PROCEEDing from surface to sensitivity

Confronting a perturbed parameter ensemble with ARM observations

UW: Travis Aerenson, Gabrielle Allen, Dana Caulton, Andrew Kirby, Daniel McCoy*, August Mikkelsen, Jacqueline Nugent, Ci Song, Geethma Werapitiya

UHM: Jennifer Griswold

LLNL: Mark Zelinka

PNNL: Susannah Burrows, Andrew Gettelman, Johannes Muelmenstaedt, Mikhail Ovchinnikov, Israel Silber, Damao Zhang

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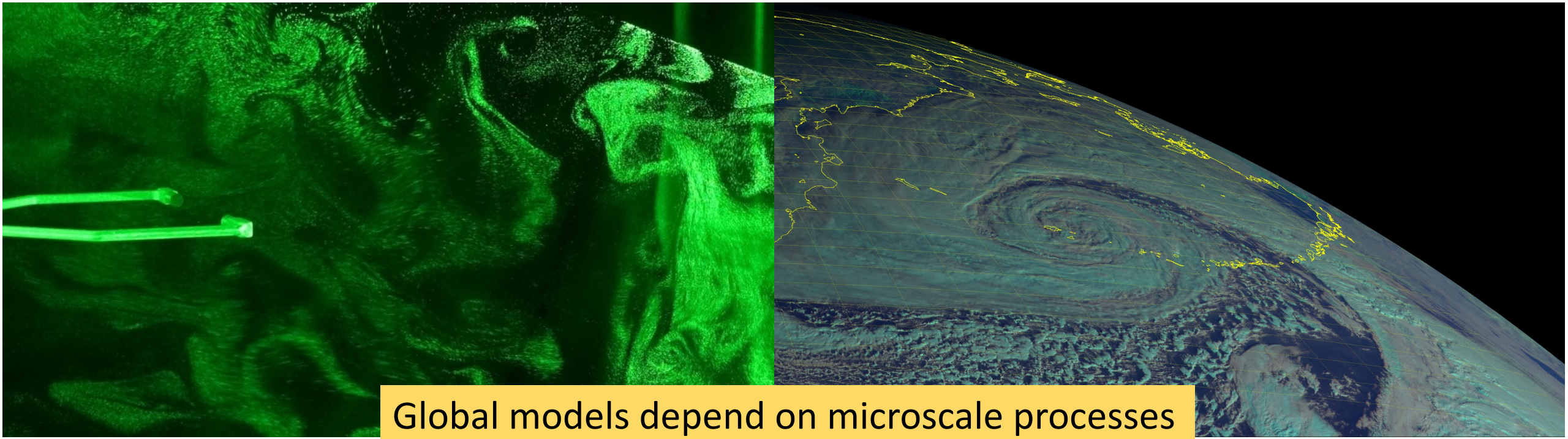
Why a perturbed parameter ensemble (PPE)?



Global models depend on microscale processes

μm ⟷ km

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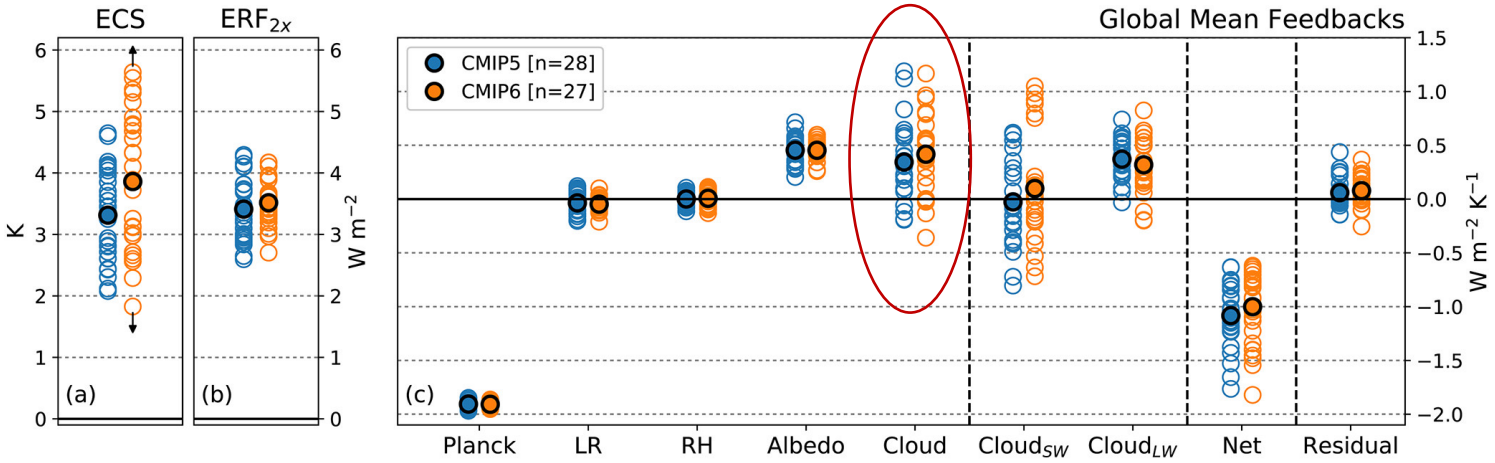
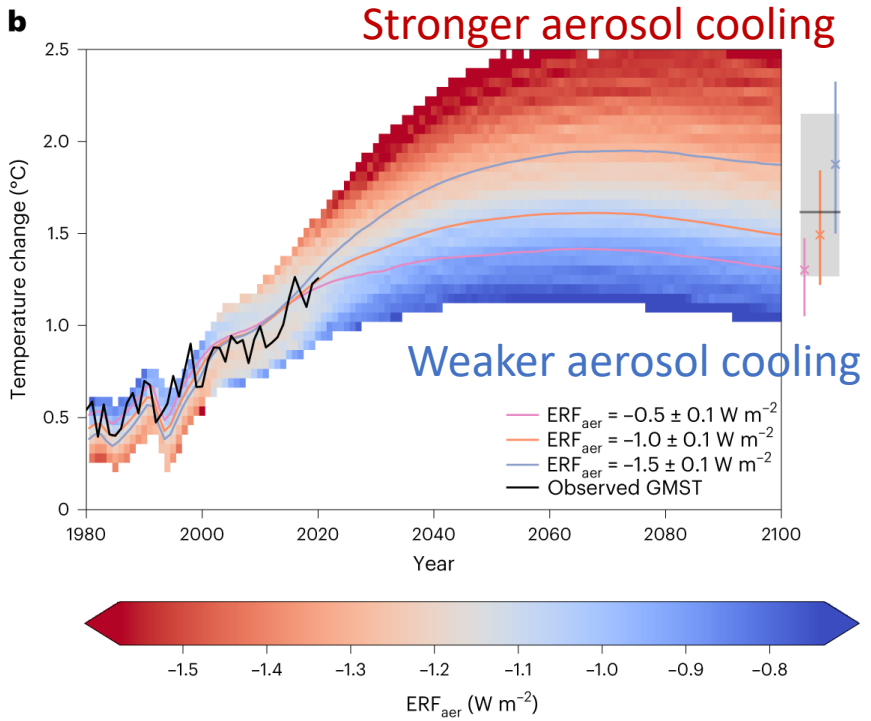
Why a perturbed parameter ensemble (PPE)?

The leading feedback and forcing uncertainties depend on microscale processes



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.

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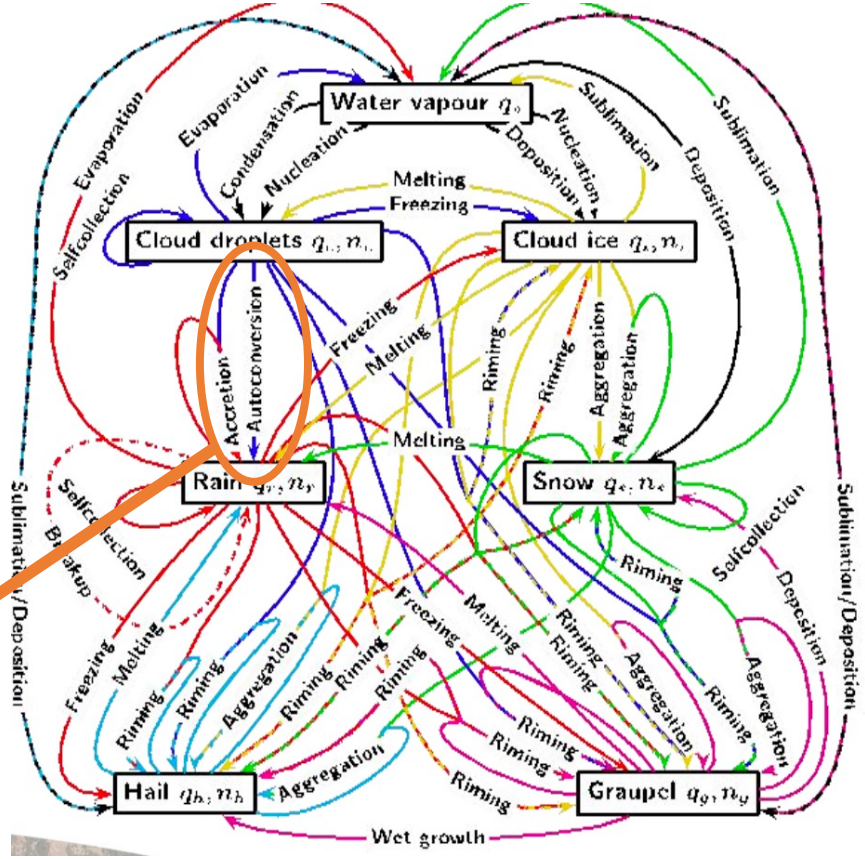
Why a perturbed parameter ensemble (PPE)?

- 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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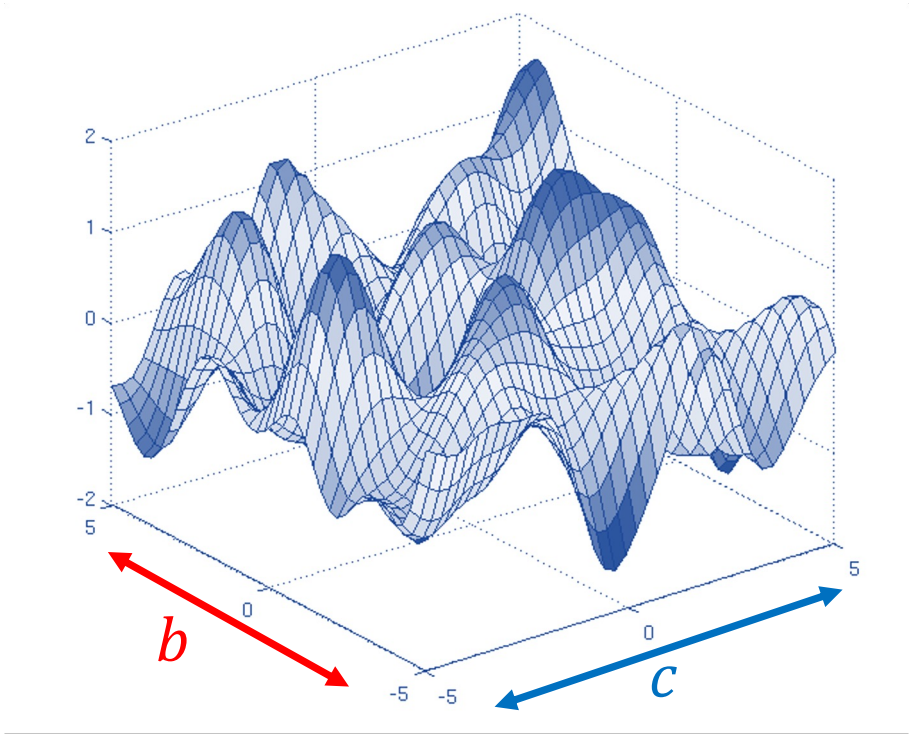
Perturbed parameter ensemble (PPE)

- Imagine a model with a single parameterization:

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

An observable (e.g. cloud fraction)



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

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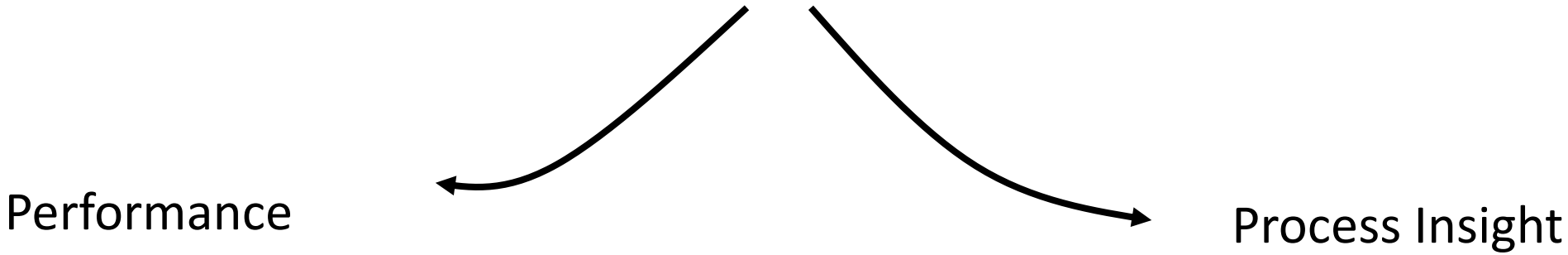
Why a perturbed parameter ensemble (PPE)?



