Using the Perturbed Parameter Ensemble of the Community Earth System Model (CESM)

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Motivation

To understand the Community Earth System Model's (CESM) sensitivity of climate to different parameters

To learn uncertainties in climate sensitivity

To best tune the model

Tool : Perturbed Parameter Ensemble (PPE)

The initial goal of the PPE is to understand sensitivity to parameters of the:

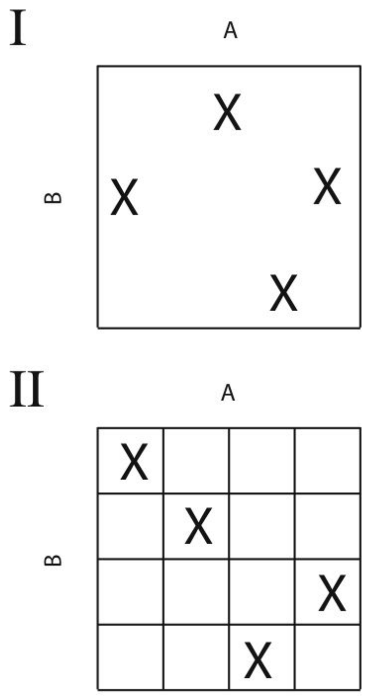
A. Mean state climate
B. Aerosol forcing
C. Cloud feedbacks

Create the PPE using *Latin Hypercube Sampling*

Latin Hypercube Sampling

1. In **random sampling** new sample points are generated without taking into account the previously generated sample points. One does not necessarily need to know beforehand how many sample points are needed.

2. In **Latin Hypercube sampling** one must first decide how many sample points to use and for each sample point remember in which row and column the sample point was taken.

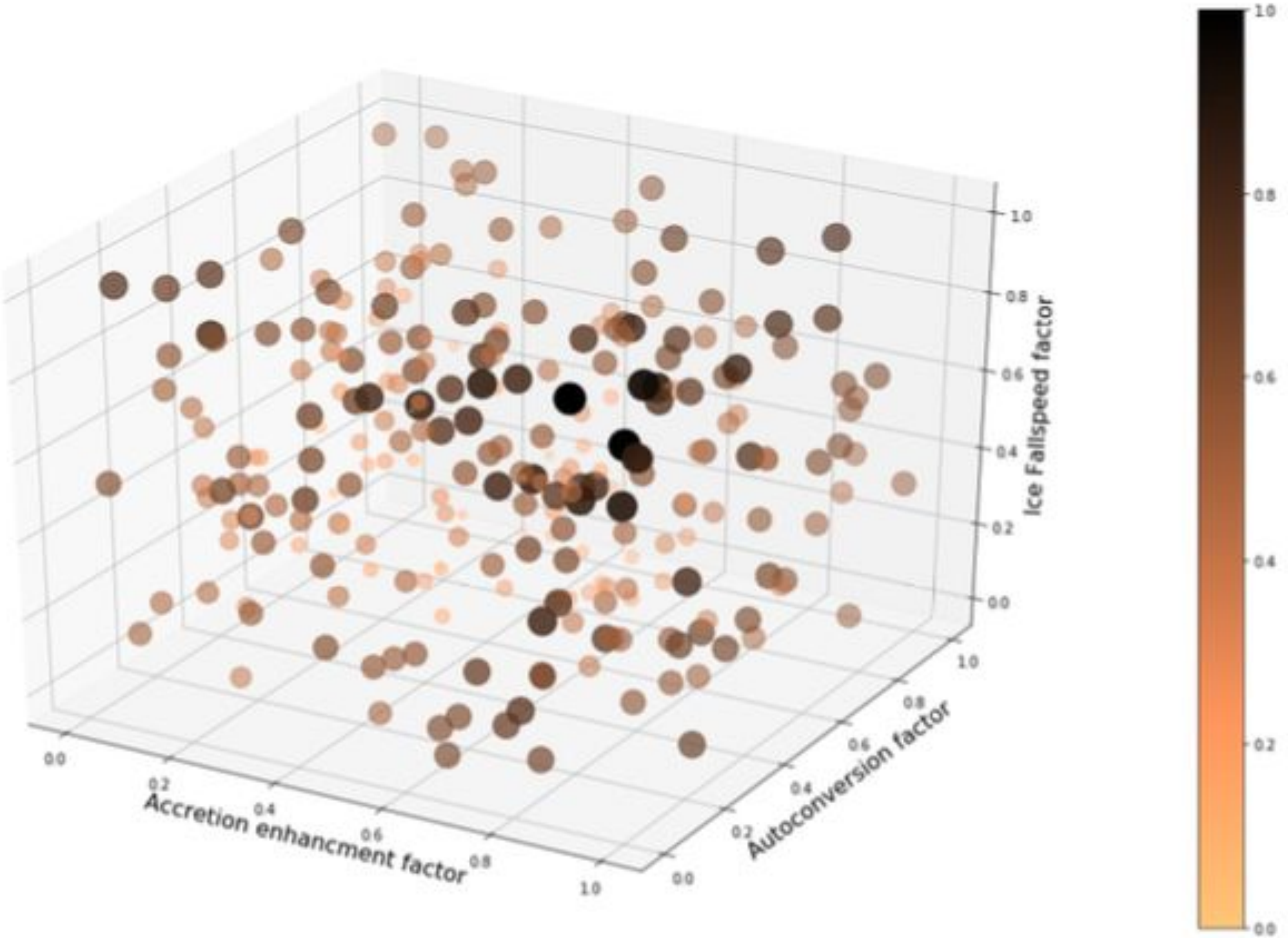


Latin Hypercube Sampling allows for reducing the number of simulations needed, and still cover the entire parameter space

