# Constraining Aerosol-Cloud Adjustments by Uniting Surface Observations with a Perturbed Parameter Ensemble

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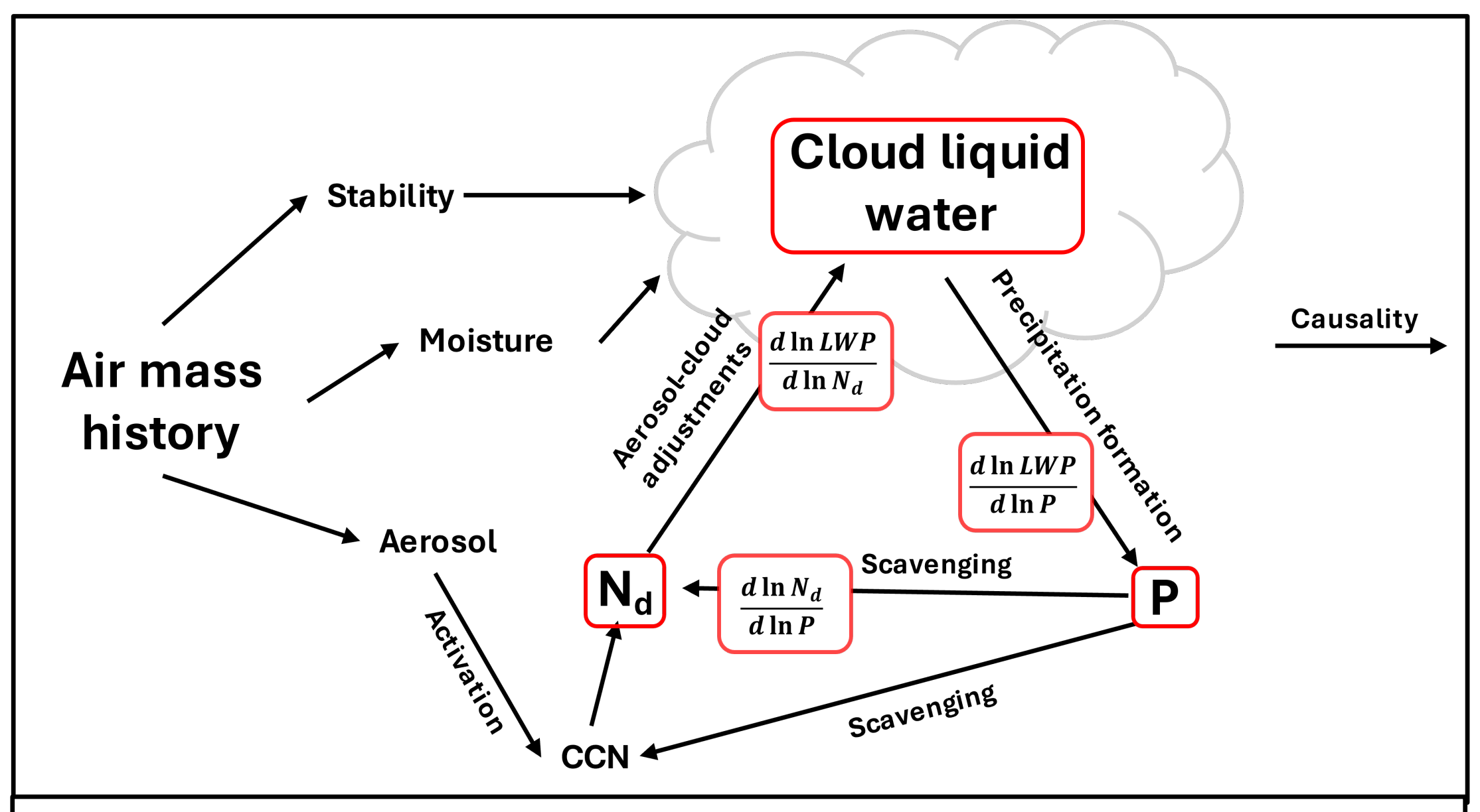
## INTRODUCTION

- **Aerosol-cloud interactions (aci)** are the largest source of uncertainty in inferring the magnitude of future warming consistent with the observational record
- Much of this uncertainty is derived from the change in LWP from enhanced aerosol, called **aerosol-cloud adjustments**
- Causal links between **droplet number concentration ($N_d$)** and **liquid water path (LWP)** are ambiguous; aerosol-cloud adjustments are poorly constrained