CAVEAT: This is in the context of parameterized processes. Structural error (un-treated or un-treatable subgrid processes are not explorable/tunable)

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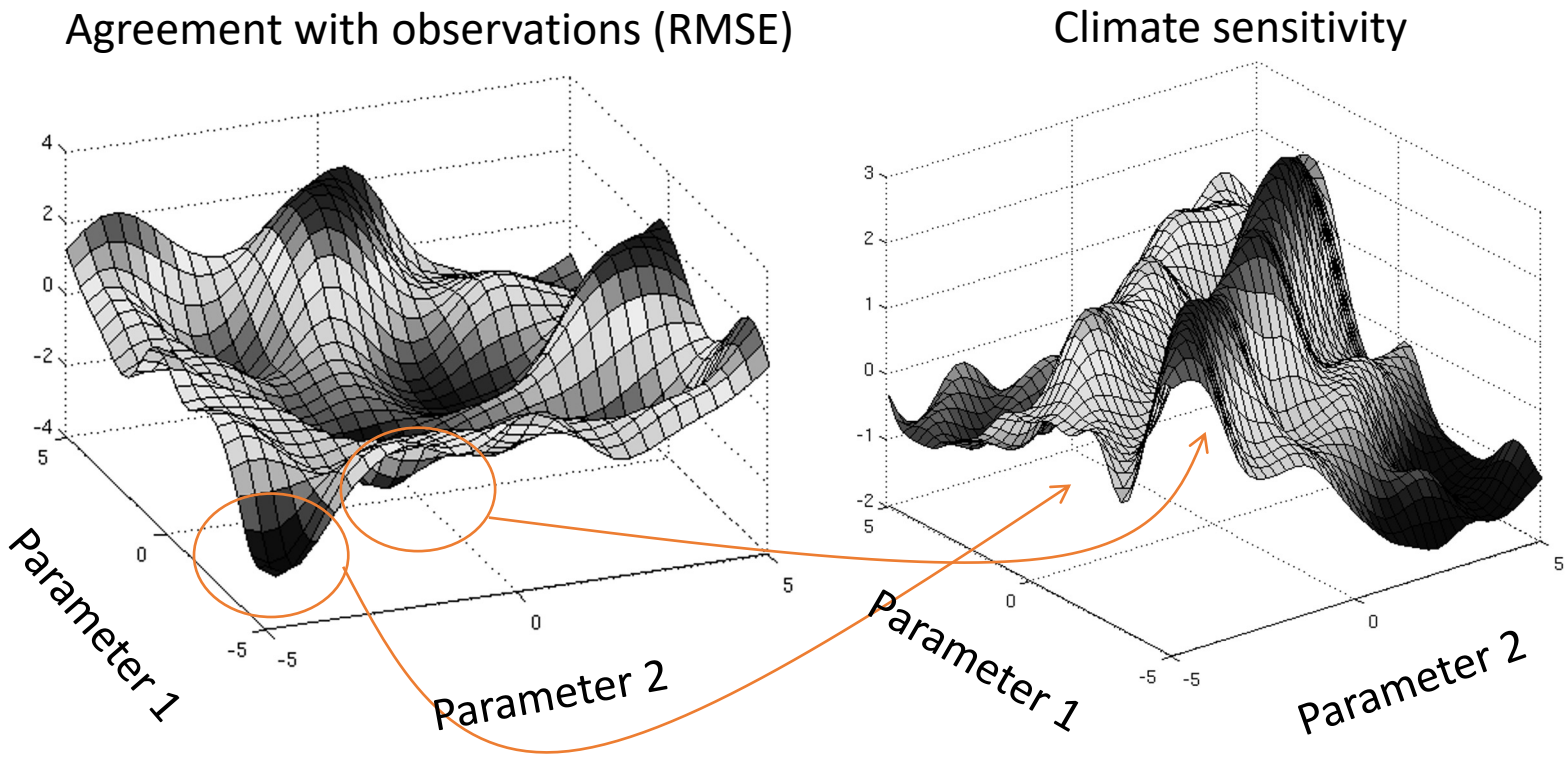
Performance

- Goes toward addressing issue of equifinality.
- Many model configurations may agree with some set of observations, but have very different behavior.



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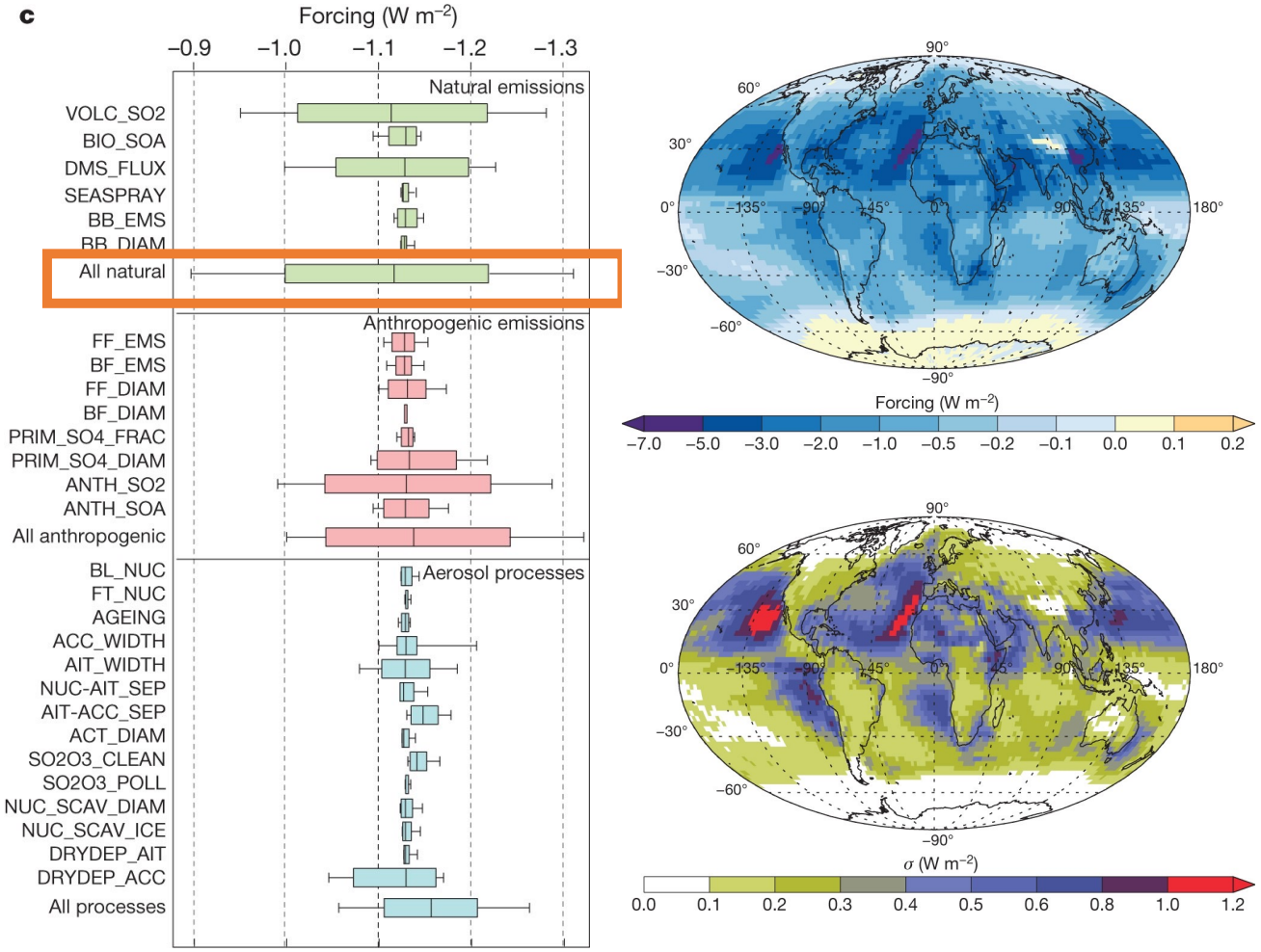
Insight

- What processes affect ESM performance.
- Allows causally-distinct evaluation of links.
- Allows examination of process-dependence in the context of parametric uncertainty.



Carslaw, K. S., L. A. Lee, C. L. Reddington, K. J. Pringle, A. Rap, P. M. Forster, G. W. Mann, et al. "Large Contribution of Natural Aerosols to Uncertainty in Indirect Forcing." *Nature* 503, no. 7474 (07/print 2013): 67–71. https://doi.org/10.1038/nature12674.

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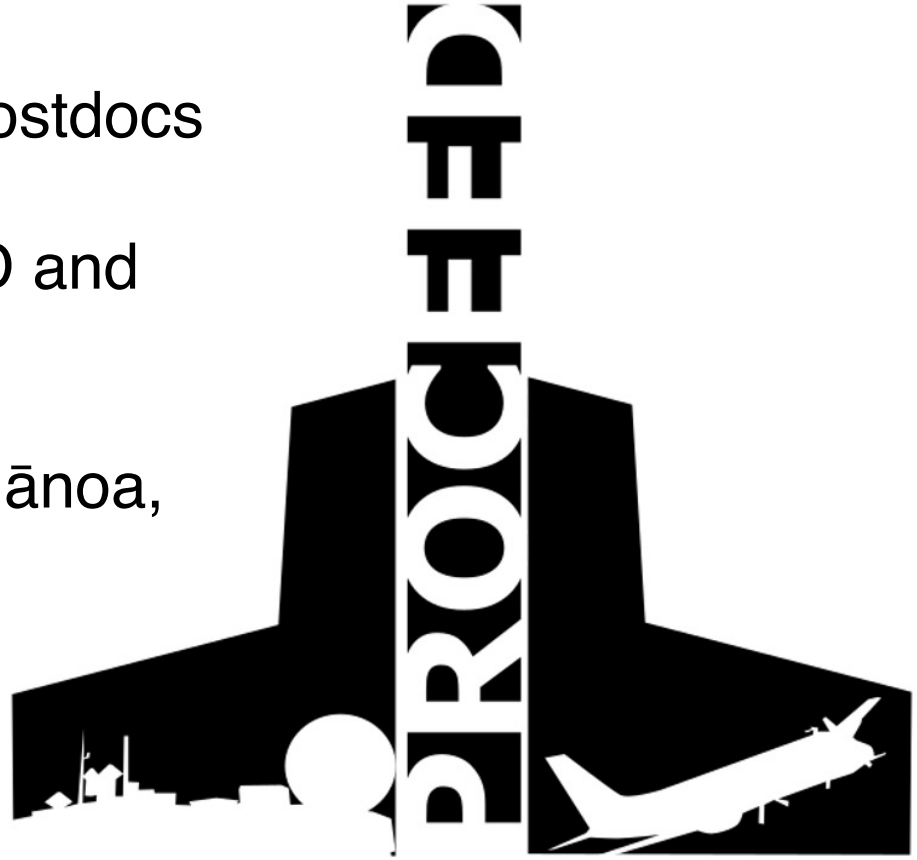
Creating the framework for the next generation Energy Exascale Earth System Model (E3SM) at

PROCEED

(Perturbed physics ensemble Regression Optimization Center for ESM Evaluation and Development)

- Project duration:
  - 2 years, funding started fall 2023, postdocs hired February 2024.
  - DOE EPSCoR funding from EESMD and ASR.
  - Collaboration between University of Wyoming, University of Hawai‘i at Mānoa, PNNL, LLNL



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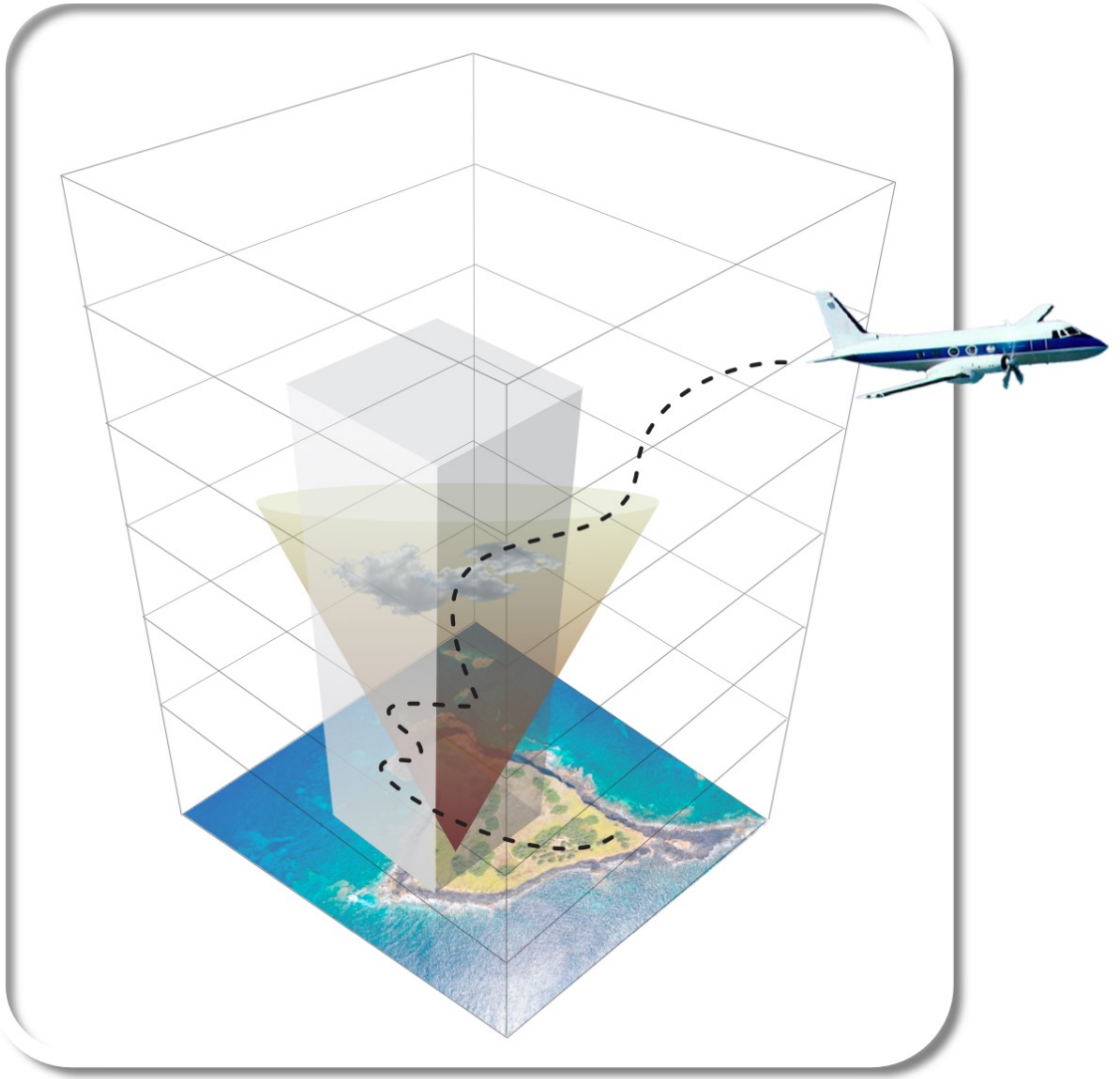
PROCEED

- Project goals (2023-2025):
  - Build adaptable PPE framework in E3SMv3 using latin hypercube (*technically EAM*).
  - Develop understanding of how to confront coarse grid global model with DOE surface and airborne observations.
  - Constraints on effective radiative forcing from aerosol-cloud interactions (ERFaci) using observations from the East North Atlantic (ENA).