source: wikipedia

Example of multivariable Latin Hypercube Sampling

Darker and larger symbols are closer to the viewer



Perturbed Parameters in CESM

Across most of the cloud physics

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

43 Parameters

263 parameter sets for simulations

3 year simulations

CAM6-CESM

Climatological AMIP, Fixed SST

NCAR | UCAR

Physics Scheme	Parameter Name	Description	Default	Min	Max
CLUBB	clubb_C2rt	damping on scalar variances	1.0	0.2	2
	clubb_C6rt	Damping on scalar fluxes	4.0	2.0	6
	clubb_C6rtb	High Skewness in C6rt Skw.	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
MG2	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	1000e-06
	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
	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
	micro_mg_vtrmi_factor	Ice fall speed scaling	1.0	0.2	5.0
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
	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
	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	10.0	0.5	2.5
	sol_factb_interstitial	Tuning for below cloud scavenging of interstitial modal aerosols	0.1	0.1	1
	sol_factic_interstitial	Tuning for in-cloud scavenging of interstitial modal aerosols	0.4	0.1	1
ZM	cldfrc_dp1	Parameter for deep convection cloud fraction	0.1	0.05	0.25
	cldfrc_dp2	Parameter for deep convection cloud fraction	500	100	1000
	zmconv_c0_lnd	Convective autoconversion Land	0.0075	0.002	0.1
	zmconv_c0_ocn	Convective autoconversion Ocean	0.03	0.02	0.1
	zmconv_capelmt	Triggering threshold for ZM convection	70	35	350
	zmconv_dmpdz		-1.0e-3	-2.0e-3	-2.0e-4
	zmconv_ke	Conv Evap Efficiency	1.0e-5	1.0e-6	1.0e-5
	zmconv_ke_lnd	Conv Evap Efficiency over land	3.0e-6	1.0e-6	1.0e-5
	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

Simulations and outputs

- 263 parameter sets, 3 types of simulations with each set (789 in total)
  - Present day (**PD**)

    Evaluation of current state of climate
  - Pre industrial (**PI**)

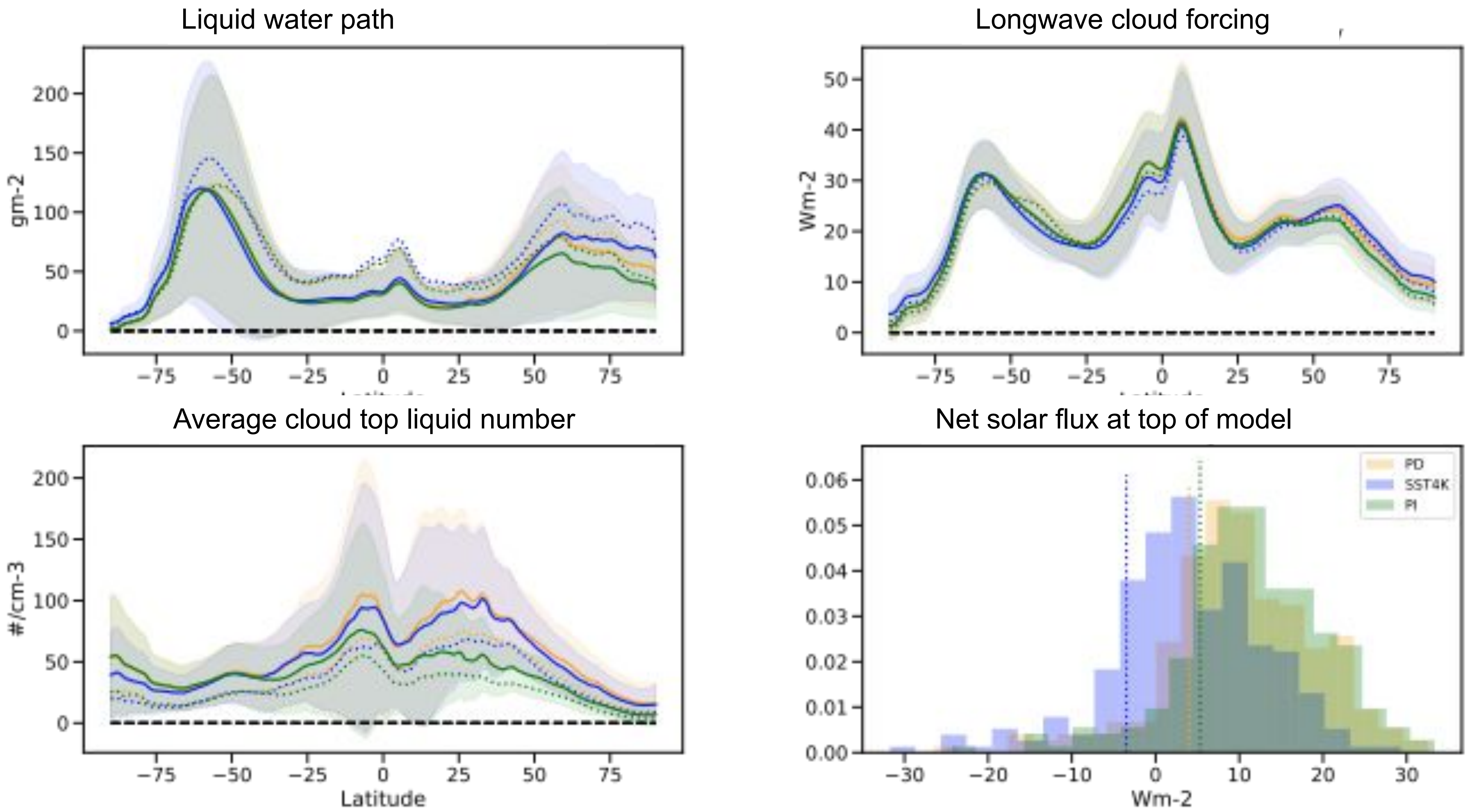
    Pre-industrial aerosol loading. Can evaluate aerosol forcing by taking differences between PD and PI. Nudged Pre-Industrial (1850) aerosols
  - +4K sea surface temperature (**SST4K**)

    Same setup as PD, but with sea surface temperature 4K higher. Can evaluate cloud feedbacks by taking difference between PD and SST4K
- Outputs:
  - Mean monthly state (181, 78 3-dimensional, 103 2-dimensional)
  - Some daily averages (22 2-dimensional)

