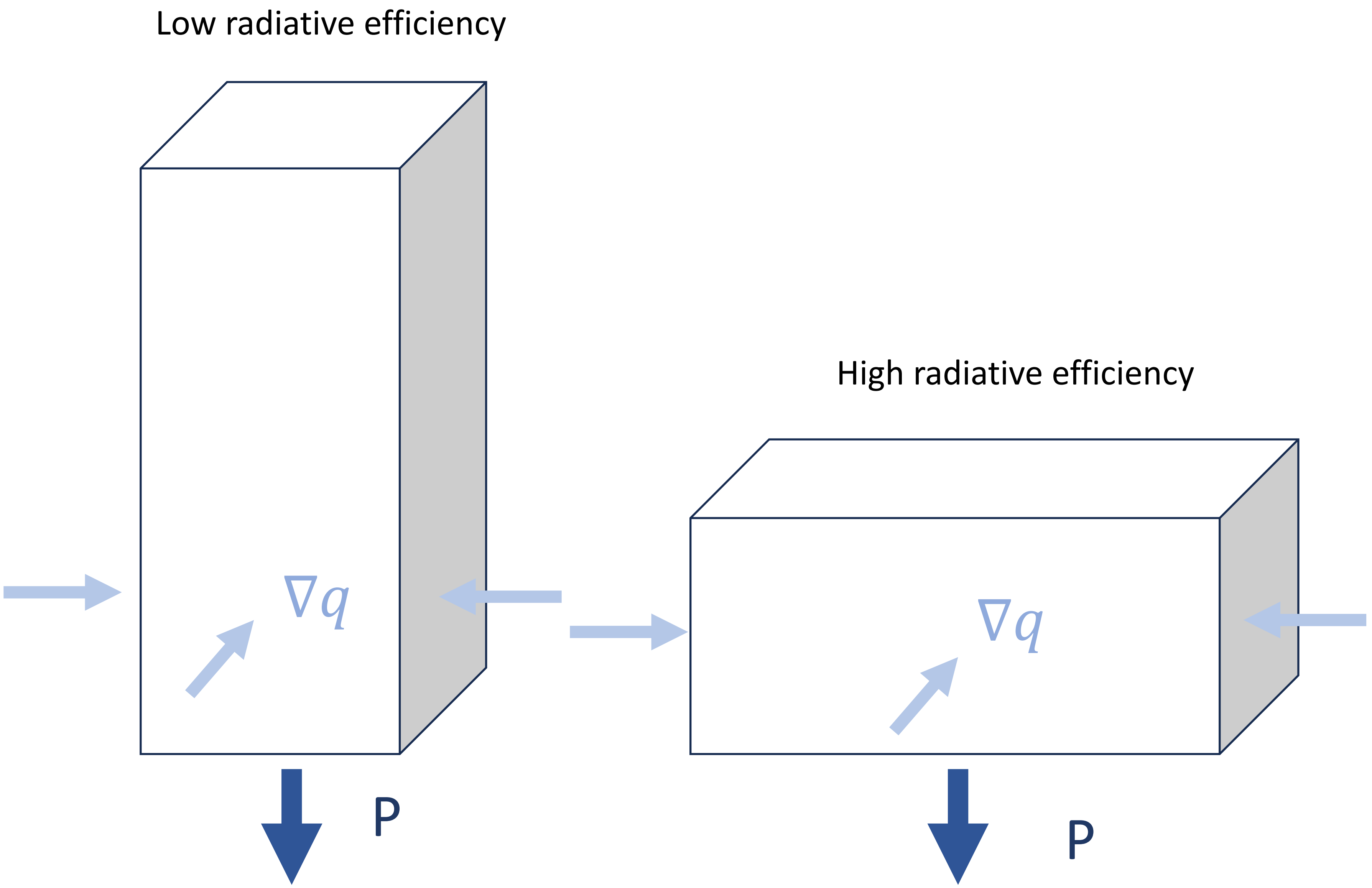


*Note that this is clearly a climate modeler's perspective



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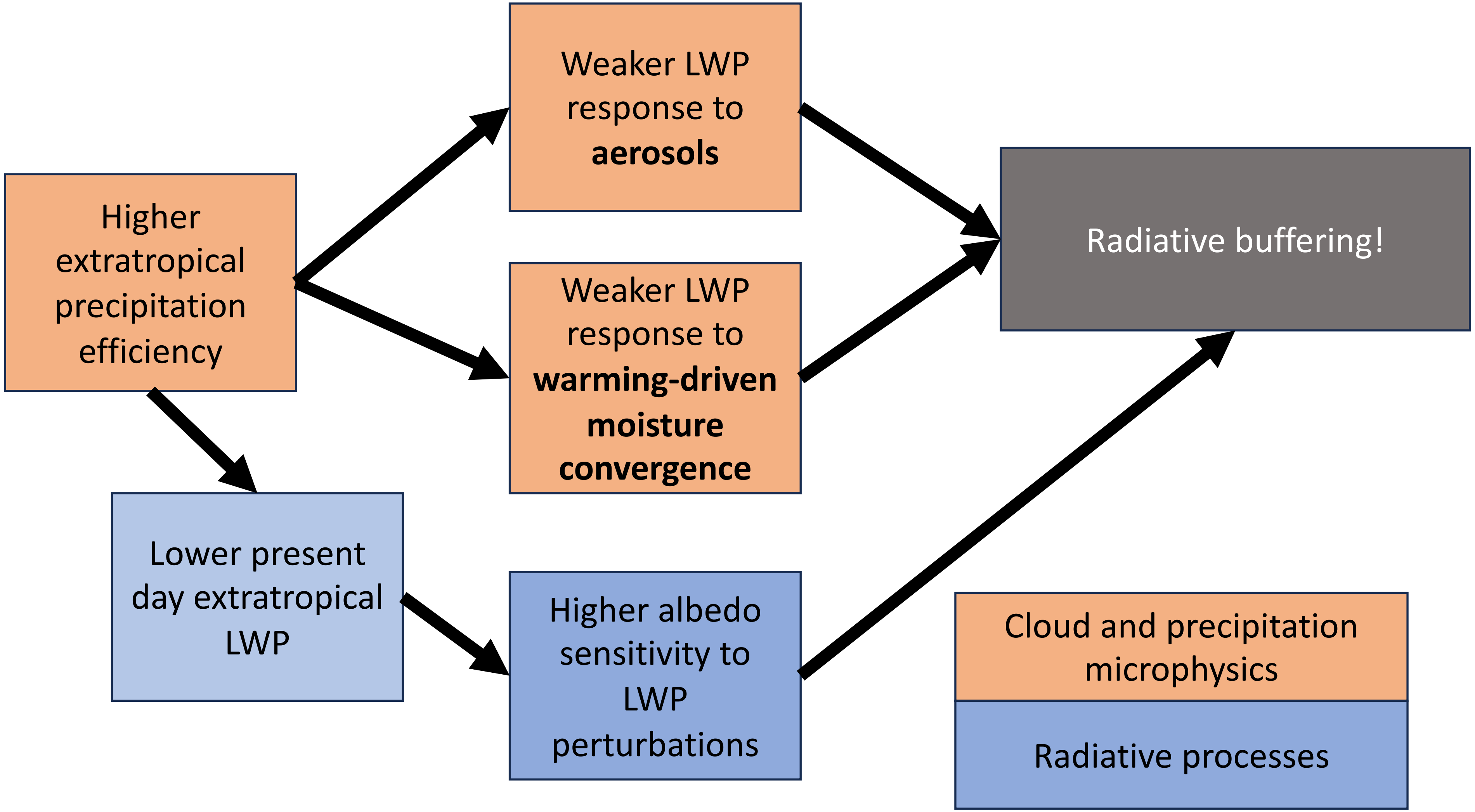
In this talk:

Extratropical feedback, forcing, and radiative buffering processes 2024 (ACP, in prep)



Geethma Werapitiya

Ci Song

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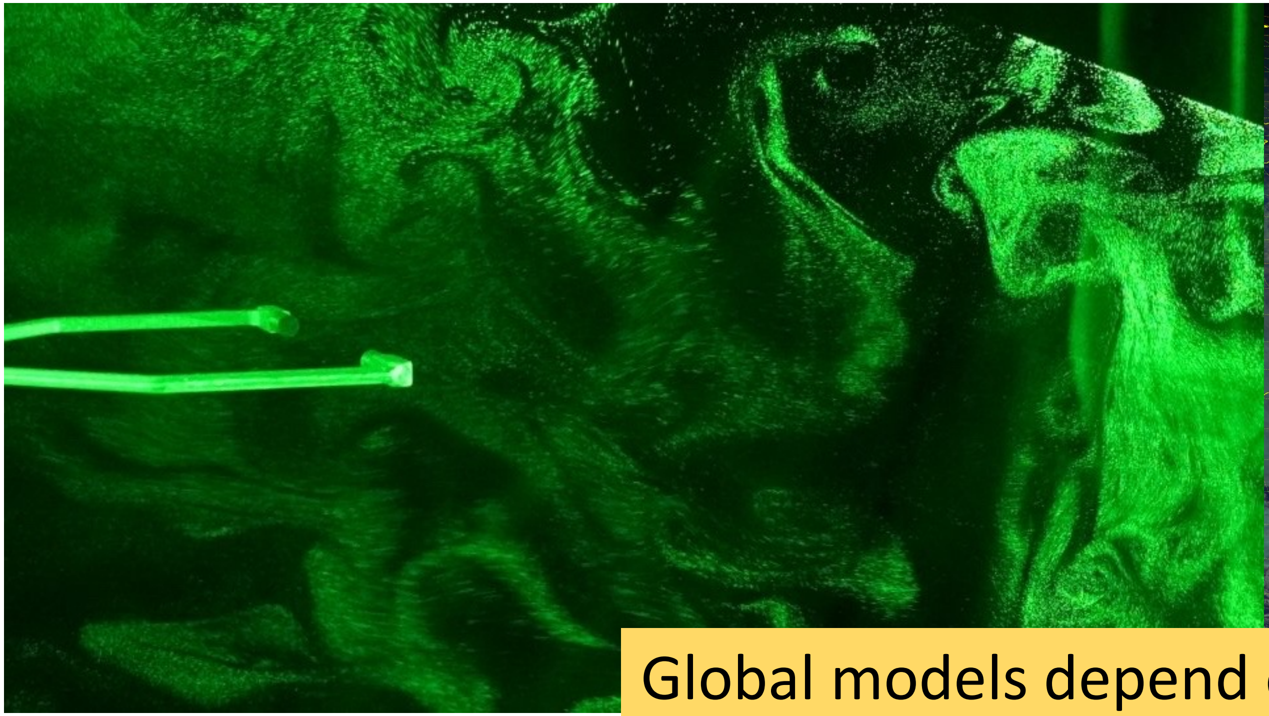
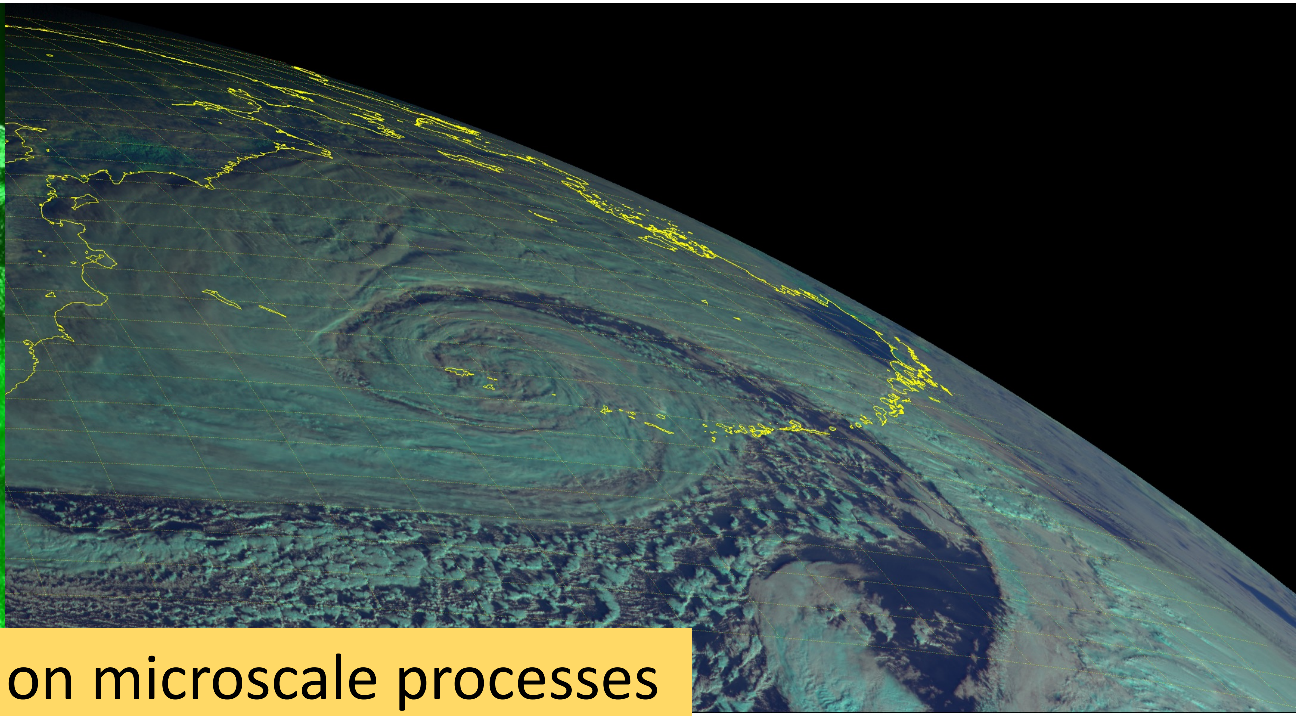
Why a perturbed parameter ensemble (PPE)?





Global models depend on microscale processes

µm ⟷ km

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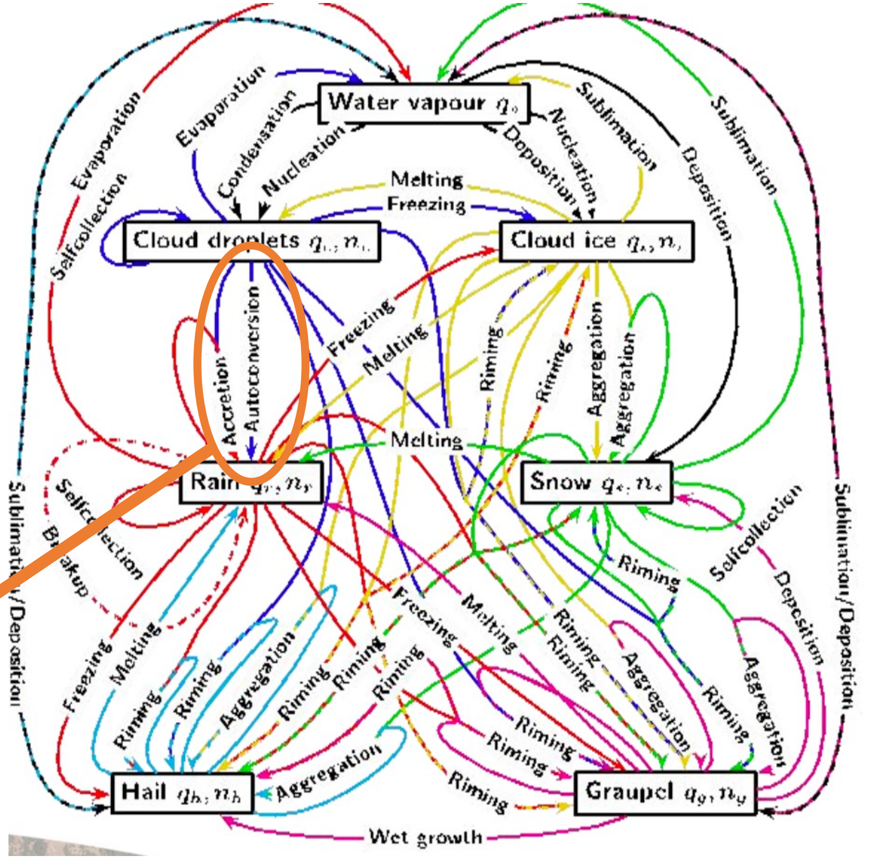
Why a perturbed parameter ensemble (PPE)?

- Parameterization:
  - How do we abstract a sub-grid-scale process?
  - How do we choose parameter values?
- PPEs are a way to explore parametric space in a model – here an ESM.



$$\dot{q}_c = a \cdot q_c^b \cdot N_d^c$$

Gettelman CESM2 workshop Seifert

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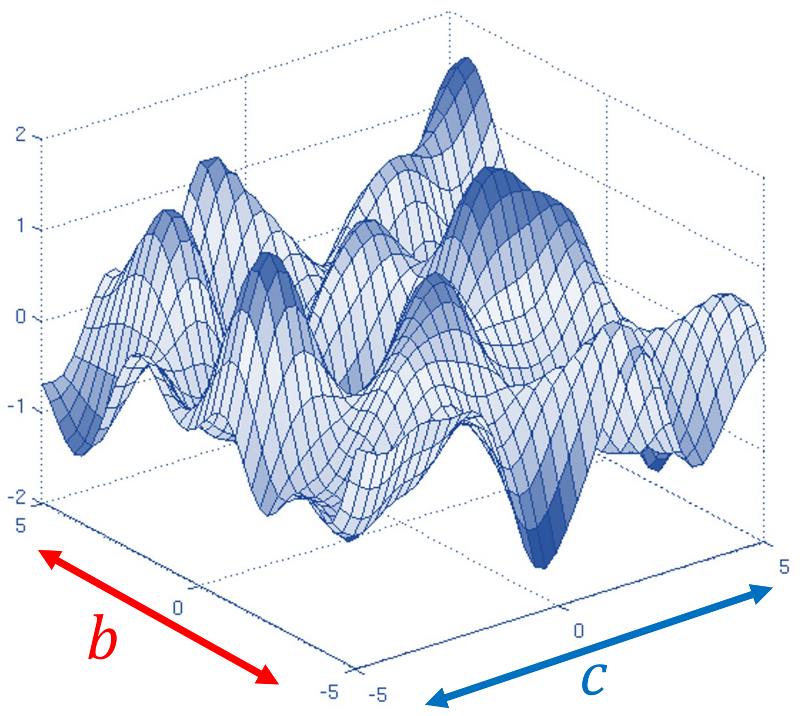
Perturbed parameter ensemble (PPE)

- Imagine a model with a single parameterization:

$$\dot{q}_c = a \cdot q_c^{b} \cdot N^{c}$$

An observable (e.g. cloud fraction)



https://www.cs.toronto.edu/~duvenaud/cookbook/

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Perturbed parameter ensemble (PPE)

