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

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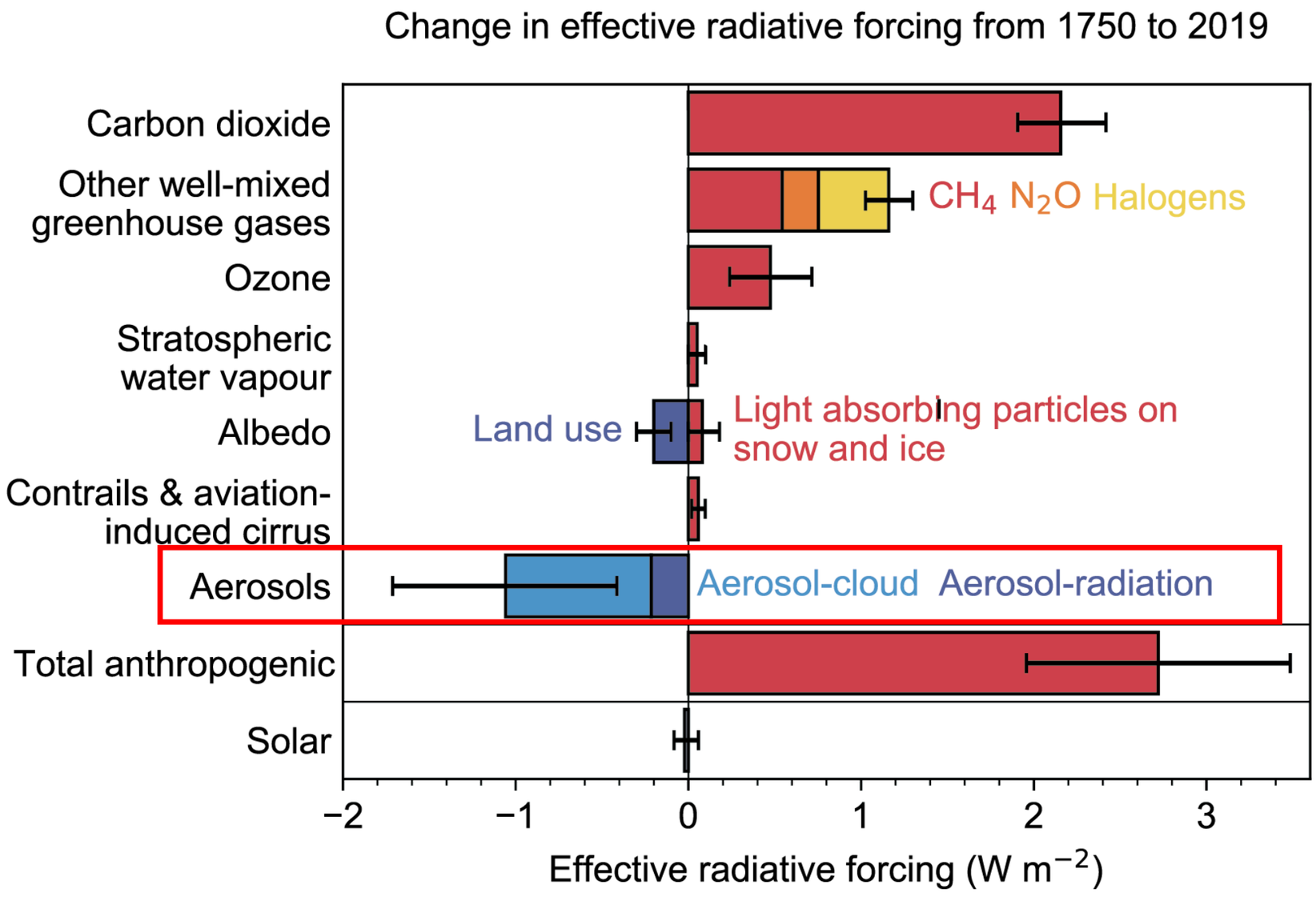
Are (Aerosol) forcing & (Cloud) Feedback related?

- Introduction: Clouds and Climate
  - Cloud feedbacks and climate sensitivity
  - Aerosol forcing
- Methodology: Perturbed Parameter Ensemble (PPE)
- Results: PPE
  - General: Emulators
  - Aerosol Forcing
  - Cloud Feedback
- Results: Interactions (Preliminary)
- Conclusions, Next Steps

Climate Forcing



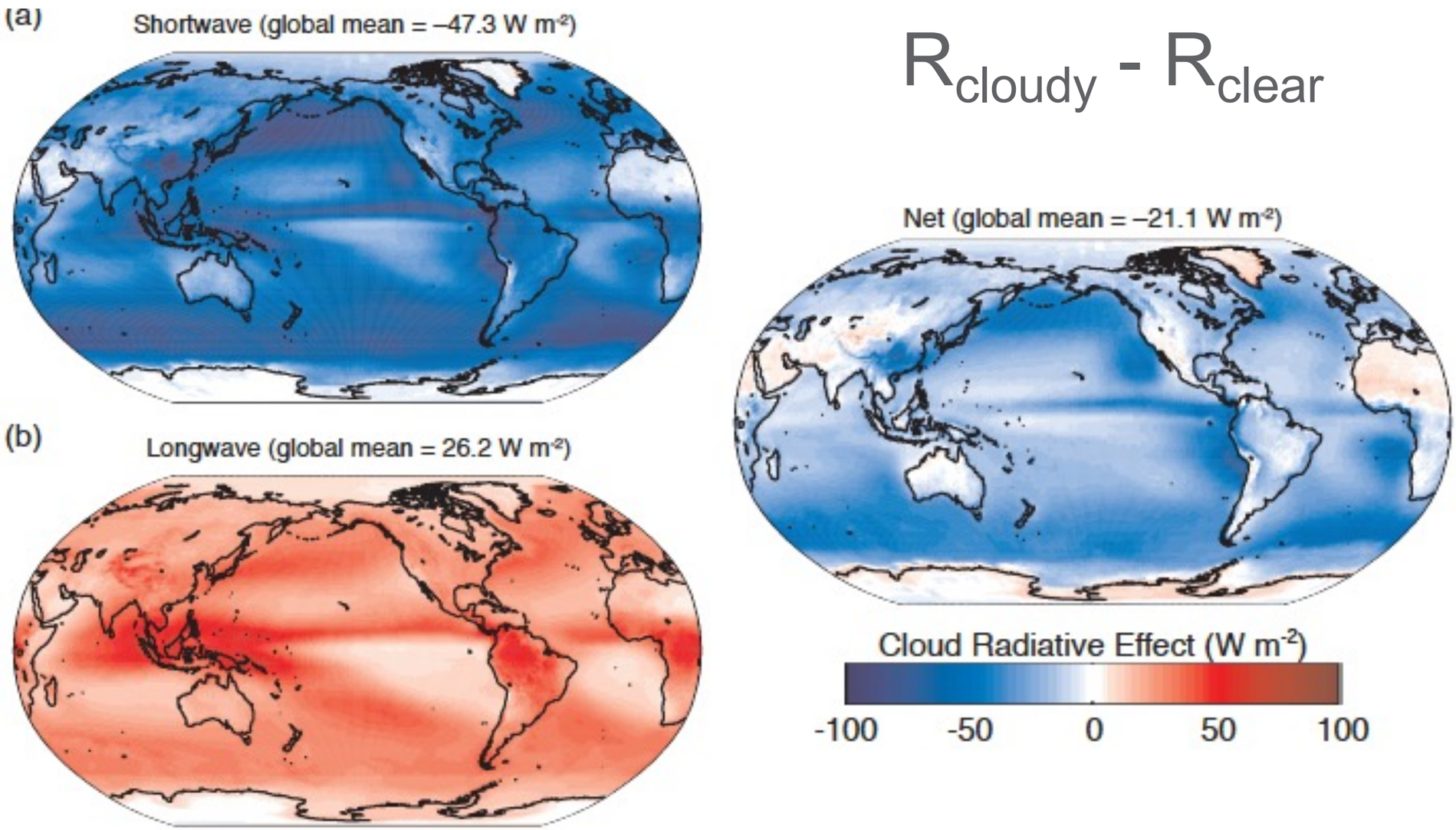
3.8 Wm^{-2}
(2.3→4.5)

-1.1 Wm^{-2}
(-1.9→-0.2)

IPCC, 2021, Fig 7.6

Climate: Cloud Radiative Effects are Large

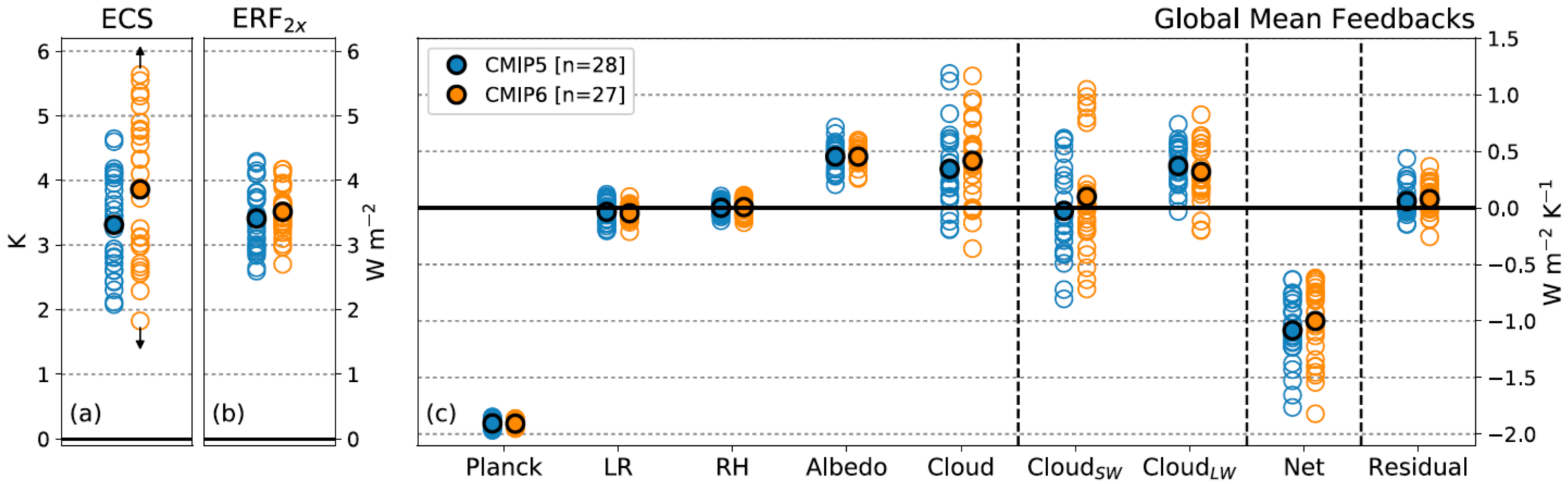
$R_{cloudy} - R_{clear}$



IPCC 2013 (Boucher et al 2013) Fig 7.7

Climate Feedbacks:
Clouds respond to climate change

Climate Sensitivity Uncertainty: *It's all about cloud feedback*



(σT^4) Lapse Rate RH Change

Zelinka et al 2020, GRL

CAM6 Perturbed Parameter Ensemble

CAM6.3 (~ E3SMv1 physical parameterizations)