https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm2.cam6.ppe.html

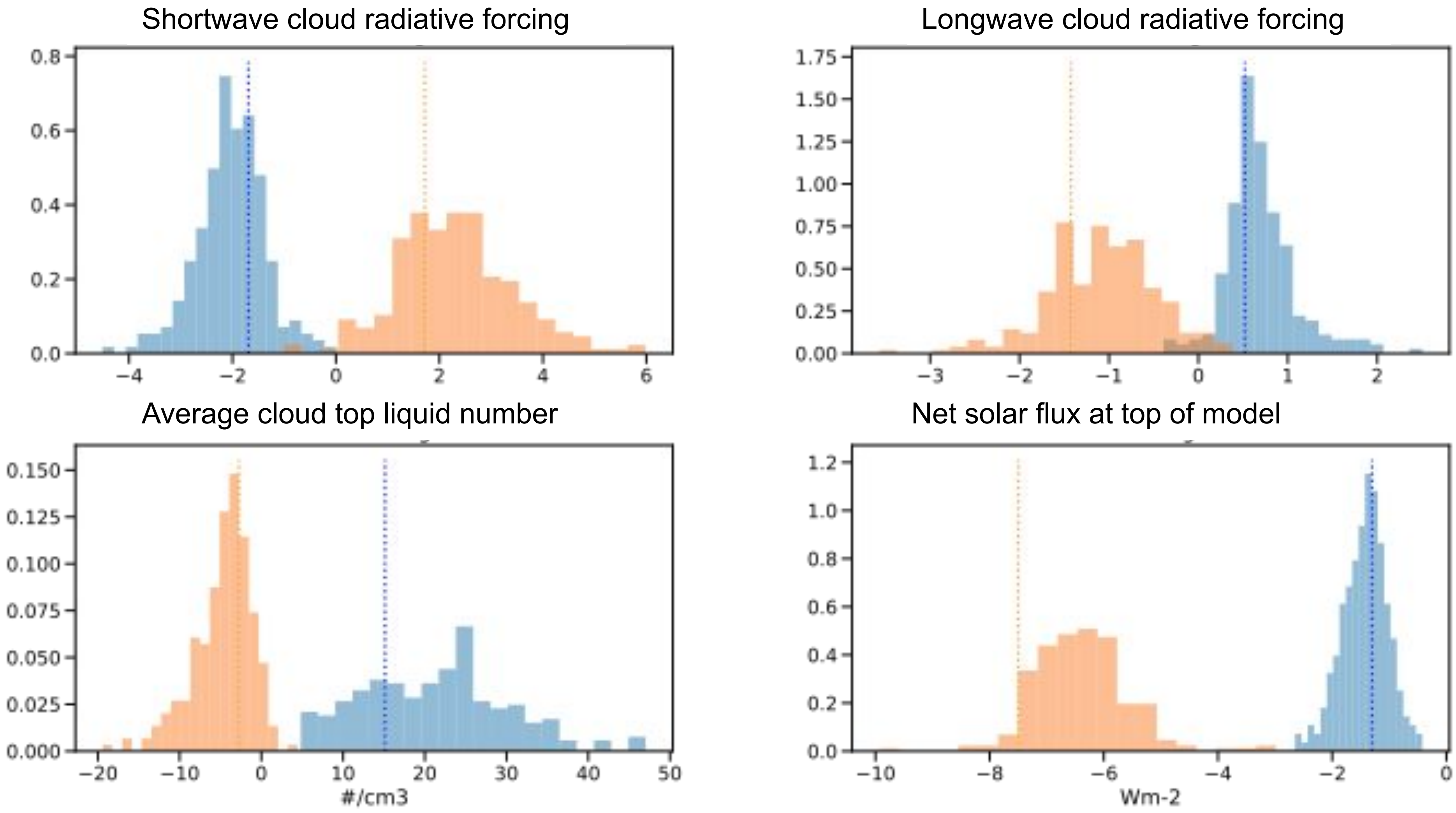
PPE spread

Control run (Baseline CAM6 parameters)
Mean over all 263 simulations

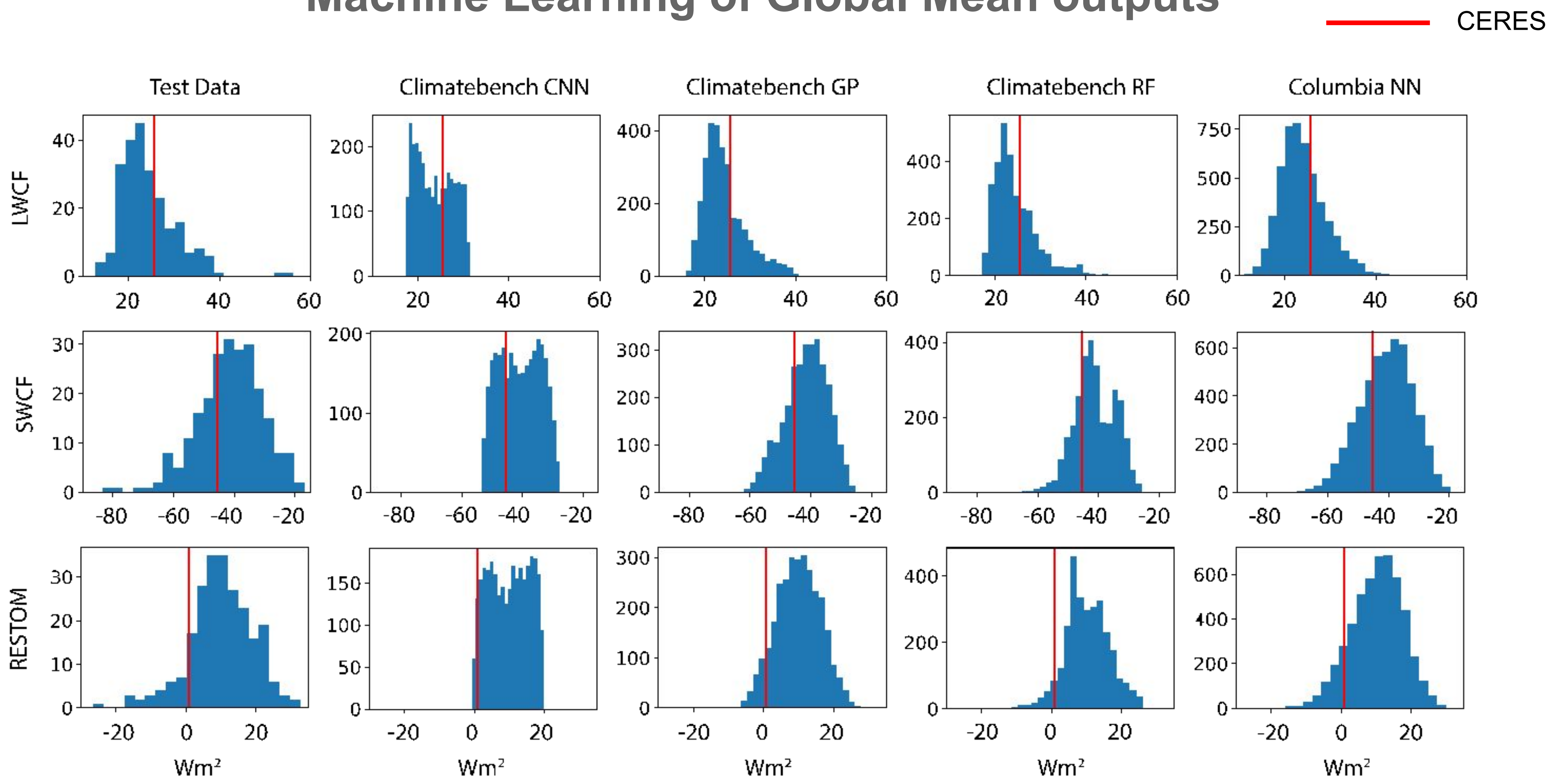


Aerosol Forcing: Present day (PD) - Pre-industrial (PI) aerosol
Cloud Feedback: 4K SST - Present day (PD)