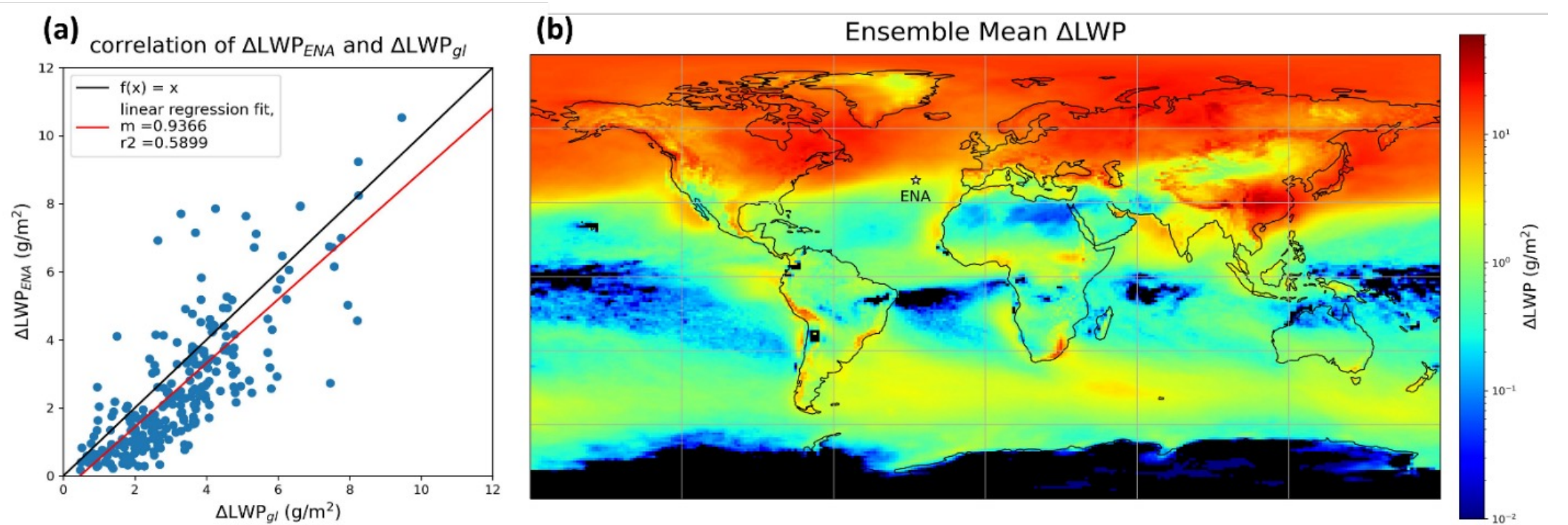
*A schematic describing the causal links on aerosol-cloud adjustments. Red bordered items are examined directly in this work.*

- **$N_d$, LWP, and precipitation rate (P)** from surface observations at the **Eastern North Atlantic (ENA)** atmospheric observatory are used to constrain global adjustments in a **Perturbed Parameter Ensemble (PPE)** of the **Community Atmospheric Model version 6 (CAM6)**
- Gaussian Process (GP) emulators are used to more thoroughly examine the model parameter space

## DATA

### Surface Observations(from ENA)

| Variable | Data Source | Primary Instrument(s) |
|---|---|---|
| LWP | MWRRET2 VAP | microwave radiometer (MWR) |
| $N_d$ | NDROP VAP | multifilter rotating shadowband radiometer (MFRSR) |
| P | VDISQUAN TS VAP | video disdrometer (VDIS) |



*ENA is useful because (a) aerosol-cloud adjustments at ENA correlate strongly with global adjustments and (b) ENA straddles the border of the extratropics and subtropics. We expect that the same aerosol, cloud, and precipitation processes being observed at ENA are relevant over the other oceans in these regions where marine stratocumulus dominates.*

### CAM6 PPE

Run at the University of Wyoming, varies 45 parameters over 262 ensemble members (Song et al., 2024) based off the setup in Duffy et al., 2023), There are two versions of each model run:

- Present day (PD), a run with full anthropogenic aerosol emissions
- Pre-industrial (PI), a run with *no* anthropogenic aerosol emissions