43 Parameters

- 11 Turbulence (CLUBB)
- 11 Microphysics (MG3/PUMAS)
- 12 Deep Convection (ZM)
- 9 Aerosol/Activation

All parameters made namelist parameters

263 parameter sets for simulations, selected using *Latin Hypercube Sampling*

cldfrc_dp1
cldfrc_dp2
clubb_C2rt
clubb_C6rt
clubb_C6rtb
clubb_C6thl
clubb_C6thlb
clubb_C8
clubb_beta
clubb_c1
clubb_c11
clubb_c14
clubb_c_K10
clubb_gamma_coef
clubb_wpxp_L_thresh
micro_mg_autocon_nd_exp
micro_mg_accre_enhan_fact
micro_mg_autocon_fact
micro_mg_autocon_lwp_exp
micro_mg_berg_eff_factor
micro_mg_dcs
micro_mg_effi_factor
micro_mg_homog_size
micro_mg_iaccr_factor
micro_mg_max_nicons
micro_mg_vtrmi_factor
microp_aero_npccn_scale
microp_aero_wsub_min
microp_aero_wsub_scale
microp_aero_wsubi_min
microp_aero_wsubi_scale
seasalt_emis_scale
dust_emis_fact
sol_factb_interstitial
sol_factic_interstitial
zmconv_c0_lnd
zmconv_c0_ocn
zmconv_capelmt
zmconv_dmpdz
zmconv_ke
zmconv_ke_lnd
zmconv_momcd
zmconv_momcu
zmconv_num_cin
zmconv_tiedke_add

How to build a PPE
(Works for E3SM too)

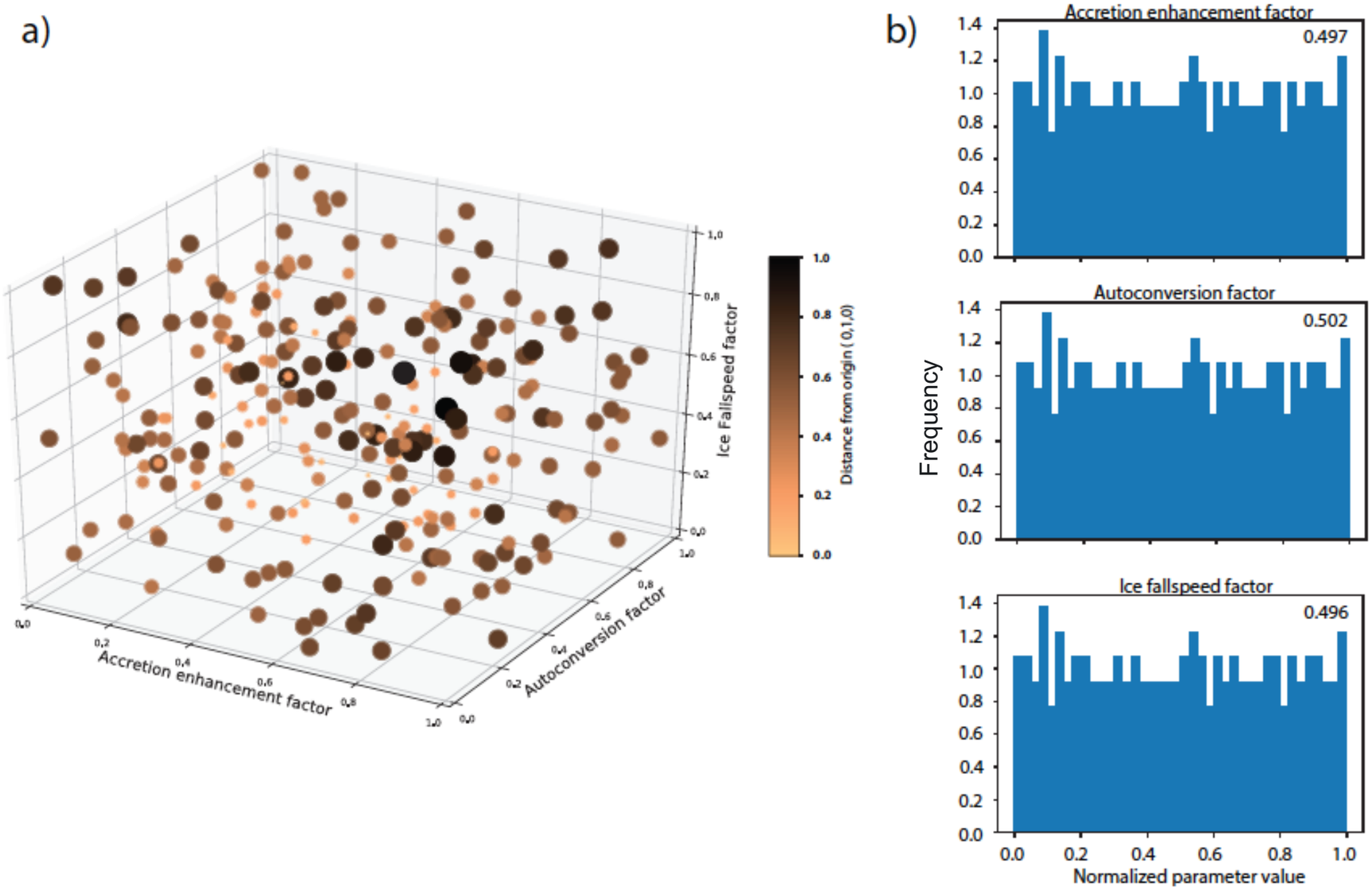
- Off-line notebook for latin-hypercube sampling of parameters
  - Parameters, ranges, number of ensembles
  - Generate a file of ensembles (names, parameter sets)

- Python script to run the ensemble
  - Single script, all CIME commands
  - Clone a ‘control’ case for each parameter set
  - Using file of parameter sets/ensemble names, update each namelist
  - Run each parameter set simulation

- Typically: run 50 at once….done in a day (mileage may vary)

- This is simple, extensible (we added 12 parameter sets to correct an error)

Latin Hypecube Sampling

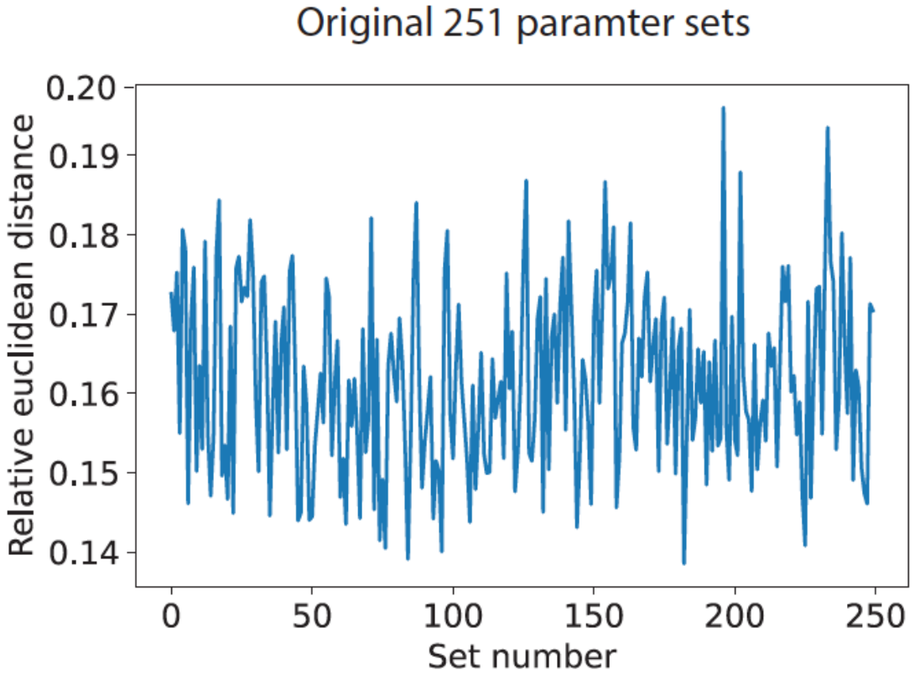


Extending the PPE

- Can run any configuration with CESM
  - E.g.: McCoy (U. Wy) has run same 263 parameter sets for nudged field exp cases
  - SCAM PPE exists (being analyzed by van Lier-Walqui)

- Extensible: added to parameter space
  - Started with 250 + 1 default cases
  - Extend range for one parameter
  - Find average 'relative Euclidean distance' between parameters
  - Run another 7500 parameter sets
  - Pick 12 with
    - param in new range
    - Euclidean distance > average