- Imagine a model with a single parameterization:

$$\dot{q}_c = a \cdot q_c^{b} \cdot N^{c}$$

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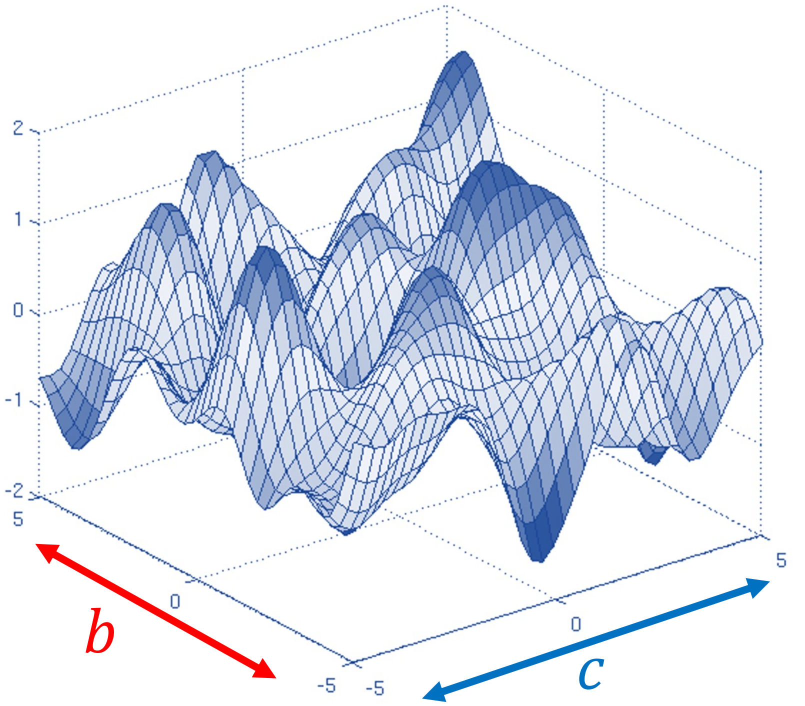
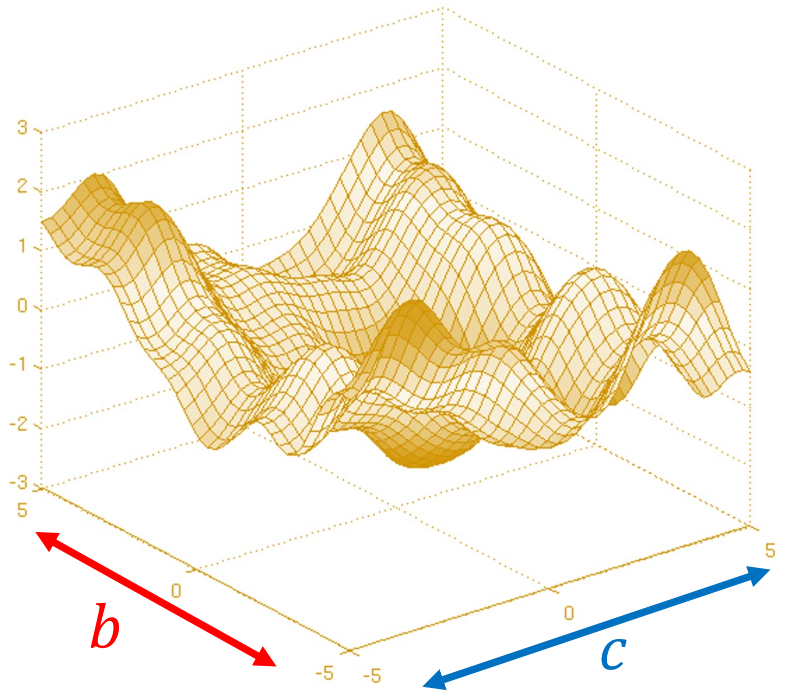


An unobservable (e.g. aerosol forcing)



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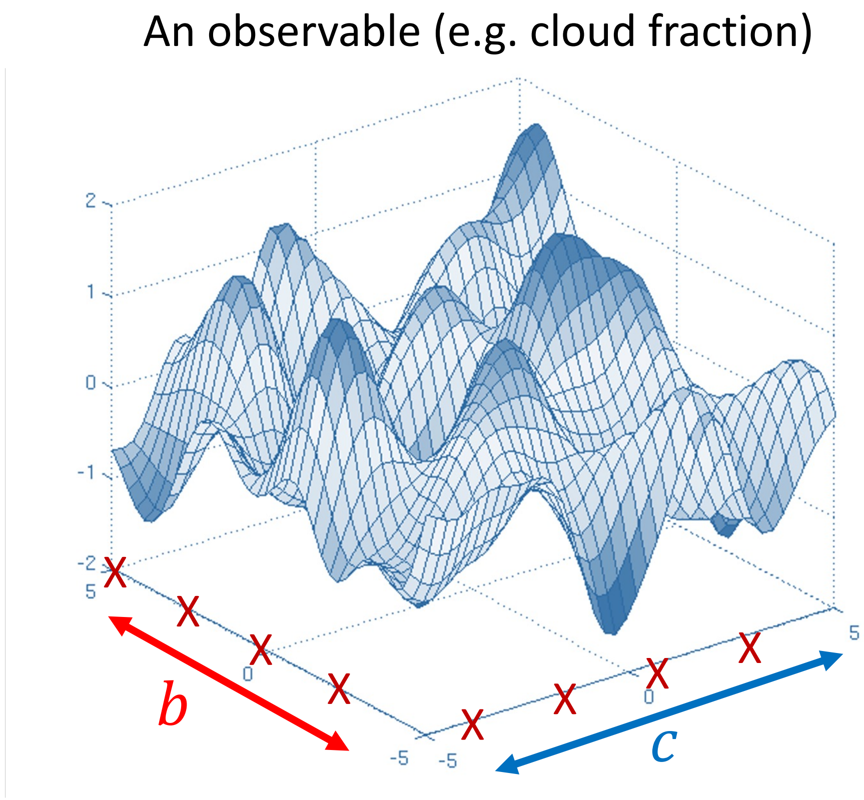
Perturbed parameter ensemble (PPE)

- Real GCMs have many more than 2 parameters governing aci.
- To sample each dimension in N dimensional parameter space with P samples we need P^N simulations.
- Expensive!



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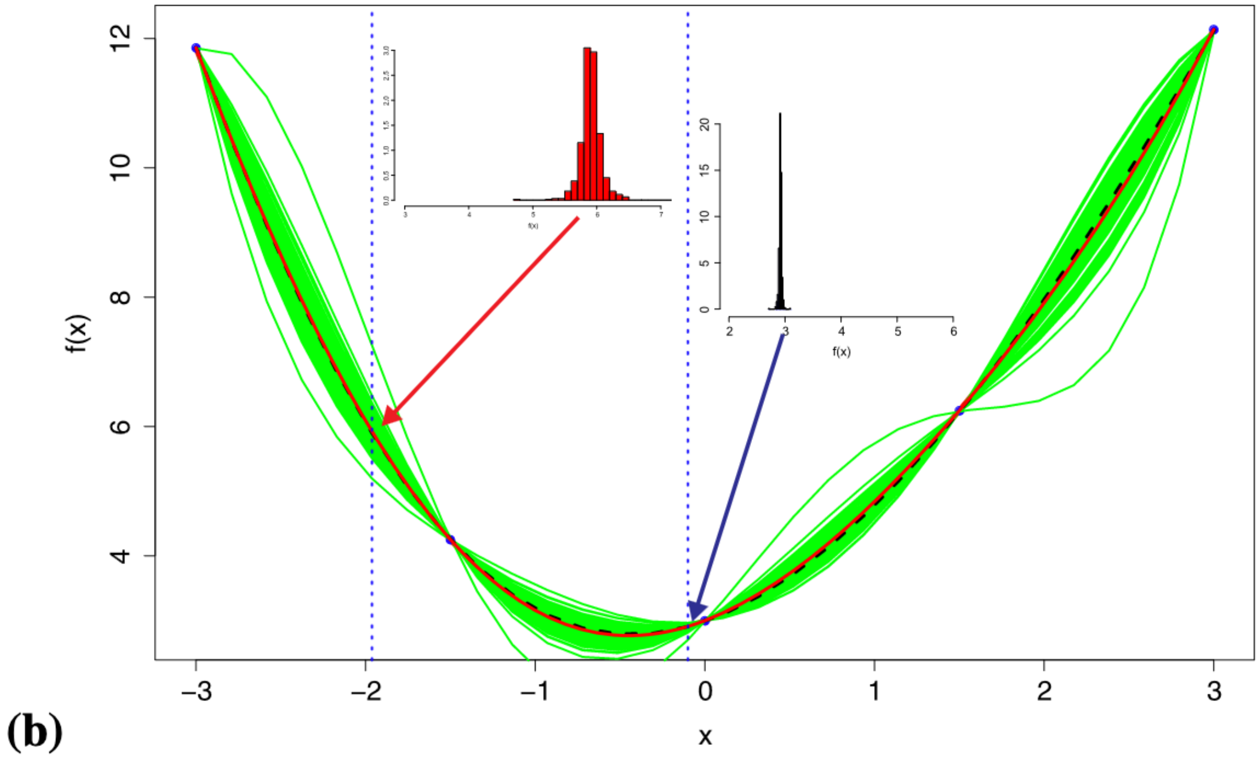
Sampling parameter space

- Randomly sample and build an emulator.
- Typically Gaussian Process.
- Use Earth System Emulator (ESEm) https://github.com/duncanwp/ESEm



Lee, L. A., K. S. Carslaw, K. J. Pringle, G. W. Mann, and D. V. Spracklen. "Emulation of a Complex Global Aerosol Model to Quantify Sensitivity to Uncertain Parameters." *Atmos. Chem. Phys.* 11, no. 23 (December 8, 2011): 12253–73. https://doi.org/10.5194/acp-11-12253-2011.

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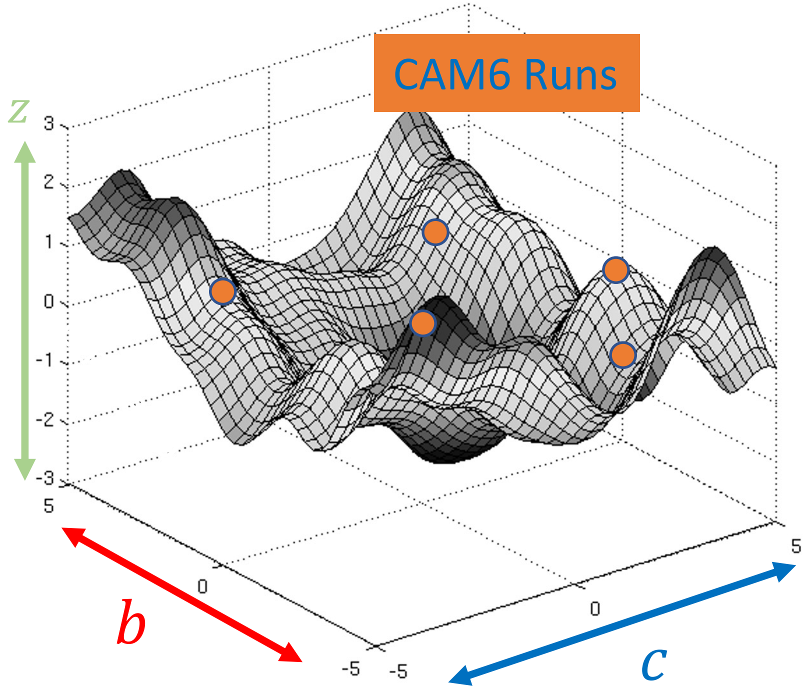
CAM6 PPE

- CAM6 run with fixed SST and ice.
- 45 parameters from clouds, convection, precipitation, aerosol, radiation are perturbed in 262 simulations.
- Sampled using latin hypercube.



Trude Eidhammer

Andrew Gettelman

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CAM6 PPE

Scenario	Details	Use
Present Day **PD**	AMIP configuration, Present day emissions, nudged and free-running atmosphere	
Preindustrial **PI**	As in PD, but with aerosol emissions set to PI	Calculate aerosol forcing
+4K SST	Cess-type experiment with SST increased by 4K. Free-running atmosphere	Calculate cloud feedback

Physics Scheme	Parameter Name	Description	Default	Min	Max	Units
$CLUBB$ (Boundary layer)	clubb_C2rt	Damping on scalar variances	1.0	0.2	2	-
	clubb_C6rt	Low skewness in C6rt skewness function	4.0	2.0	6	-
	clubb_C6rtb	High skewness in C6rt skewness function	6.0	2.0	8	-
	clubb_C6thl	Low skewness in C6thl skewness function	4.0	2.0	6	-
	clubb_C6thlb	High skewness in C6thl skewness function	6.0	2.0	8	-
	clubb_C8	Coef. #1 in C8 skewness Equation	4.2	1.0	5	-
	clubb_beta	Set plume widths for theta_l and rt	2.4	1.6	2.5	-
	clubb_c1	Low Skewness in C1 Skw.	1.0	0.4	3	-
	clubb_c11	Low Skewness in C11 Skw	0.7	0.2	0.8	-
	clubb_c14	Constant for u'^2 and v'^2 terms	2.2	0.4	3	-
	clubb_c_K10	Momentum coefficient of Kh_zm	0.5	0.2	0.6	-
	clubb_gamma_coef	Low Skw.: gamma coef. Skw	0.308	0.25	0.35	-
	clubb_wpxp_L_thresh	Lscale threshold, damp C6 and C7	60	20	200	m
$MG2$ (Microphysics)	micro_mg_accre_enhan_fact	Accretion enhancing factor	1.0	0.1	10.0	-
	micro_mg_autocon_fact	Autoconversion factor	0.01	0.005	0.2	-
	micro_mg_autocon_lwp_exp	KK2000 LWP exponent	2.47	2.10	3.30	-
	micro_mg_autocon_nd_exp	KK2000 autoconversion exponent	-1.1	-0.8	-2	-
	micro_mg_berg_eff_factor	Bergeron efficiency factor	1.0	0.1	1.0	-
	micro_mg_dcs	Autoconversion size threshold ice-snow	500e-06	50e-06	1.000e-06	m
	micro_mg_effi_factor	Scale effective radius for optics calculation	1.0	0.1	2.0	-
	micro_mg_homog_size	Homogeneous freezing ice particle size	25e-6	10e-6	200e-6	m
	micro_mg_iaccr_factor	Scaling ice/snow accretion	1.0	0.2	1.0	-
	micro_mg_max_nicons	Maximum allowed ice number concentration	100e6	1e5	10000e6	# kg^{-1}
	micro_mg_vtrmi_factor	Ice fall speed scaling	1.0	0.2	5.0	$m\ s^{-1}$
$Aerosol$ (Aerosol)	microp_aero_npccn_scale	Scale activated liquid number	1	0.33	3	-
	microp_aero_wsub_min	Min subgrid velocity for liq activation	0.2	0	0.5	$m\ s^{-1}$
	microp_aero_wsub_scale	Subgrid velocity for liquid activation scaling	1	0.1	5	-
	microp_aero_wsubi_min	Min subgrid velocity for ice activation	0.001	0	0.2	$m\ s^{-1}$
	microp_aero_wsubi_scale	Subgrid velocity for ice activation scaling	1	0.1	5	-
	dust_emis_fact	Dust emission scaling factor	0.7	0.1	1.0	-
	seasalt_emis_scale	Seasalt emission scaling factor	1.0	0.5	2.5	-
	sol_factb_interstitial	Below cloud scavenging of interstitial modal aerosols	0.1	0.1	1	-
	sol_factic_interstitial	In-cloud scavenging of interstitial modal aerosols	0.4	0.1	1	-
ZM (Convection)	cldfrc_dp1	Parameter for deep convection cloud fraction	0.1	0.05	0.25	-
	cldfrc_dp2	Parameter for deep convection cloud fraction	500	100	1.000	-
	zmconv_c0_lnd	Convective autoconversion over land	0.0075	0.002	0.1	m^{-1}
	zmconv_c0_ocn	Convective autoconversion over ocean	0.03	0.02	0.1	m^{-1}
	zmconv_capelmt	Triggering threshold for ZM convection	70	35	350	$J\ kg^{-1}$
	zmconv_dmpdz	Entrainment parameter	-1.0e-3	-2.0e-3	-2.0e-4	m^{-1}
	zmconv_ke	Convective evaporation efficiency	5.0e-6	1.0e-6	1.0e-5	$(kg\ m^{-2}\ s^{-1})^{0.5}\ s^{-1}$
	zmconv_ke_lnd	Convective evaporation efficiency over land	1.0e-5	1.0e-6	1.0e-5	$(kg\ m^{-2}\ s^{-1})^{0.5}\ s^{-1}$
	zmconv_momcd	Efficiency of pressure term in ZM downdraft CMT	0.7	0	1	-
	mconv_momcu	Efficiency of pressure term in ZM updraft CMT	0.7	0	1	-
	zmconv_num_cin	Allowed number of negative buoyancy crossings	1	1	5	-
	zmconv_tiedke_add	Convective parcel temperature perturbation	0.5	0	2	K

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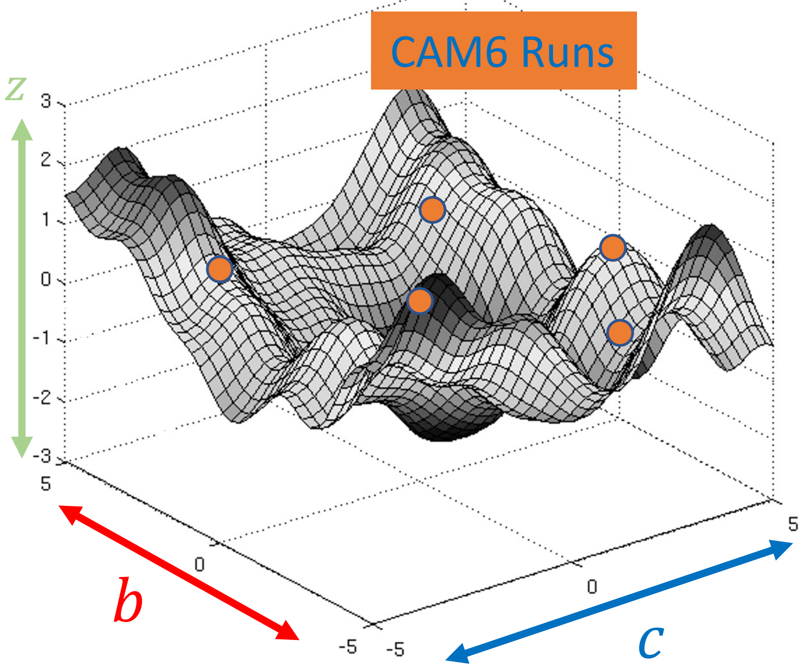
CAM6 PPE

- Eidhammer, T., A. Gettelman, K. Thayer-Calder, D. Watson-Parris, G. Elsaesser, H. Morrison, M. van Lier-Walqui, C. Song, and D. McCoy. “An Extensible Perturbed Parameter Ensemble (PPE) for the Community Atmosphere Model Version 6.” *EGUsphere* 2024 (January 15, 2024): 1–27. https://doi.org/10.5194/egusphere-2023-2165.



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Aerosol-cloud interactions

Extratropical feedback, forcing, and radiative buffering processes 2024 (ACP, in prep)

Higher extratropical precipitation efficiency

Weaker LWP response to aerosols

Weaker LWP response to warming-driven moisture convergence

Lower present day extratropical LWP

Higher albedo sensitivity to LWP perturbations

Radiative buffering!

Cloud and precipitation microphysics

Radiative processes

Geethma Werapitiya

Ci Song

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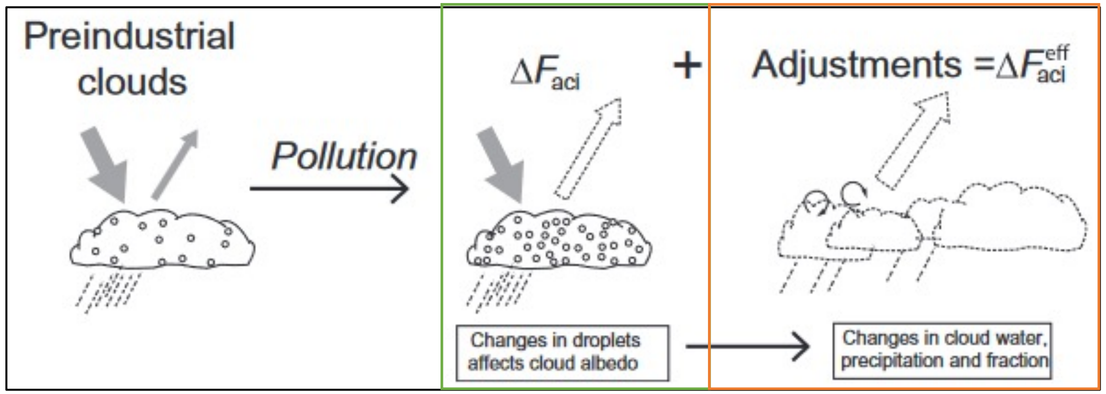
Constraints on ERFaci

- The effective radiative forcing due to aerosol-cloud interactions (ERFaci) can be linearized as:

$$\frac{dR}{dlnN_d} \approx \left.\frac{\partial R}{\partial lnN_d}\right|_{\mathcal{L},C} + \frac{\partial R}{\partial C}\frac{dC}{dlnN_d} + \frac{\partial R}{\partial \mathcal{L}}\frac{d\mathcal{L}}{dlnN_d}$$

Radiative forcing   Aerosol-cloud adjustments



Carslaw, Ken S. "Chapter 2 - Aerosol in the Climate System." In *Aerosols and Climate*, edited by Ken S. Carslaw, 9–52. Elsevier, 2022. https://doi.org/10.1016/B978-0-12-819766-0.00008-0.