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PROCEED

Jacqueline Nugent
(Postdoctoral Scholar)

Travis Aerenson
(Postdoctoral Scholar)

Hunter Brown
(Postdoctoral Scholar)

Some of my students (not paid under PROCEED, but did a lot of work creating the ideas in PROCEED)

Ci Song

Geethma Werapitiya

August Mikkelsen

Funded EPSCoR University Faculty

Gabrielle Allen (UW)

Dana Caulton (UW)

Jennifer Griswold (UHM)

Andrew Kirby (UW)

Daniel McCoy (UW)

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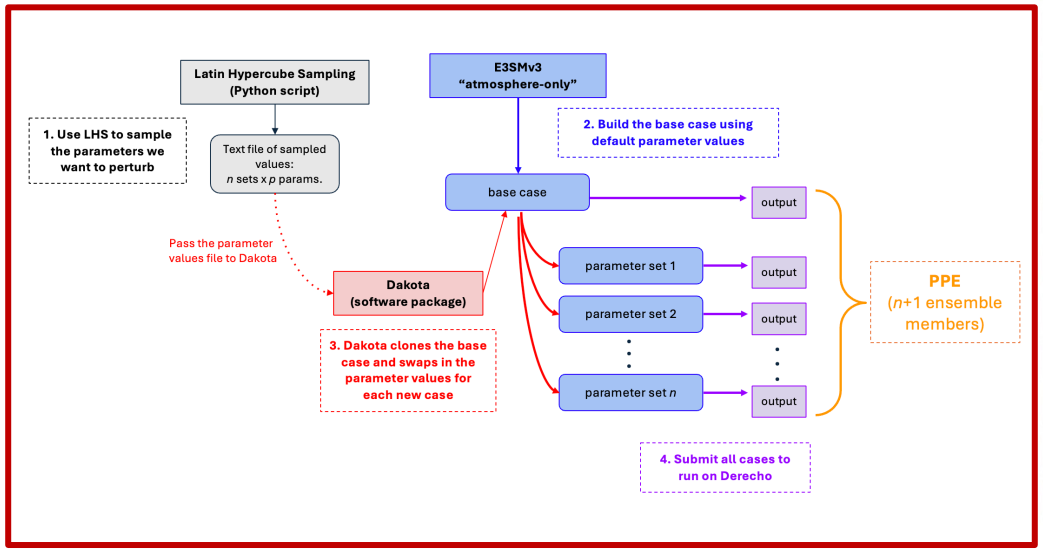
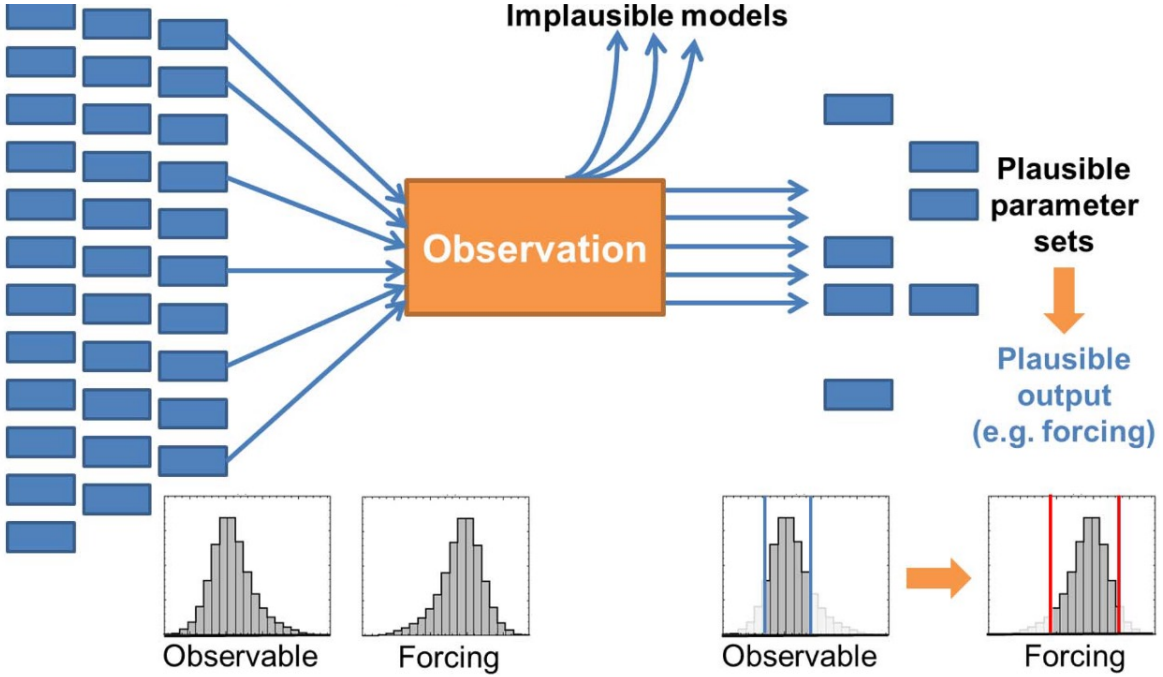
Jacqueline Nugent

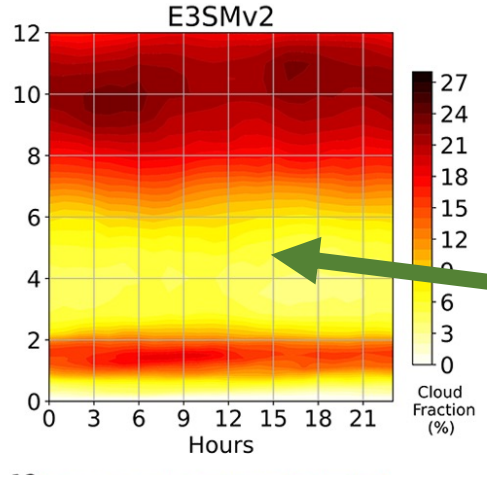
Andrew Kirby

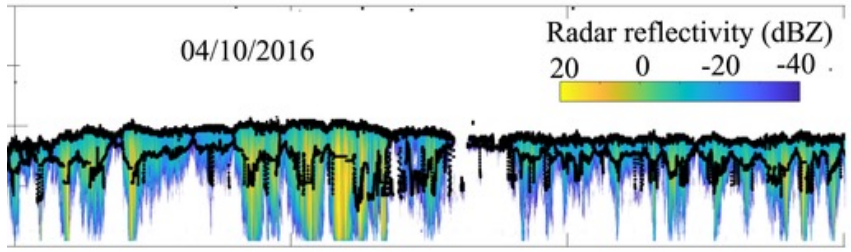


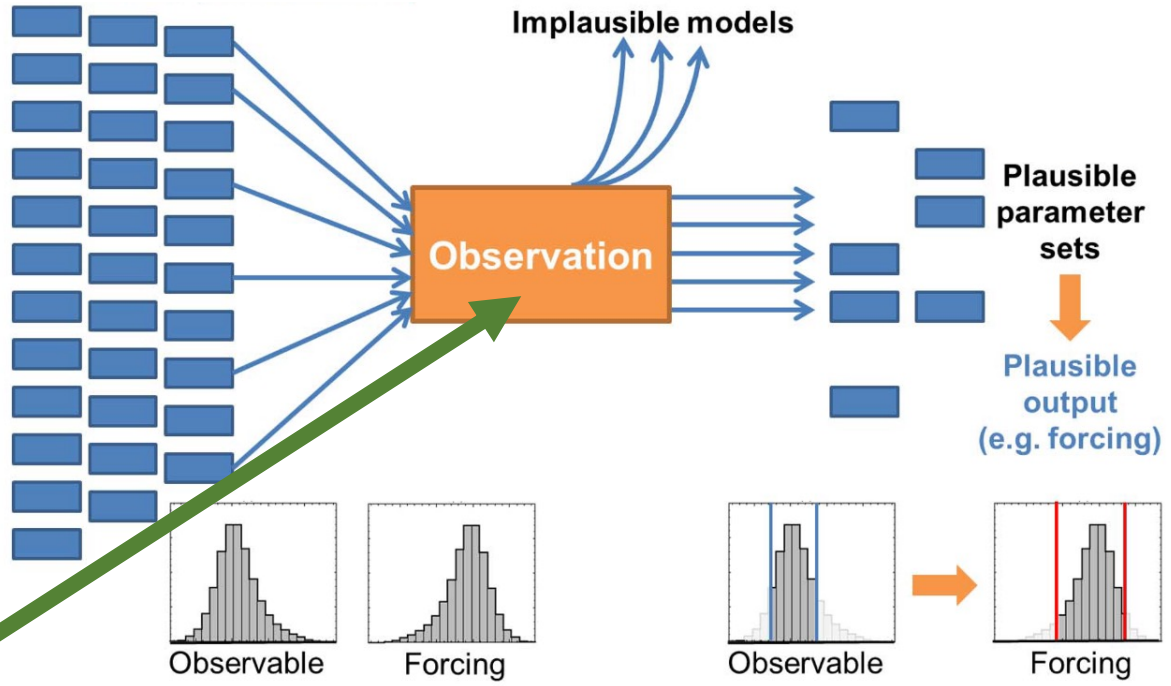


Johnson, Jill S., Leighton A. Regayre, Masaru Yoshioka, Kirsty J. Pringle, Lindsay A. Lee, David MH Sexton, John W. Rostron, Ben BB Booth, and Kenneth S. Carslaw. "The Importance of Comprehensive Parameter Sampling and Multiple Observations for Robust Constraint of Aerosol Radiative Forcing." *Atmospheric Chemistry and Physics* 18, no. 17 (2018): 13031–53.

Tang, S., A. C. Varble, J. D. Fast, K. Zhang, P. Wu, X. Dong, F. Mei, M. Pekour, J. C. Hardin, and P.-L. Ma. "Earth System Model Aerosol–Cloud Diagnostics (ESMAC Diags) Package, Version 2: Assessing Aerosols, Clouds, and Aerosol–Cloud Interactions via Field Campaign and Long-Term Observations." *Geosci. Model Dev.* 16, no. 21 (November 8, 2023): 6355–76. https://doi.org/10.5194/gmd-16-6355-2023.







Lamer, Katia, Catherine M. Naud, and James F. Booth. "Relationships Between Precipitation Properties and Large-Scale Conditions During Subsidence at the Eastern North Atlantic Observatory." *Journal of Geophysical Research: Atmospheres* 125, no. 7 (April 16, 2020): e2019JD031848. https://doi.org/10.1029/2019JD031848.

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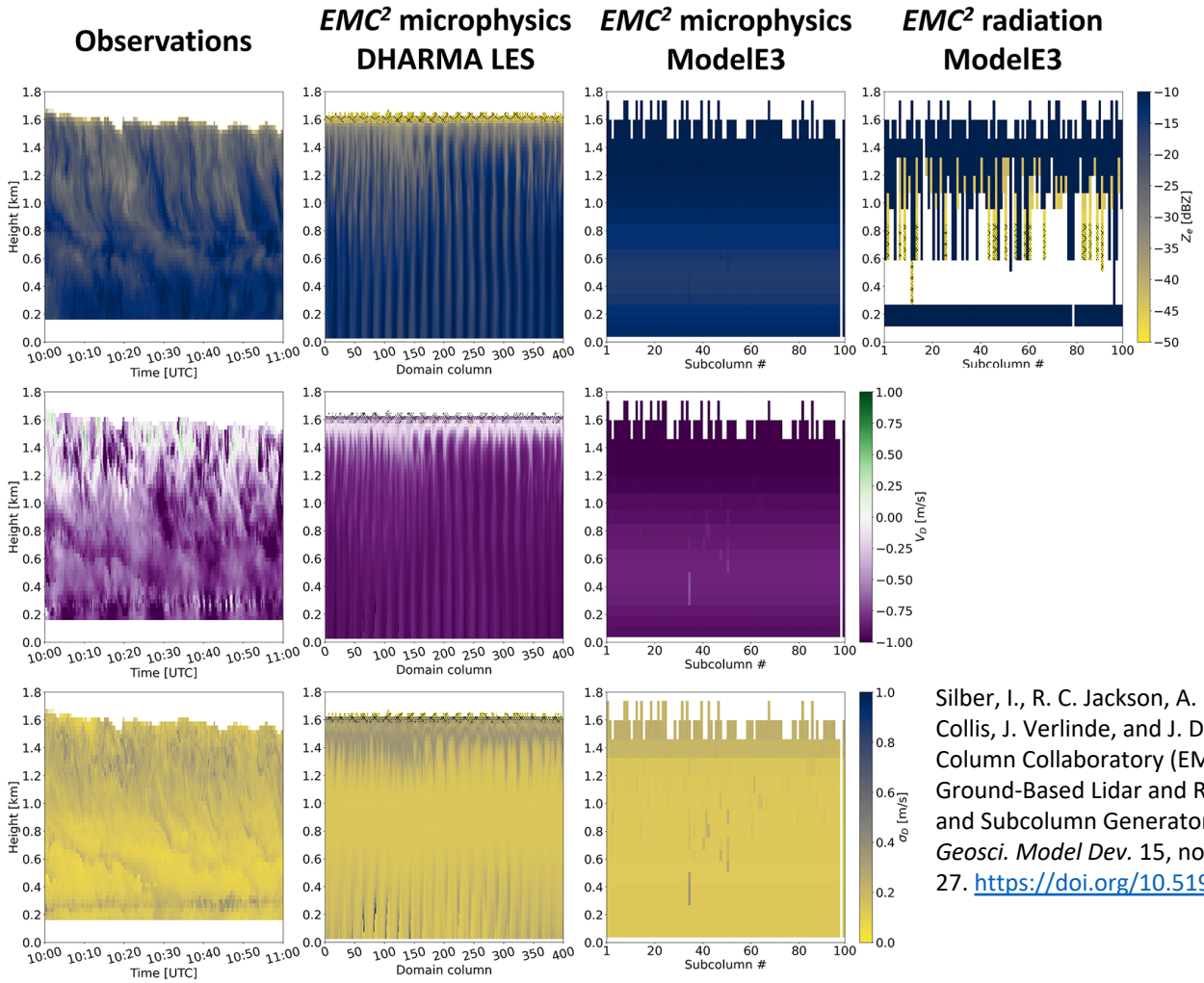
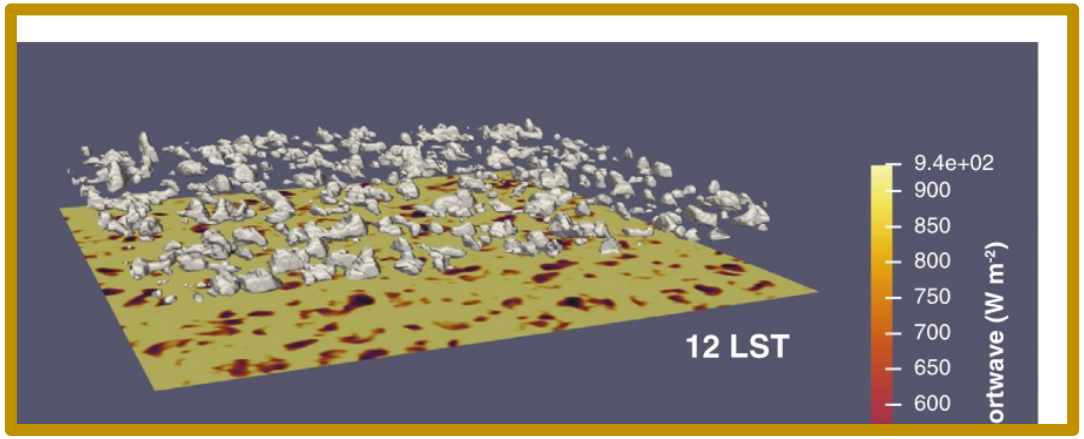
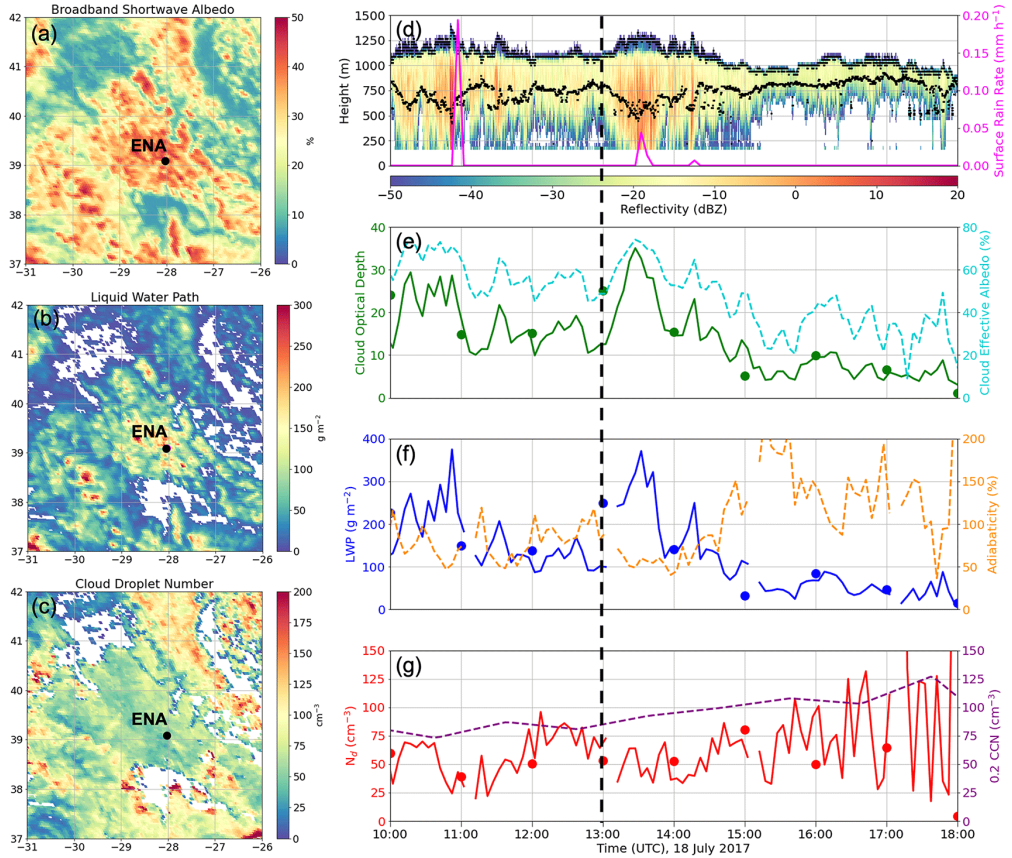
Instrument simulators