Forcing and Feedback



Machine Learning of Global Mean outputs

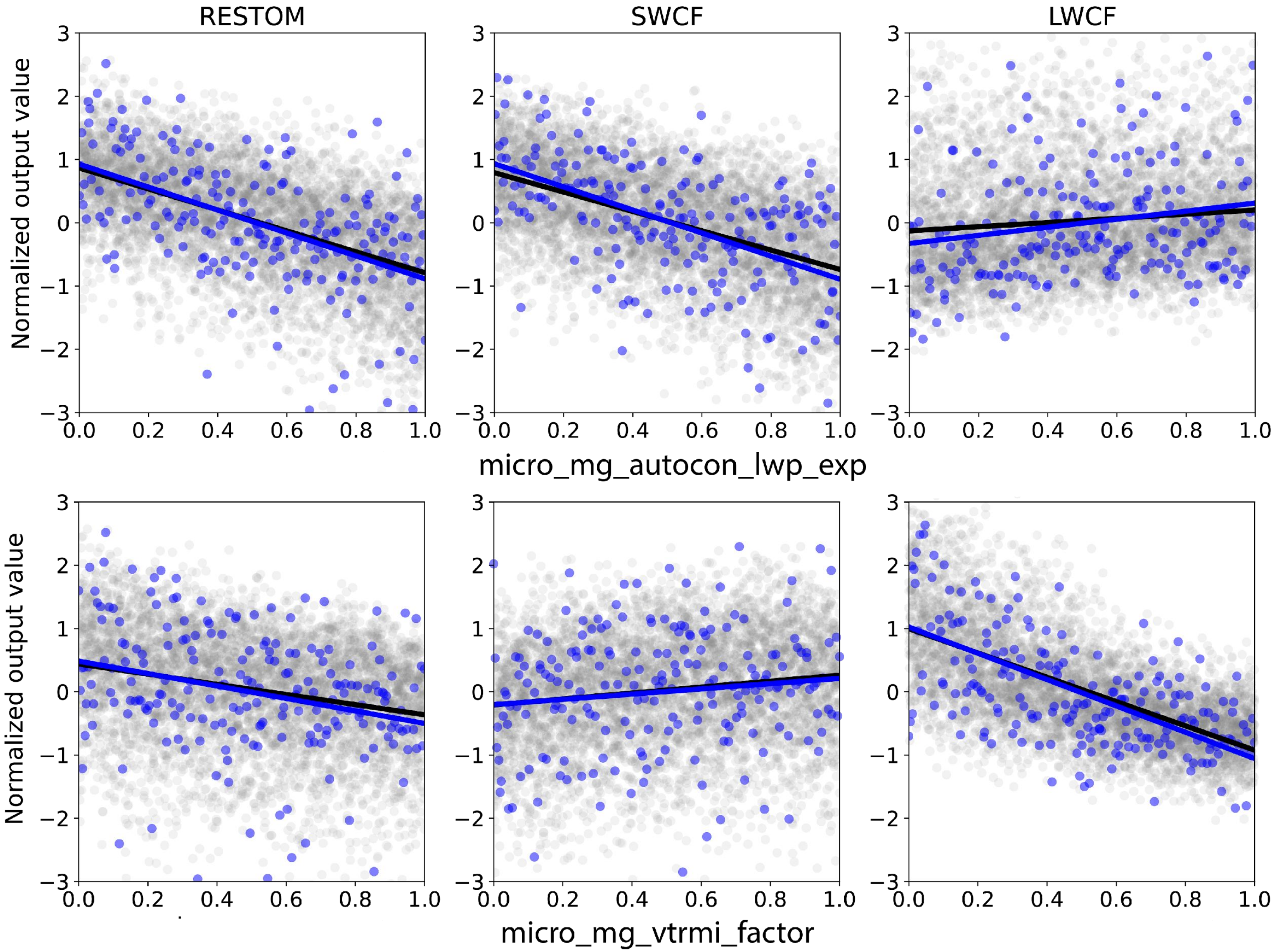


Climatebench: Watson-Parris et al., 2021, GMD
Columbia NN : Elsaesser et al., in prep