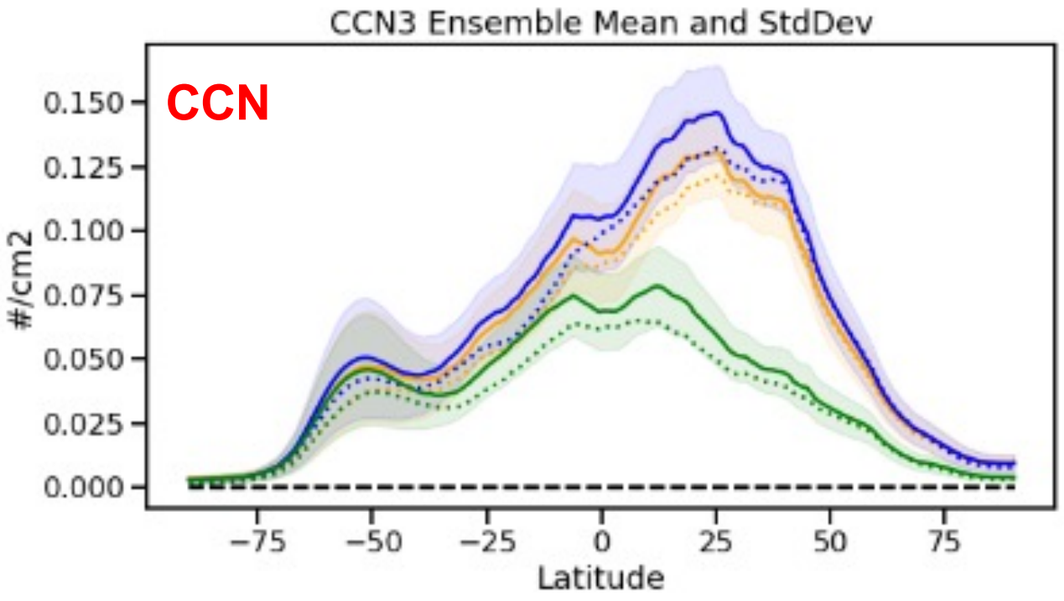
  =263 parameter sets

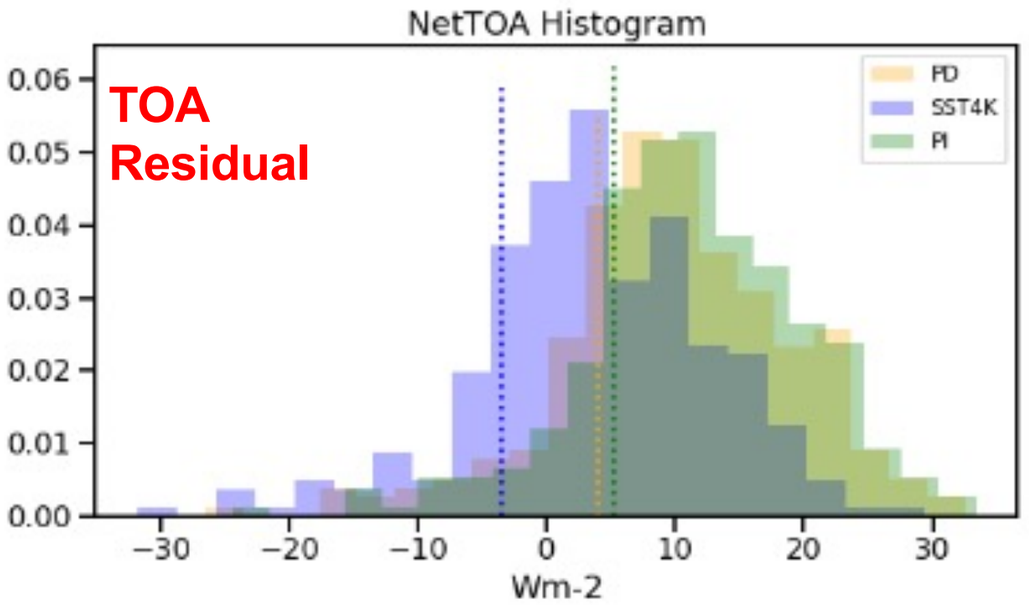


Explore Forcing and Cloud Feedback: CAM6 Perturbed Parameter Ensemble

- Three types of simulations (3 years): all fixed SST ('Climatological AMIP')
  - **PD:** Present Day forcing, SSTs
  - **PI:** Pre-Industrial (1850) Aerosol Emissions
  - **SST4K:** Present day with SST + 4K (Cess et al 1989)
- Data available (https://doi.org/10.26024/bzne-yf09)

