PROCEED: Perturbed physics ensemble Regression Optimization Center for ESM Evaluation and Development

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I. PROCEED Background

- Evaluate and constrain earth system model (ESM) uncertainty in the parameterized cloud and aerosol sub-grid processes via generation of perturbed physics ensemble (PPE) experiments and their evaluation against surface and aircraft observations.
- Use version 3 of the DOE Energy Exascale Earth System Model (E3SMv3) to generate different PPEs with a focus on targeting cloud radiative feedbacks/adjustments and aerosol-cloud interactions
- Leverage large eddy simulations (LES) to bridge between global-scale, 1˚ resolution E3SMv3 and in situ observations by providing sampling uncertainty estimates.

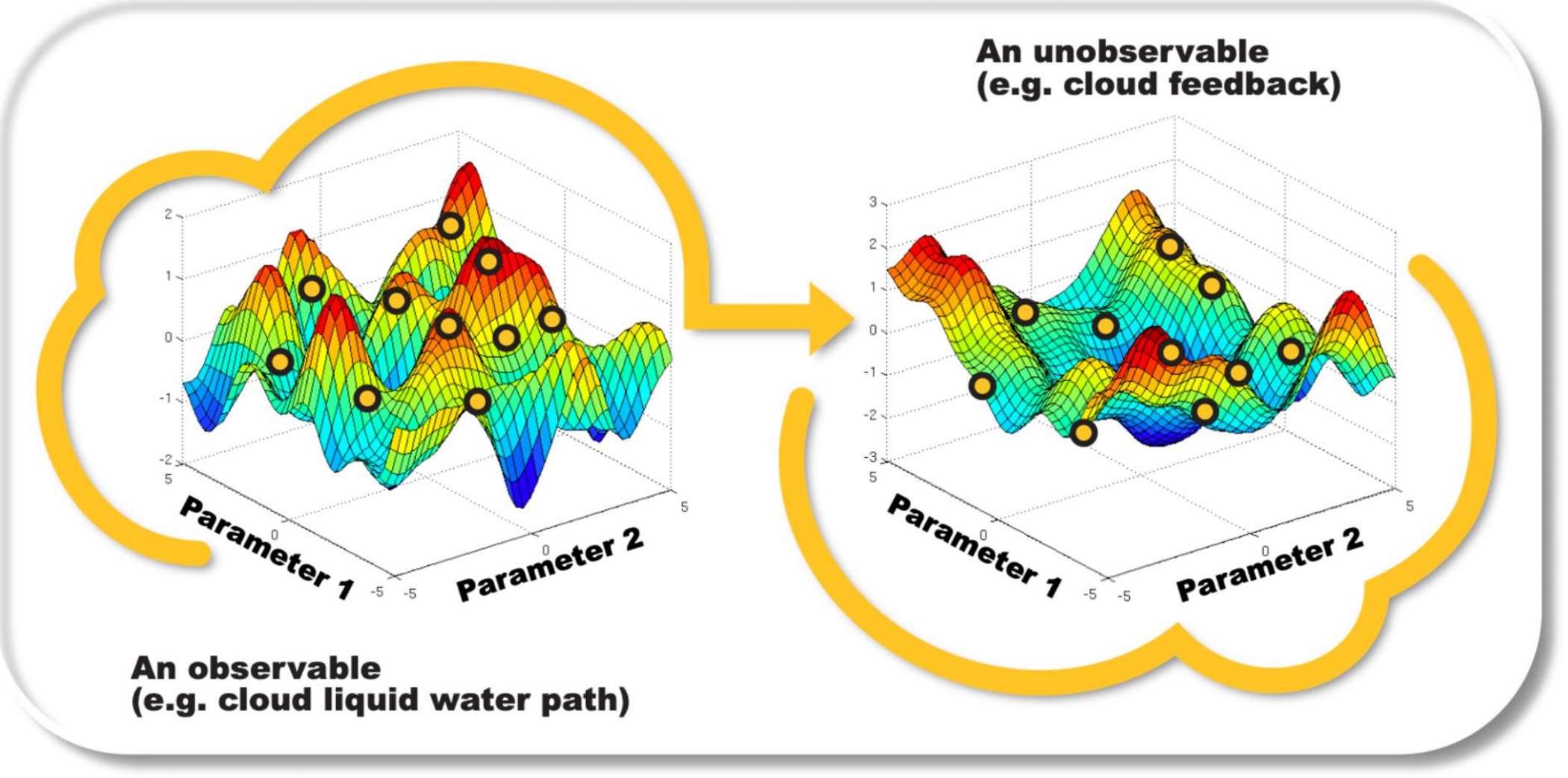
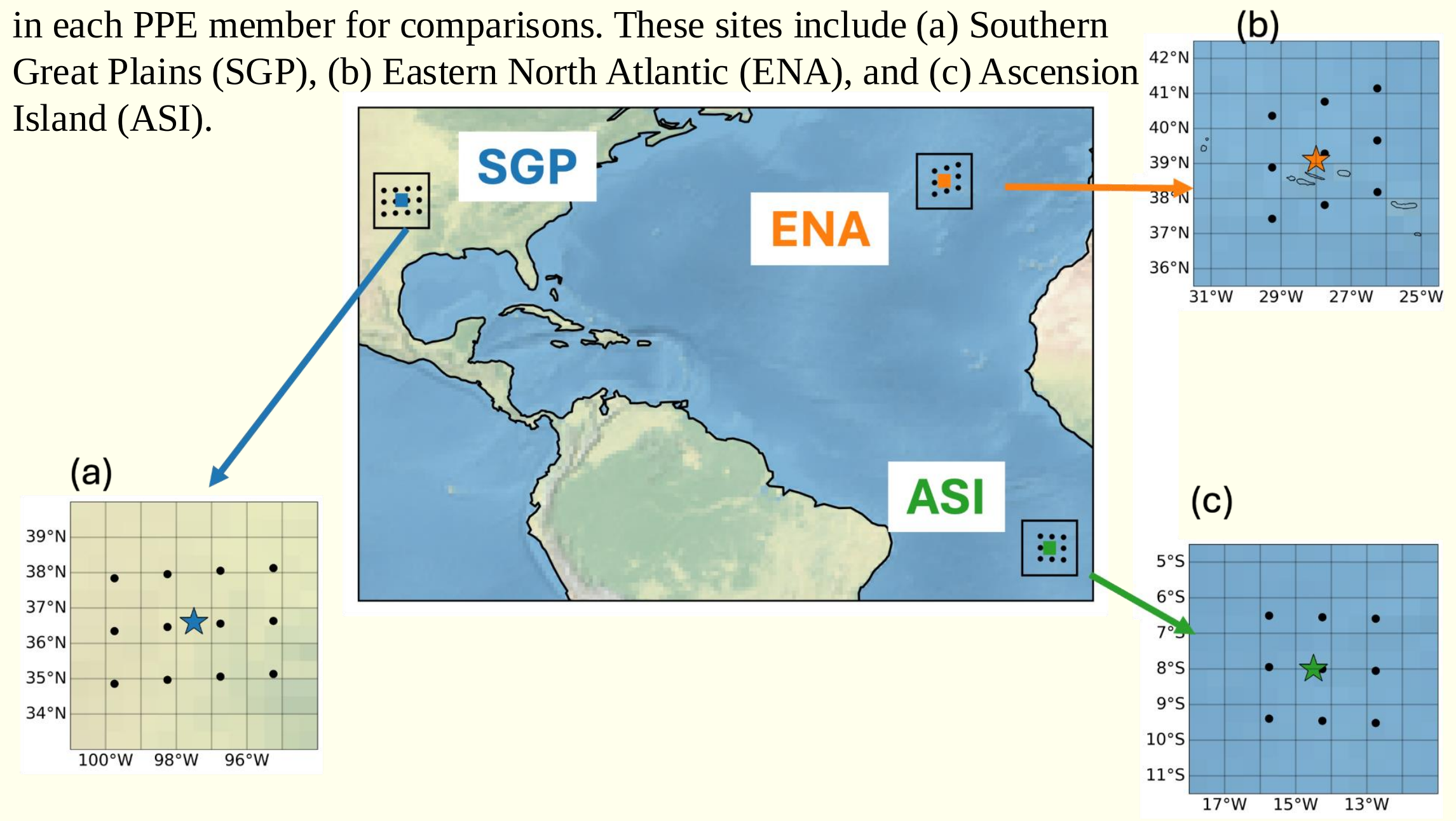