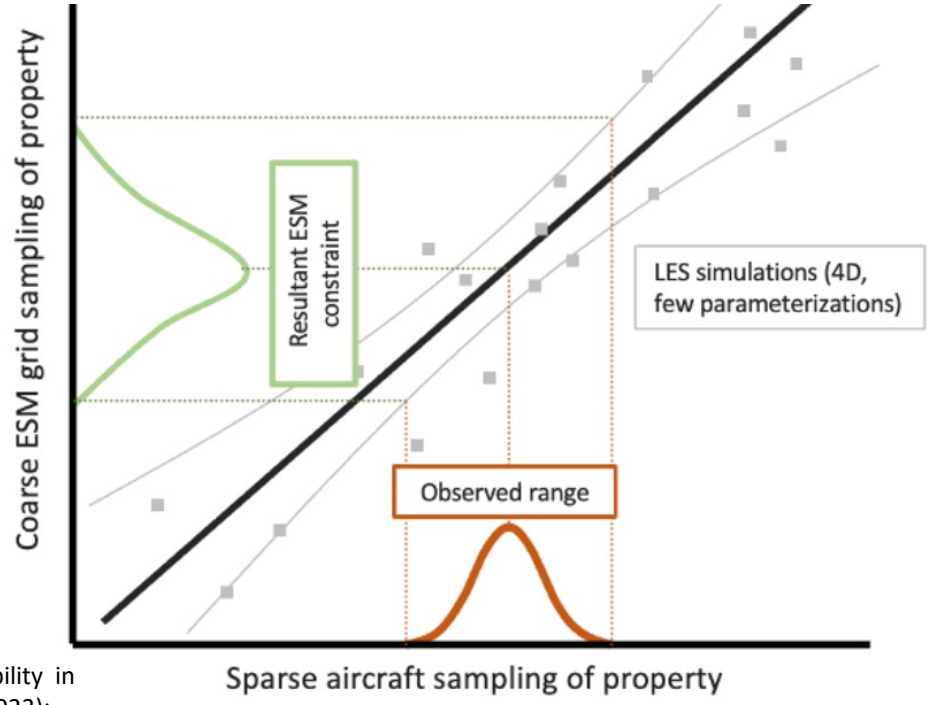


Silber, I., R. C. Jackson, A. M. Fridlind, A. S. Ackerman, S. Collis, J. Verlinde, and J. Ding. "The Earth Model Column Collaboratory (EMC2) v1.1: An Open-Source Ground-Based Lidar and Radar Instrument Simulator and Subcolumn Generator for Large-Scale Models." *Geosci. Model Dev.* 15, no. 2 (February 1, 2022): 901–27. https://doi.org/10.5194/gmd-15-901-2022.

Spatial sampling



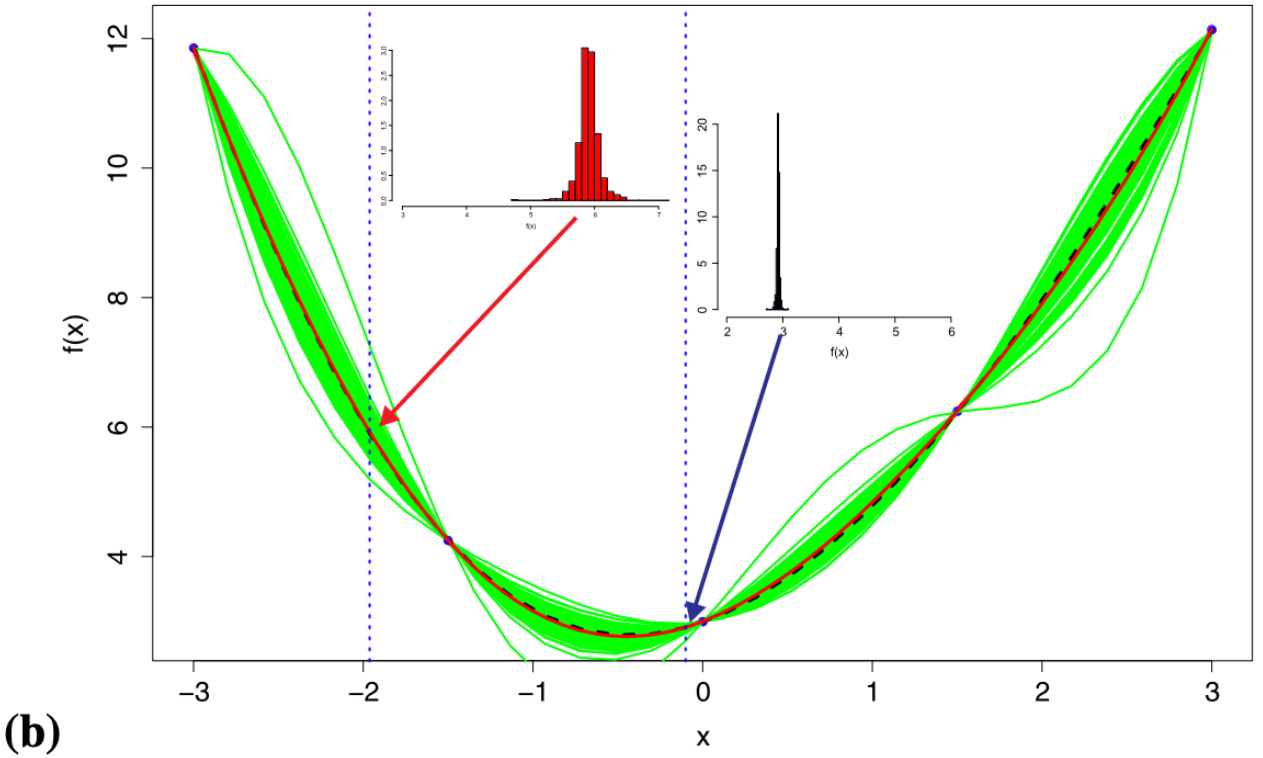




Varble, A. C., P.-L. Ma, M. W. Christensen, J. Mülmenstädt, S. Tang, and J. Fast. "Evaluation of Liquid Cloud Albedo Susceptibility in E3SM Using Coupled Eastern North Atlantic Surface and Satellite Retrievals." *Atmos. Chem. Phys.* 23, no. 20 (October 27, 2023): 13523–53. https://doi.org/10.5194/acp-23-13523-2023.

Sampling parameter space

- Sampling P dimensional parameter space with N points is N^P ensemble members. Expensive!
- Randomly sample and build an emulator.
- Typically Gaussian Process.
- Use Earth System Emulator (ESEm) https://github.com/duncanwp/ESEm



(b)

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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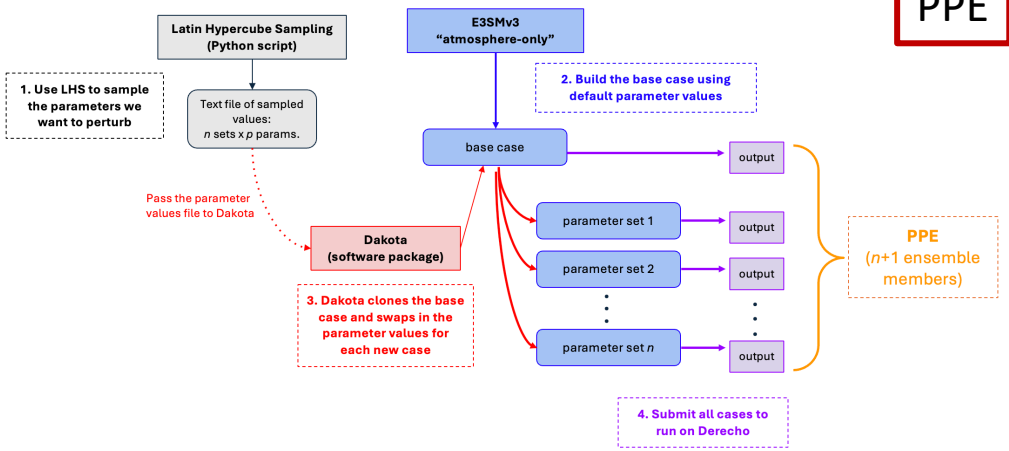
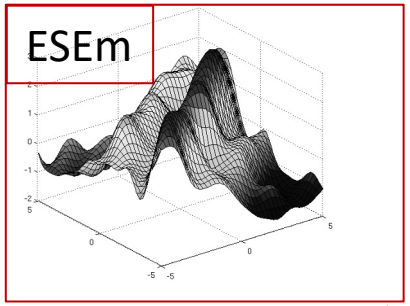
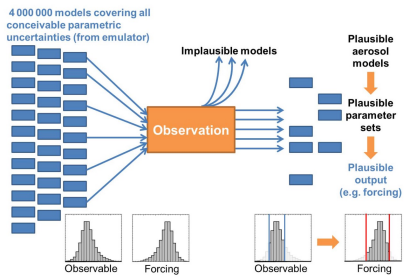
PPE