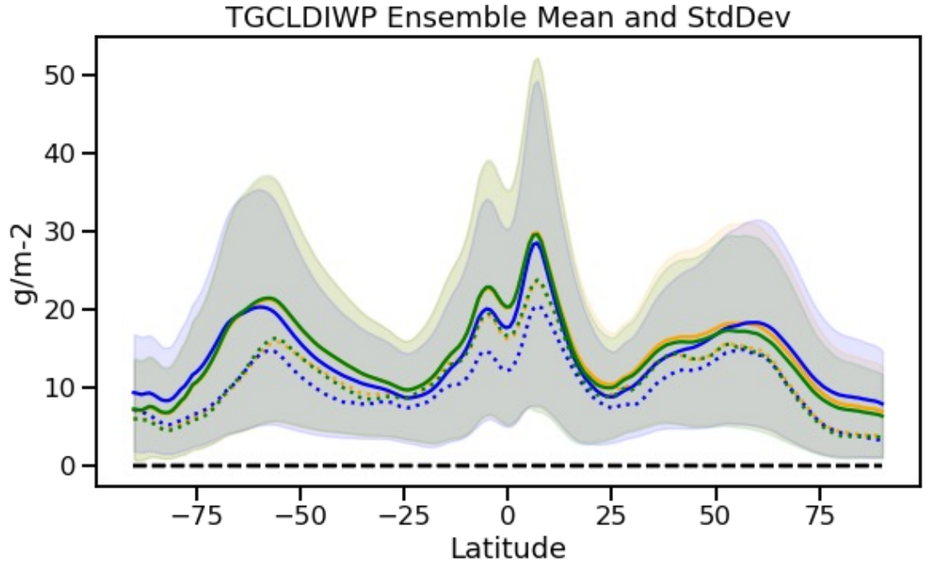
PPE Spread

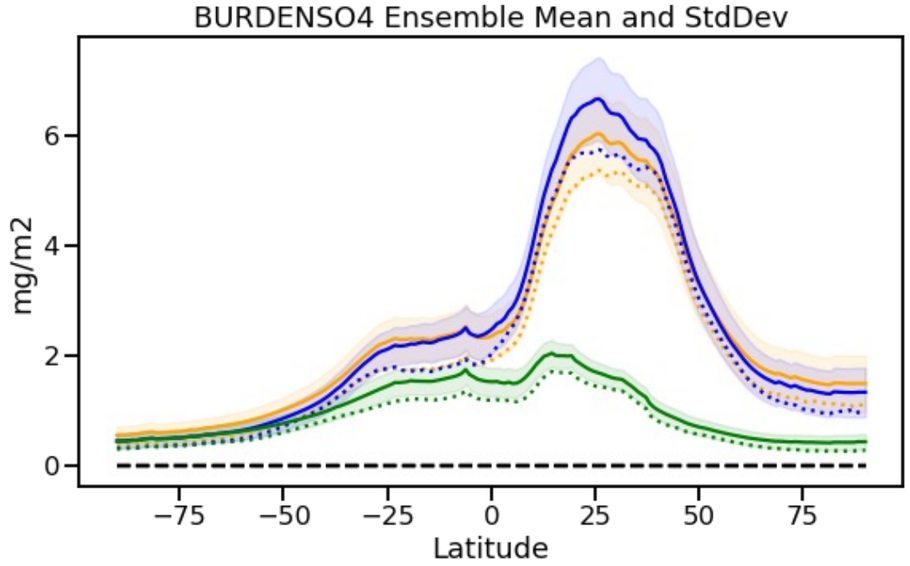




Large Spread Across the PPE

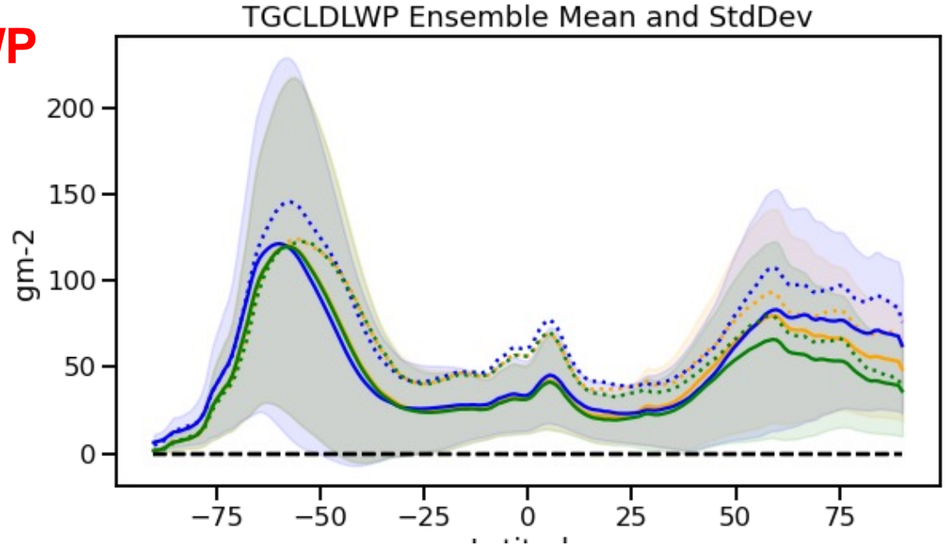
IWP

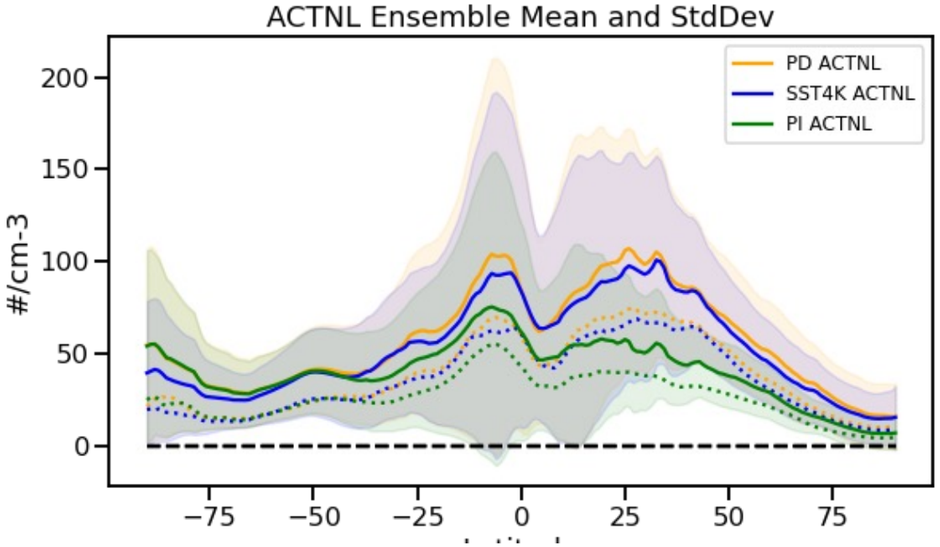




Column SO_4

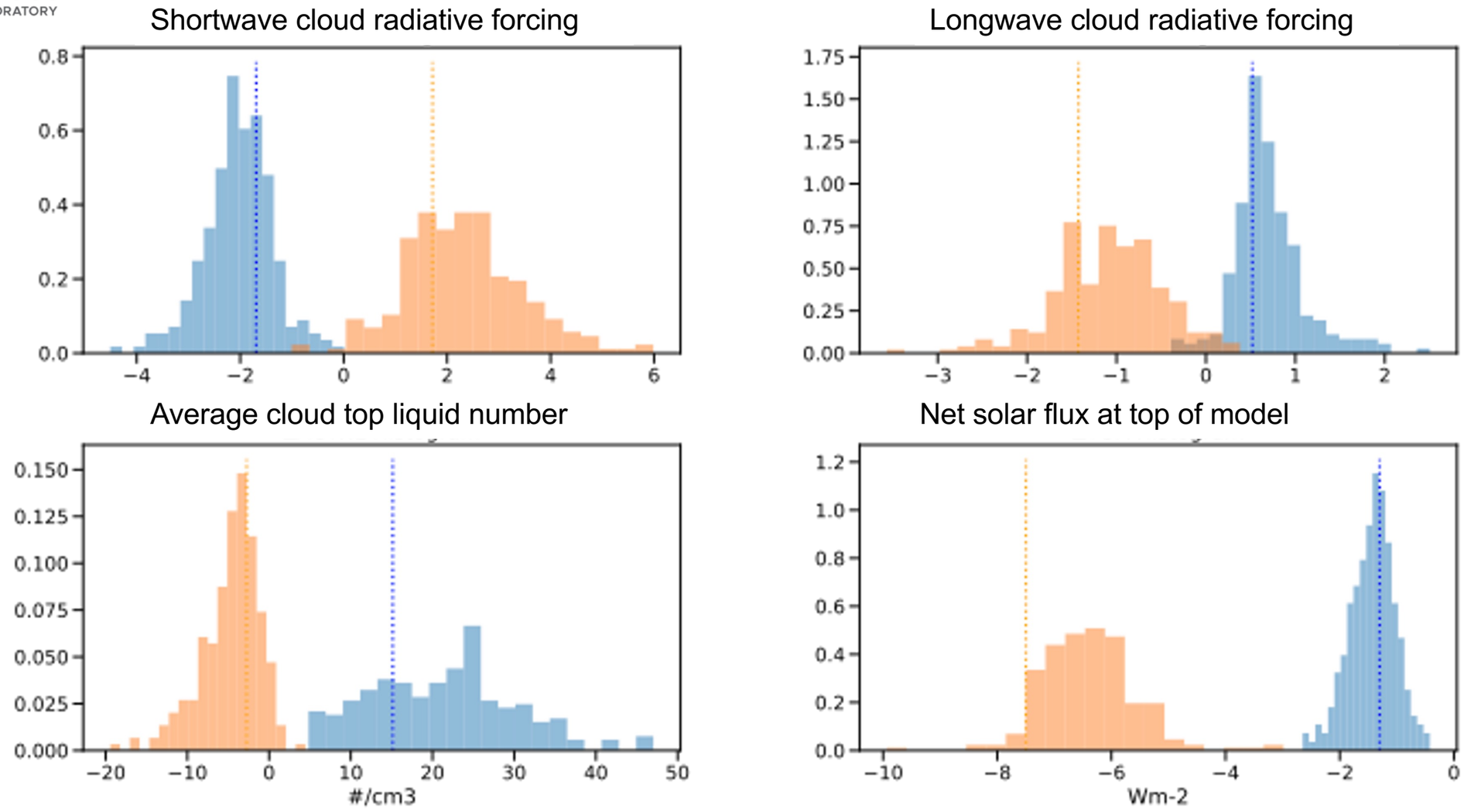
LWP





N_c

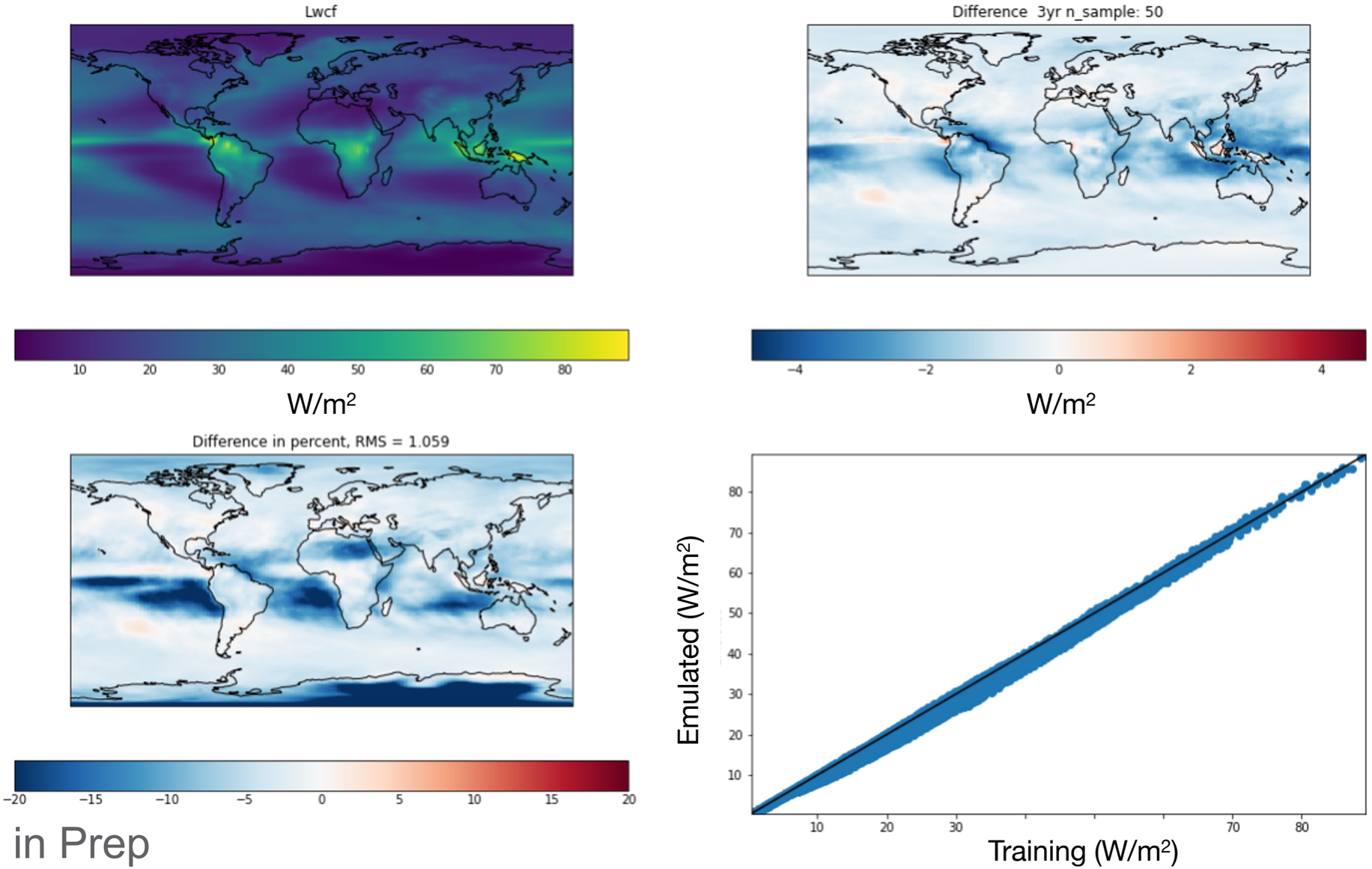
PPE Forcing and Feedback



Forcing: Present day (PD) - Pre-industrial (PI) aerosol

Feedback: 4K SST - Present day (PD)

Emulating Longwave Cloud Radiative Forcing
Gaussian Process Emulator (*University of Oxford*)