Figure 1: Visualization of a perturbed physics ensemble (PPE) with two uncertain parameters. (Left) an observable such as cloud liquid water path; (Right) an observable prediction such as cloud radiative feedback on warming. Original simulations shown as orange dots randomly distributed about parameter space. A surrogate model fit is shown in colored shading.

II. Observational Evaluation from ARM datasets

- This project will use precipitation, cloud, aerosol, and radiation products from Aerosol Radiation Measurement (ARM) surface sites (Fig. 2) to validate E3SMv3 PPEs.
- PPEs include constrained model output over the three sites in Fig. 2 (black dots = model grid output), with immediate plans to include the Tropical Western Pacific (TWP) ARM site to the existing three.

Figure 2: ARM sites of interest and the corresponding model grid output in each PPE member for comparisons. These sites include (a) Southern Great Plains (SGP), (b) Eastern North Atlantic (ENA), and (c) Ascension Island (ASI).



III. Setup of the first E3SMv3 PPE (PPEv0)

- PPEv0 overview:

251 (250 + default) ensemble members for each scenario (PI & PD)
PI = 1850 forcings; PD = 2010 forcings
Entire PPE took ~3% of our yearly allocated core hours (lots of room for more!)

2-year nudged simulations
Free-tropospheric winds (u, v) nudged to MERRA2 reanalysis
Hourly, daily output saved in a small grid surrounding 3 ARM sites (ENA, SGP, ASI)

25 parameters perturbed simultaneously with Latin Hypercube sampling
7 microphysics (P3)
7 convective microphysics (Zhang-McFarlane)
11 aerosol (MAM, aerosol activation, aerosol/microphysics interface)

Figure 3: Parameters and parameter ranges chosen in the PPEv0 experiment. These are separated into the atmospheric processes they regulate: P3 microphysics (*Milbrandt et al., 2021*), Zhang-McFarlane convective microphysics (*Zhang and McFarlane, 1995*), and modal aerosol model (MAM) (*Liu et al., 2012*).

Scheme	Parameter	Min	Max	v3 default
Microphysics *(P3)*	p3_mincdnc	5e6	30e6	20e6
	p3_nc_autocon_expon	-2	0	-1.1
	p3_qc_autocon_expon	2.10	3.67	3.19
	p3_autocon_coeff	15250	45750	30500
	p3_accret_coeff	58	235	117.25
	p3_wbf_coeff	0.1	1	1
	p3_embryonic_rain_size	1.50e-5	4.00e-5	2.5e-5
Convective microphysics *(Zhang-McFarlane)*	zmconv_accr_fac	0.1	10	1.5
	zmconv_auto_fac	0.1	10	7
	zmconv_micro_dcs	50e-6	1000e-6	150e-6
	zmconv_autocon_coeff	15250	45750	30500
	zmconv_accret_coeff	58	235	67
	zmconv_nc_autocon_expon	-2	0	-1.2
	zmconv_qc_autocon_expon	2.10	3.67	3.19
Aerosol	n_so4_monolayers_pcage	1	8	3
	seasalt_emis_scale	0.5	2.5	0.55
	sol_facti_cloud_borne	0.5	1	1
	dms_emis_scale	0.5	3	2
	microp_aero_wsubmin	0	0.5	0.001
	microp_aero_wsub_scale	0.1	5	1
	POM_hygroscopicity_param	0	0.1	0.04
	aer_sol_factb	0.03	0.1	0.1
	so2_oh_gprx_scale	0.3	3	1
	so2_o3_aqrx_scale	0.5	2	1
	so2_h2o2_aqrx_scale	0.5	2	1