ESEm

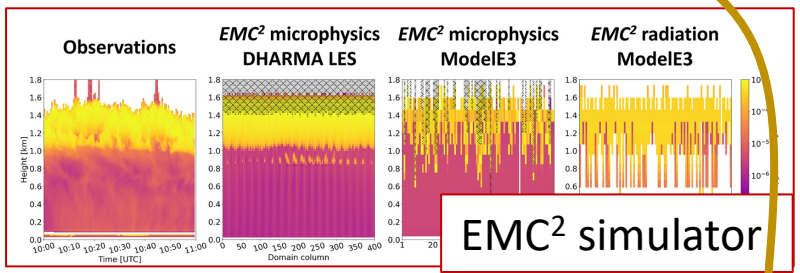




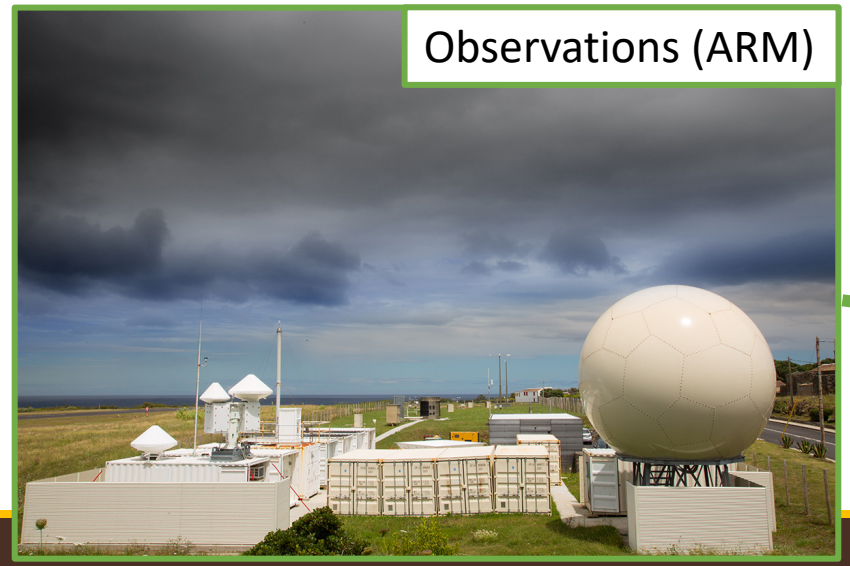
Subset of parameter space

Process understanding

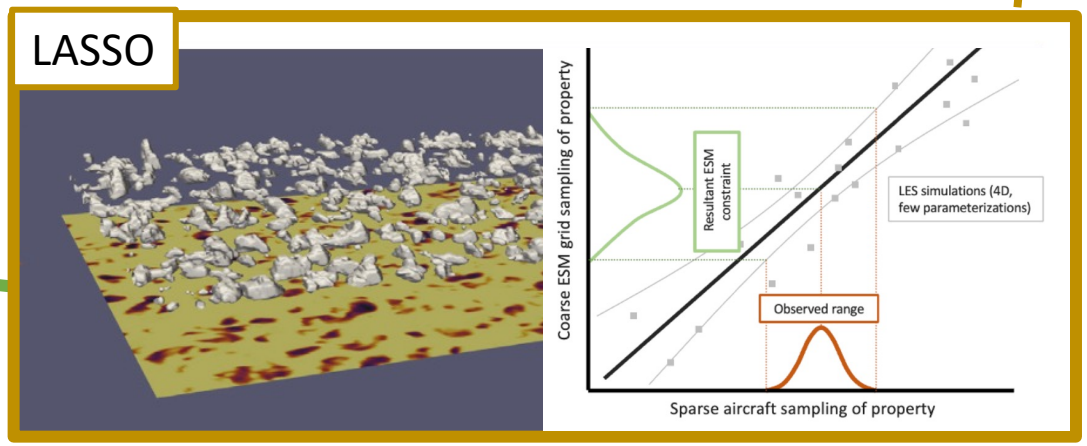
Climate prediction



EMC² simulator

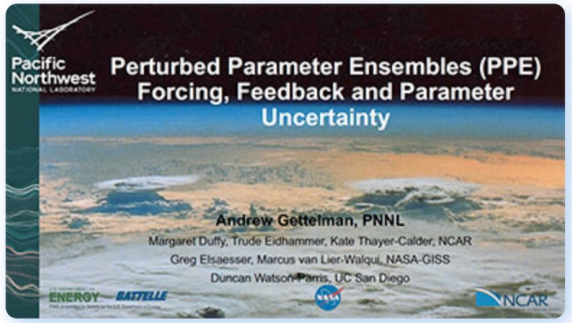


LASSO



Preliminary results

- Leveraging CAM6 PPE.
- This was already described in Andrew Gettelman's presentation on May 25, 2023: https://www.youtube.com/watch?v=1daDQGL3DHQ&feature=youtu.be
- Briefly, 45 parameters sampled using Latin hypercube, ~260 members, PI, PD, and +4K simulations.
- For details see: https://egusphere.copernicus.org/preprints/2024/egusphere-2023-2165/



All-Hands Presentation: May 25, 2023

Perturbed Parameter Ensembles (PPE) Forcing, Feedback and Parameter Uncertainty

by Andrew Gettelman

PDF of Presentation

MP4 Movie (on the E3SM YouTube Channel)

https://doi.org/10.5194/egusphere-2023-2165
Preprint. Discussion started: 15 January 2024

EGUsphere
Preprint repository

An Extensible Perturbed Parameter Ensemble (PPE) for the Community Atmosphere Model Version 6

Trude Eidhammer[1], Andrew Gettelman[1,2], Katherine Thayer-Calder[1], Duncan Watson-Parris[3], Gregory Elsaesser[4,5], Hugh Morrison[1], Marcus van Lier-Walqui[4,5], Ci Song[6], and Daniel McCoy[6]

[1]National Center for Atmospheric Research, Boulder, CO, USA
[2]Now at: Pacific Northwest National Laboratory, Richland, WA, USA
[3]Scripps Institution of Oceanography and Halıcıoğlu Data Science Institute, University of California San Diego, La Jolla, CA, USA
[4]Columbia University, New York, NY, USA
[5]NASA Goddard Institute for Space Studies, New York, NY, USA
[6]Department of Atmospheric Science, University of Wyoming, Laramie, WY, USA

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Abstract. This paper documents the methodology and preliminary results from a Perturbed Parameter Ensemble (PPE) technique, where multiple parameters are varied simultaneously and the parameter values are determined with Latin hypercube

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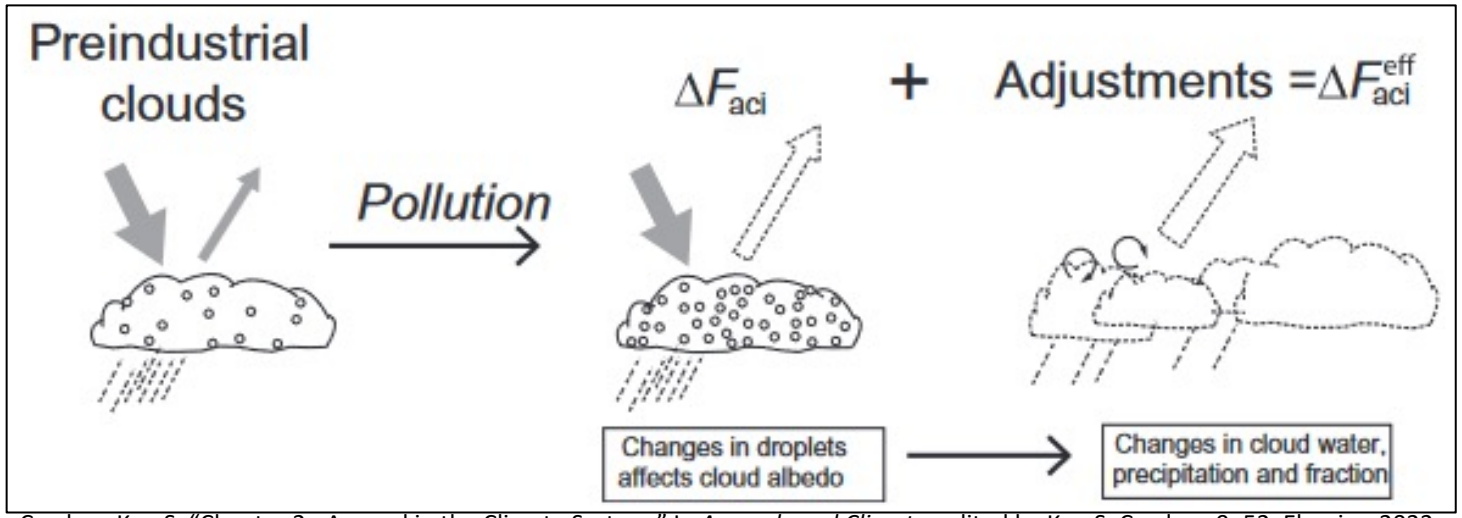
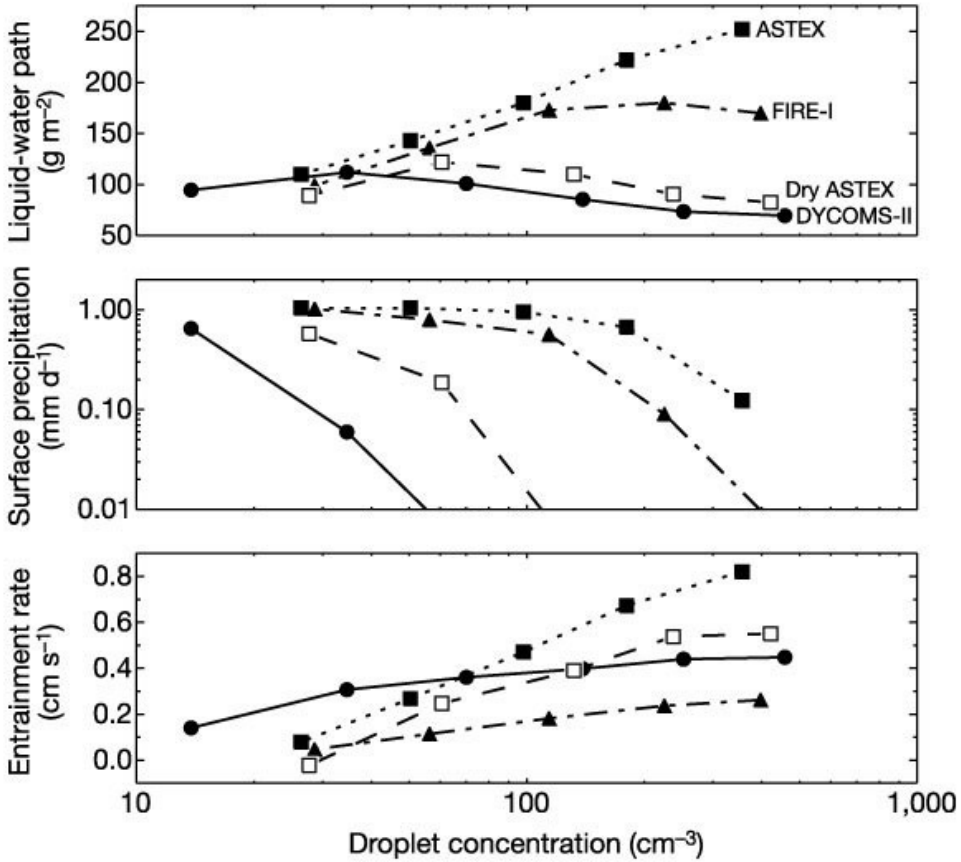
Using ARM to constrain aerosol-cloud adjustments

- Precipitation suppression:
  +Nd → +LWP → Cooling

- Size-dependent entrainment:
  +Nd → -LWP → Warming



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.



Ackerman, A. S., M. P. Kirkpatrick, D. E. Stevens, and O. B. Toon. "The Impact of Humidity above Stratiform Clouds on Indirect Aerosol Climate Forcing." *Nature* 432, no. 7020 (December 23, 2004): 1014–17. https://doi.org/10.1038/nature03174.

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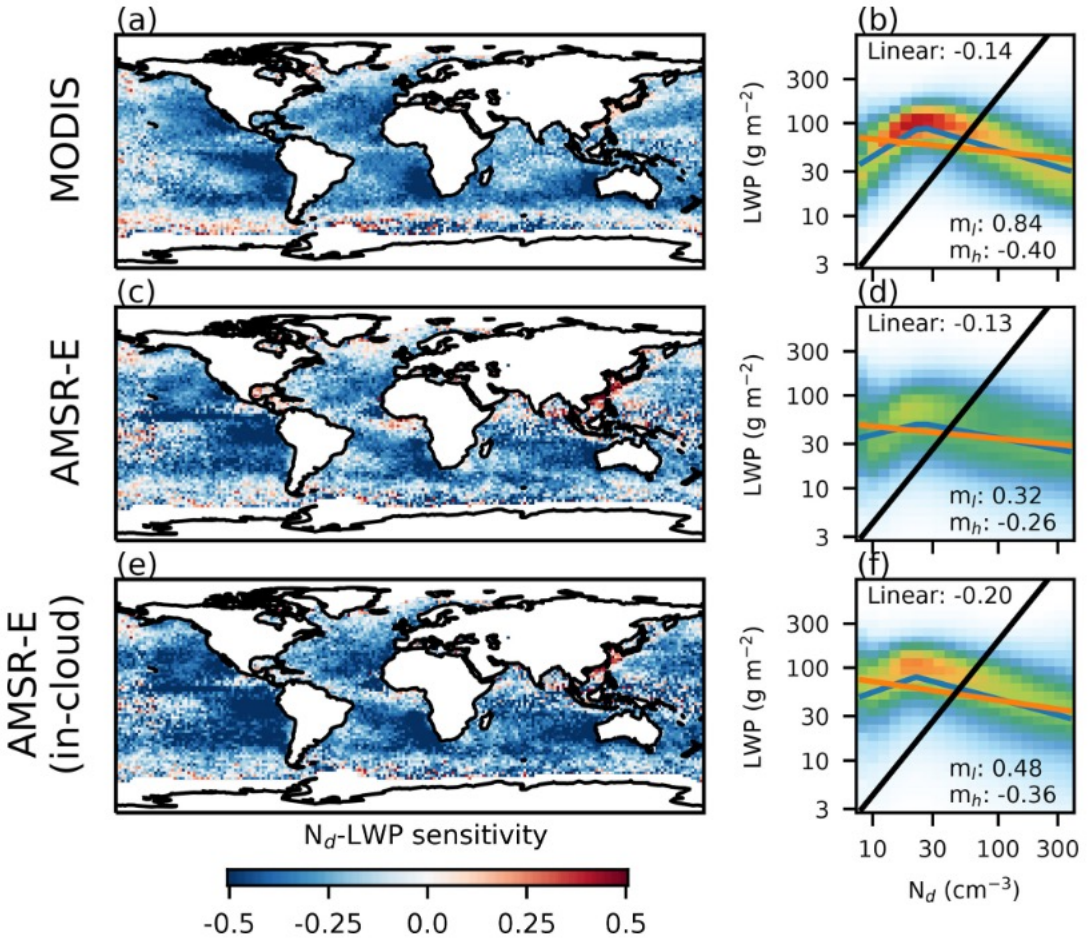
Using ARM to constrain aerosol-cloud adjustments

- Precipitation suppression and sedimentation is parameterized.
- Size-dependent entrainment is not.
- Is this a huge bias in our models?



Gryspeerdt, E., T. Goren, O. Sourdeval, J. Quaas, J. Mülmenstädt, S. Dipu, C. Unglaub, A. Gettelman, and M. Christensen. "Constraining the Aerosol Influence on Cloud Liquid Water Path." *Atmospheric Chemistry & Physics* 19, no. 8 (2019): 5331–47. https://doi.org/10.5194/acp-19-5331-2019.