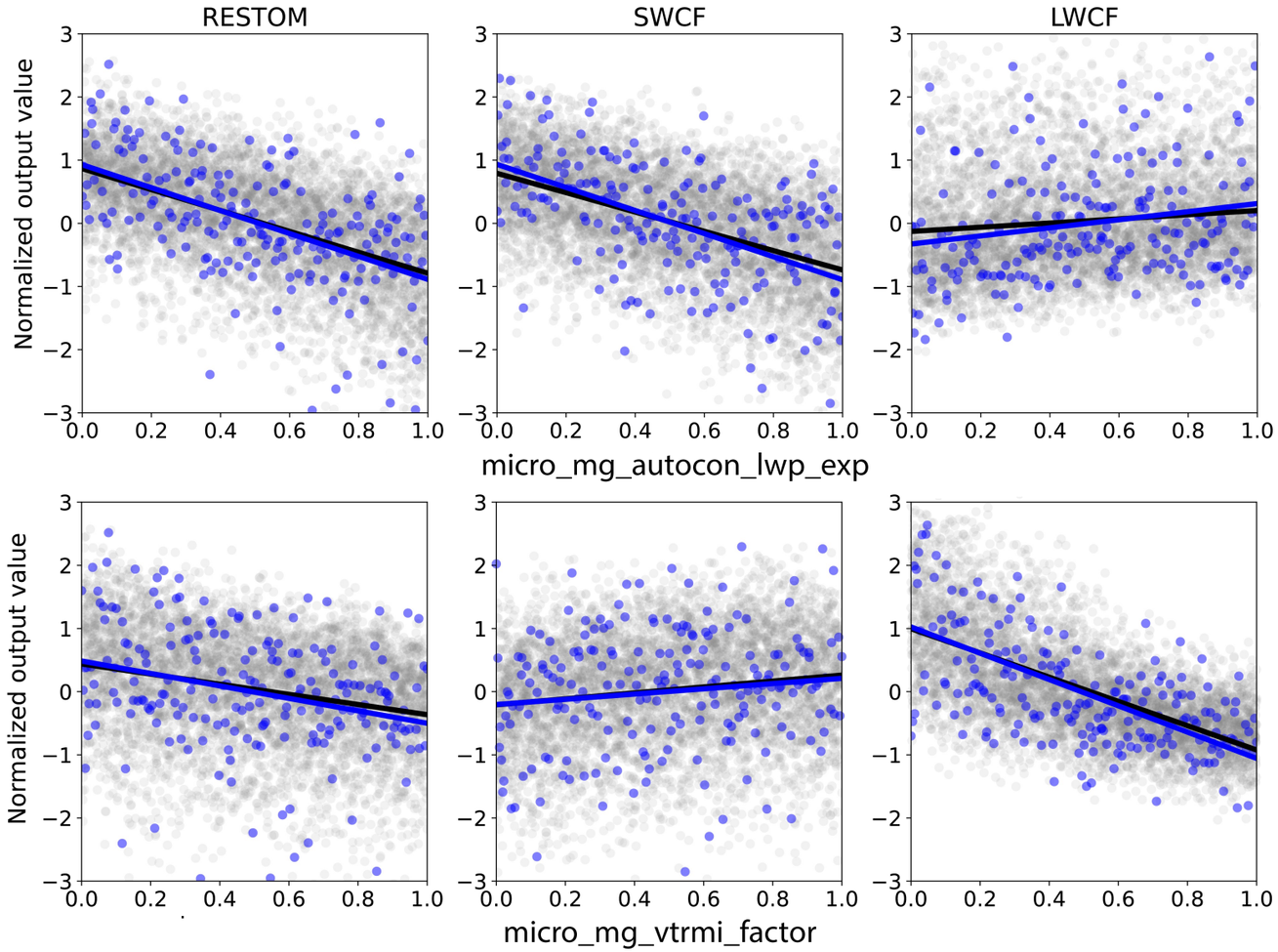


Eidhammer, in Prep

Emulator Parameter Sweep

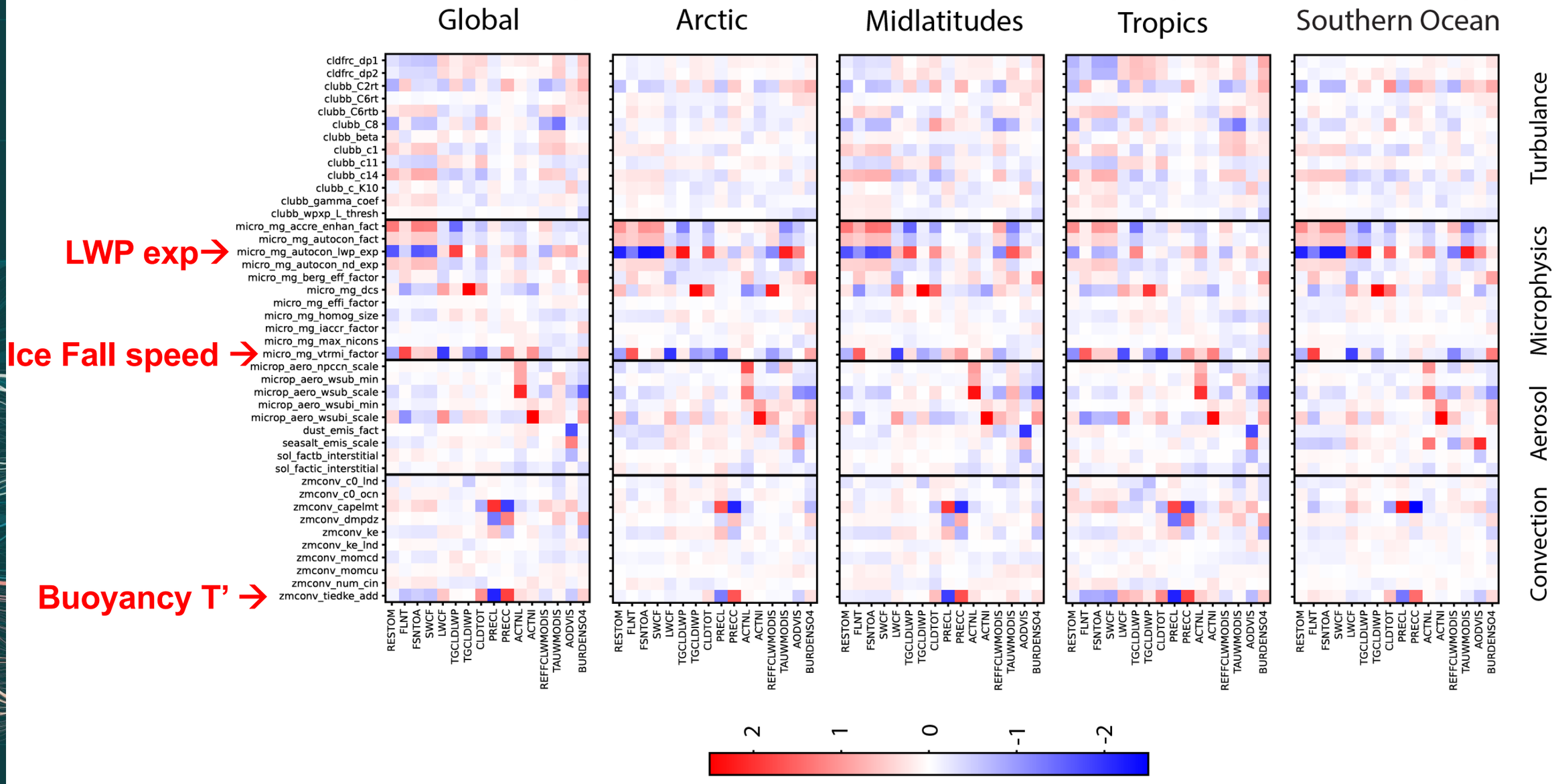
LWP exponent in Autoconversion

Ice & Snow fall speed scaling



Normalized Slopes

Output field (horiz axis) v. Parameter (vertical Axis)



Forcing and Feedback Interaction

Question:

- Are (aerosol) forcing and (cloud) feedback related?
- If so, what are the key interactions and processes?
- Start with some earlier work (Gettelman et al 2016)
- Then explore these questions using PPE with parameter uncertainty

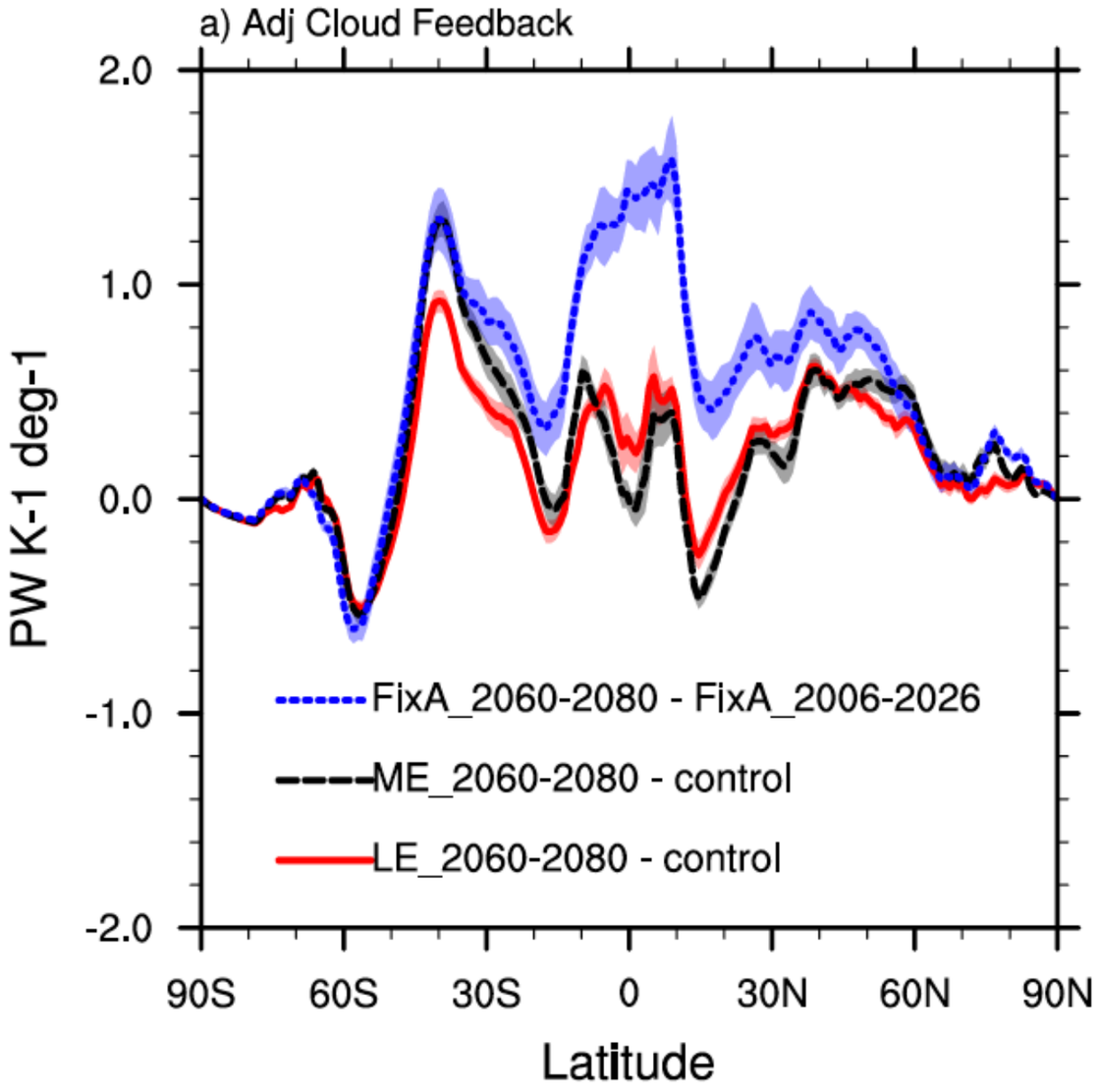
Aerosol Mediated Cloud Feedback

3 Sets of Coupled Runs

- **Constant 21st Century Aerosol, High warming**
- **Decreasing Aerosol, High Warming**
- **Decreasing Aerosol, Moderate warming**