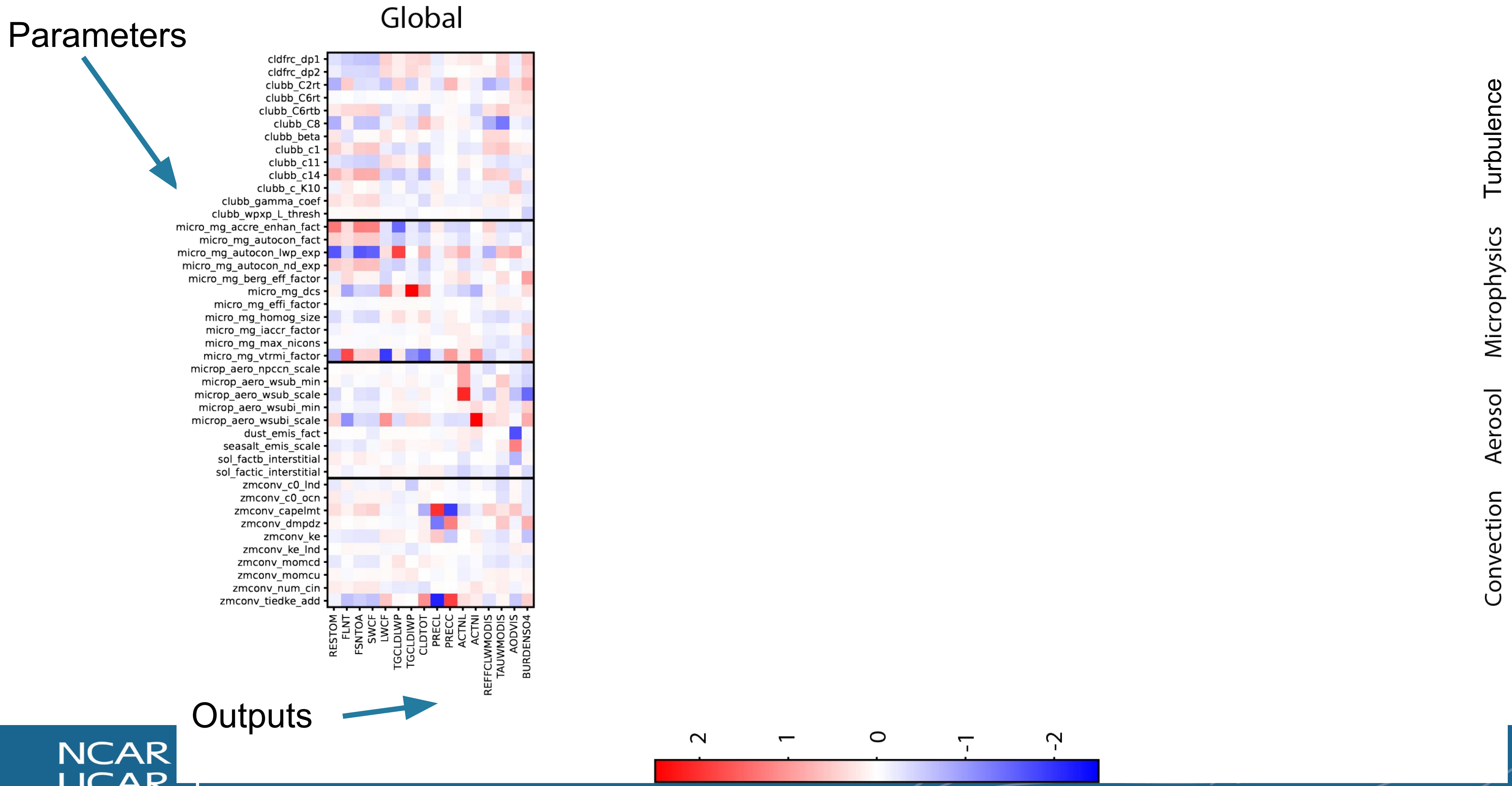
Global mean output dependence on parameter values

Blue: Simulated output for each individual simulation (263 ensembles)

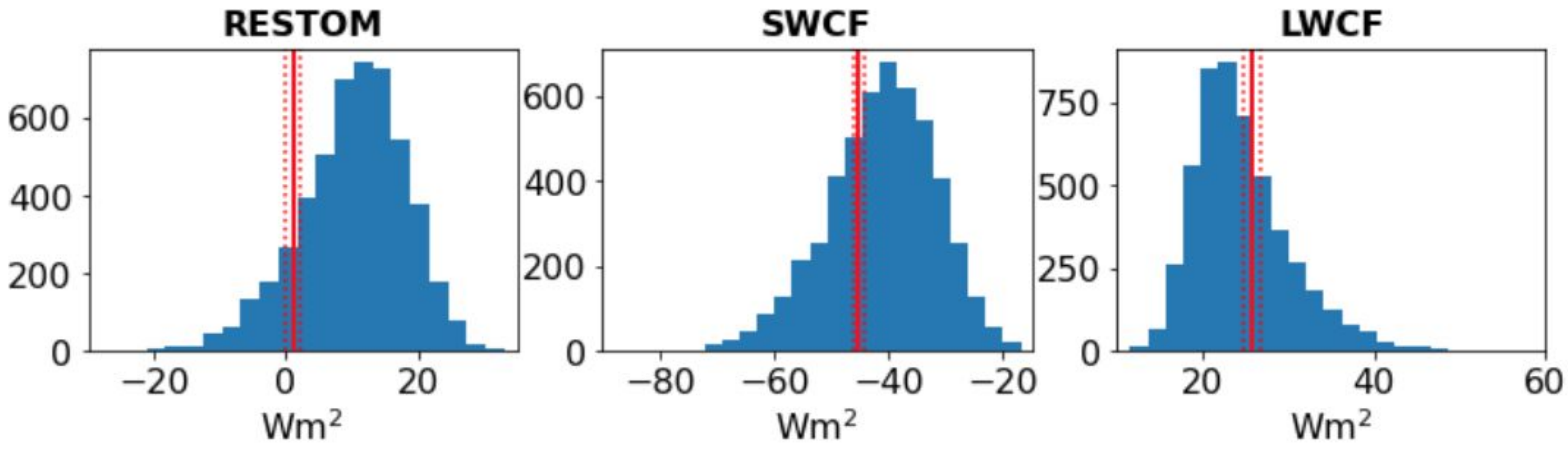
Black: Emulated outputs (5000 samples) Columbia NN emulator



SLOPE of *emulated* output dependence on parameters

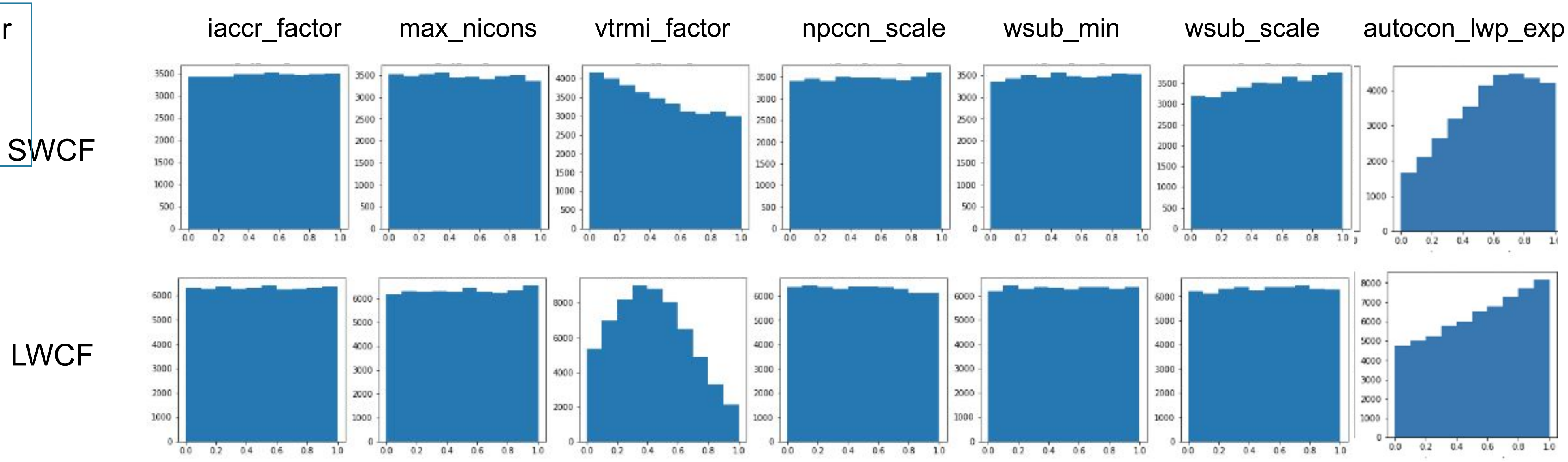


Tuning of certain outputs towards CERES global mean values



Use Machine Learning (Colombia NN), 500,000 samples
Find all sample close to CERES values