IV. Cloud effective radiative forcing (ERFaci)

- ERFaci is calculated from a difference in present day (PD) and pre-industrial (PI) shortwave cloud radiative effect (SWCRE): $ERFaci = \Delta_{PD-PI}SWCRE$
- The modeled PPEv0 ERFaci (Fig. 4) has a weaker cooling than estimates from a recent Community Atmosphere Model (CAM6) PPE (-2.72–-1.31; *Song et al., 2024*) and appears closer to an observational range of (-2.65–-0.07 Wm^2; *Bellouin et al., 2020*).
- Some ESMs cannot simulate positive ERFaci. The ability of E3SMv3 to do this (Fig. 4) gives confidence in this model's abilities and suggests that there are not a priori, unphysical limitations on the sort of aerosol-cloud forcings that this ESM can create.

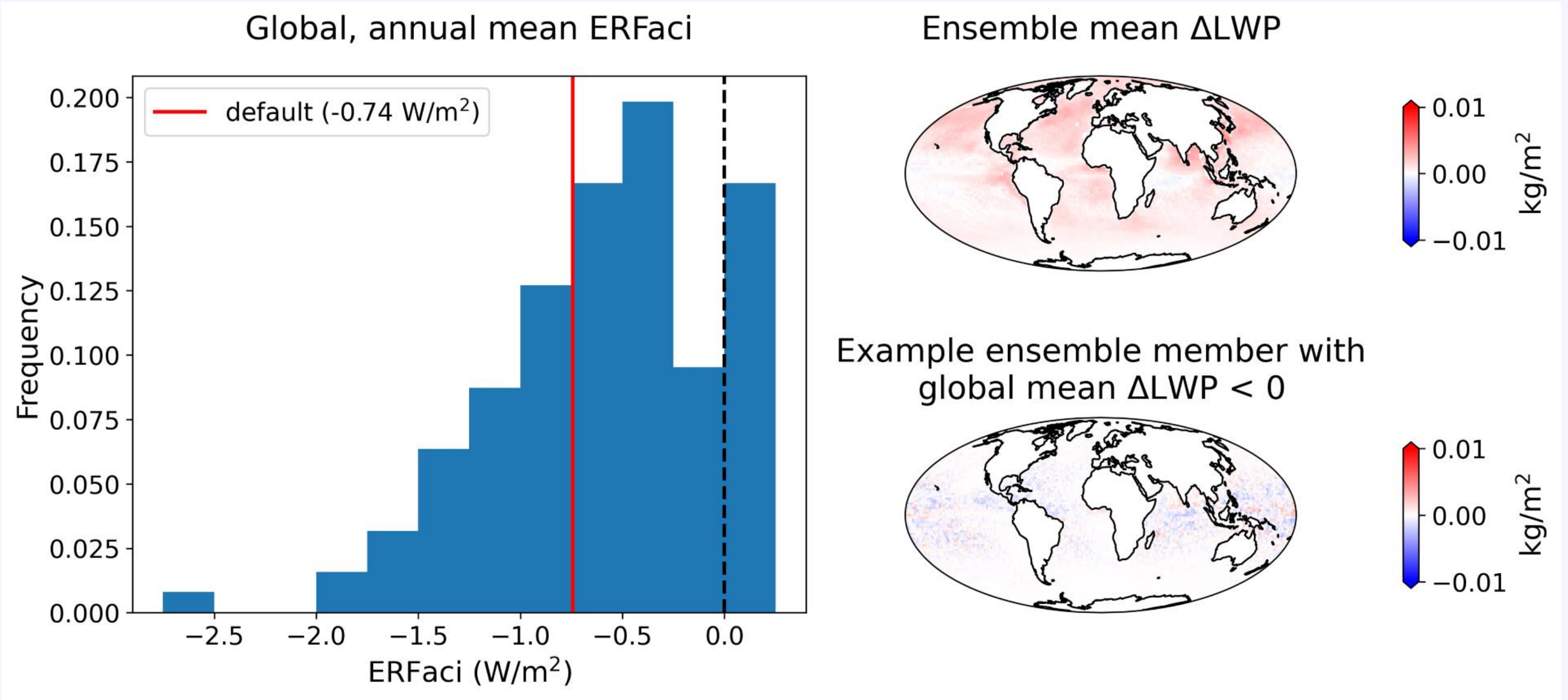


Figure 4: (a) The distribution of effective radiative forcing (ERFaci) from v0 of the PROCEED PPE. (b) the strength of aerosol-cloud adjustments diagnosed using the response in liquid water path (LWP) to anthropogenic aerosol and (c) for an example ensemble member where cloud amount is reduced by aerosol.