Total cloud feedbacks
Includes differences in Aerosol

Now Apply 'Aerosol Kernel' to remove changes in clouds due to aerosol (dR/dAOD)



Gettelman et al 2016, J. Climate

Aerosol Mediated Cloud Feedback

Aerosol cooling misdiagnosed as cloud feedback (Feedbacks get more positive)

NH Mid-lat feedback differences smaller

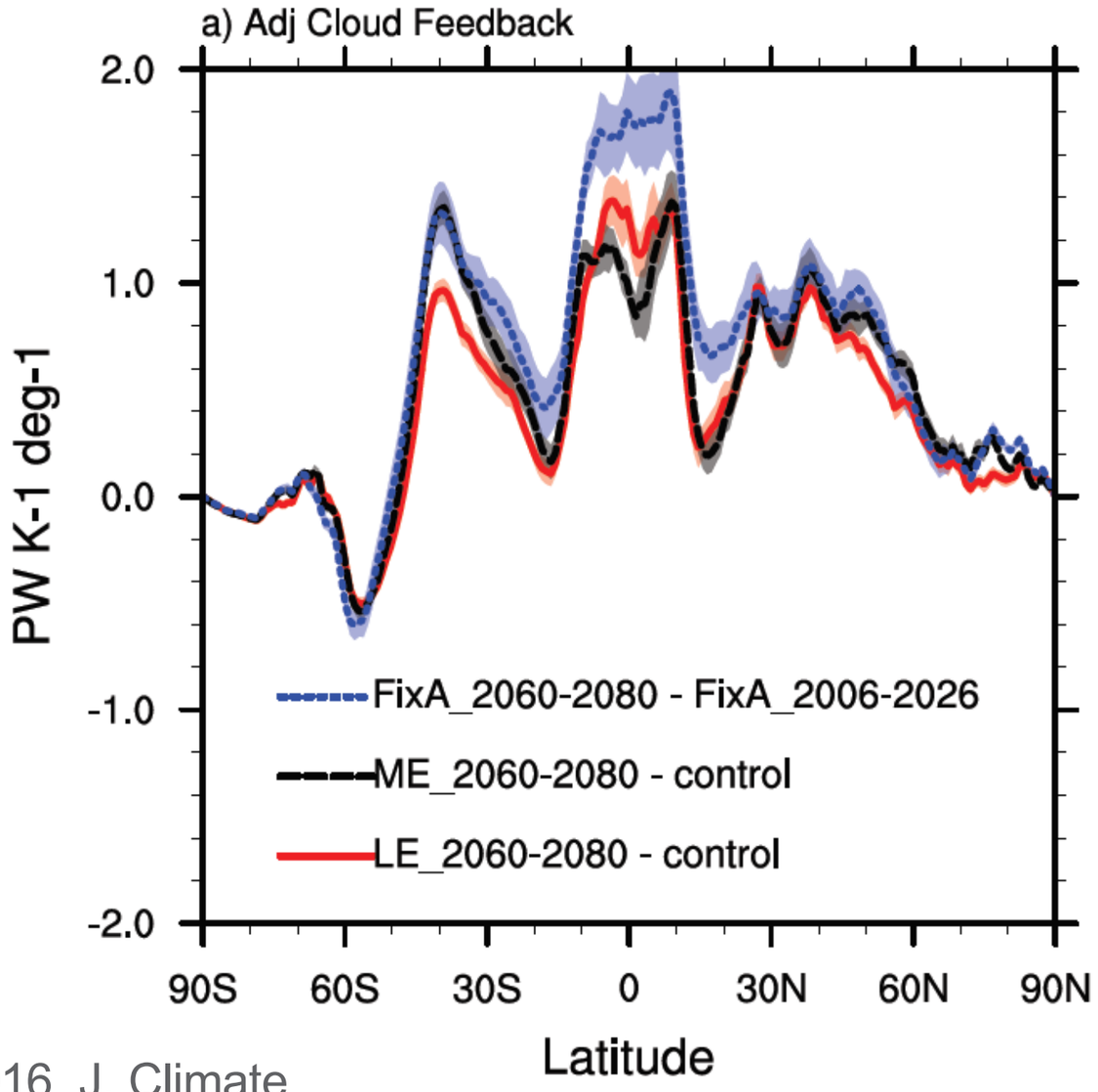
Total difference between **Decreasing** and **Fixed** Aerosol cloud feedbacks is 50%

S. Ocean: same aerosol emissions

$\Delta U \rightarrow \Delta AOD(\text{sea salt}) \rightarrow \Delta CCN \rightarrow \Delta SWCF$

= 'Aerosol Mediated cloud feedback'
the change in clouds is through aerosols
(not temperature)

Adjust Feedbacks for Aerosol



Gettelman et al 2016, J. Climate

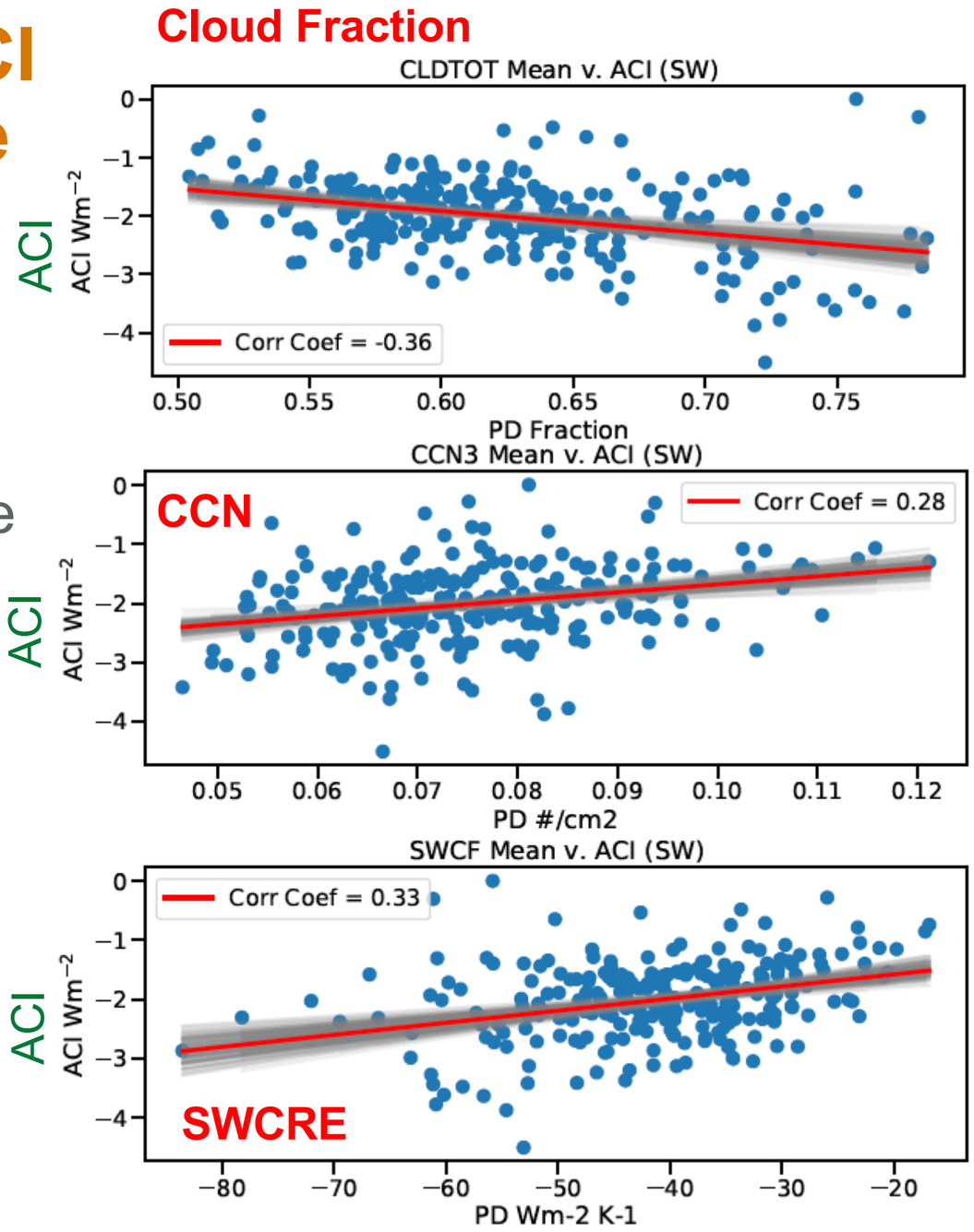
Preliminary Results: ACI Depends on Mean State

Why is ACI spread limited (-2.5 → 0 Wm^{-2})?

ACI (ΔSWCRE, y-axis) depends on mean state

Stronger Negative ACI with:

- Larger cloud fraction
- Lower CCN (and lower present day SO_4)
- Larger negative shortwave cloud effect
- Mean state is limiting ('susceptibility')
  - Marginal clouds are more susceptible?