The model runs from January 2016 through January 2018 and is nudged to MERRA2 daily temperatures and winds based on Gettelman et al. 2020

## METHODOLOGY

The relationship between $N_d$ and LWP does not exist in isolation. Confounding sources of variability make it difficult to discern the causal link flowing from $N_d$ to LWP based on observed covariability between these terms. To determine a causal link, we take measurements of mean/median state of and covariances between LWP, $N_d$, and P (as highlighted by the diagram in the Introduction) and then constrain emulators of the PPE with these variables. **Covariances are measured by taking the slope of the linear regression between variables.**

$10^7$ emulated ensemble members (hereafter referred to as "emulates") are created randomly sampling the 45 input parameters within their individual minimum and maximum bounds,. Emulates have a mean and a variance and are constrained by removing any emulates where the observed value does not fall within the bounds of the variance. By examining this constrained subset, we can make inferences about model causality and constrain PD-PI adjustments.

| Variable | Description |
|---|---|
| median-state ln LWP | natural logarithm of the median-state liquid water path |
| median-state ln $N_d$ | natural logarithm of median-state droplet number concentration |
| mean-state P | the mean-state precipitation rate |
| $\frac{d\ln LWP}{d\ln P}$ | The covariance of ln (LWP) with ln(P), for autoconversion, the process by which cloud droplets collide with each other to form drizzle drops, which ultimately leave the cloud via precipitation. |
| $\frac{d\ln LWP}{d\ln N_d}$ | The covariance of ln(LWP) with ln(P), for the observed susceptibility of cloud liquid water content to different droplet number concentrations. This can be thought of as an "observed adjustments term", although as discussed above, it does not describe a causal relationship between $N_d$ and LWP. |
| $\frac{d\ln N_d}{d\ln P}$ | The covariance of ln($N_d$) with ln(P), for below-cloud scavenging of droplets from precipitation. |