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Constraints on ERFaci

Sensitivity of cloud fraction and in cloud liquid water path to Nd

$$\frac{dR}{dlnN_d} \approx \left.\frac{\partial R}{\partial lnN_d}\right|_{\mathcal{L},C} + \frac{\partial R}{\partial C}\boxed{\frac{dC}{dlnN_d}} + \frac{\partial R}{\partial \mathcal{L}}\boxed{\frac{d\mathcal{L}}{dlnN_d}}$$

Radiative forcing

Aerosol-cloud adjustments

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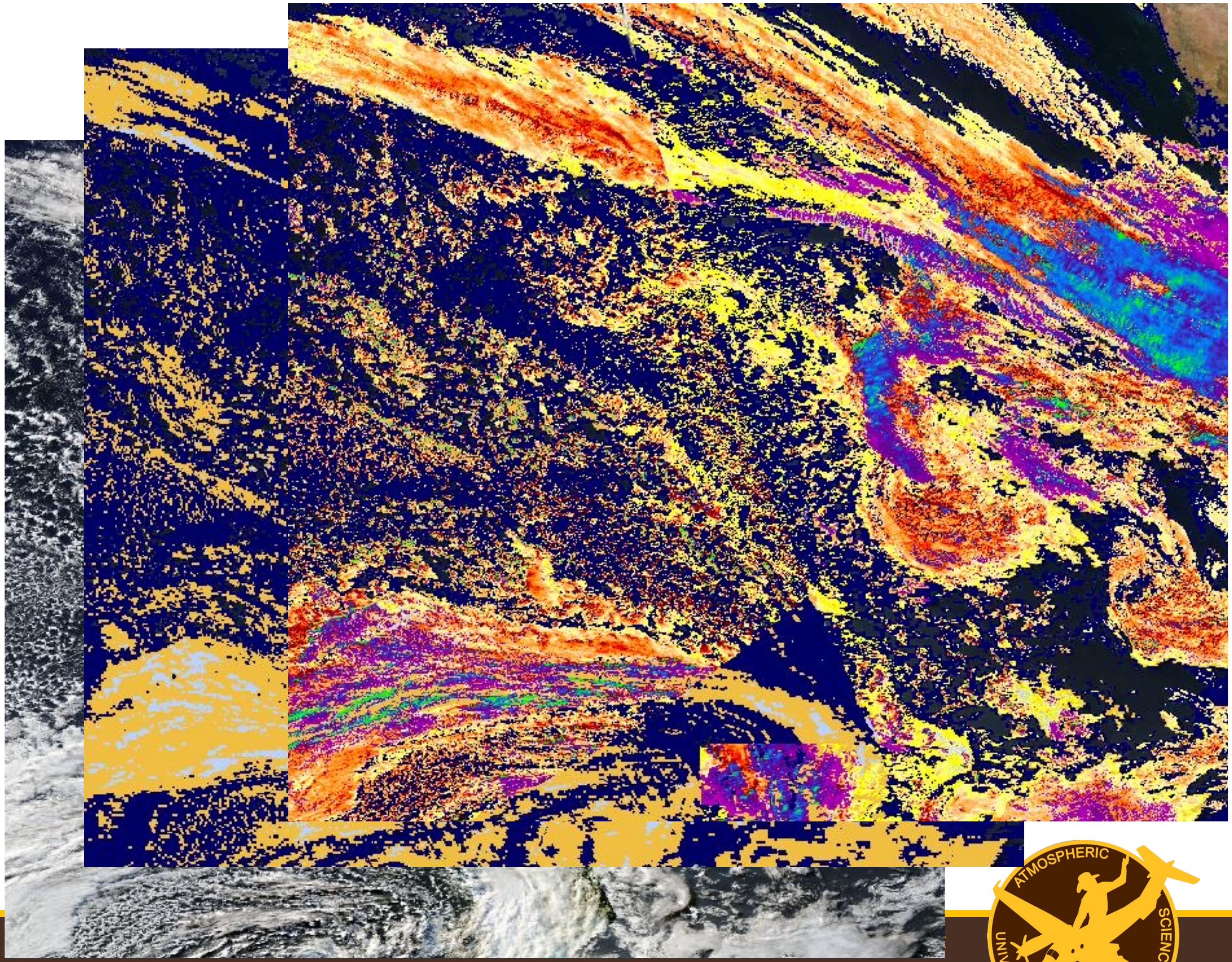
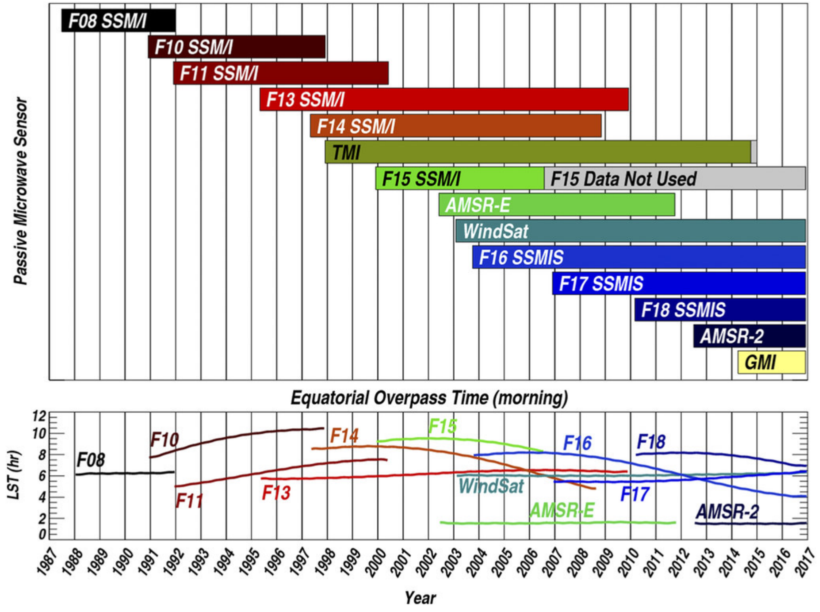
Cloud macrophysical properties

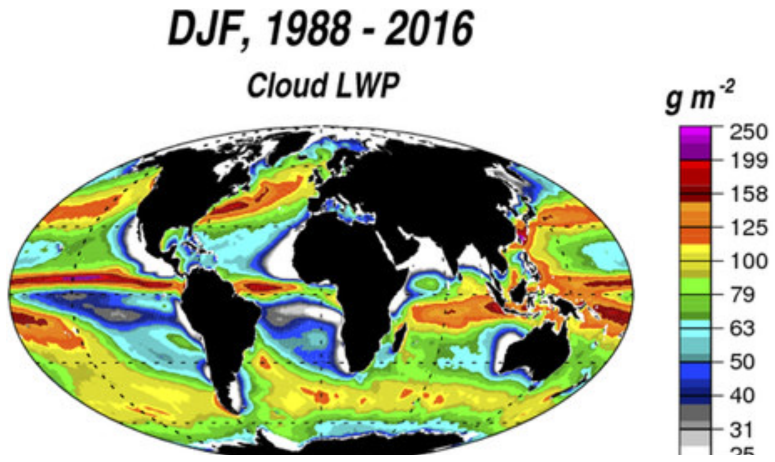
- In this talk we use microwave radiometer liquid water path (LWP).
- Not in-cloud.
- Not as sensitive to broken cloud.
- Doesn't care about multi-layer and ice-topped cloud.

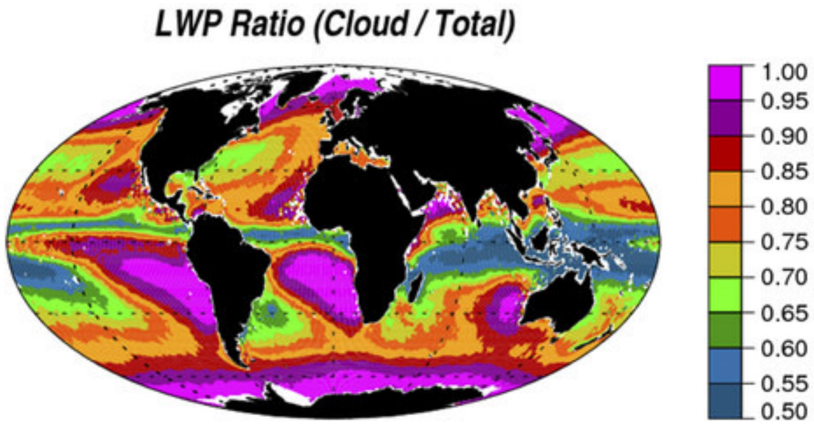


Cloud macrophysical properties

- MAC-LWP product.
- Even sampling through diurnal cycle.
- Use in extratropics minimizes rain/cloud partitioning issues.







Elsaesser, G. S., Christopher W. O'Dell, Matthew D. Lebsock, Ralf Bennartz, Thomas J. Greenwald, and Frank J. Wentz. "The Multi-Sensor Advanced Climatology of Liquid Water Path (MAC-LWP)." *Journal of Climate* 0, no. 0 (2017): null. https://doi.org/10.1175/jcli-d-16-0902.1.

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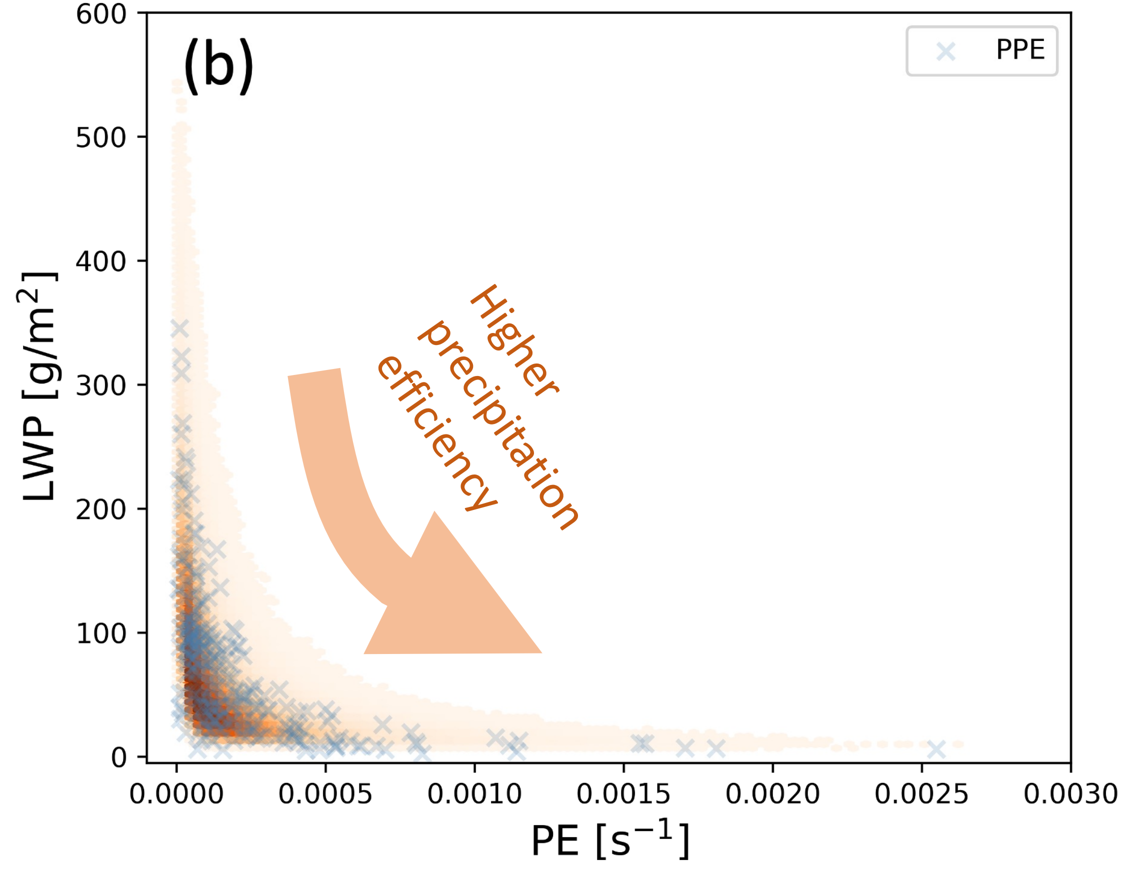
Precipitation efficiency controls extratropical LWP

- Mean state LWP scales very strongly with precipitation efficiency.
- Precipitation efficiency should be important for aerosol cloud adjustments too!

Extratropical LWP vs. precipitation efficiency across PPE members



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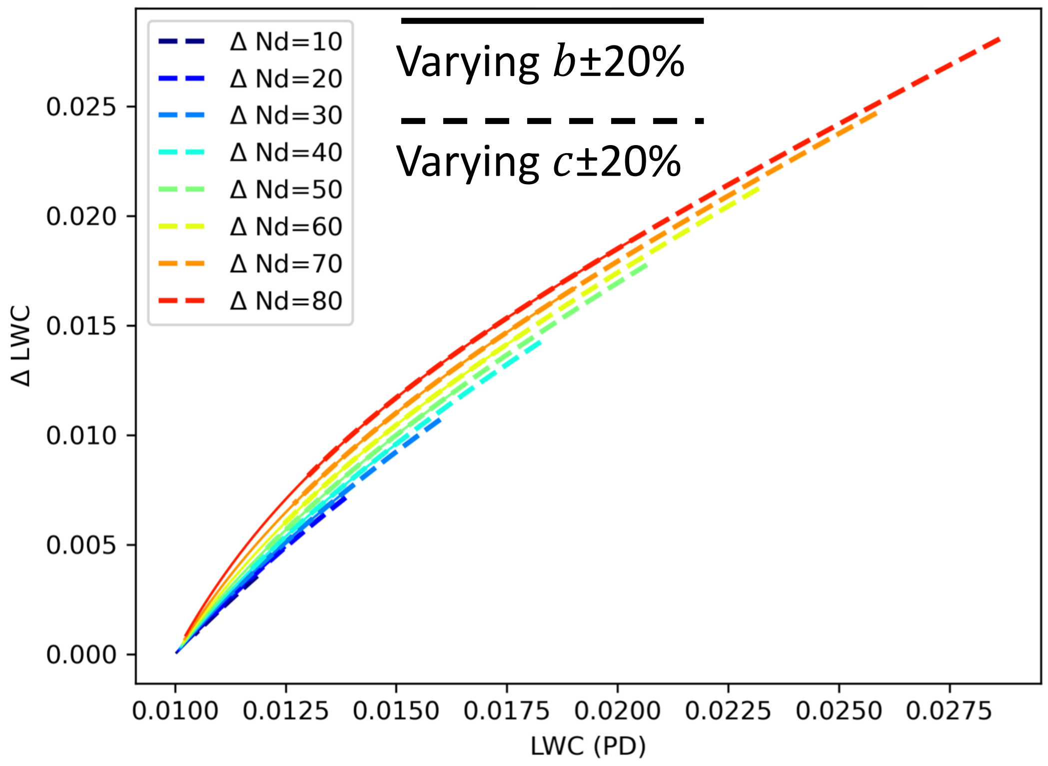
Aerosol-cloud adjustments

- Mean-state LWP tells us about precipitation efficiency.
- Assume condensation same in PI and PD.
- Condensation balanced by precipitation sink
- Solve
  $\dot{q}_c = a \cdot q_{c\,PD}^{b} \cdot N_{PD}^{c} = a \cdot q_{c\,PI}^{b} \cdot N_{PI}^{c}$
- For change in liquid water content.

Algebra based on autoconversion scheme (Khairoutdinov and Kogan 2000)



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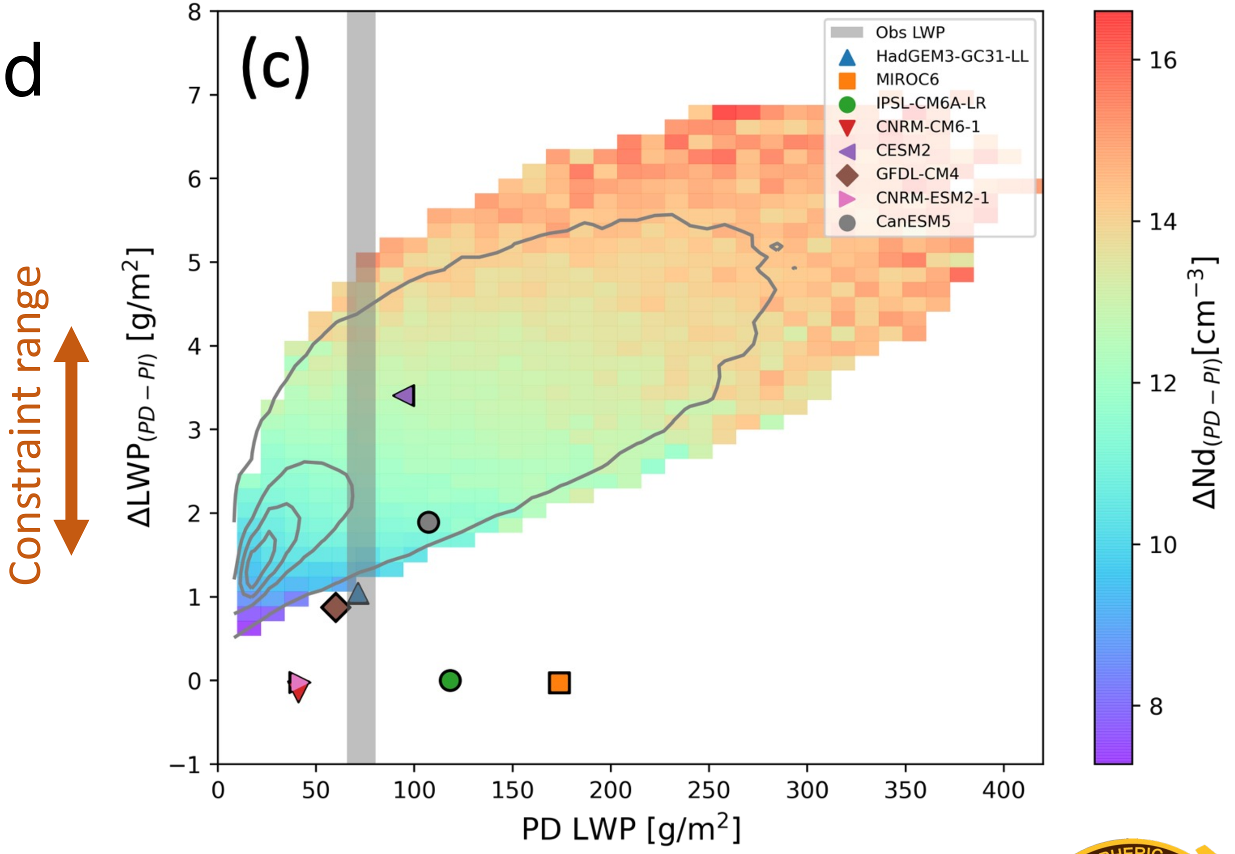
Aerosol-cloud adjustments

- PPE also produces a positive correlation between PD LWP and PI->PD ΔLWP.
- More spread. More than one parameterization moderating precipitation efficiency being perturbed.



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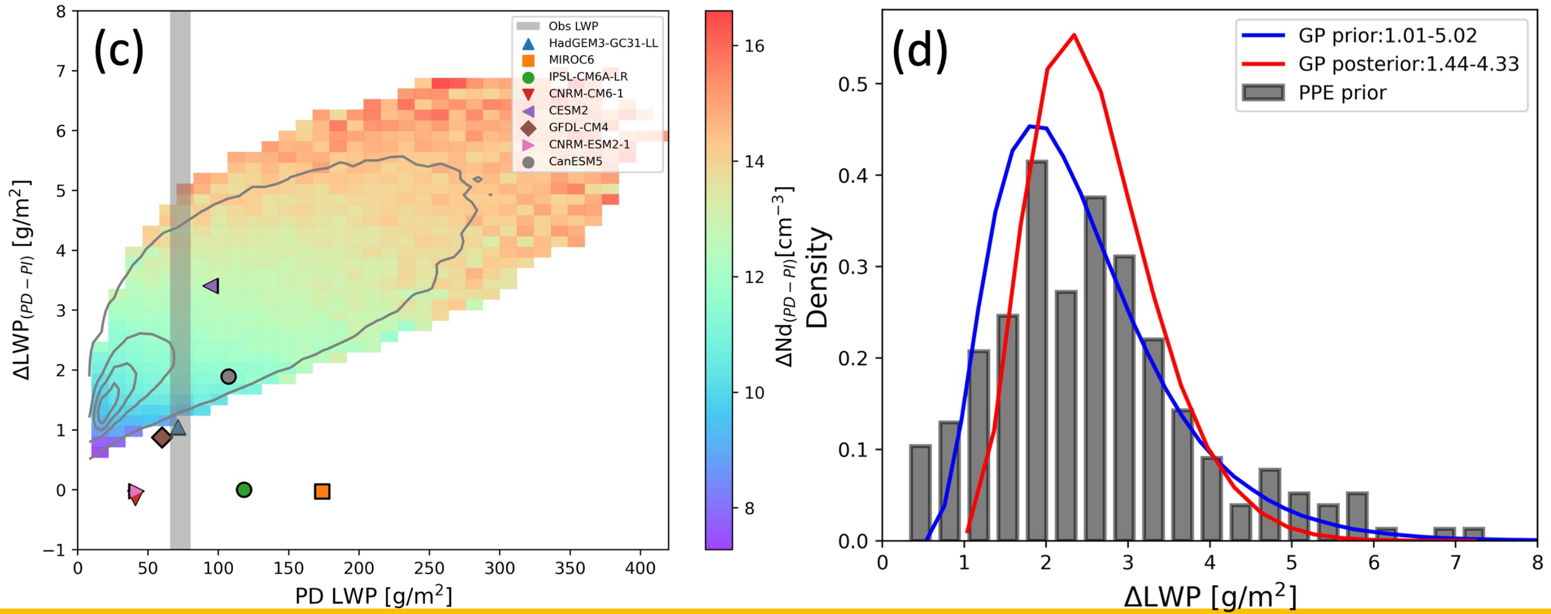
ERFaci constraint

- Does our constraint on ΔLWP constrain ERFaci?

$$\frac{dR}{dlnN_d} \approx \left.\frac{\partial R}{\partial lnN_d}\right|_{\mathcal{L},C} + \frac{\partial R}{\partial C}\frac{dC}{dlnN_d} + \frac{\partial R}{\partial \mathcal{L}}\frac{d\mathcal{L}}{dlnN_d}$$

- No constraint on ERFaci!