V. ARM site parameter sensitivity

- Preliminary comparisons of ARM site model data show strong dependence of cloud mass, size, optical depth, precip, and number on autoconversion (p3/zmconv nc_autoco and qc_autocon).
- Aerosol activation parameters (microp_aero_wsub) are linked to cloud number, and altering emission/formation of different aerosol species (i.e., sea salt and sulfate) can be seen to impact aerosol outputs at the ARM sites differently.

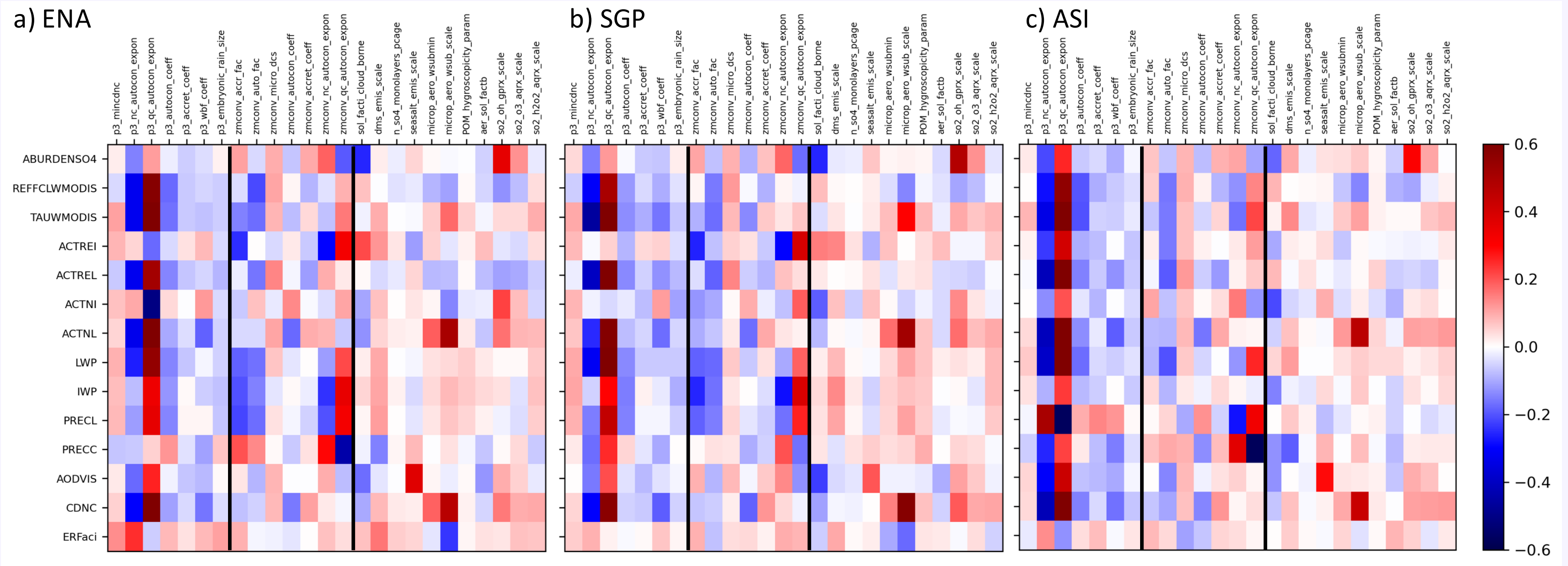
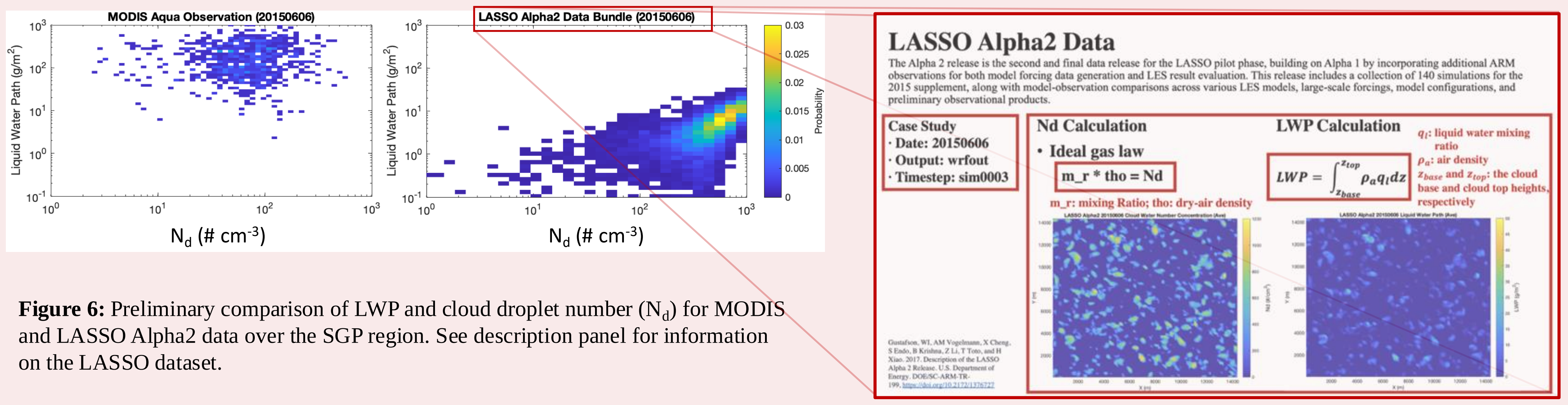