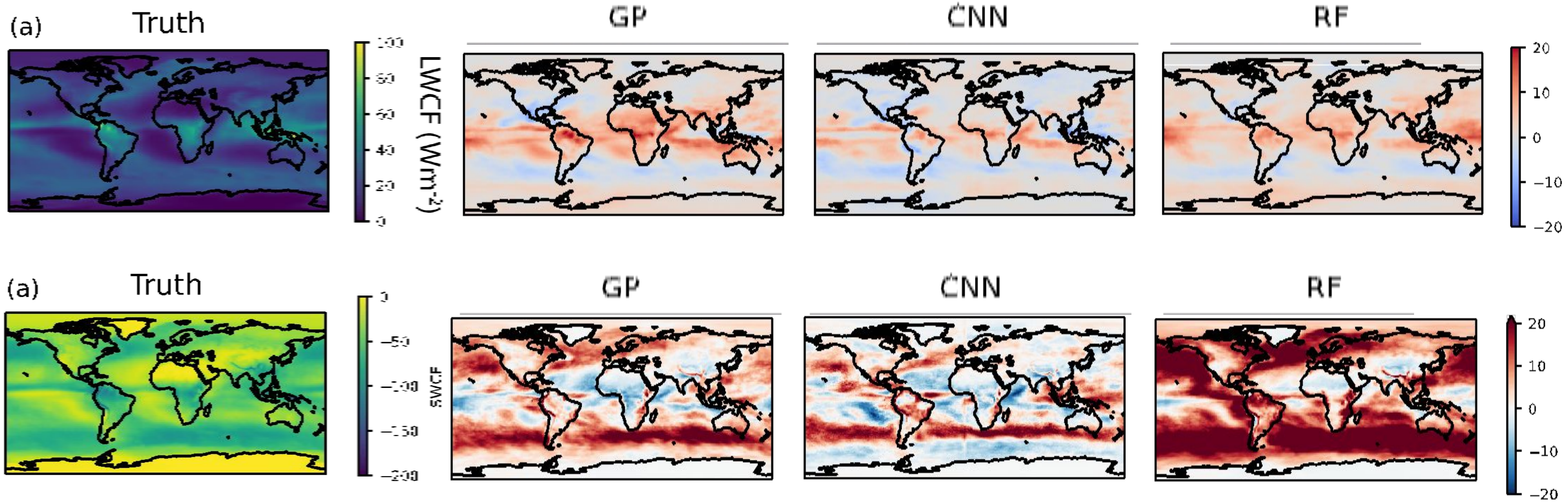
Histogram of parameter values in the samples that compares with CERES observations