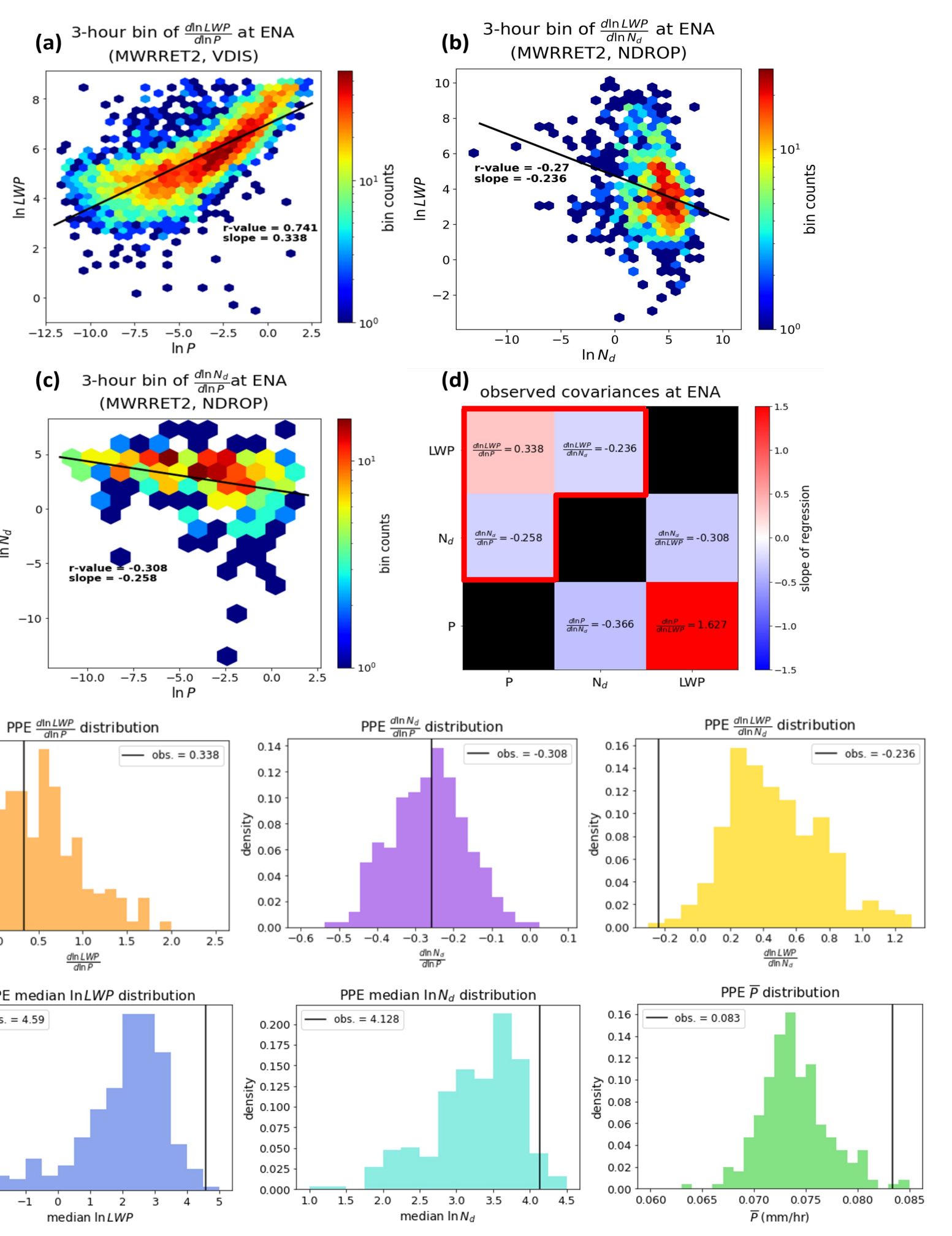
### GP Emulators

To explore parameter space efficiently we leverage the Earth System Emulator (ESEm) package (Watson-Parris et al., 2021) to build Gaussian Process (GP) emulators.

We create emulators for ENA median ln LWP (med. ln $LWP_{ENA}$), ENA median ln $N_d$ (med. ln $N_{d,\,ENA}$), ENA mean-state P ($\overline{P_{ENA}}$), ENA ($\frac{d\ln N_d}{d\ln P}$), ENA ($\frac{d\ln LWP}{d\ln P}$), ENA ($\frac{d\ln LWP}{d\ln N_d}$), the PD-PI change in average global LWP ($\Delta LWP_{gl}$), and the PD-PI change in average global $N_d$ ($\Delta N_{d,\,gl}$).