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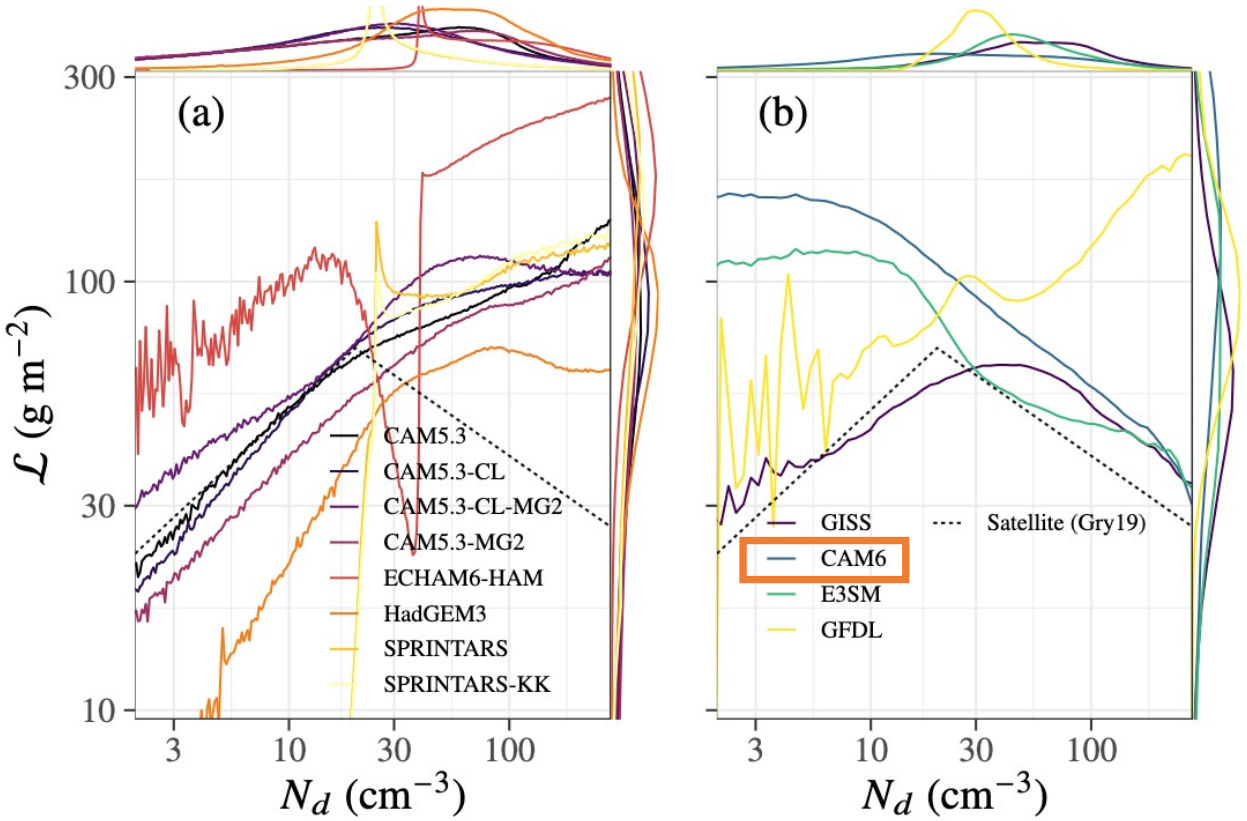
Using ARM to constrain aerosol-cloud adjustments

- Most ESMs actually represent this behavior pretty well.
- What is going on?
- How do we constrain ESM behavior?



Mülmenstädt, J., E. Gryspeerdt, S. Dipu, J. Quaas, A. S. Ackerman, A. M. Fridlind, F. Tornow, et al. "General Circulation Models Simulate Negative Liquid Water Path–Droplet Number Correlations, but Anthropogenic Aerosols Still Increase Simulated Liquid Water Path." *EGUsphere* 2024 (January 9, 2024): 1–29. https://doi.org/10.5194/egusphere-2024-4.

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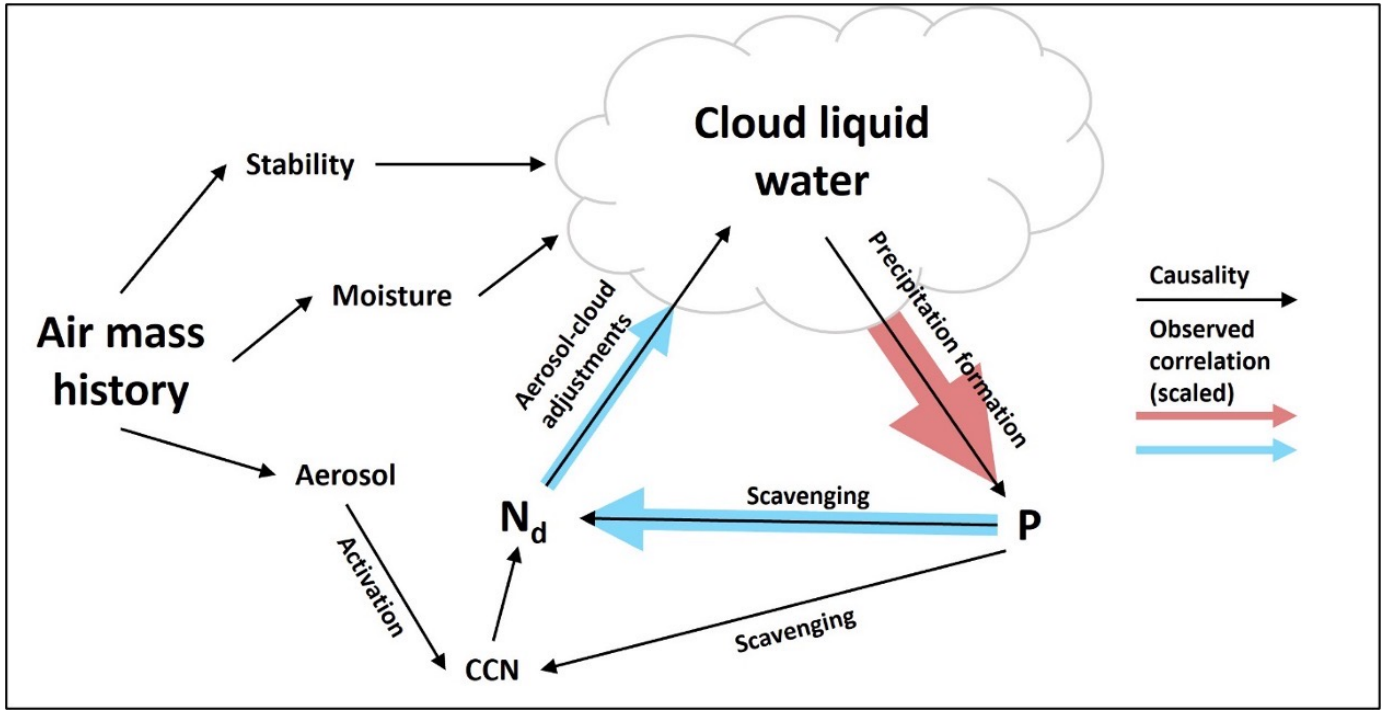
Using ARM to constrain aerosol-cloud adjustments

- As discussed in Gryspeerdt et al. 2019, numerous confounders.
- ARM observations are uniquely suited to address this problem.



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

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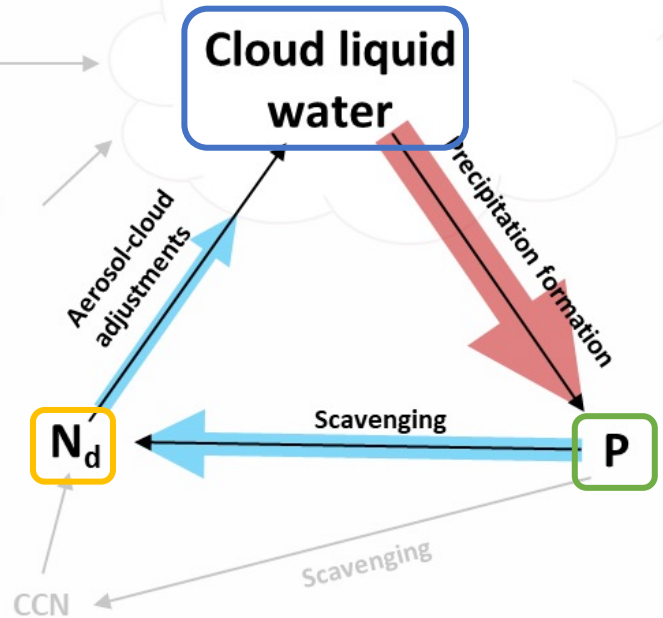
Using ARM to constrain aerosol-cloud adjustments

Liquid water path from radiometer MWRRET2 VAP (microwave radiometer retrievals) (kg/m^2)

Droplet number concentration from NDROP VAP (#/cc)



Precipitation rate from video disdrometer (mm/hr)

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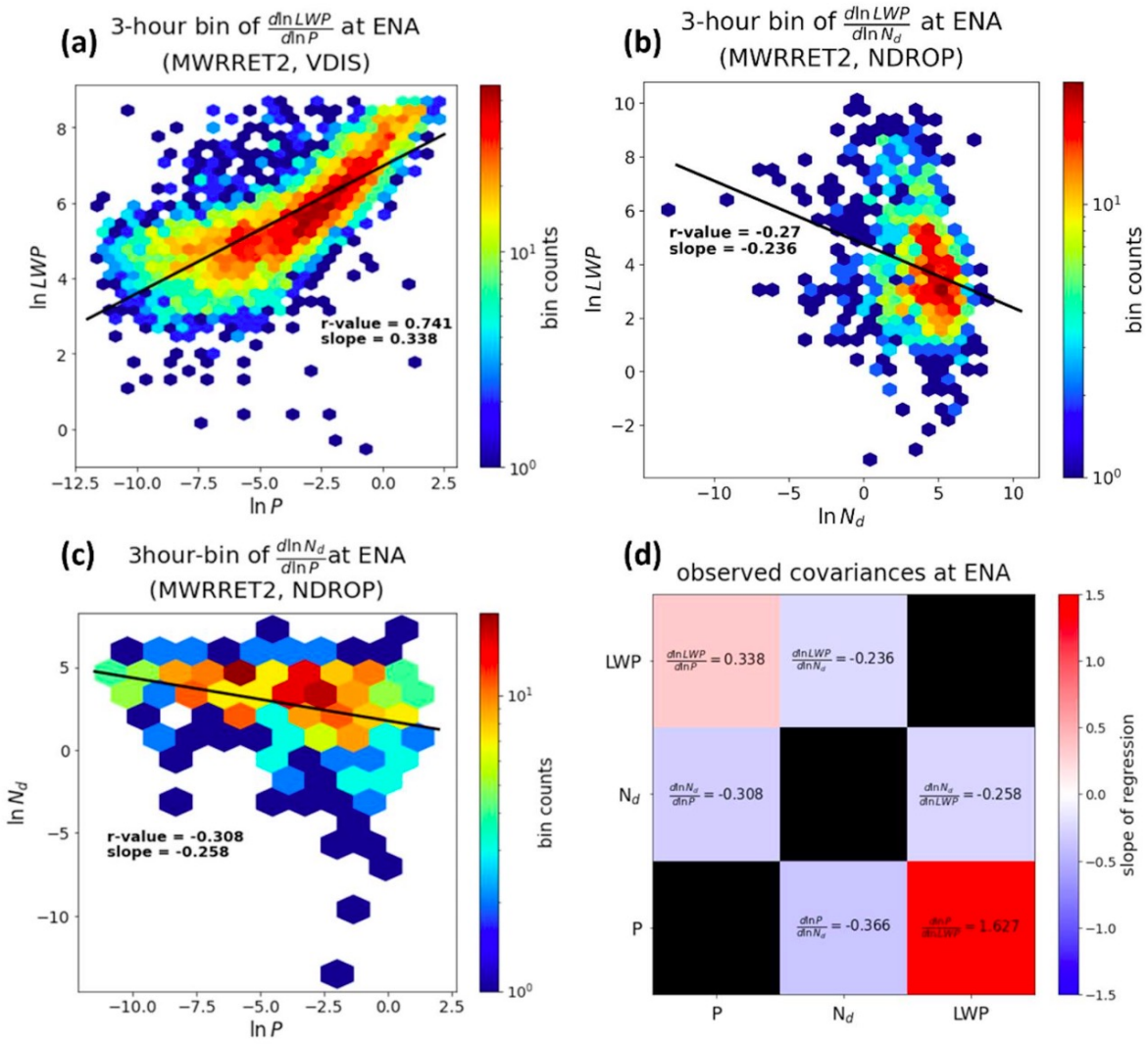
Using ARM to constrain aerosol-cloud adjustments



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

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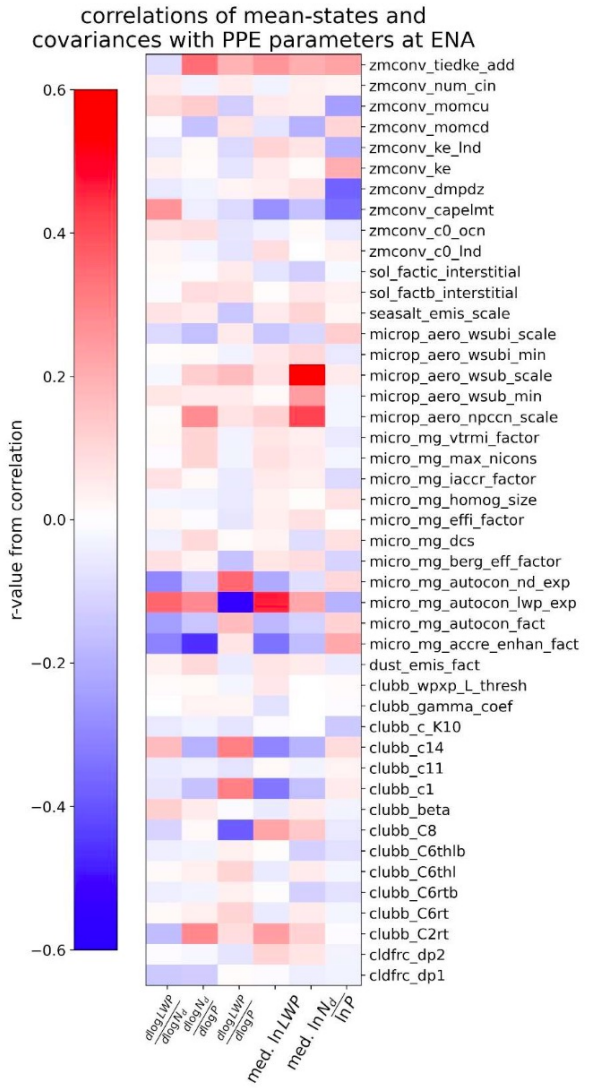
Using ARM to constrain aerosol-cloud adjustments

- We can perform the same analysis in the CAM6 PPE.
- Allows us to look at how processes project onto observables.