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Constraints on ERFaci

Radiative susceptibility to changes in cloudiness

$$\frac{dR}{dlnN_d} \approx \left.\frac{\partial R}{\partial lnN_d}\right|_{\mathcal{L},C} + \boxed{\frac{\partial R}{\partial C}}\frac{dC}{dlnN_d} + \boxed{\frac{\partial R}{\partial \mathcal{L}}}\frac{d\mathcal{L}}{dlnN_d}$$

Radiative forcing

Aerosol-cloud adjustments

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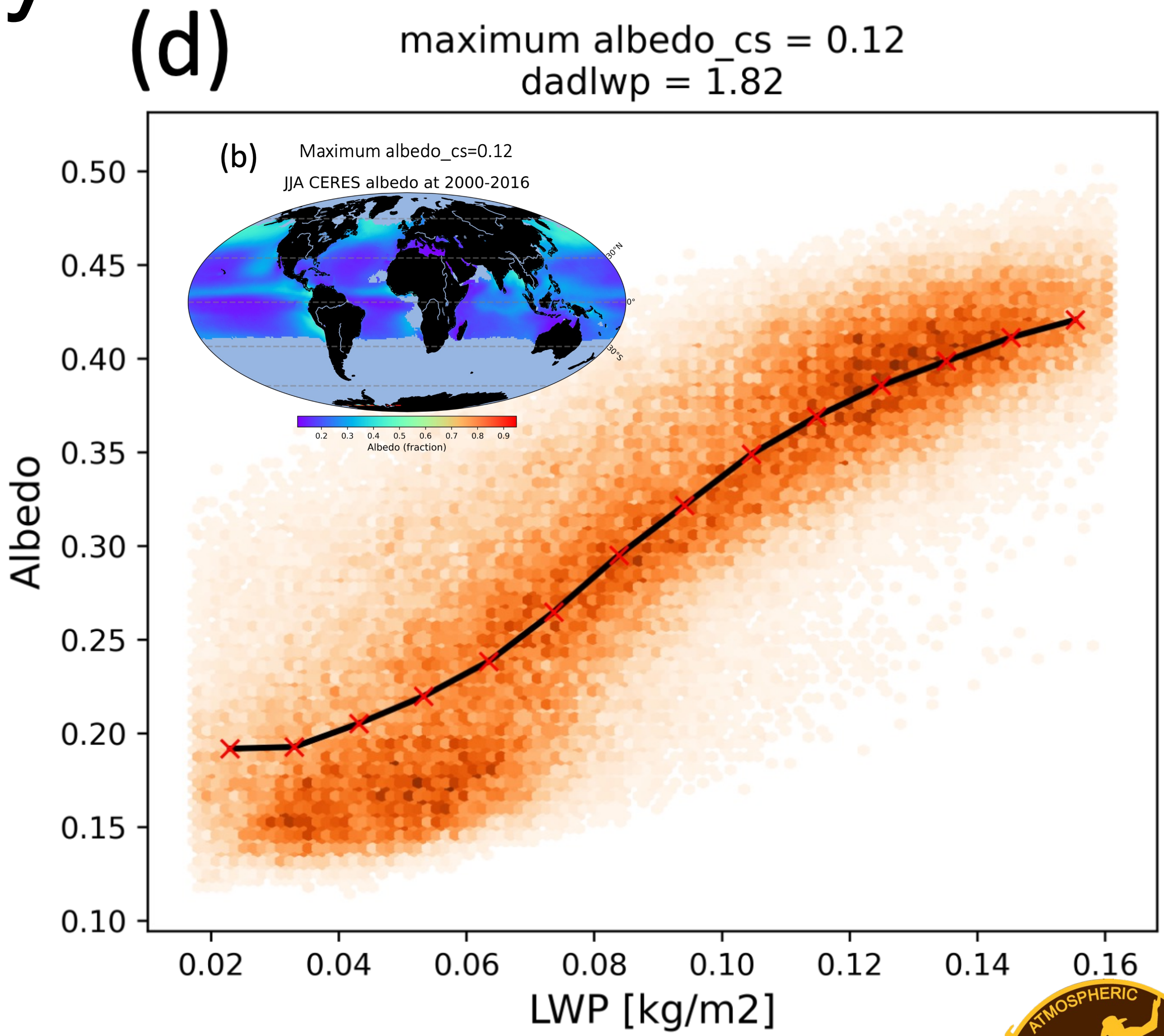
Radiative susceptibility

- How does albedo scale with microwave LWP?
- Albedo calculated from CERES EBAF Ed4.1
- High clear-sky albedo (>0.12) is removed.



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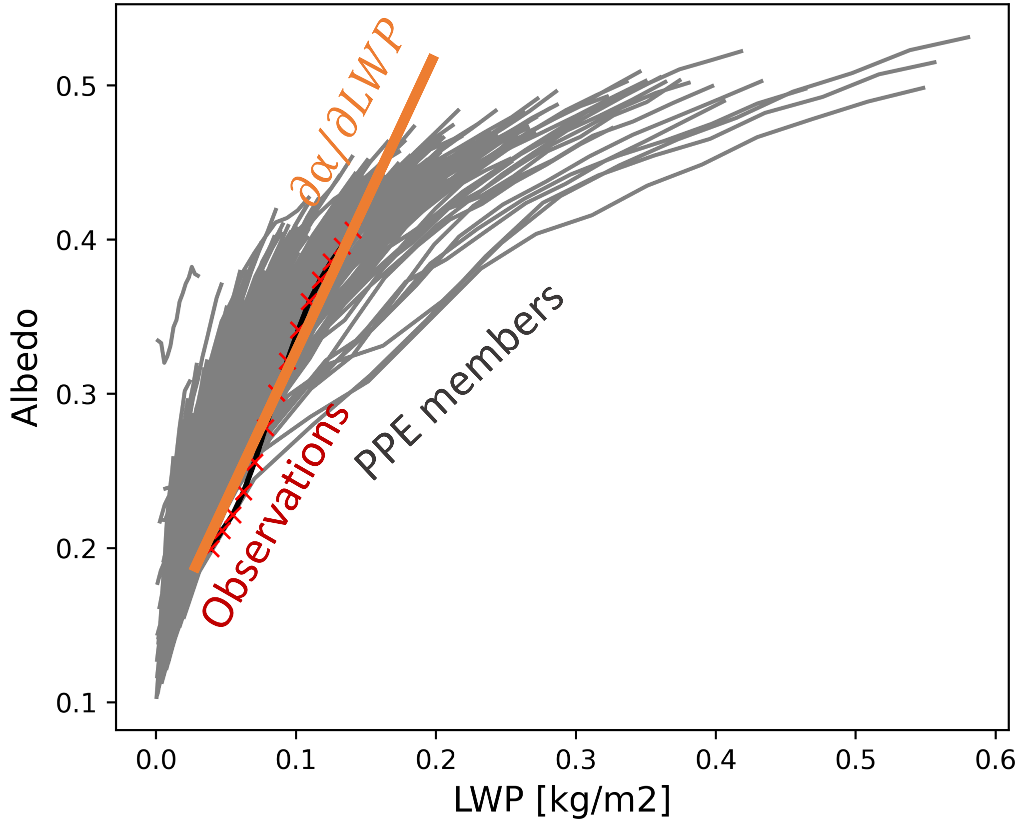
Radiative susceptibility

- Albedo calculation is repeated for every PPE member.



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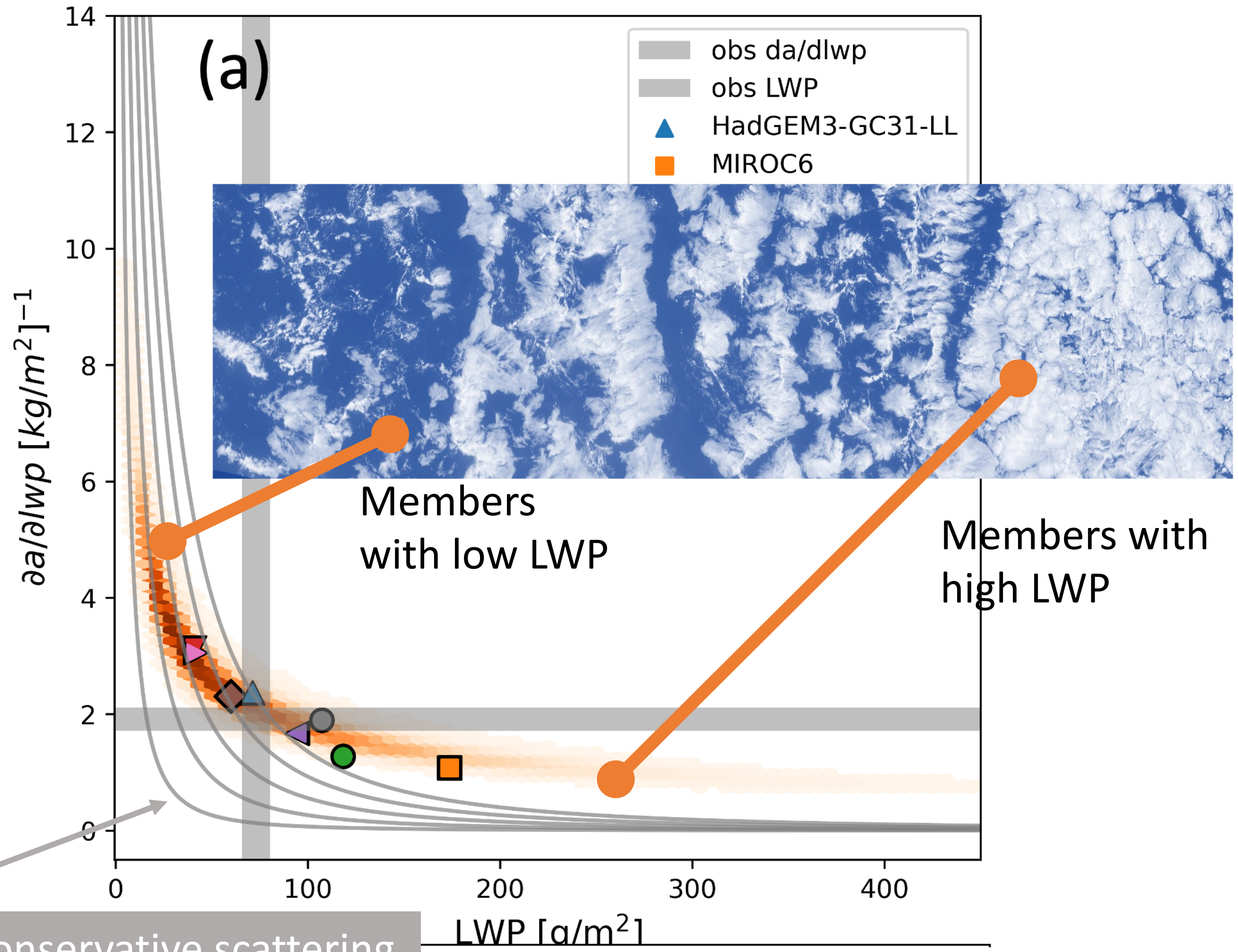
Radiative susceptibility



Some algebra with conservative scattering

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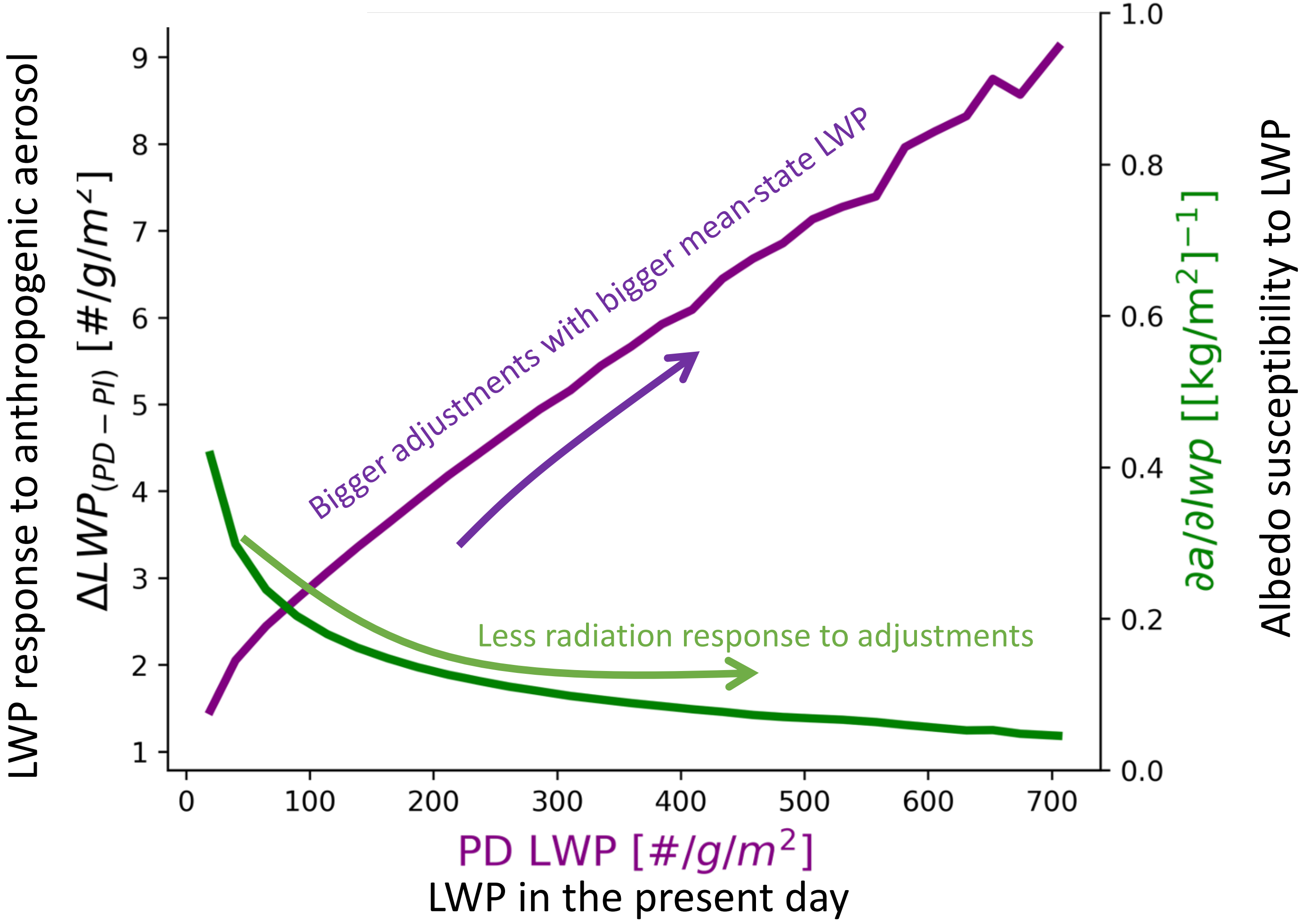
Radiative buffering



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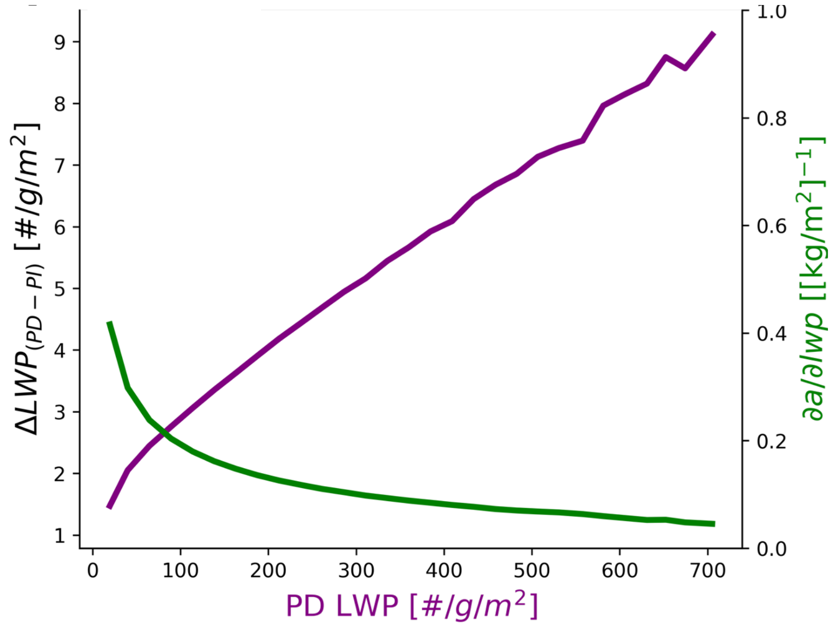
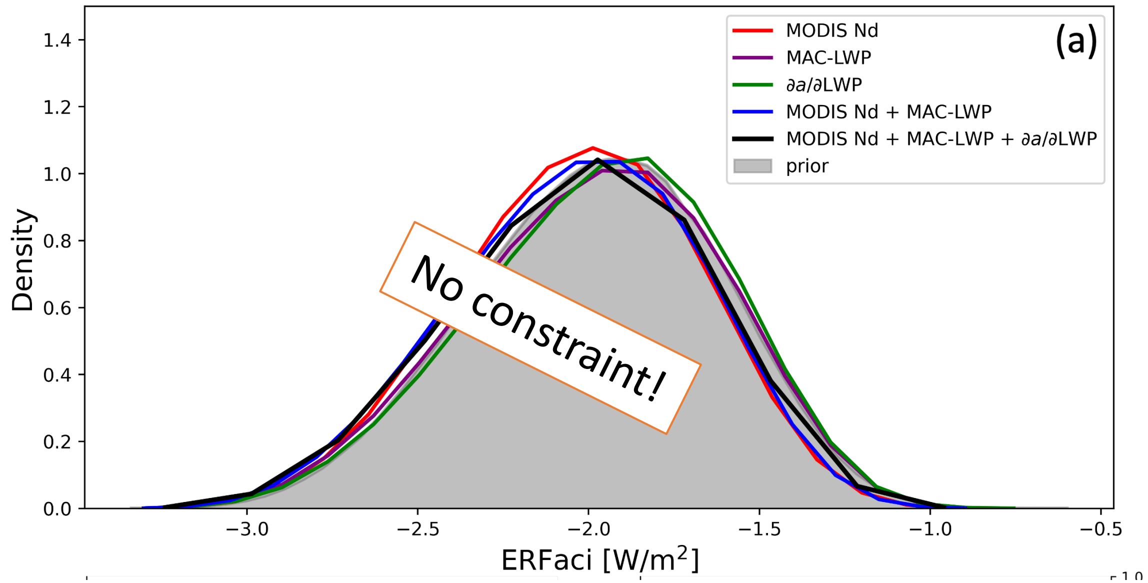
Radiative buffering through adjustments