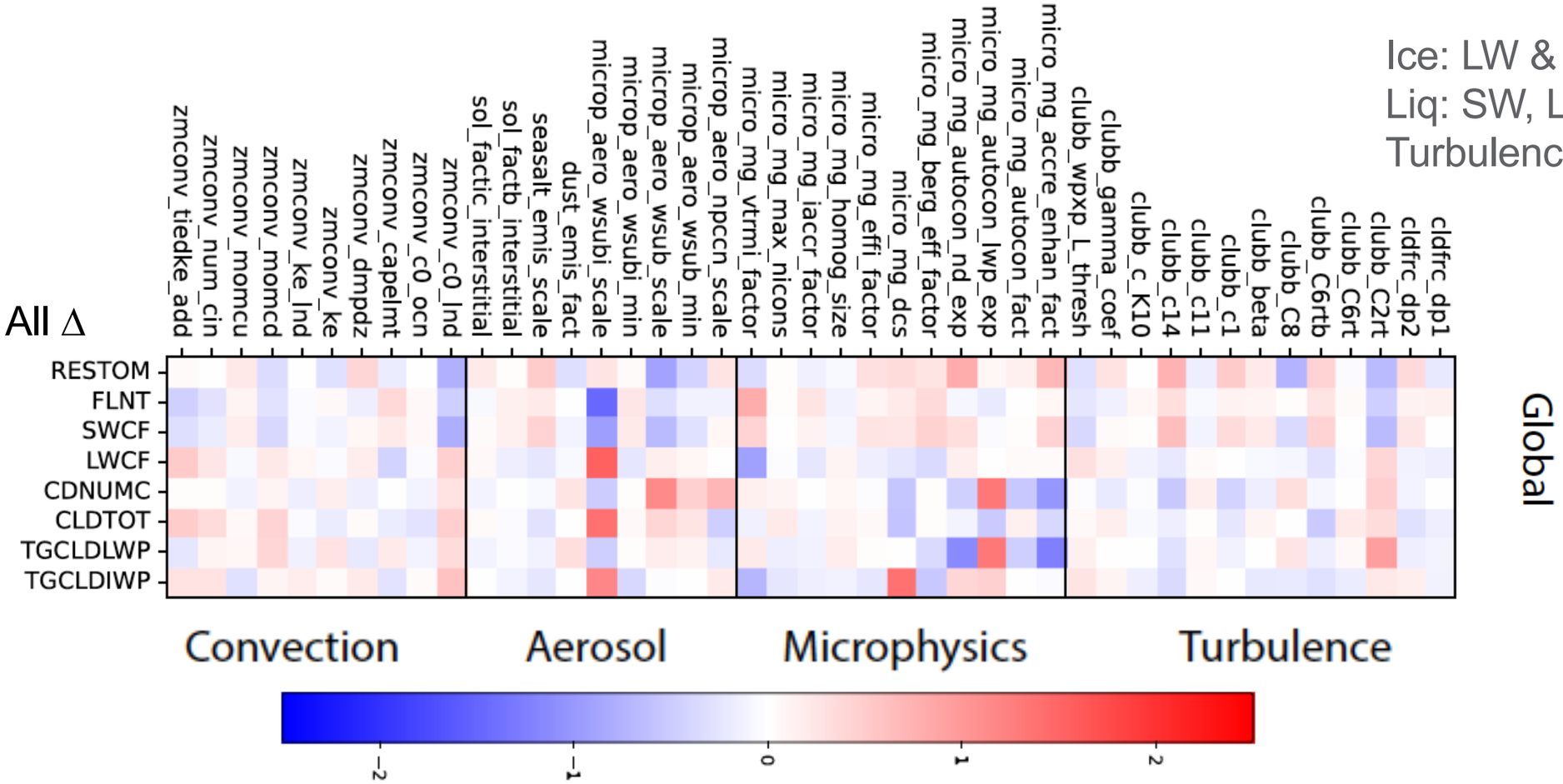


ACI (Forcing) Relationships to Parameters

These processes/parameters increase –ΔSWCRE:

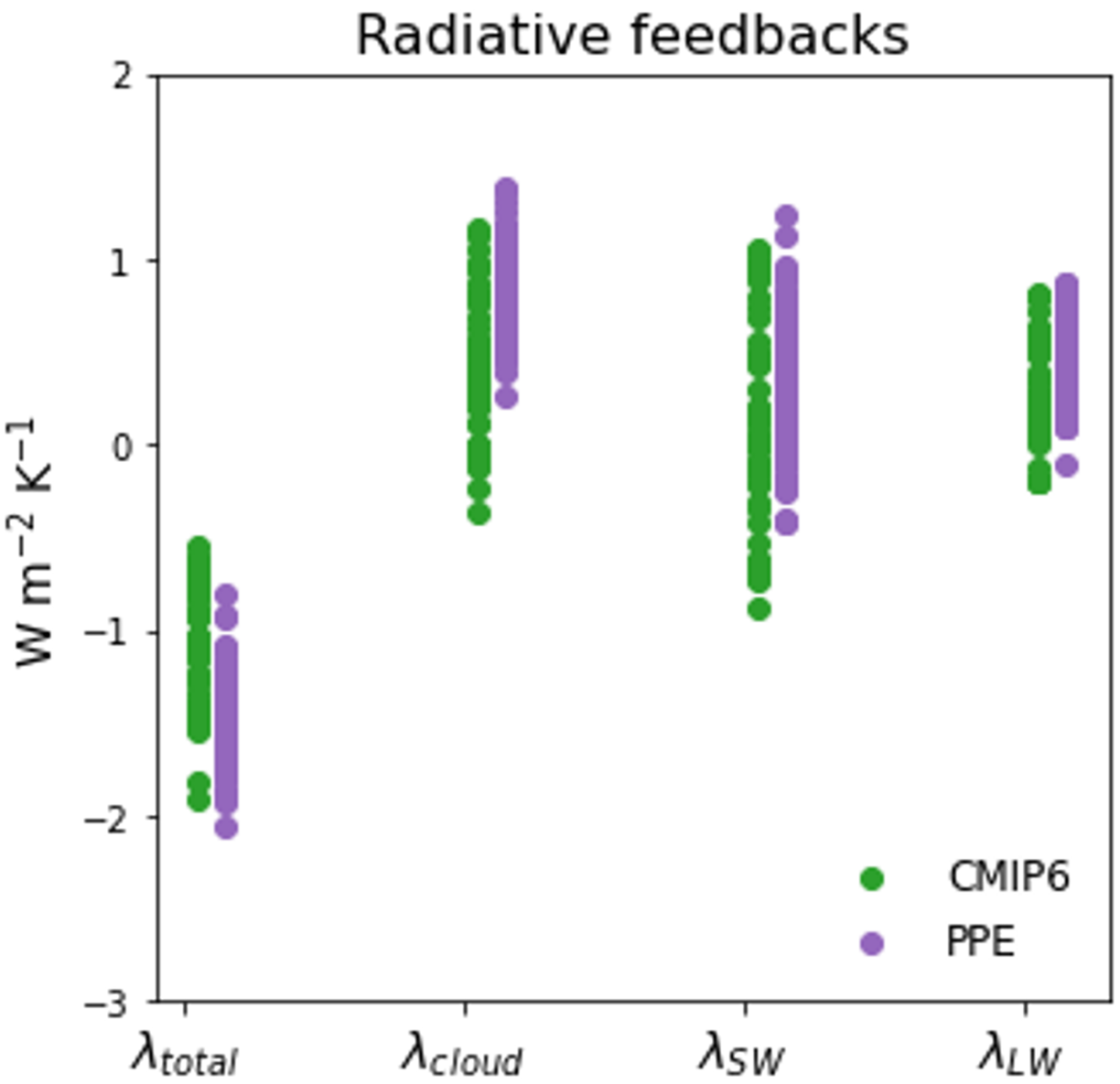
- Precipitation: Autoconversion & Accretion
- Stratiform Ice & Liquid activation: Sub-grid vertical velocity & ice fall speed
- Turbulence: Horizontal variance, vertical vel skewness, LWP variance

Ice: LW & Cloud Fraction
Liq: SW, LWP & Nc
Turbulence: Nc & LWP



Cloud Feedback

Spread in radiative feedbacks across PPE is comparable to spread across CMIP6 models



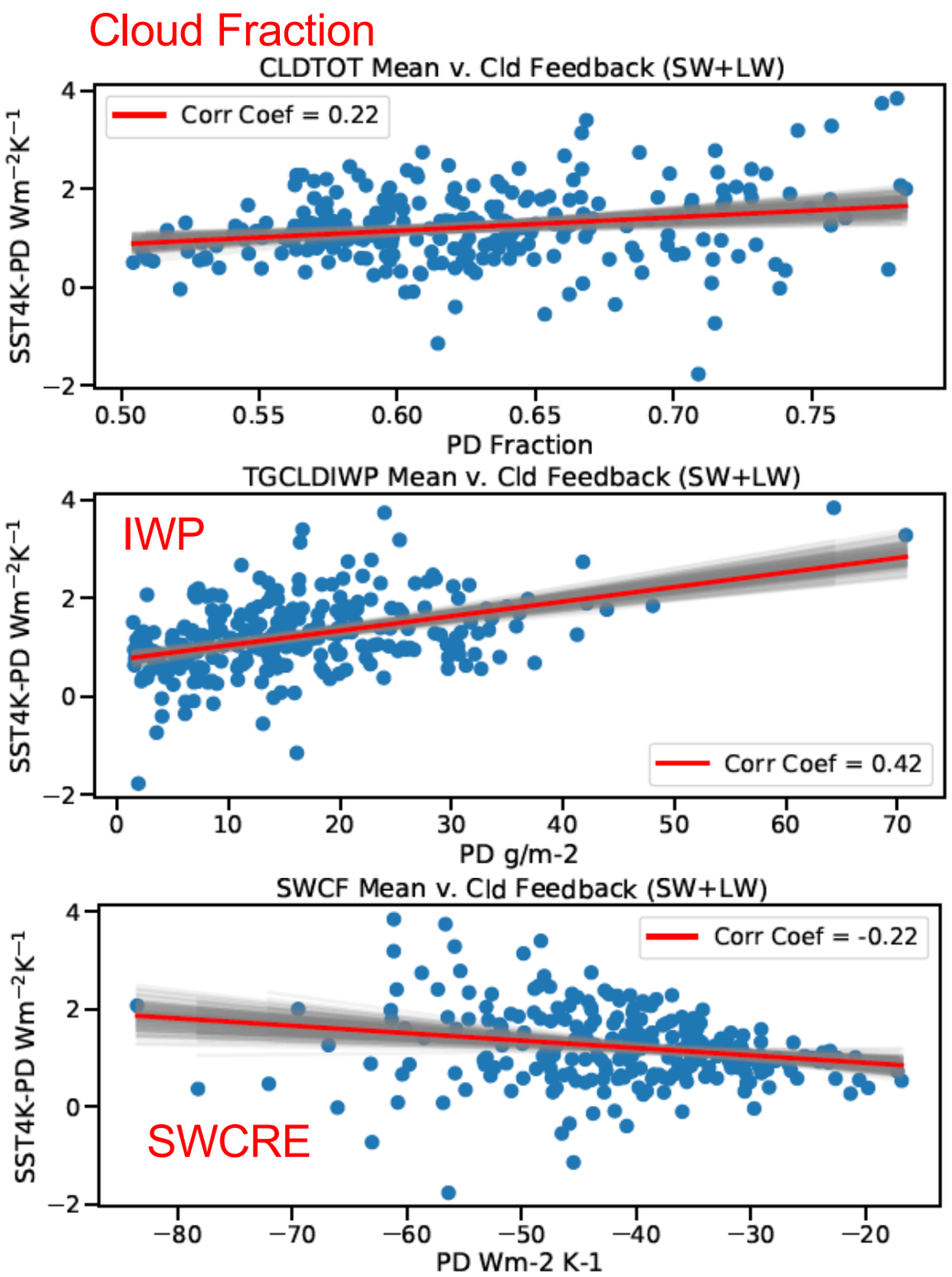
M. Duffy

Cloud Feedback Depends on Mean State

Cloud Feedback (y-axis, ΔSWCF+ΔLWCF) also depends on mean state properties.