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

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Using ARM to constrain aerosol-cloud adjustments

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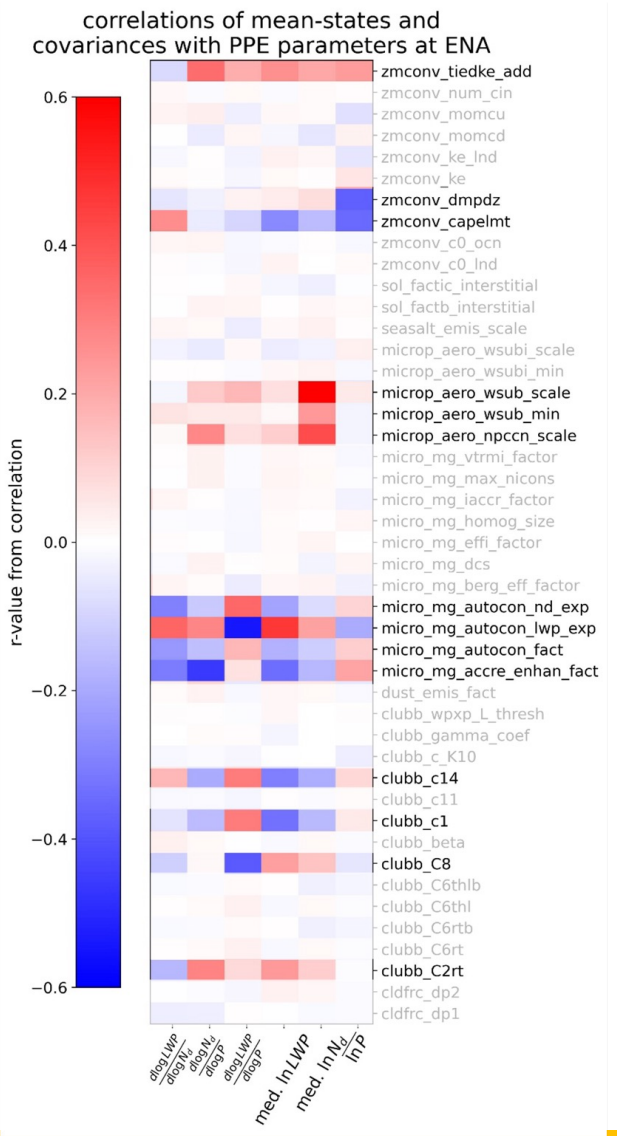

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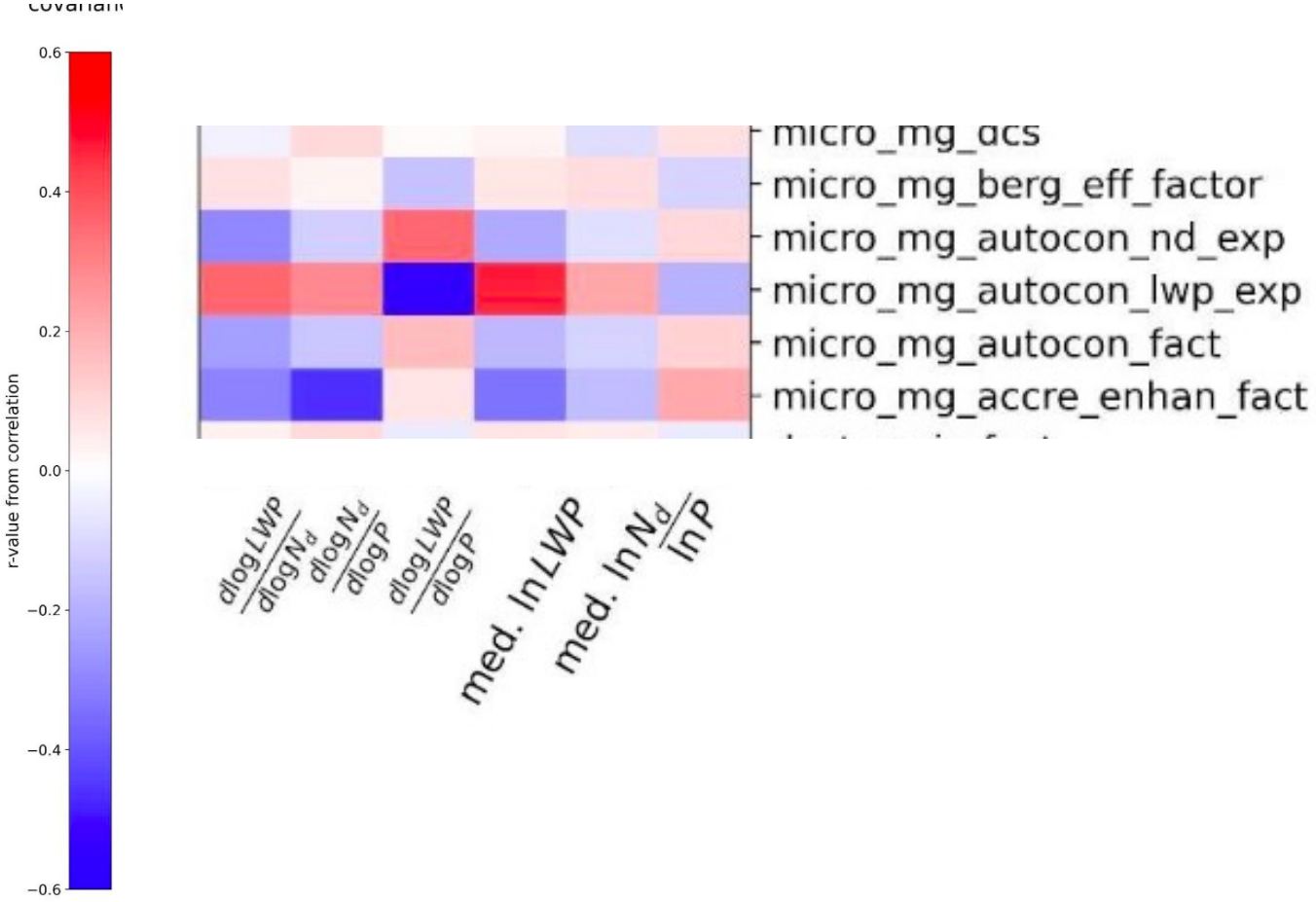
Using ARM to constrain aerosol-cloud adjustments

- We can see linkages to autoconversion.
- We can also see a strong covariance between observables and accretion.



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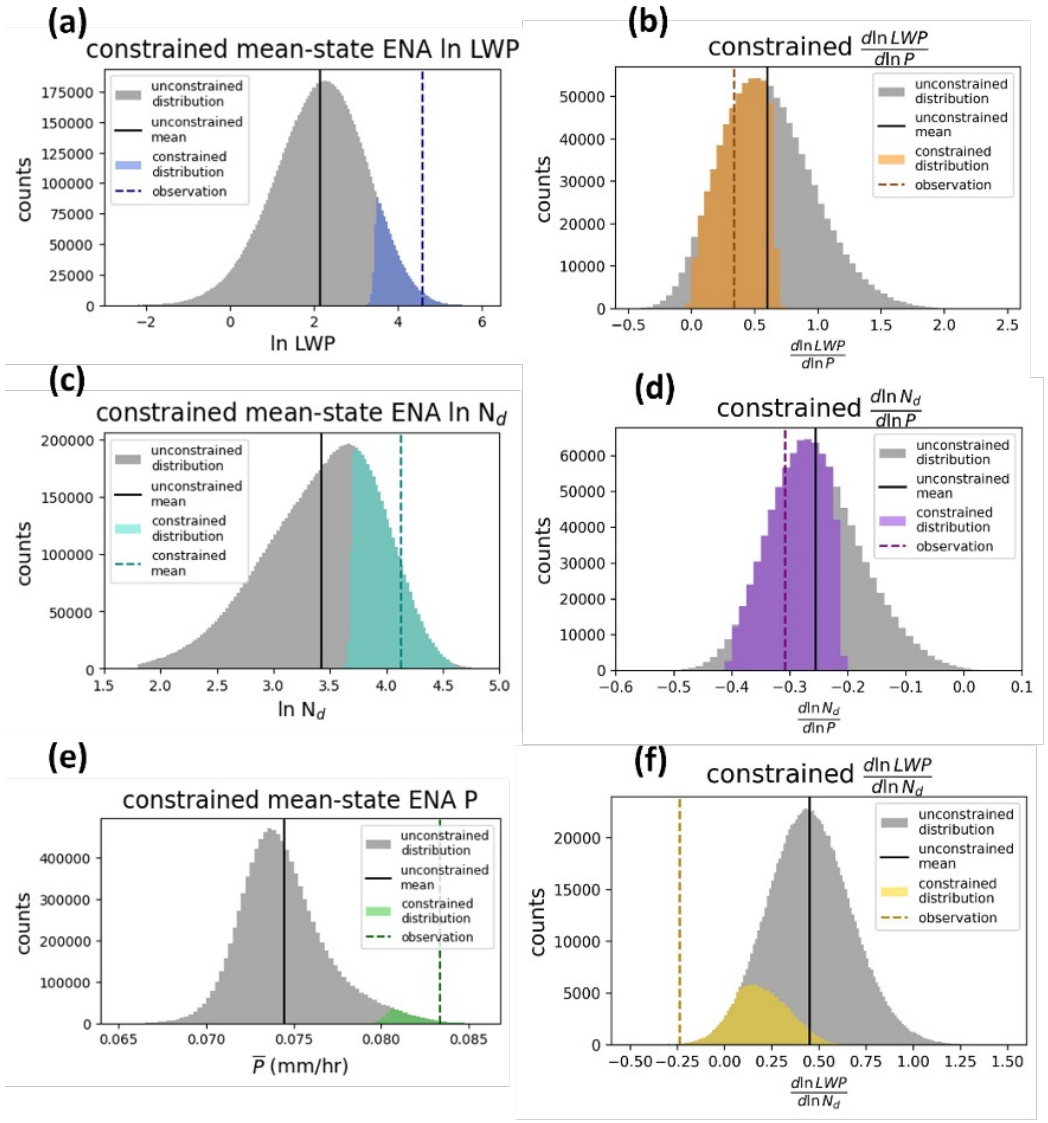
Using ARM to constrain aerosol-cloud adjustments

- The CAM6 PPE is capable of mimicking the negative correlation between Nd and LWP in observations.



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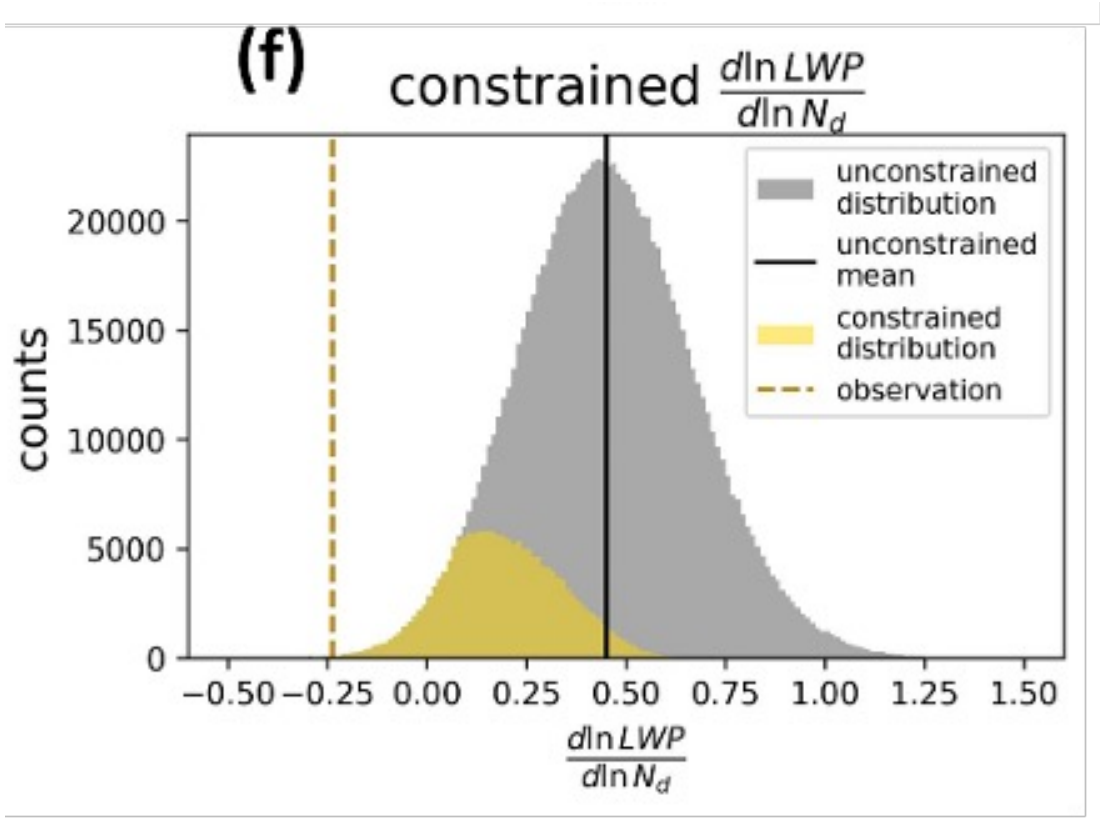