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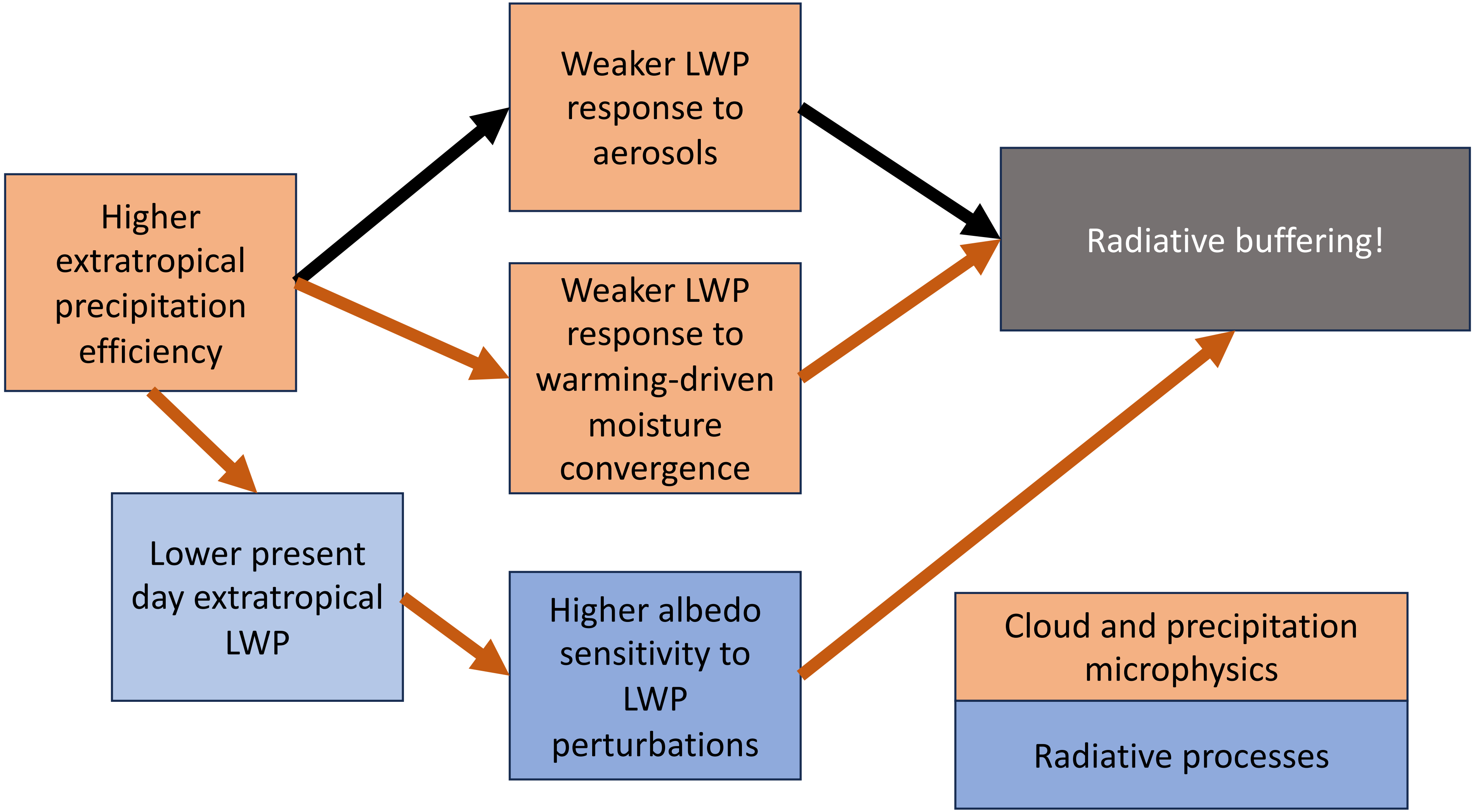
Cloud feedback

Extratropical feedback, forcing, and radiative buffering processes 2024 (ACP, in prep)

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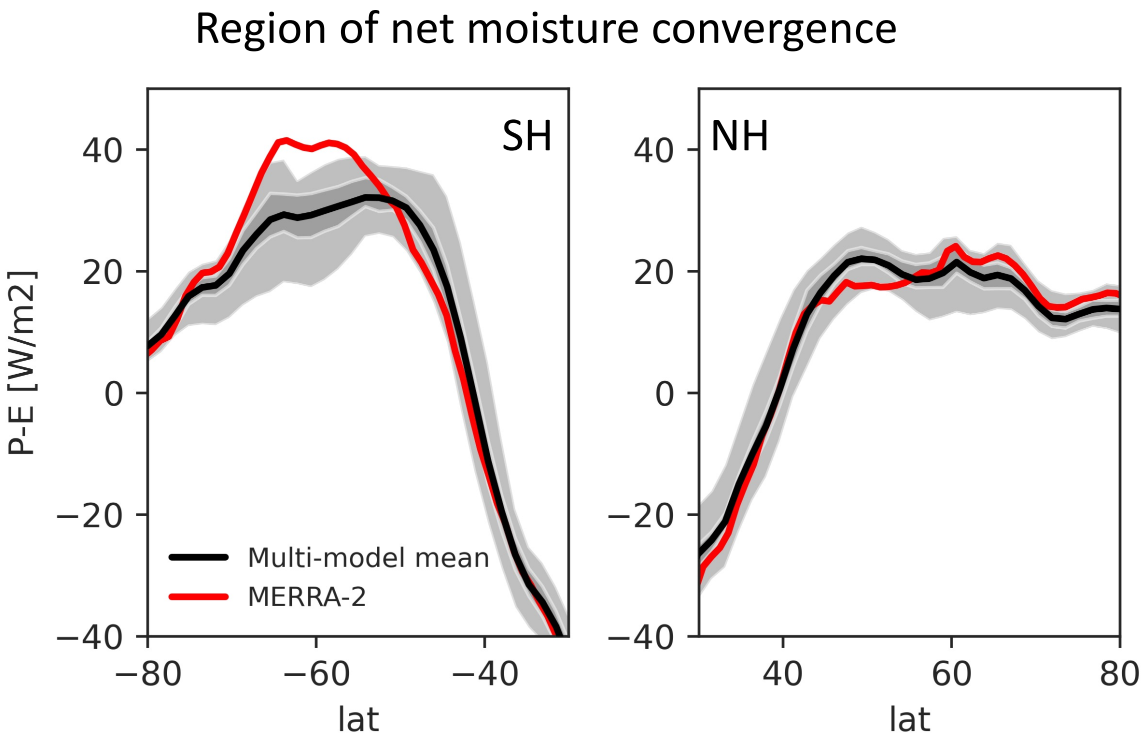
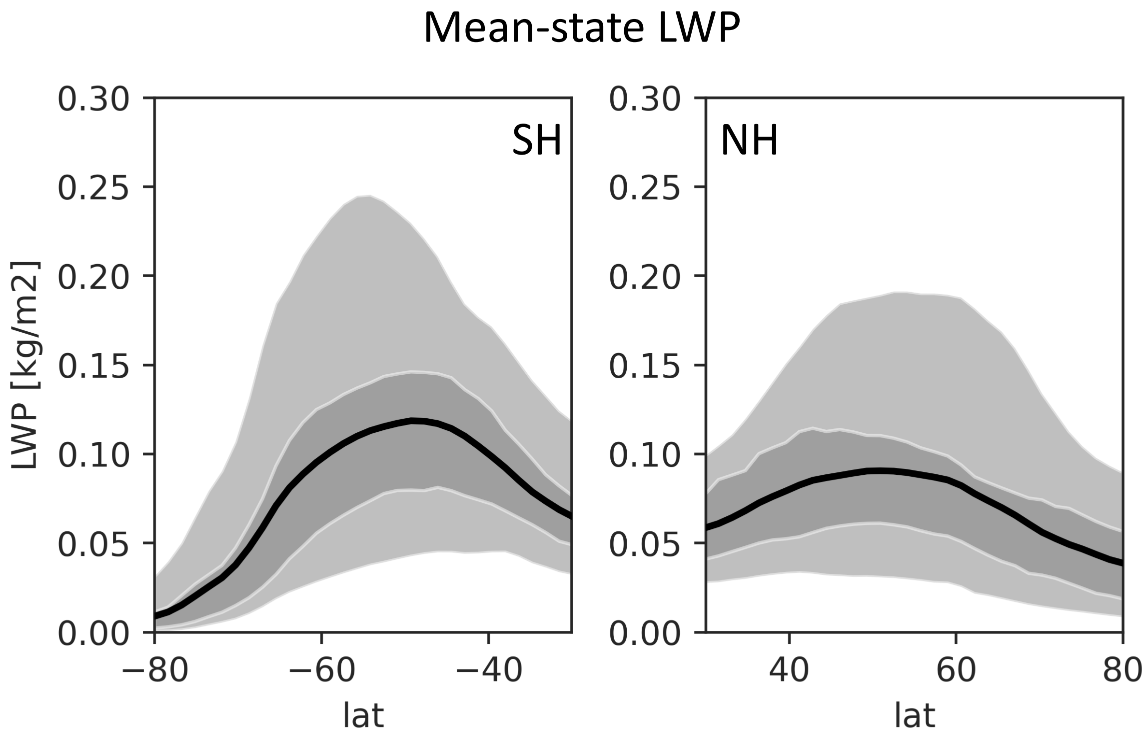
Extratropical moisture convergence and cloud (CMIP5+CMIP6)





McCoy, Daniel T., Michelle E. Frazer, Johannes Mülmenstädt, Ivy Tan, Christopher R. Terai, and Mark D. Zelinka. "Extratropical Cloud Feedbacks." In *Clouds and Their Climatic Impacts*, 133–57. Geophysical Monograph Series, 2023. https://doi.org/10.1002/9781119700357.ch6.

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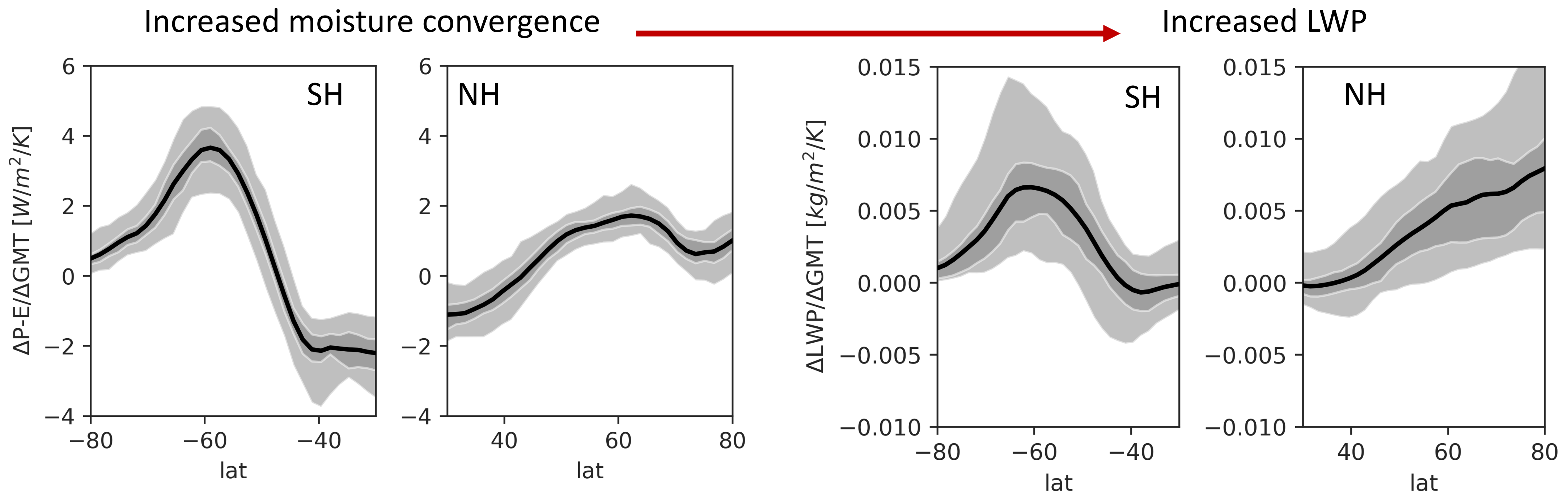
Extratropical response to CO2 quadrupling



McCoy, Daniel T., Michelle E. Frazer, Johannes Mülmenstädt, Ivy Tan, Christopher R. Terai, and Mark D. Zelinka. "Extratropical Cloud Feedbacks." In *Clouds and Their Climatic Impacts*, 133–57. Geophysical Monograph Series, 2023. https://doi.org/10.1002/9781119700357.ch6.

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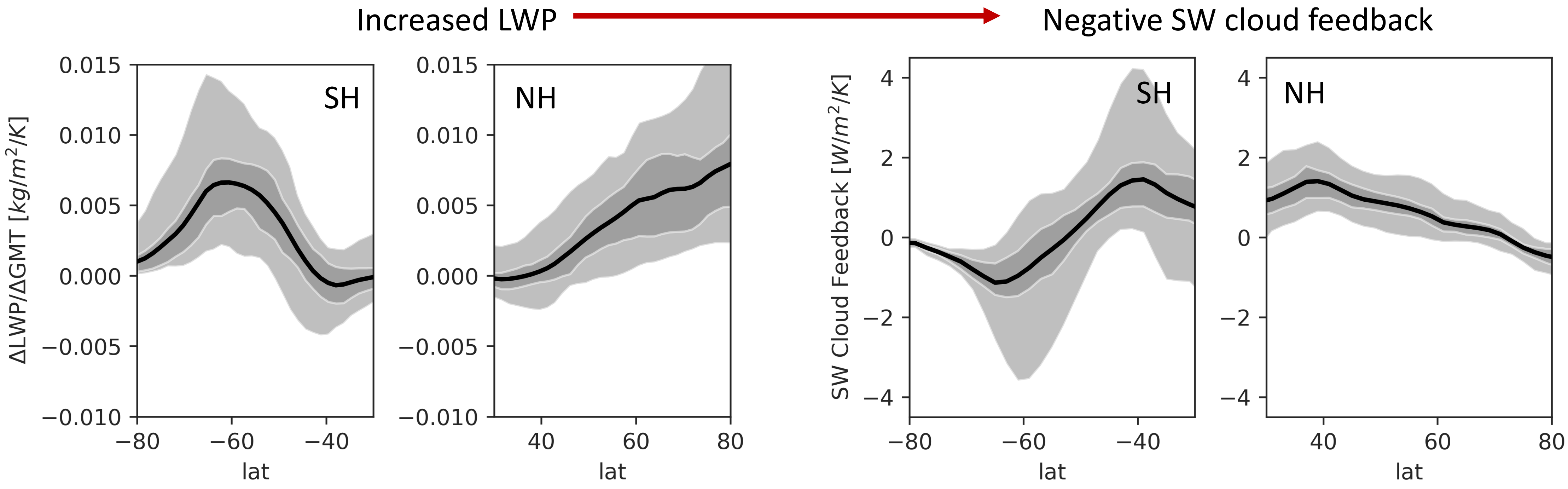

McCoy, Daniel T., Michelle E. Frazer, Johannes Mülmenstädt, Ivy Tan, Christopher R. Terai, and Mark D. Zelinka. "Extratropical Cloud Feedbacks." In *Clouds and Their Climatic Impacts*, 133–57. Geophysical Monograph Series, 2023. https://doi.org/10.1002/9781119700357.ch6.

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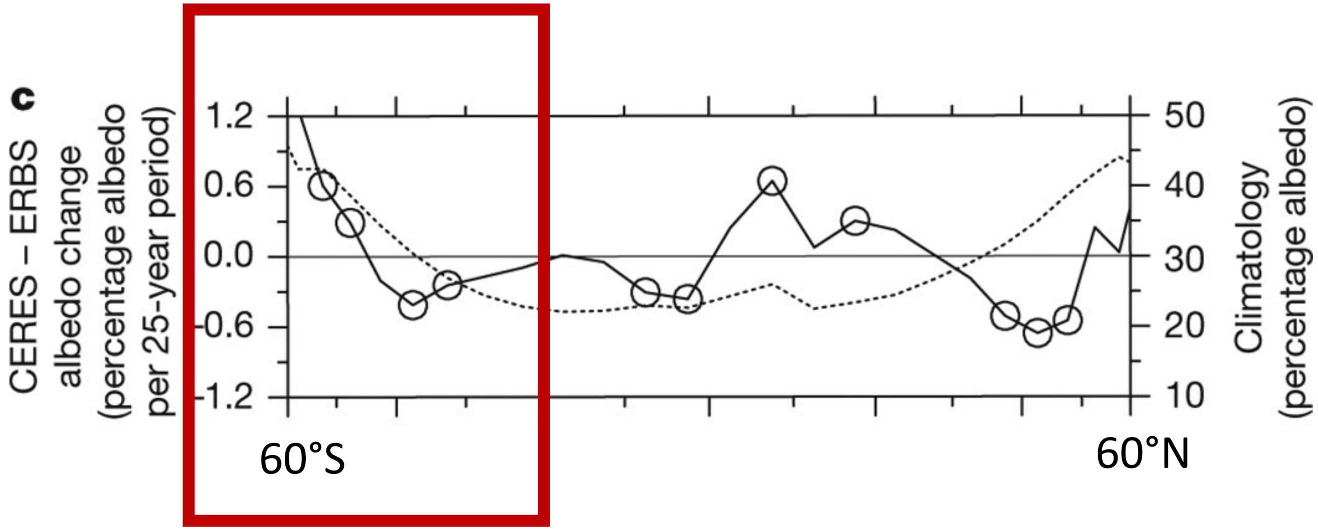
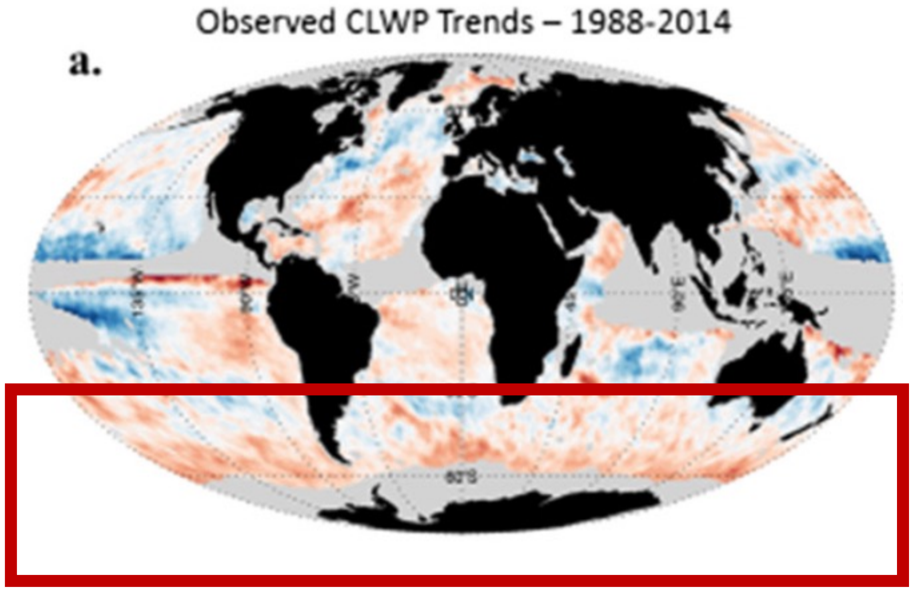
Long term trend in Southern Ocean cloud





Manaster, A, Christopher W. O’Dell, and Gregory Elsaesser. “Evaluation of Cloud Liquid Water Path Trends Using a Multidecadal Record of Passive Microwave Observations.” *Journal of Climate* 30, no. 15 (2017): 5871–84. https://doi.org/10.1175/jcli-d-16-0399.1.

Norris, Joel R., Robert J. Allen, Amato T. Evan, Mark D. Zelinka, Christopher W. O’Dell, and Stephen A. Klein. “Evidence for Climate Change in the Satellite Cloud Record.” *Nature* 536, no. 7614 (04/print 2016): 72–75. https://doi.org/10.1038/nature18273.