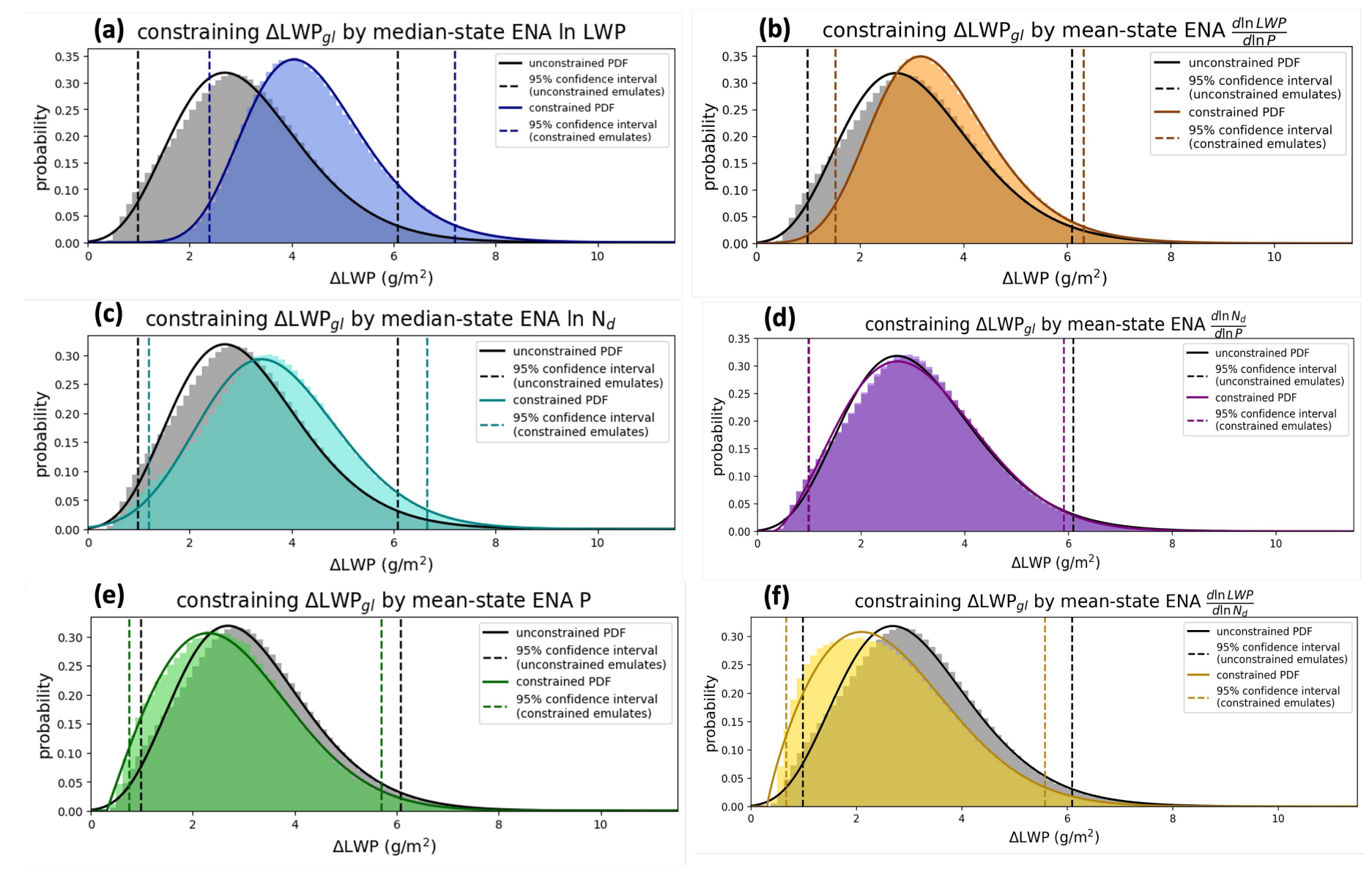
## RESULTS AND ANALYSIS

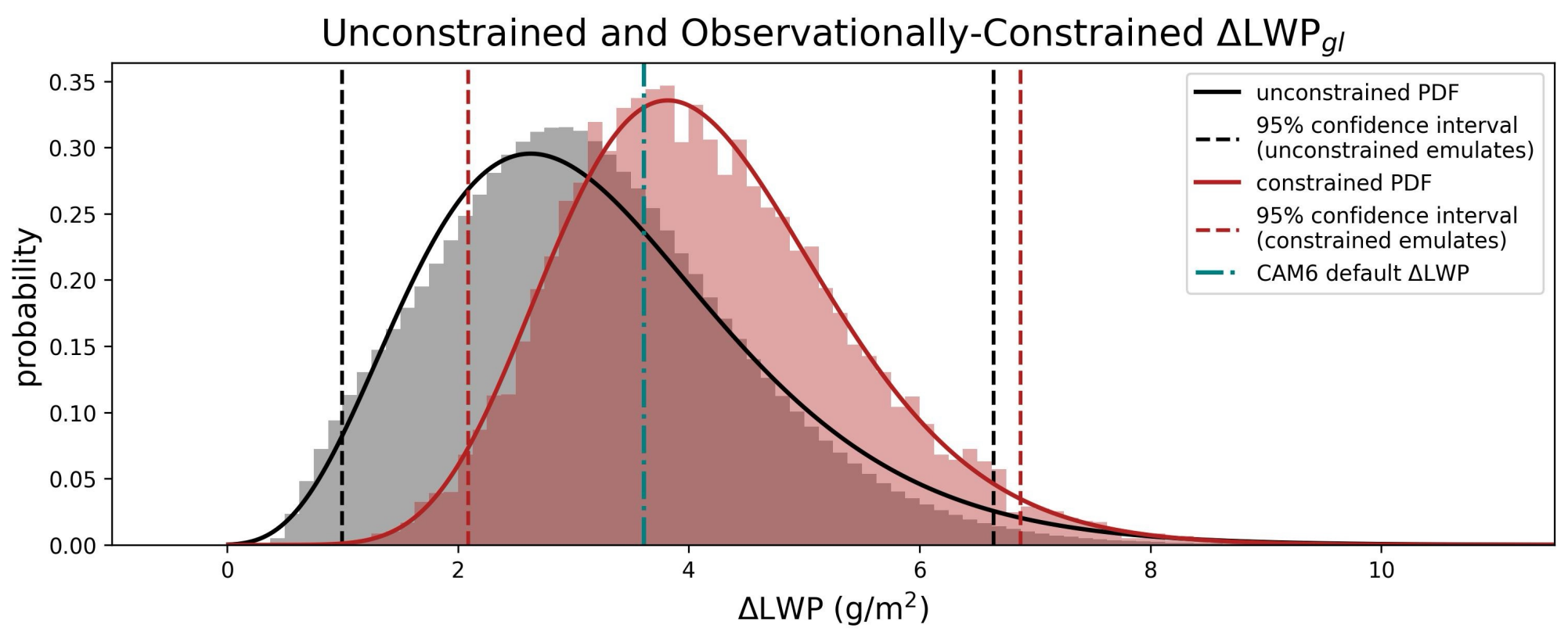
### Retrievals



- $\frac{d\ln LWP}{d\ln P}$, $\frac{d\ln N_d}{d\ln P}$ are relatively close to ensemble mean values
- $\frac{d\ln LWP}{d\ln N_d}$ is very negative- a value possible within CAM6 but quite rare
- Observed state variables are all on the upper end of CAM6 PPE values