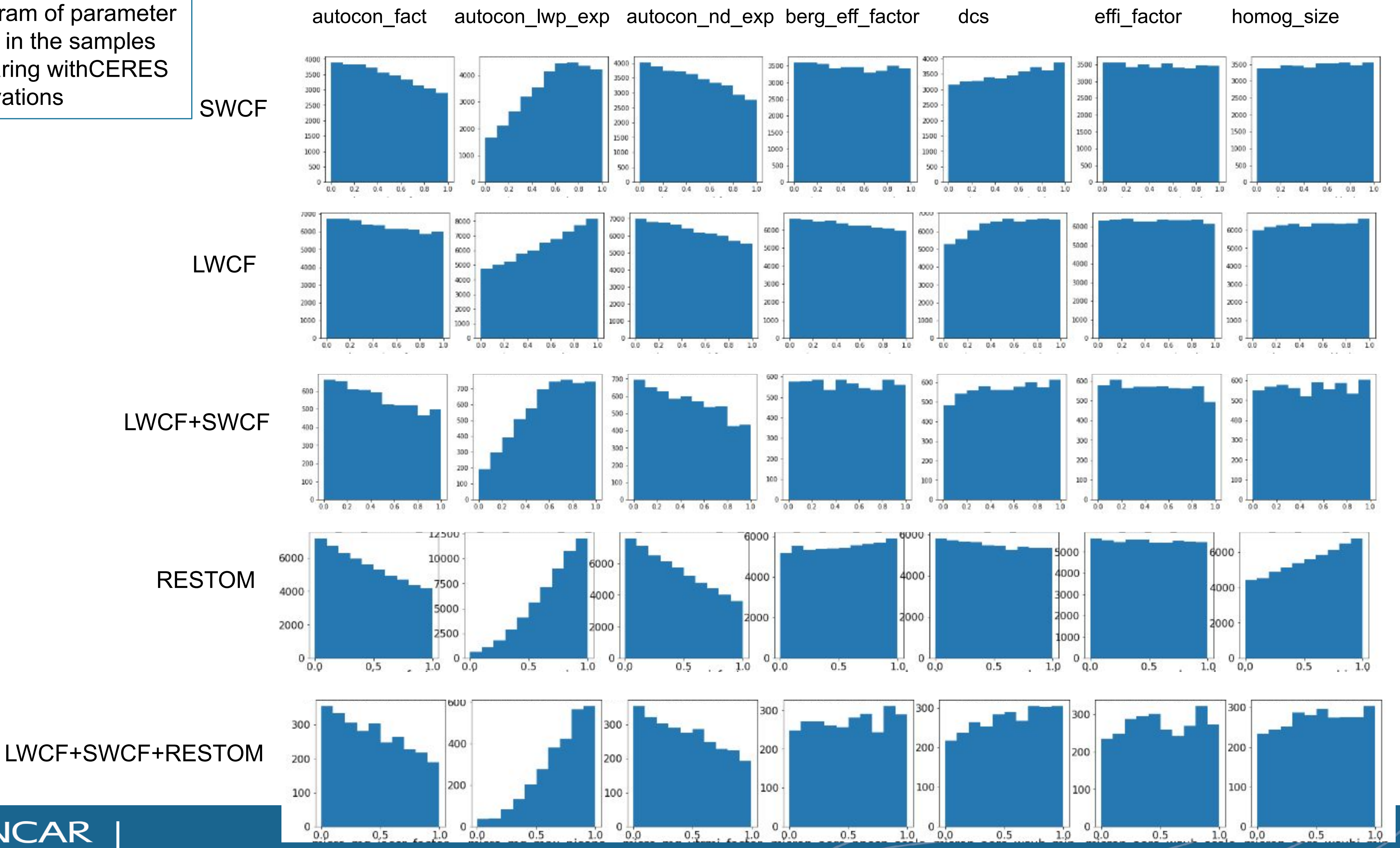
Summary

- PPE is a good way to probe sensitivity of CESM physics
  - Have 3 sets with 250 ensembles each. 46 different parameters, 200 output variables.
- Large spread in results
- Working with 2 different emulator tools to isolate effects of individual parameters and co-variance of parameters
- Evaluating how to use PPE to tune the model

- Community project
  - Outputs are available
  - https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm2.cam6.ppe.html
  - Scripts to create PPE parameter files and build files are available
  - Extensible: any CESM configuration can be run (Single Column, Aquaplanet, coupled). Same or different parameters


(a)
Truth
GP
CNN
RF
LWCF (Wm-2)
20
10
0
−10
−20
(a)
Truth
GP
CNN
RF
SWCF
20
10
0
−10
−20

Histogram of parameter values in the samples comparing withCERES observations



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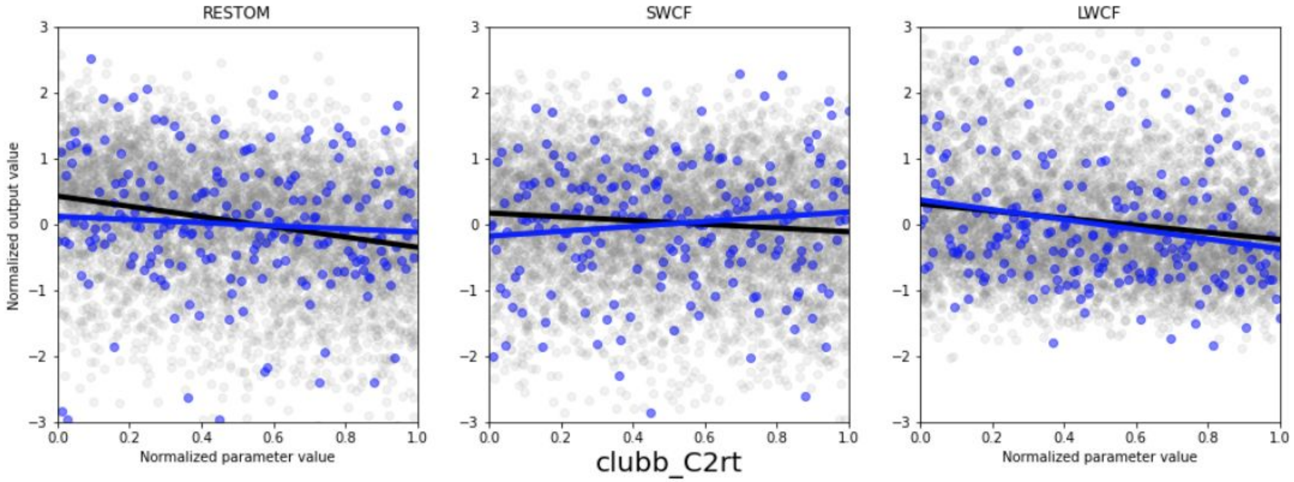
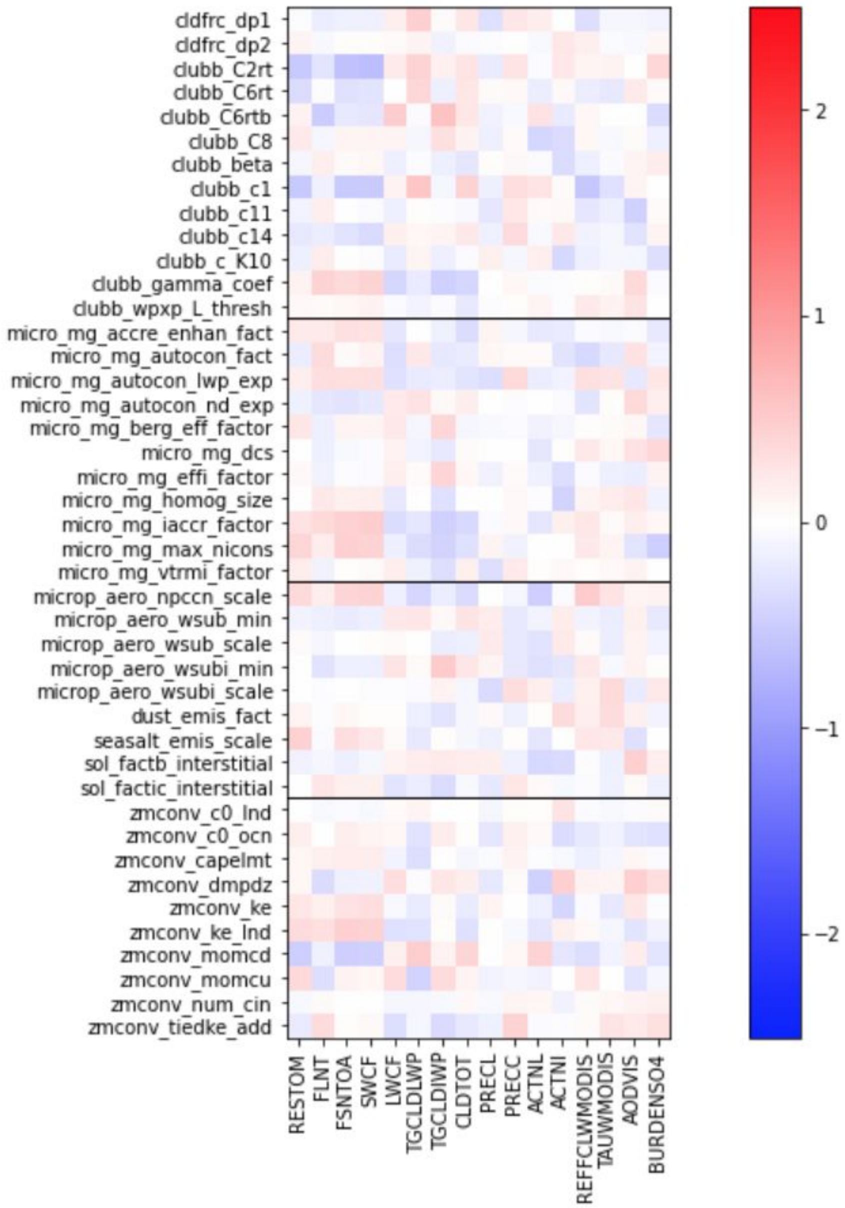
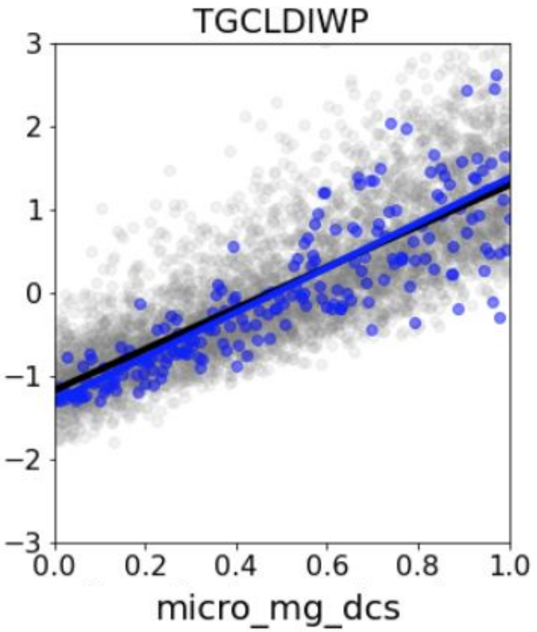
Example of output/parameter pair with the largest error in slope