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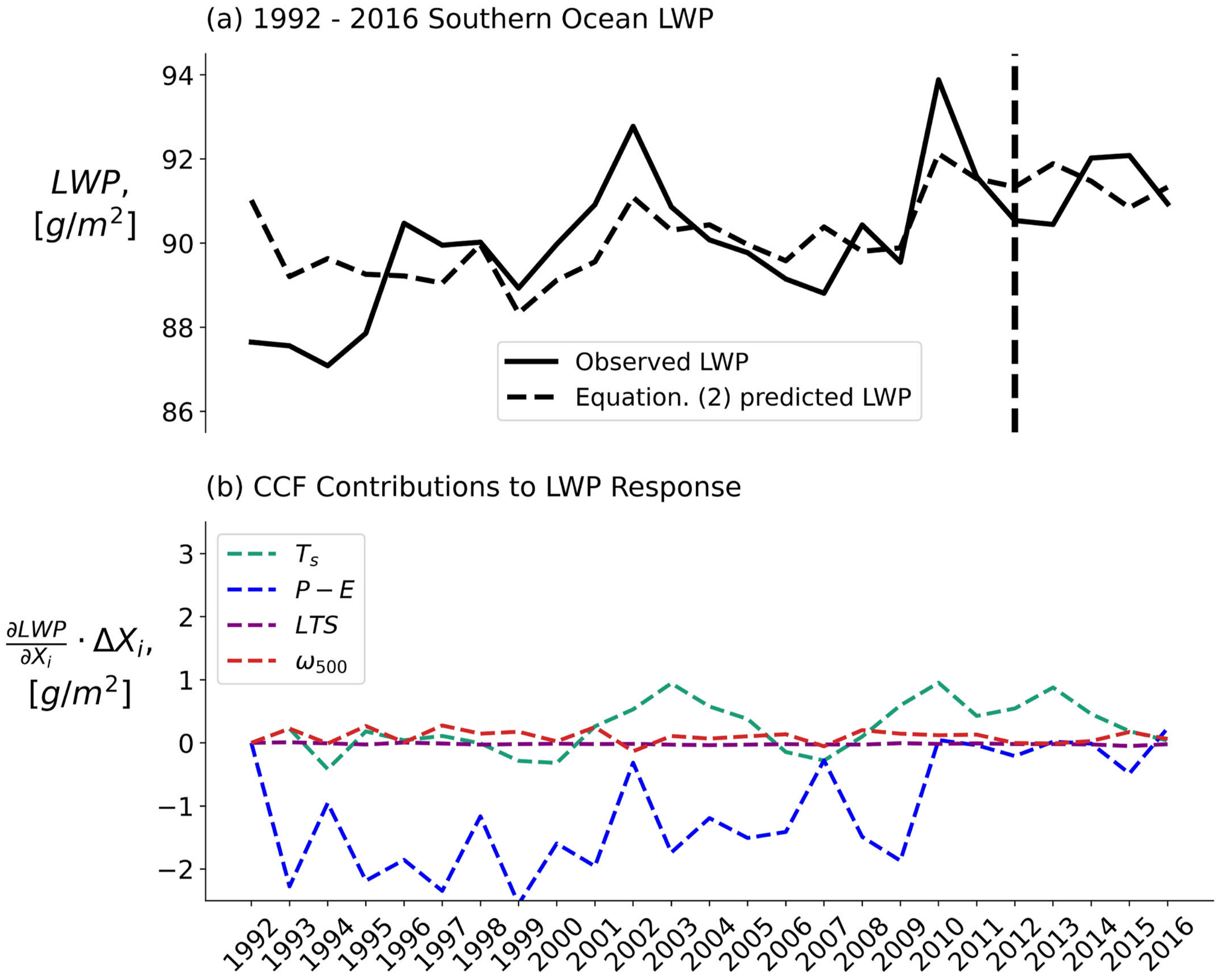
Extratropical LWP trend

- Observed trend is dominated by moisture convergence.
- LWP trends in ESMs not strongly correlated with LWP trend!



Tan, Chuyan, Daniel T. McCoy, and Gregory S Elsaesser. "Constraints on Southern Ocean Shortwave Cloud Feedback from the Hydrological Cycle." *Journal of Geophysical Research-Atmospheres (in Revision)*, 2024. https://doi.org/essoar.168286840.00256265.

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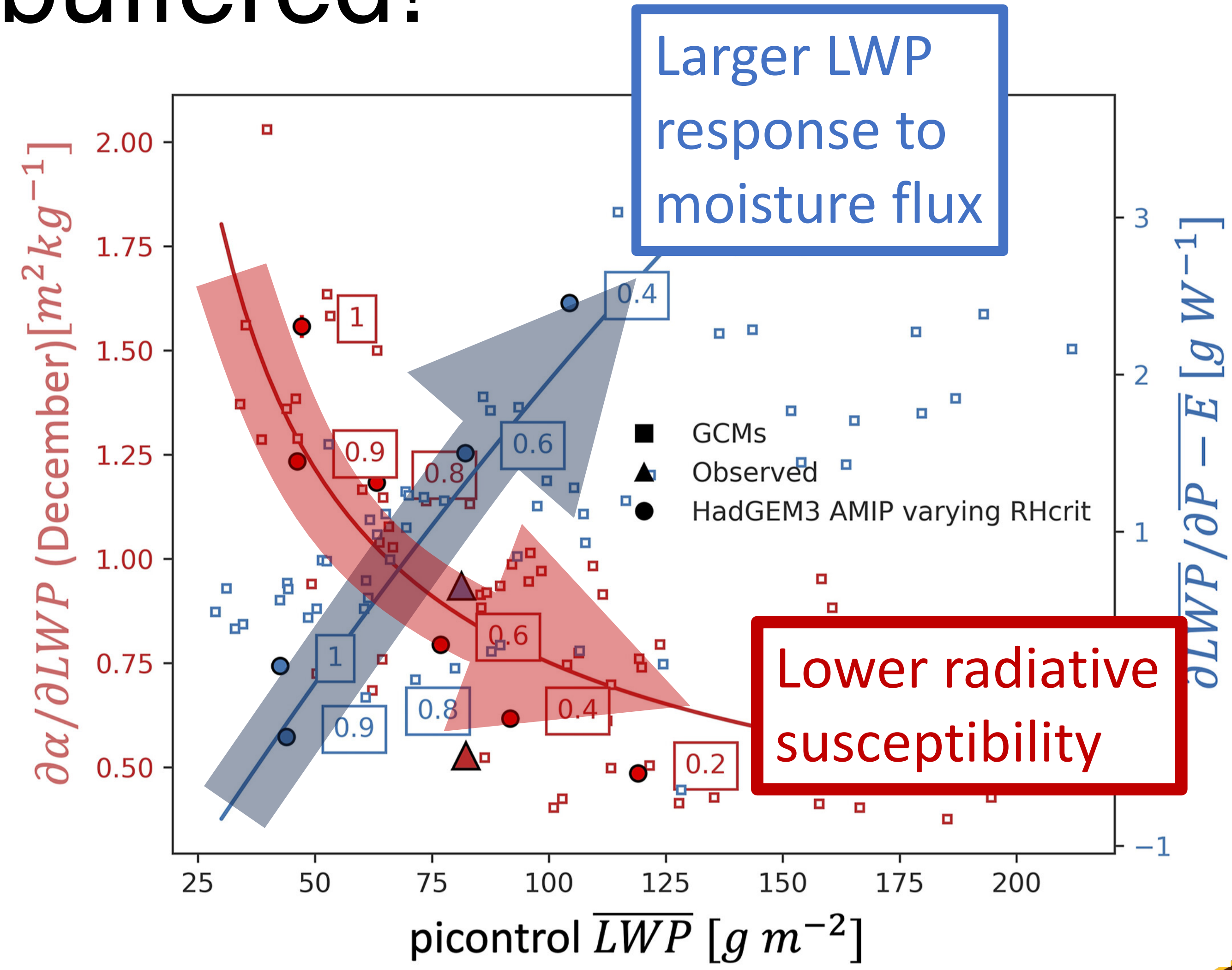
Radiative impact buffered!

- Big range in LWP response to warming and mean state LWP over CMIP models.
- Shown at right, regional means over Southern Ocean.



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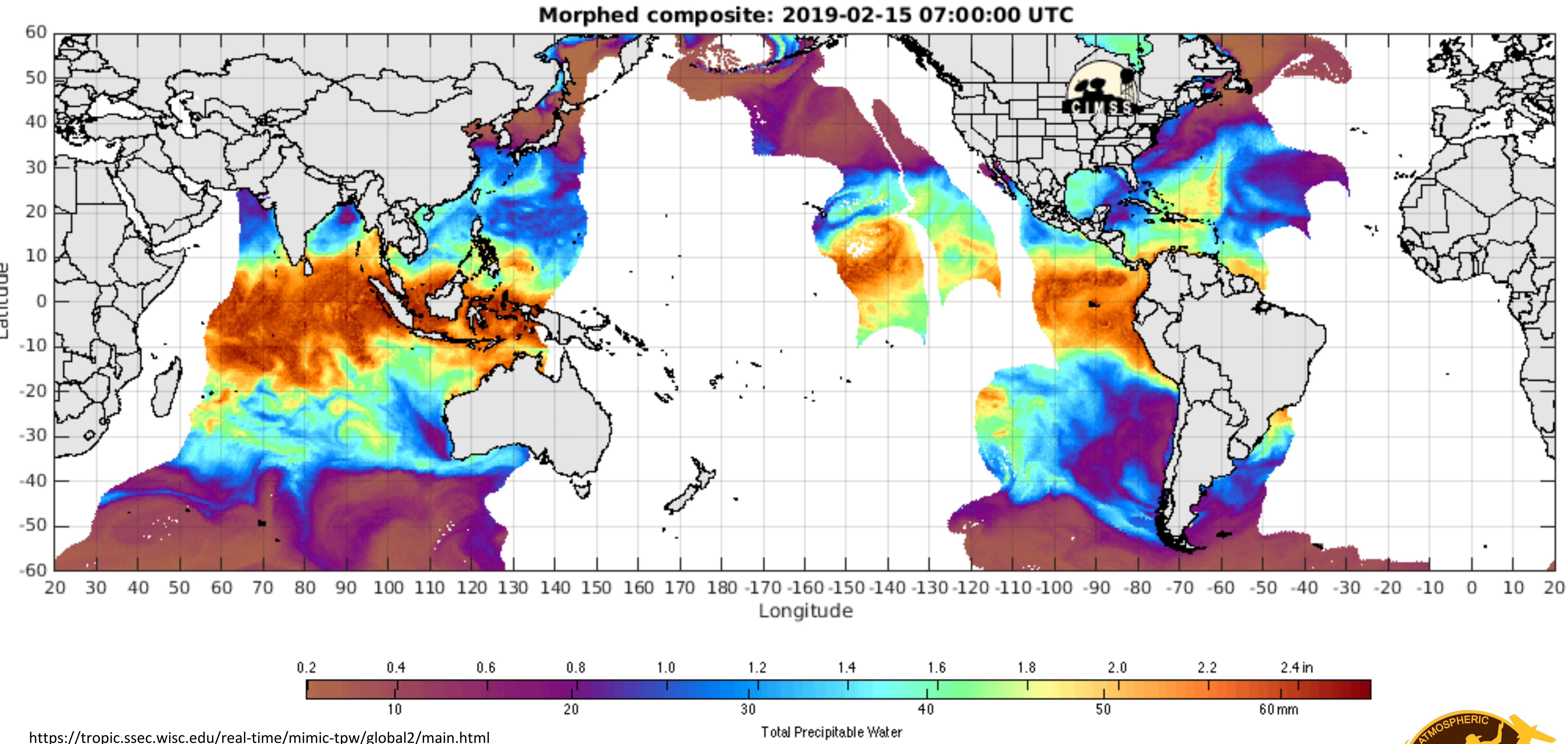
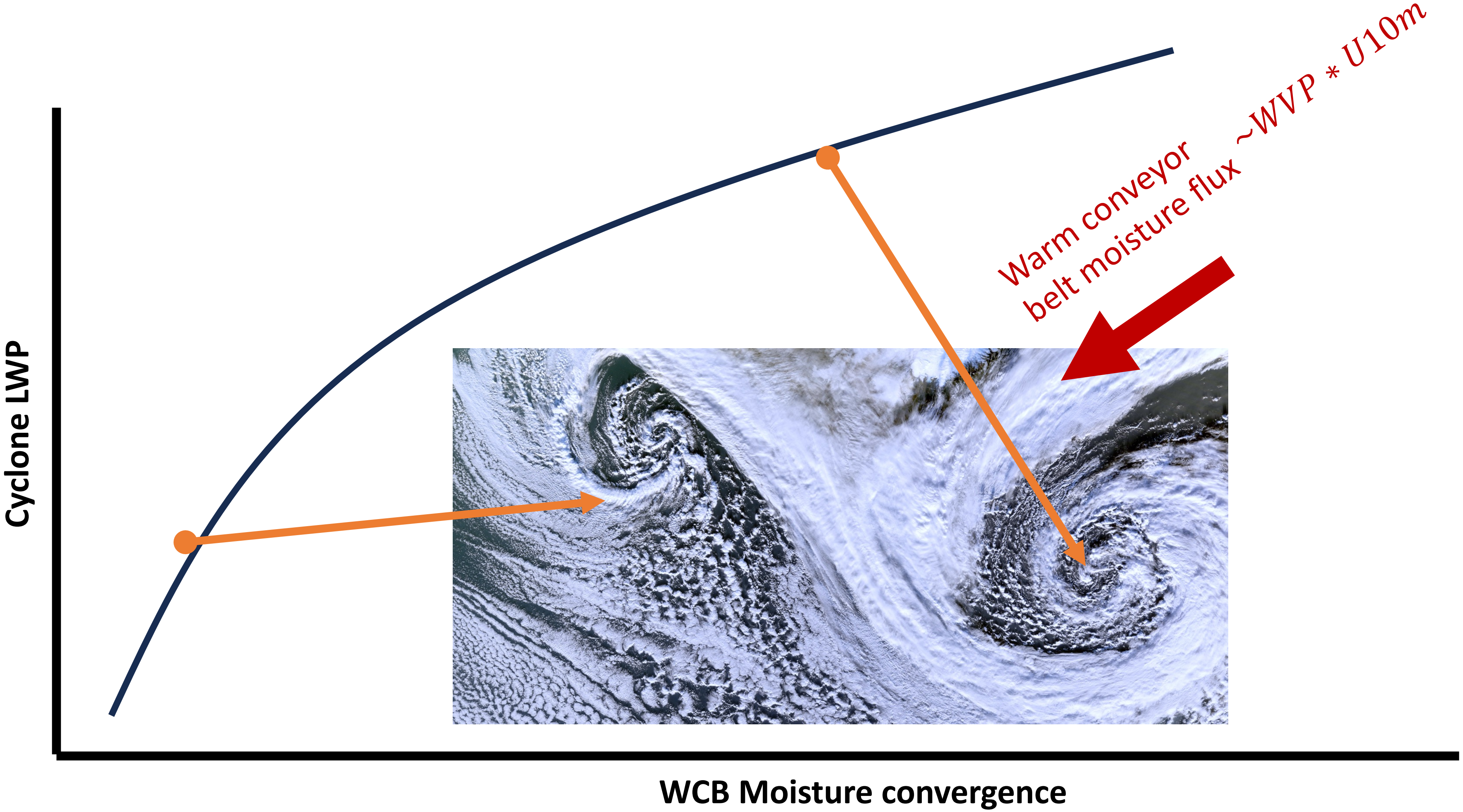


https://tropic.ssec.wisc.edu/real-time/mimic-tpw/global2/main.html

Moisture convergence driven cloud feedback



Climate Model Extratropical Cloud Feedback Constrained by Cloud Sources and Sinks in Cyclones
Werapitiya et al. 2024 (JCLI, in prep)

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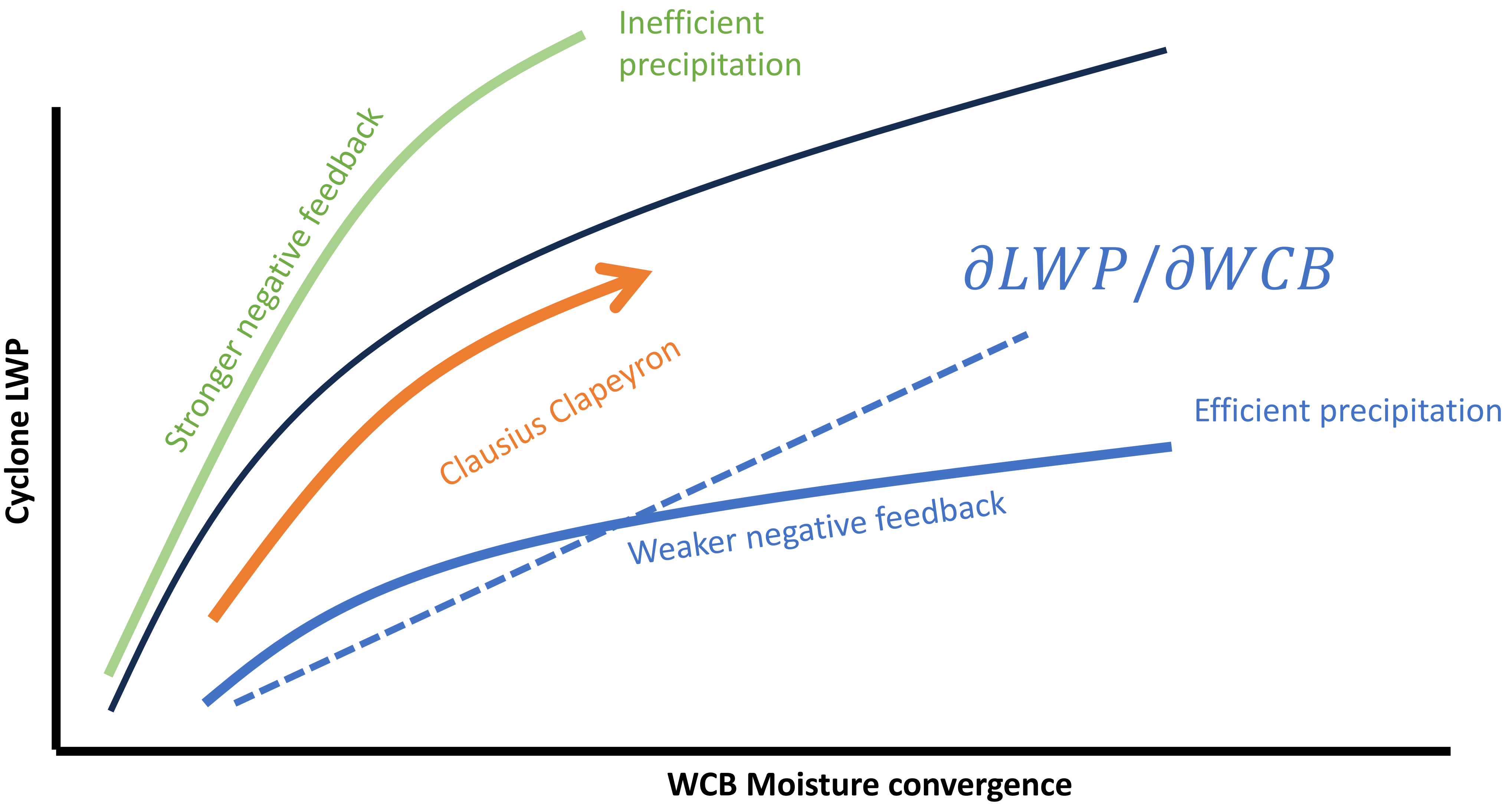
Funding: NASA-PMMST 80NSSC22K0609

Moisture convergence driven cloud feedback



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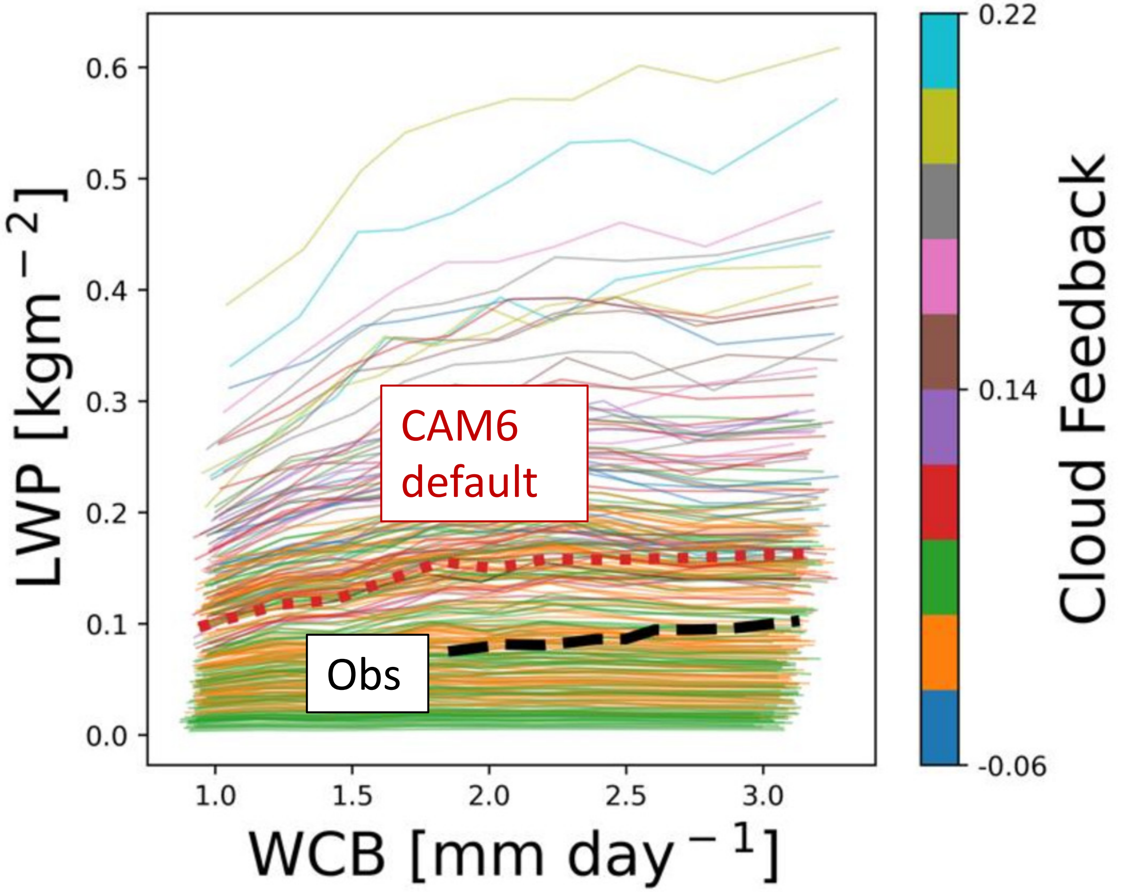
Funding: NASA-PMMST 80NSSC22K0609

Moisture convergence driven cloud feedback

- PPE members show approximately the same behavior as the simple heuristic model.