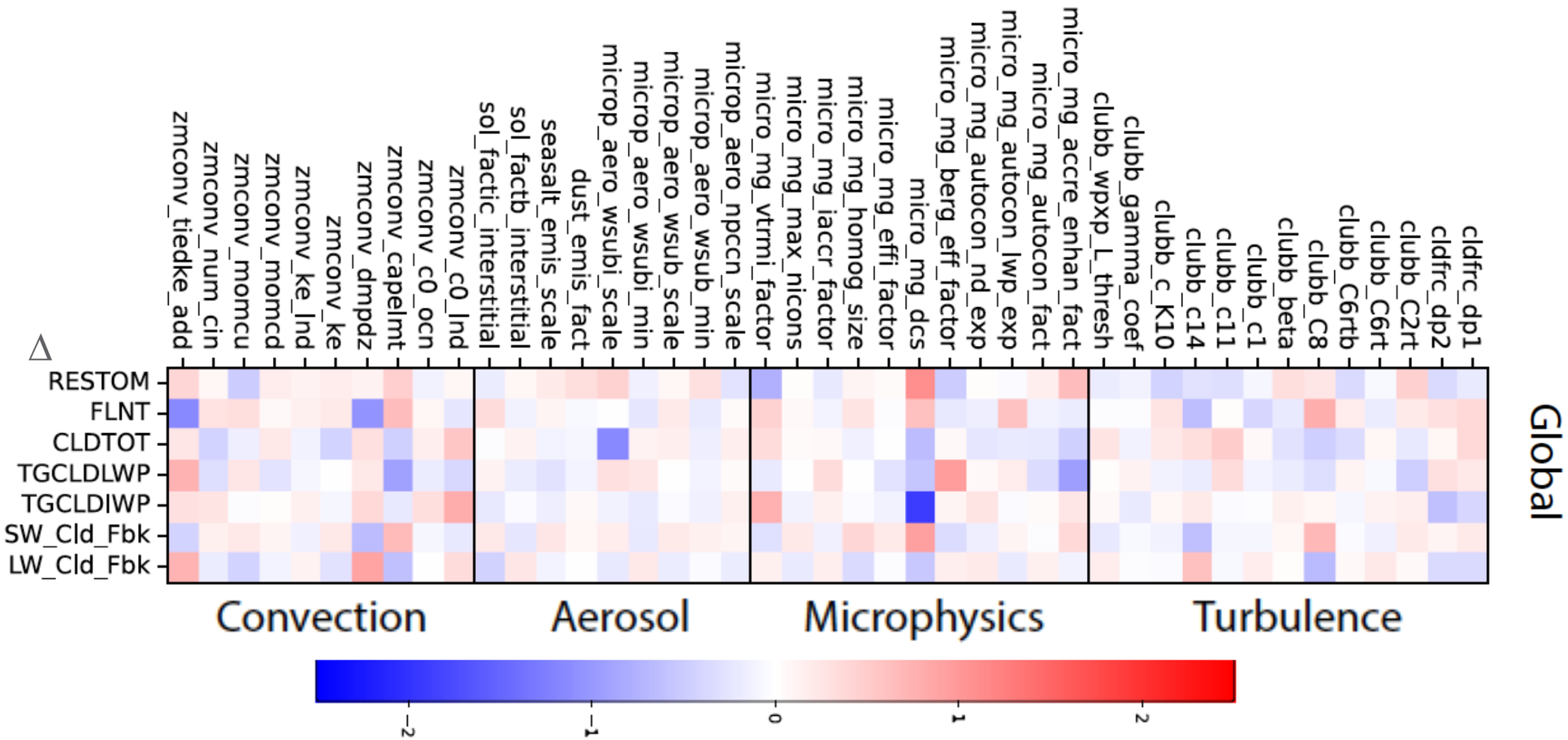
Stronger Positive Feedback with:

- Larger cloud fraction (more cloud to lose)
- Larger negative shortwave cloud effect
- Higher Ice Water Path



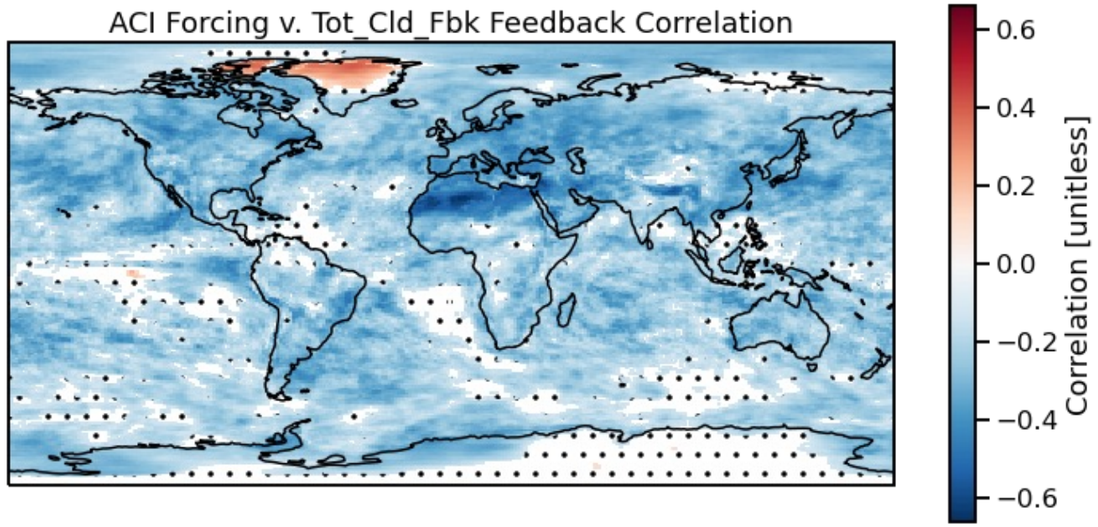
Feedback Relationships to Parameters

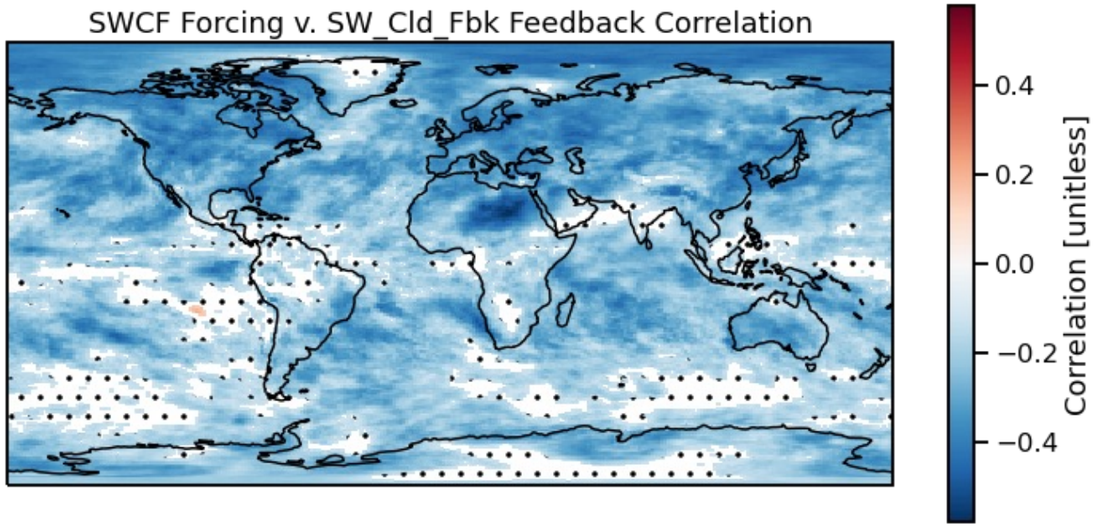
- Deep Convection: Increasing ice increases LW feedback
- Microphysics: Ice: fall speed, autoconversion change ice mass & LW
  - W_{sub} for ice nucleation changes total cloudiness, not much feedback effect
- Turbulence: Damping horiz vel variance and vertical velocity skewness



Correlation Between Forcing and Feedback

Generally negative correlation between ACI (SW mostly) strength and Feedback Strength
Where aerosol forcing is significant (NH), relatively uniform correlations.





Preliminary Conclusions/Next Steps

Comments/Suggestions welcome…

- Aerosol mediated cloud feedbacks exist in complex GCMs, need to be analyzed.
  - Causes spread across models due to aerosol diversity
- ACI (forcing) seems 'limited': stronger with thicker (+Nc, +LWP) base state clouds
  - Matches parameters that control: LWP, Nc processes (CCN, SO_4, Auto/Accre)
- Cloud Feedbacks larger with thicker clouds (more ice, higher cloud fraction)
  - Ice processes, accretion critical
- Microphysics important for cloud feedbacks:
  - Nc and Precipitation formation processes key: not just mean radiative effect
- Significant correlations between aerosol ACI and cloud feedbacks
  - Larger (negative) ACI is associated with stronger (positive) cloud feedbacks
  - Stronger cloud forcing, higher PD drop number results in stronger ACI & Cloud Feedback
  - Lower drop numbers/sulfate burdens are more 'sensitive'