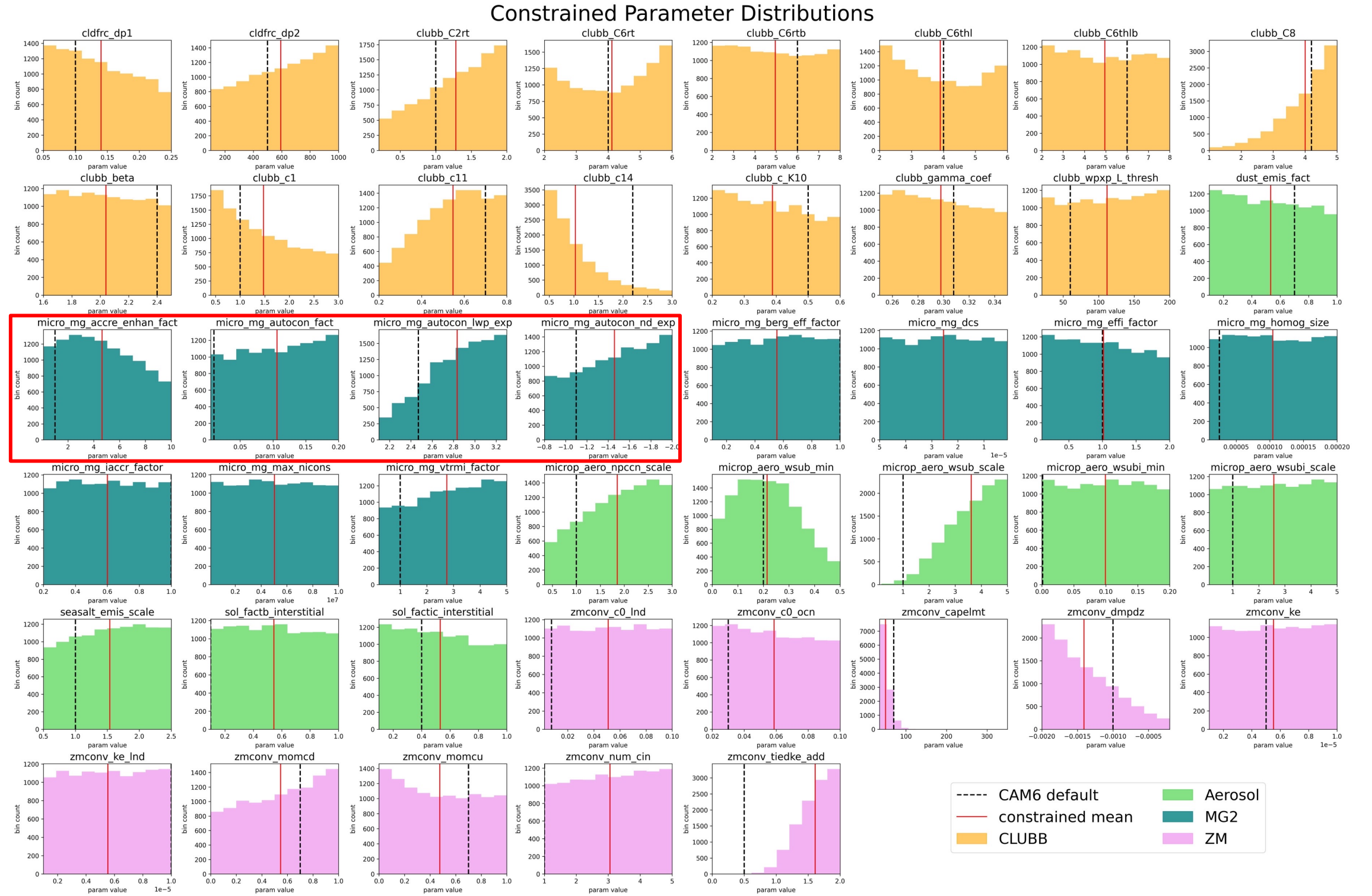
### Constrained Adjustments



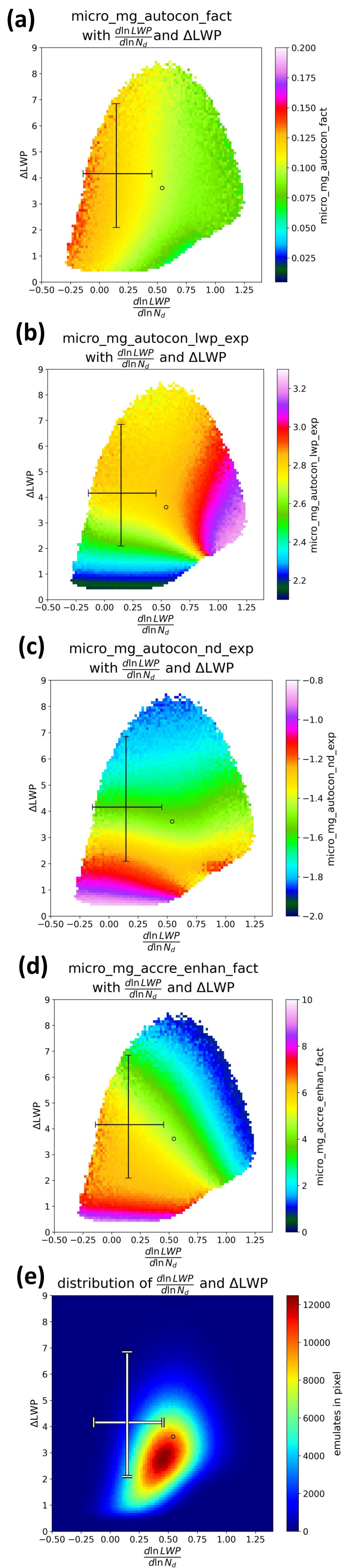


- Constraining variables pull the constrained ΔLWP in different directions; observational constraint does not uniformly pull ΔLWP one way or another
- When constraining adjustments by all variables at once, the constrained mean is close to the CAM6 prior, range of adjustments reduced by 15%

### Interpreting the Constrained Parameters



- Of the 45 perturbed parameters, 17 show constraint, including the 4 parameters relating strongly to coalescence scavenging (*micro_mg_autocon_fact, micro_mg_accre_enhan_fact, micro_mg_autocon_lwp_exp, micro_mg_autocon_nd_exp*); these relationships are explored in the figures to the right
- Observed covariability between $N_d$ and LWP is driven by coalescence scavenging and is strongly determined by the autoconversion enhancement factor and more moderately determined by the accretion enhancement factor
- The explained variance ($R^2$) in adjustment strength by $\frac{d\ln LWP}{d\ln N_d}$ **(e)** is only 12%. This highlights the importance of considering other confounding processes when attempting to use observed covariation between $N_d$ and LWP as a constraint on aerosol cloud adjustments



## TAKEAWAYS

- ***Our framework unites casually-ambiguous present-day observations and a PPE hosted in CAM6***
- ***Adjustments are constrained by 15% from the total CAM6 PPE range towards relatively stronger adjustments***
- ***Constrained parameters match our a priori expectations for processes that are relevant to adjustments, including autoconversion and accretion parameterizations.***
- ***Confounding effects from coalescence scavenging can operate in conjunction with autoconversion-driven precipitation suppression to reproduce a negative correlation between LWP and $N_d$ as seen in prior observational studies***

## ACKNOWLEDGEMENTS AND REFERENCES

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This work funded by:
- DOE-ASR Grant DE-SC002227
- DOE EPSCoR Grant DE-SC0024161

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