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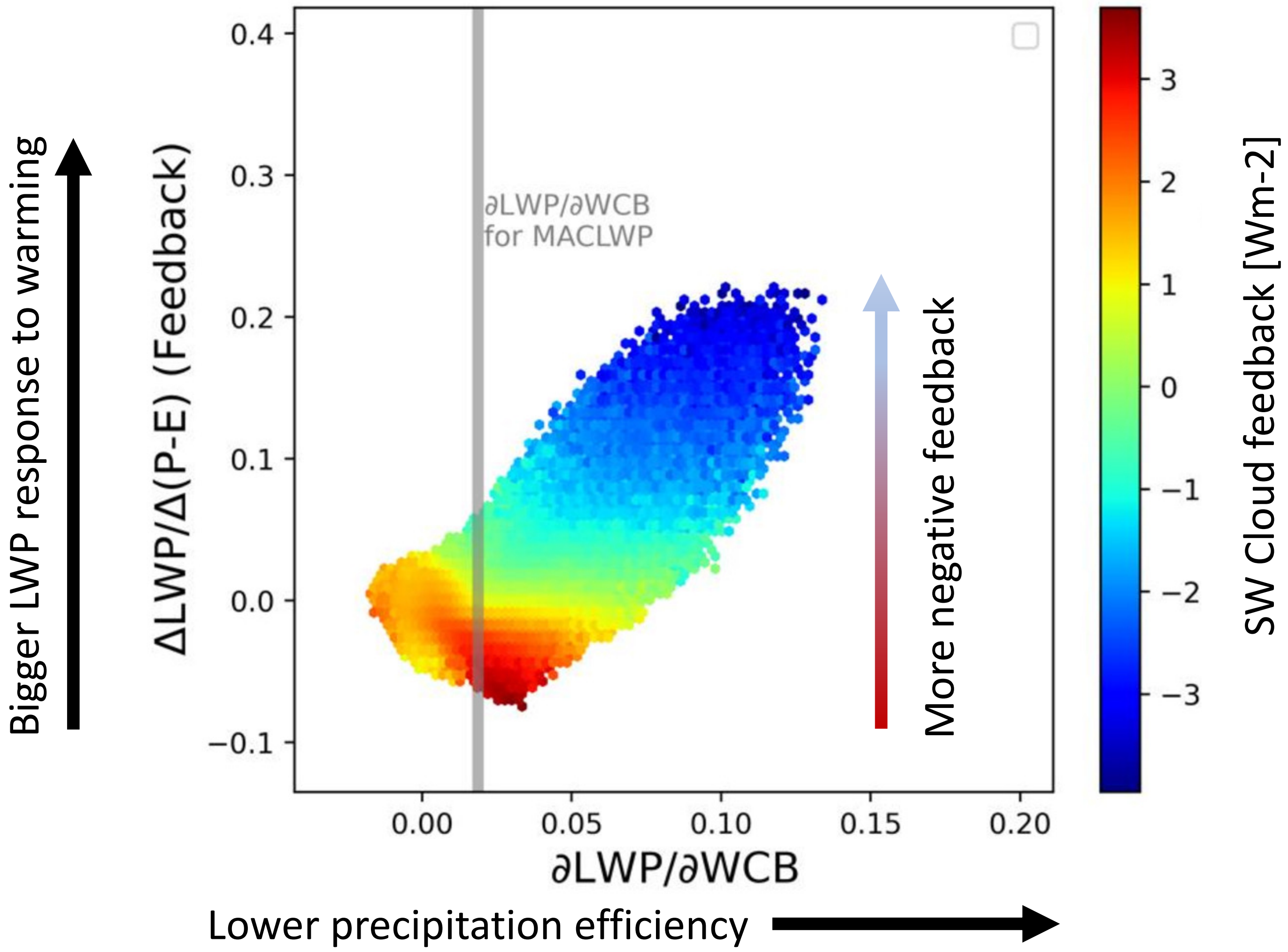
Extratropical cloud feedback



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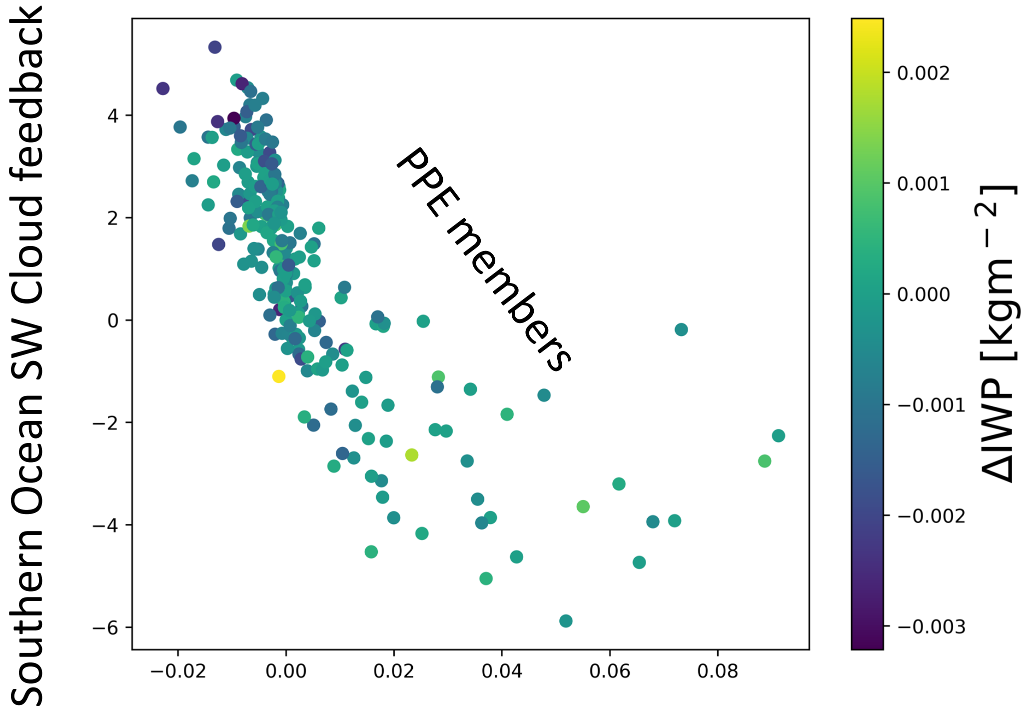
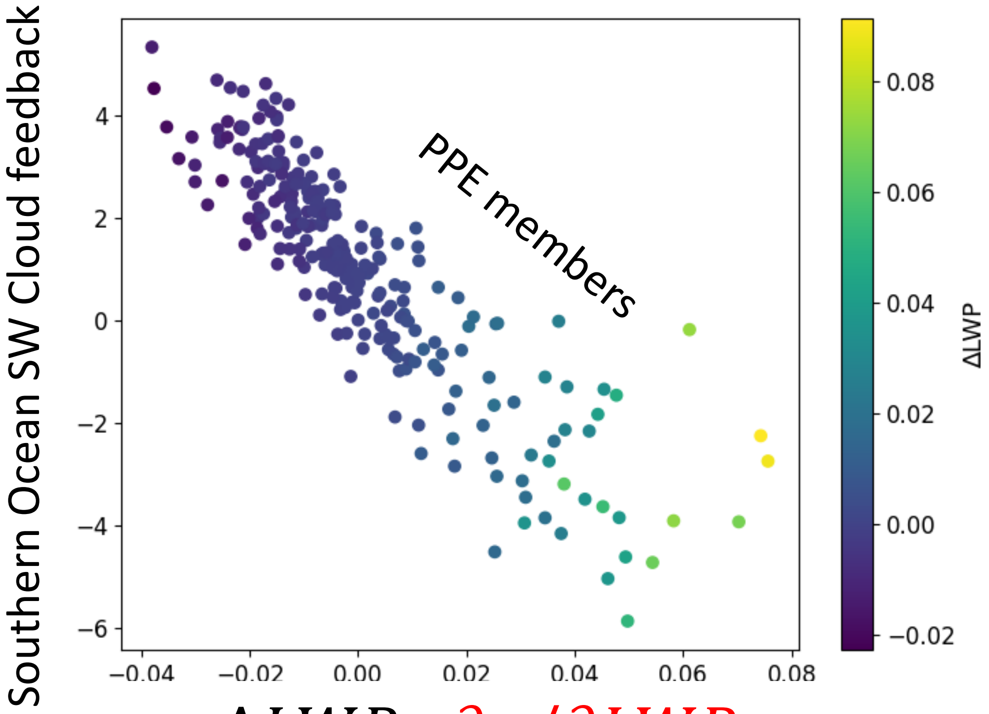
Radiative feedback



ΔLWP



$\Delta LWP \cdot \partial\alpha/\partial LWP$

- Change in cloud properties scaled by albedo susceptibility is linear in cloud feedback.

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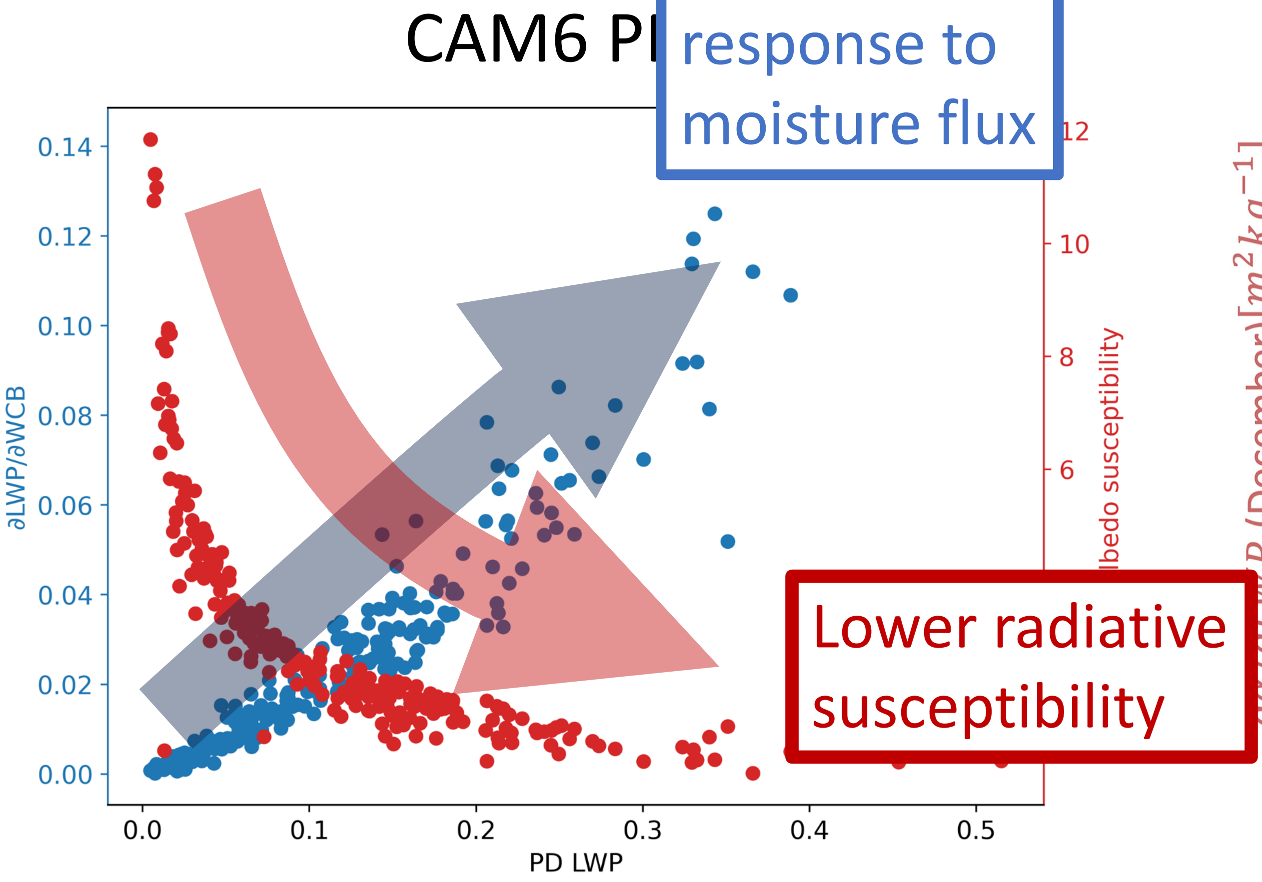
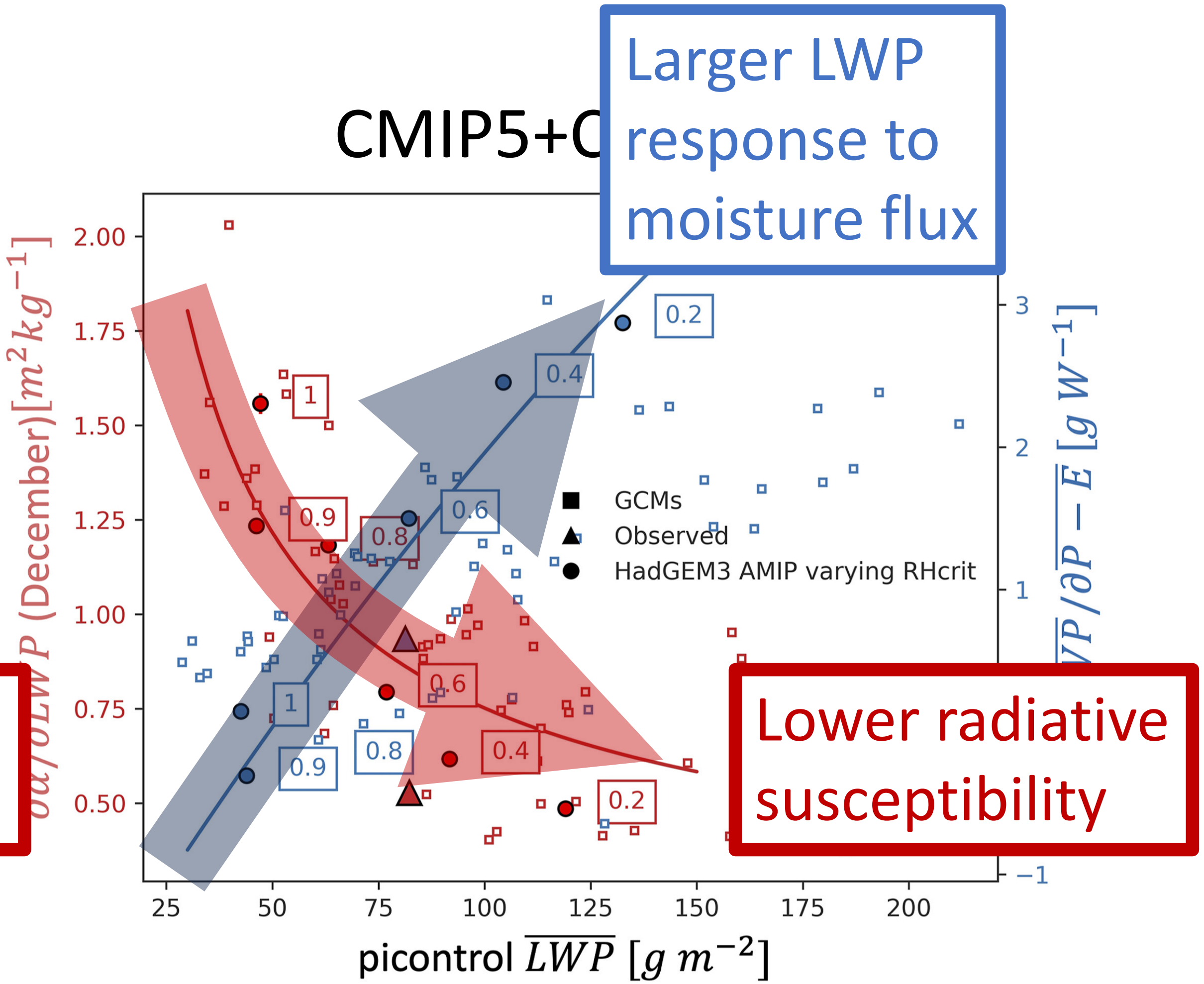
Radiative susceptibility





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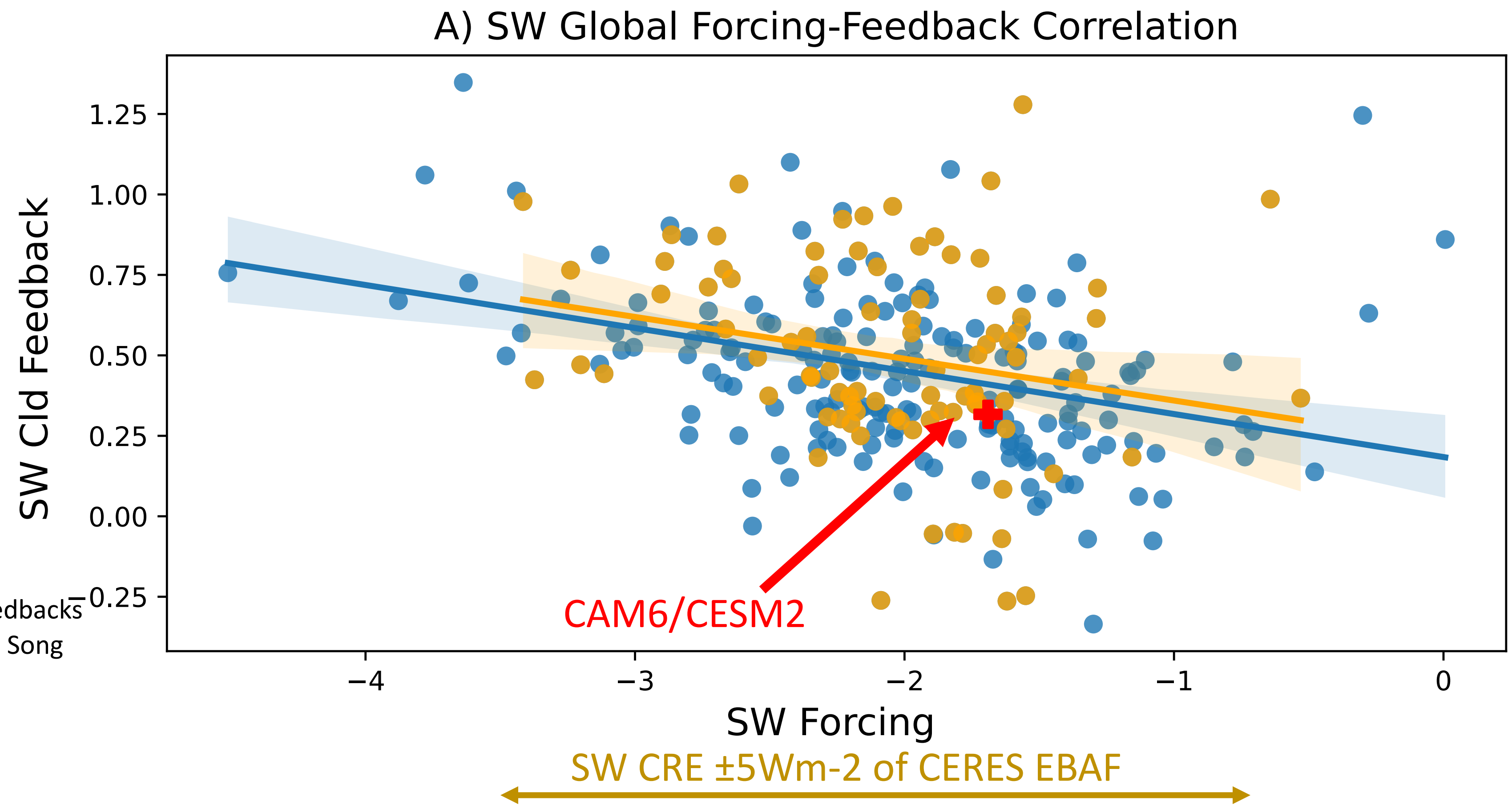
CAM6 PPE shows links between forcing and feedback



The Interaction Between Climate Forcing and Feedbacks
Gettelman A, Eidhammer T, Duffy ML, McCoy DT, Song C, Watson-Parris D
JGR:A 2024 accepted, review

Also:
Gettelman, A., and S. C. Sherwood. "Processes Responsible for Cloud Feedback." *Current Climate Change Reports*, 2016, 1–11. https://doi.org/10.1007/s40641-016-0052-8.