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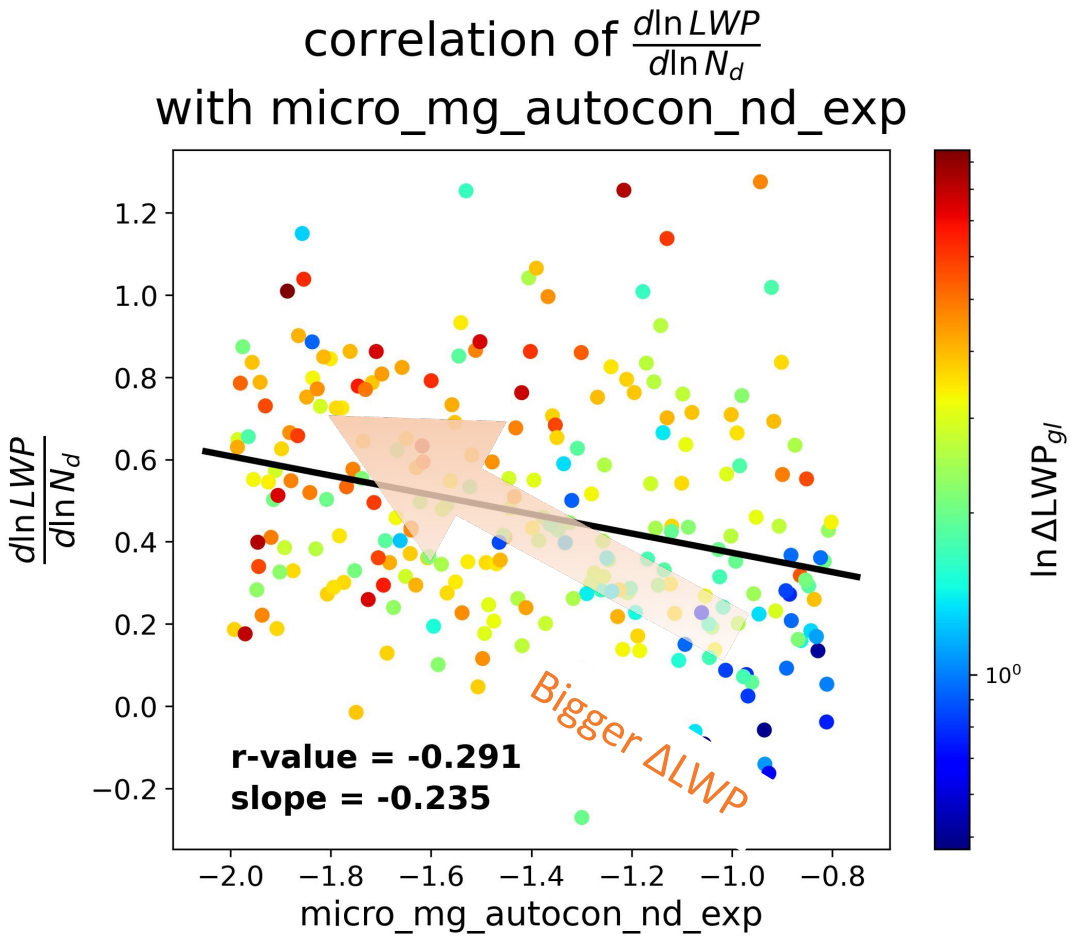
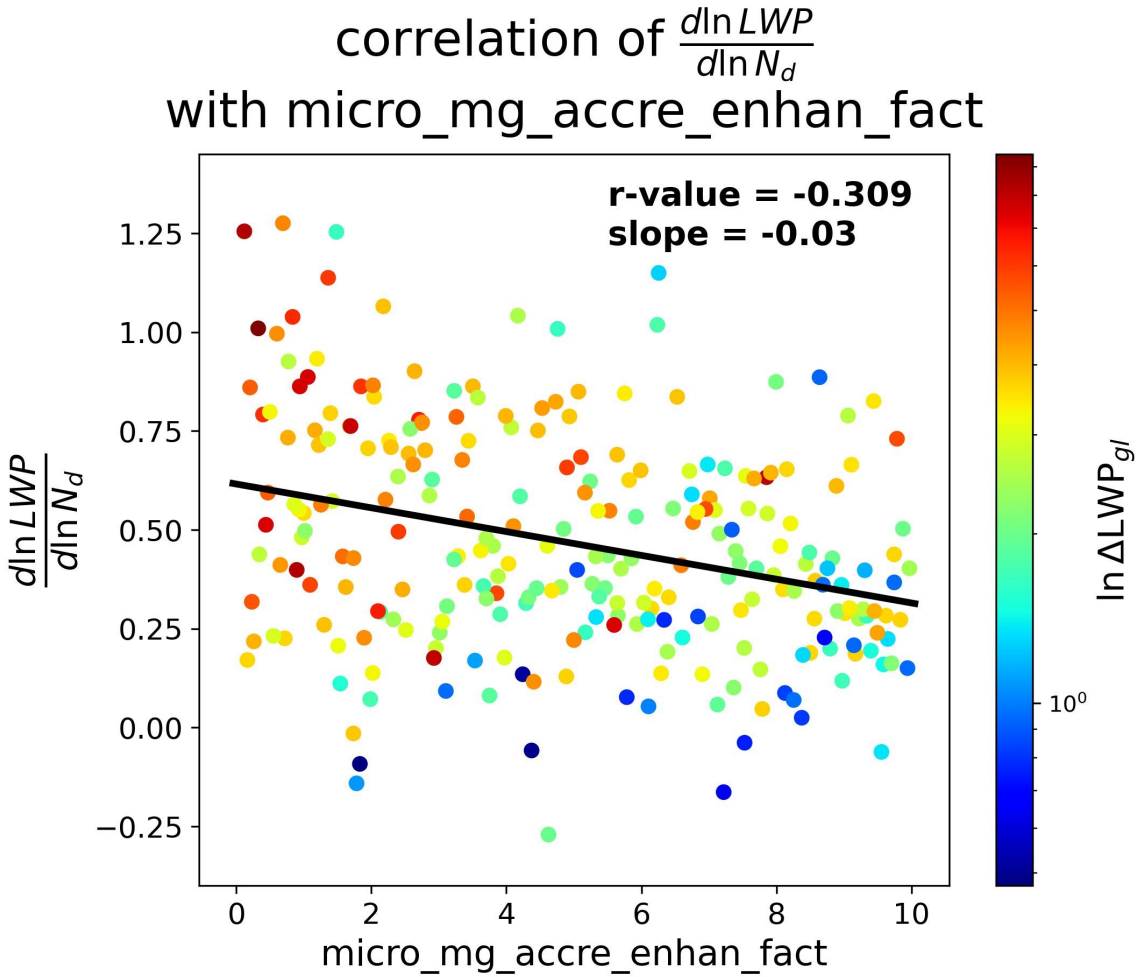


Stronger precipitation suppression



Stronger accretion

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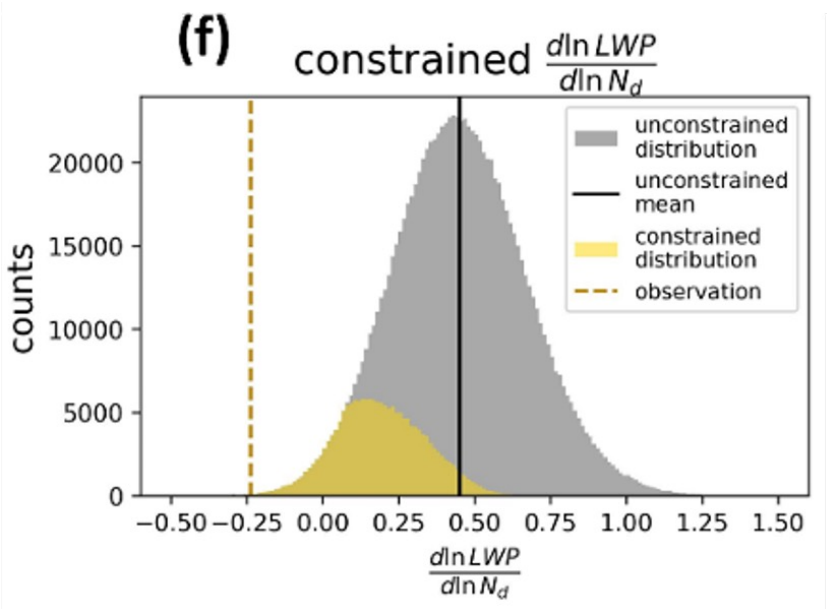
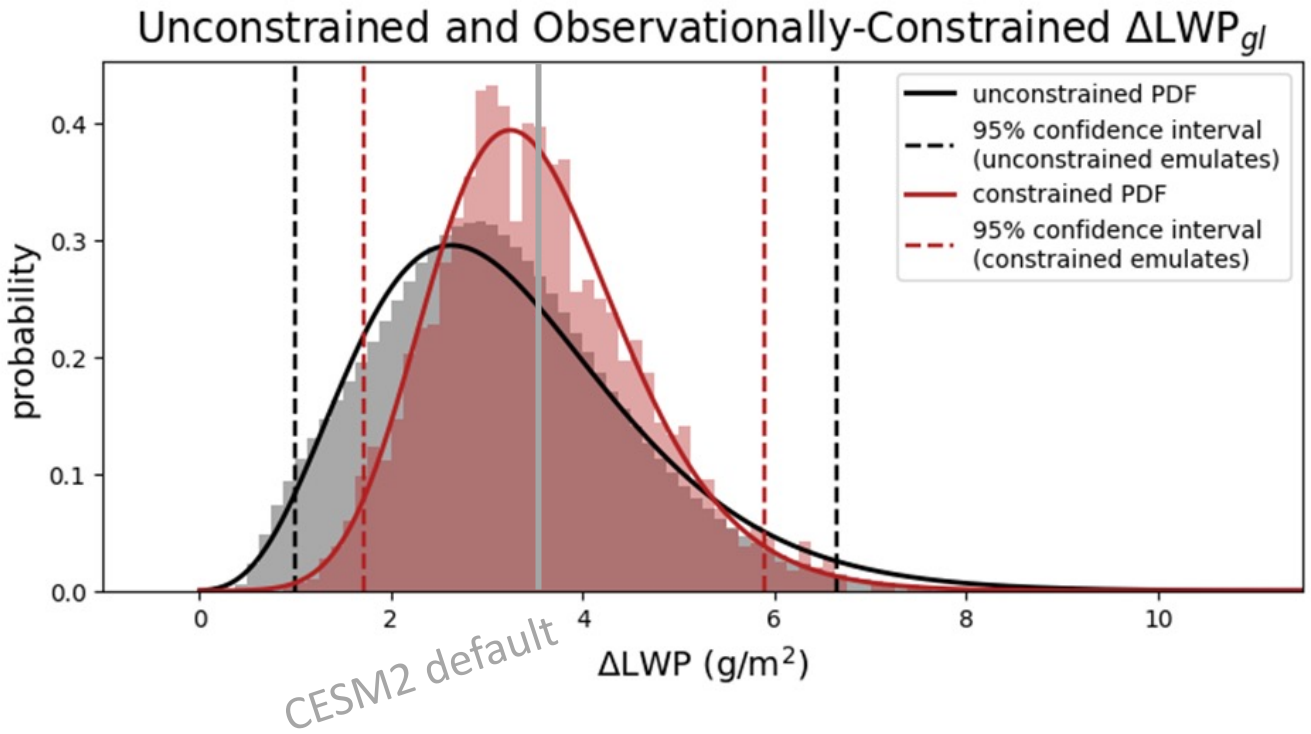
Using ARM to constrain aerosol-cloud adjustments





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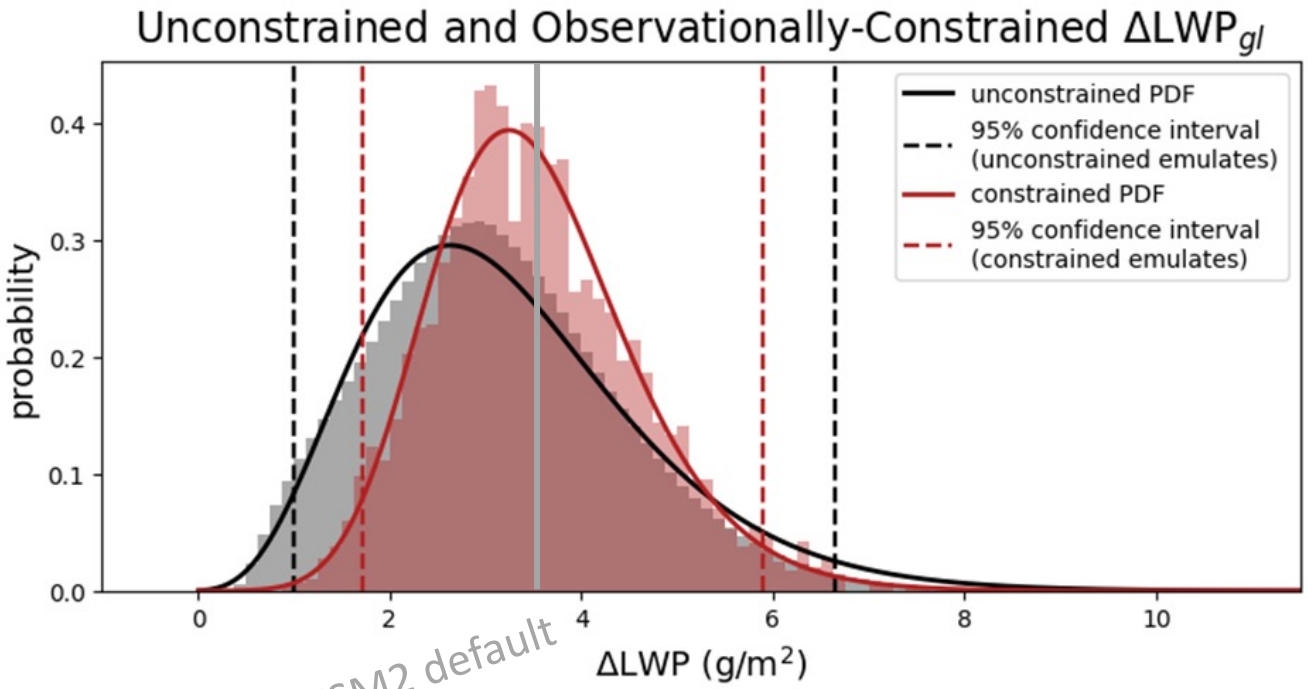
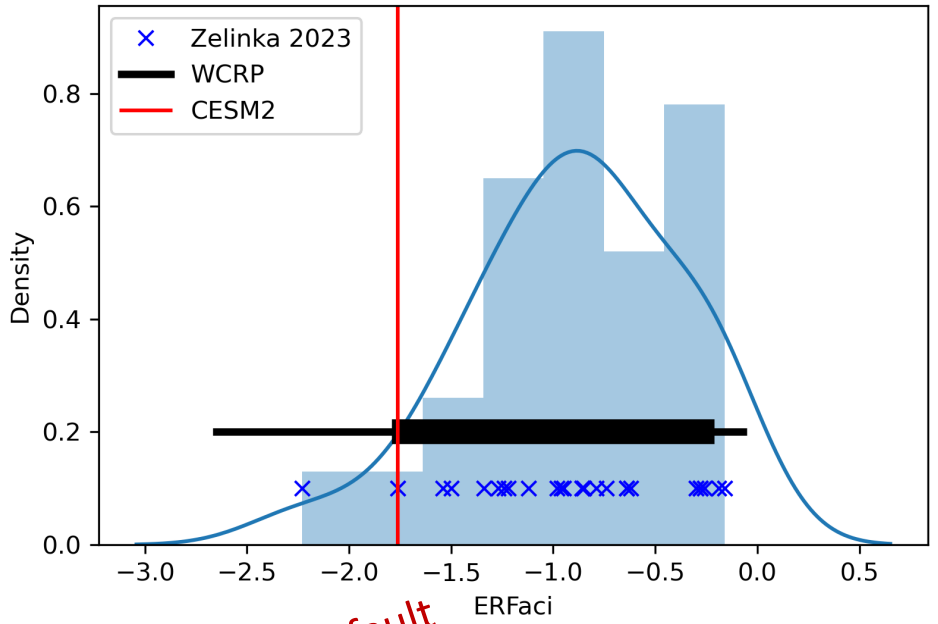
Using ARM to constrain aerosol-cloud adjustments





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Summary

- Preliminary results illustrate the utility of leveraging ARM and a PPE to understand processes and predict climate.
- Jacqueline and Andrew are working fast and we have a pre-alpha PPE working in E3SMv2 that is very flexible.
- A stub right now, but check out our GitHub (https://github.com/PROCEED-ESM) – we will keep updating this throughout the project.
- More of these themes discussed by Johannes Muelmenstaedt Aug 29 in this webinar series!

Relevant CLIVAR workshop October 28-30 at University of Wyoming – abstract submission opening next month

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