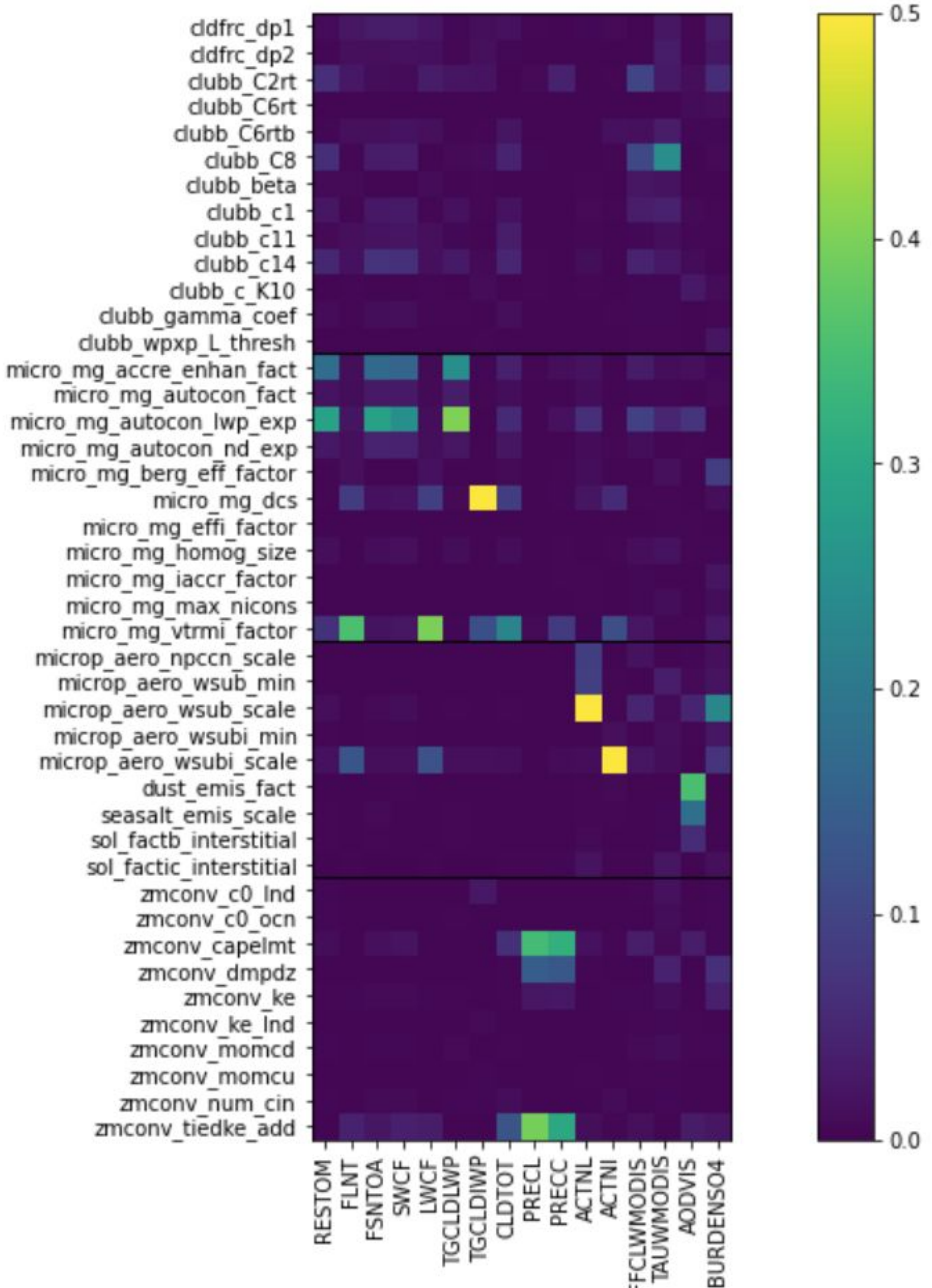
Error in emulated slope



Correlation coefficient



Example of output-parameter pair with high correlation coefficient.



Developed tools

- Latin Hypercube code
  - Read in parameters and ranges
  - Generate sets of namelist parameter values and save as netCDF file
- CAM run script for ensembles
  - Read in netCDF file of parameter values, and loop over sets of parameters to clone a case and create new simulations
  - Can be used with many different comp sets
- Emulator code
  - Takes CAM ensemble output with different parameter sets and builds an emulator of the model with it.
  - Emulator can be sampled randomly to generate lots (millions) of model variants
- Pieces available as 3 scripts. Can be iterated (add parameter sets), or different compsets run on the same parameter sets (e.g., forcing or feedback questions).
  - Files make it traceable and extensible: new science questions or fill in parts of parameter space in more detail.