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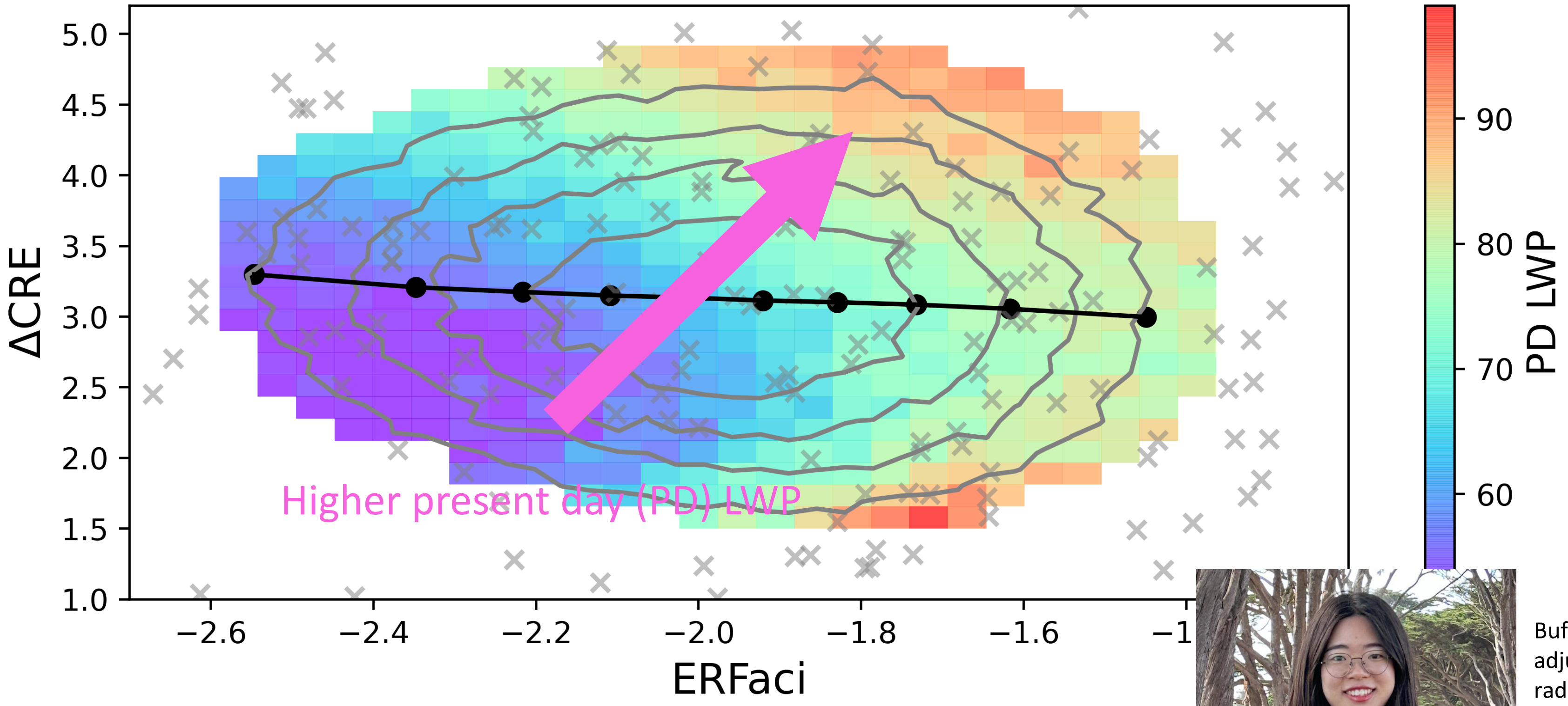
Climate Model Extratropical Cloud Feedback Constrained by Cloud Sources and Sinks in Cyclones
Werapitiya et al. 2024 (JCLI, in prep)

Stronger negative extratropical cloud feedback



Stronger aerosol cooling

Buffering of aerosol-cloud adjustments by coupling between radiative susceptibility and precipitation efficiency
Song et al. 2024 (GRL, in press)

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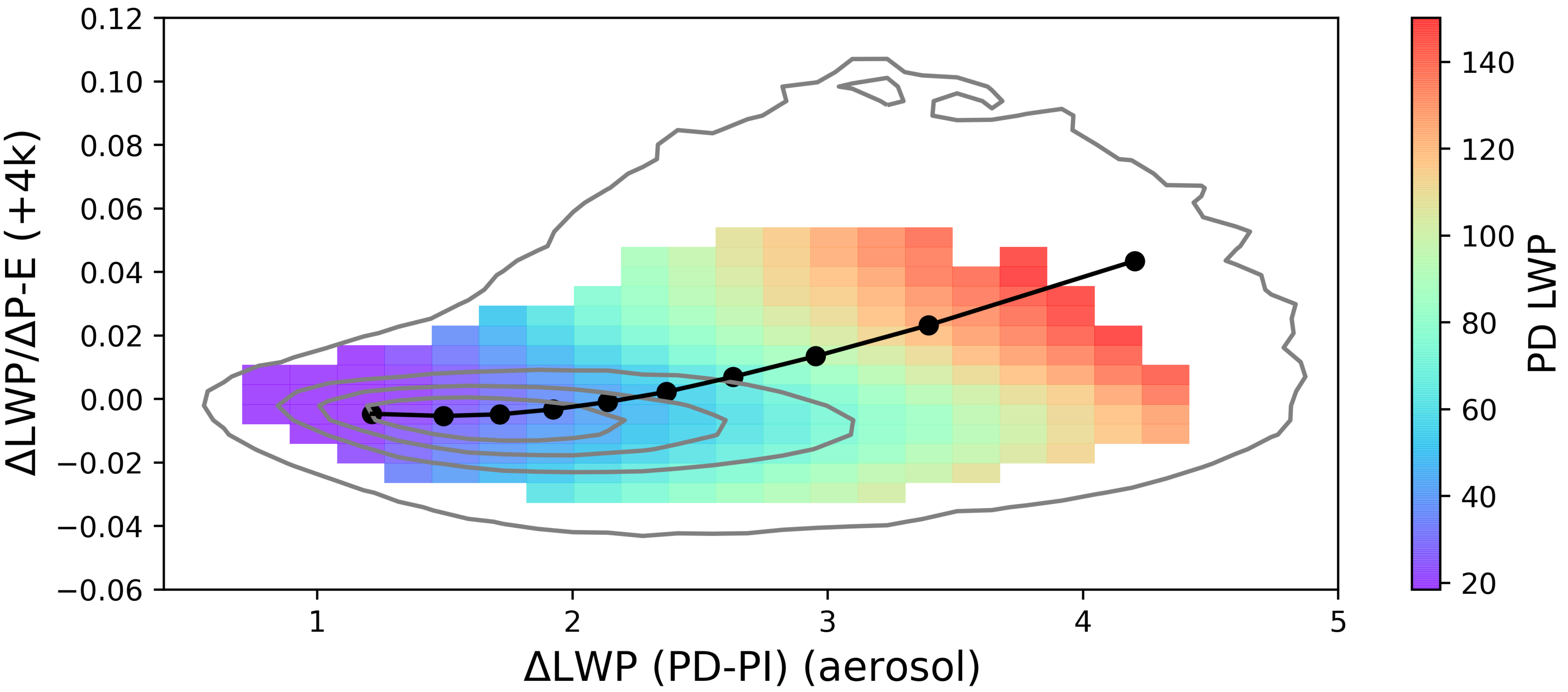
Precipitation efficiency drives LWP response to aerosol and warming



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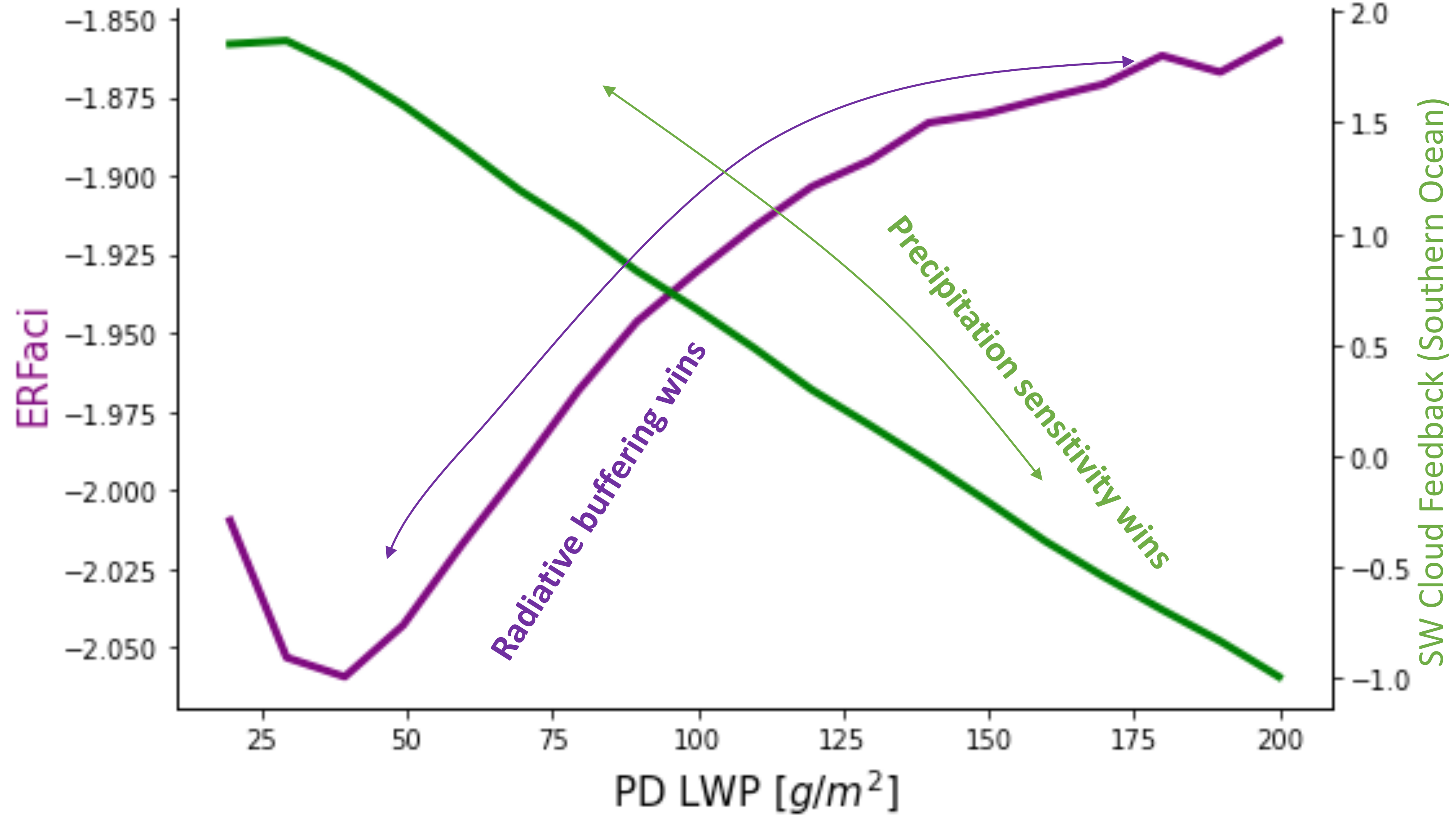

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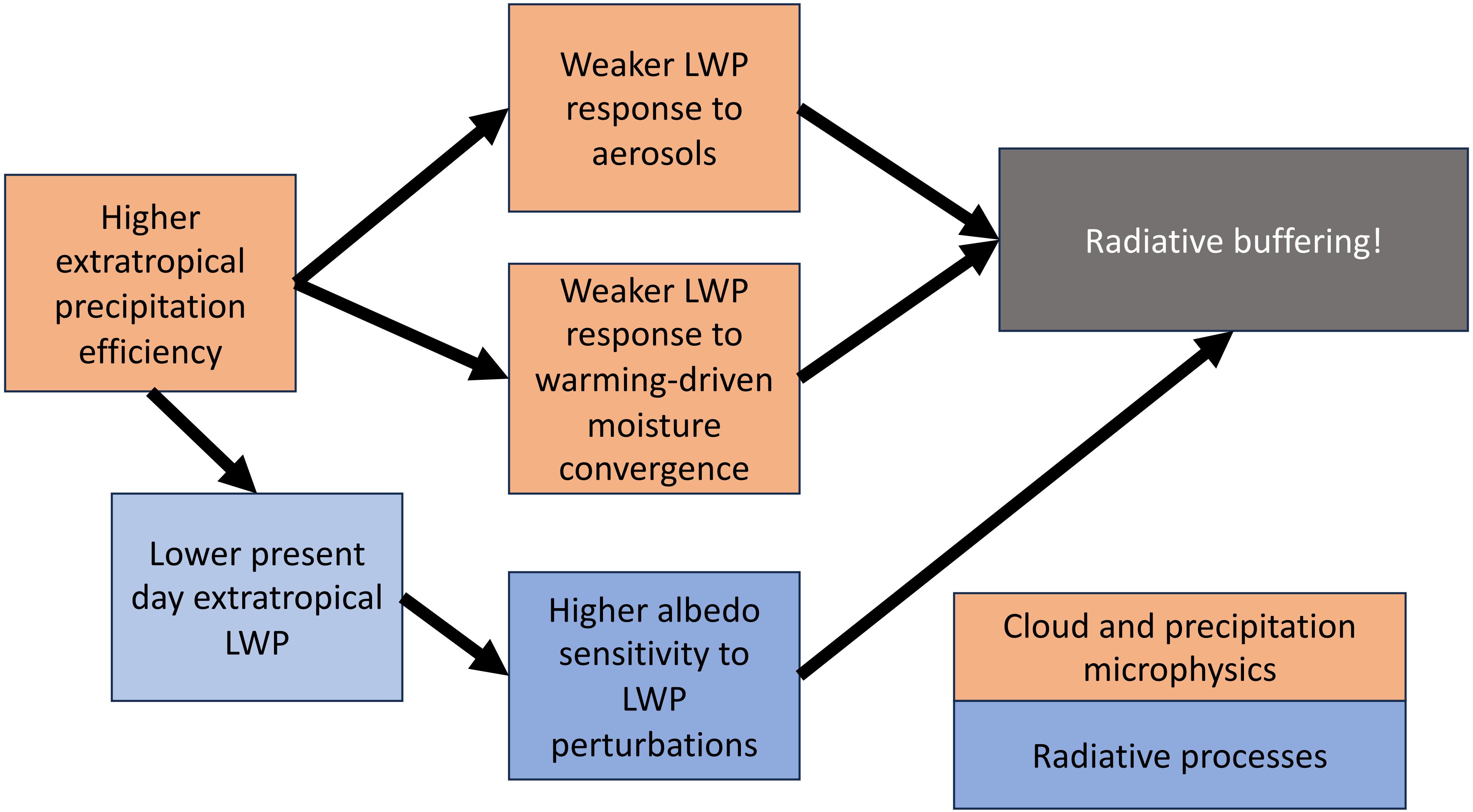
Summary

Extratropical feedback, forcing, and radiative buffering processes 2024 (ACP, in prep)



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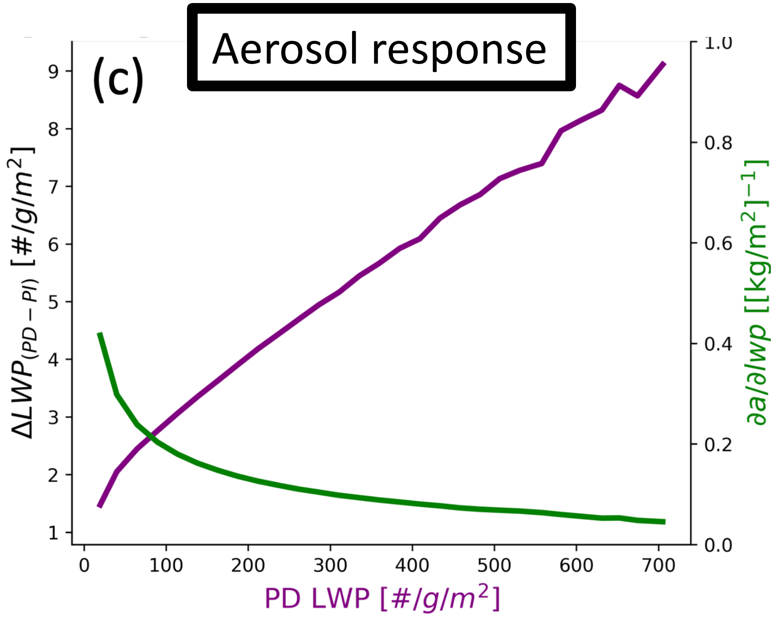
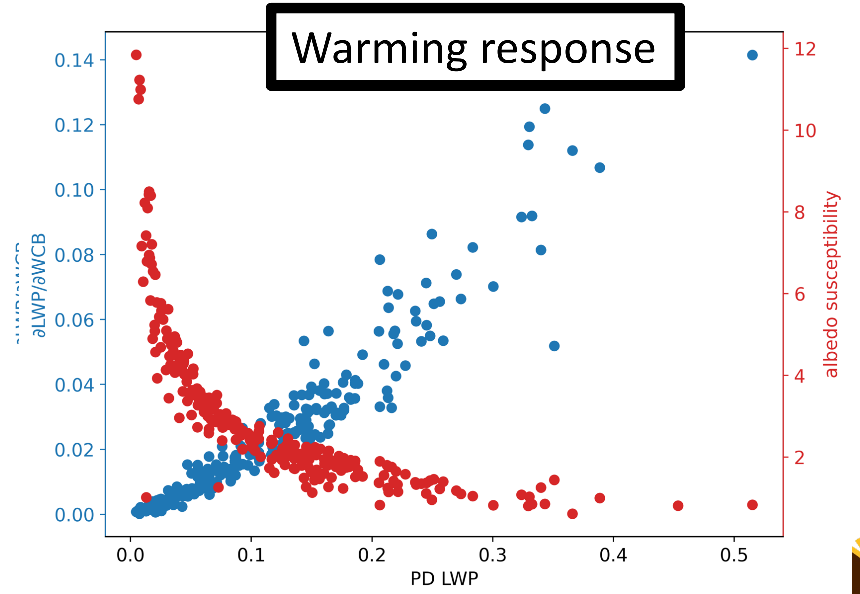
Summary

- Extratropical LWP response to aerosol and warming is occurring in the context of moisture convergence.
- Bus driven by precipitation processes.
- Buffered by albedo susceptibility.
- Albedo susceptibility and LWP response linked.
- ERFaci – SW cloud feedback correlation negative, LWP response correlation positive. Strong ERFaci buffering (Song et al. 2024).





Workshop in Laramie, WY October 28-30 – hope to see you there!

Micro2Macro

Origins of Climate Change Uncertainty

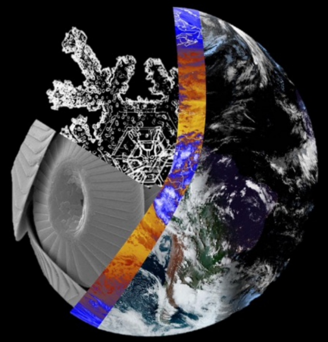


Image credit: Jeremy Young and Gabor Vali

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