Figure 5: Normalized linear regression slope for 14 model outputs (y-axis) against the 25 parameters in Fig. 3. These are shown for the three ARM sites in Fig. 2 ((a) ENA, (b) SGP, and (c) ASI), with parameters separated by solid lines into their pertinent atmospheric processes (microphysics (left), convective microphysics (middle), and aerosol (right)). The model outputs chosen are sulfate burden (ABURDENSO4), MODIS simulated cloud effective radius (R_{eff}) (REFFCLWMODIS), MODIS-simulated cloud optical depth (TAUWMODIS), cloud-top ice R_{eff} (ACTREI), cloud-top droplet R_{eff} (ACTREL), cloud-top ice number (ACTNI), cloud-top droplet number (ACTNL), cloud liquid water path (LWP), cloud ice water path (IWP), large-scale precipitation rate (PRECL), convective precipitation rate (PRECC), visible aerosol optical depth (AODVIS), cloud droplet number concentration (CDNC), cloud effective radiative forcing (ERFaci).

VI. LES modeling

- The relationship between Liquid Water Path (LWP) and Droplet Number Concentration (Nd) is explored by using the joint-probability histograms, following the approach from *Gryspeerdt et al., (2019)*.
- The LASSO Alpha2 Data Bundle is examined by comparing it with Satellite observations from MODIS Level3 data for the SGP region.
- We are currently awaiting access to the ARM Cluster to access preliminary LASSO ENA runs for future analysis.



LASSO Alpha2 Data

The Alpha 2 release is the second and final data release for the LASSO pilot phase, building on Alpha 1 by incorporating additional ARM observations for both model forcing data generation and LES result evaluation. This release includes a collection of 140 simulations for the 2015 supplement, along with model-observation comparisons across various LES models, large-scale forcings, model configurations, and preliminary observational products.

Case Study
· Date: 20150606
· Output: wrfout
· Timestep: sim0003

Nd Calculation
- Ideal gas law

m_r * tho = Nd

m_r: mixing Ratio; tho: dry-air density

LWP Calculation

$$LWP = \int_{z_{base}}^{z_{top}} \rho_a q_l dz$$

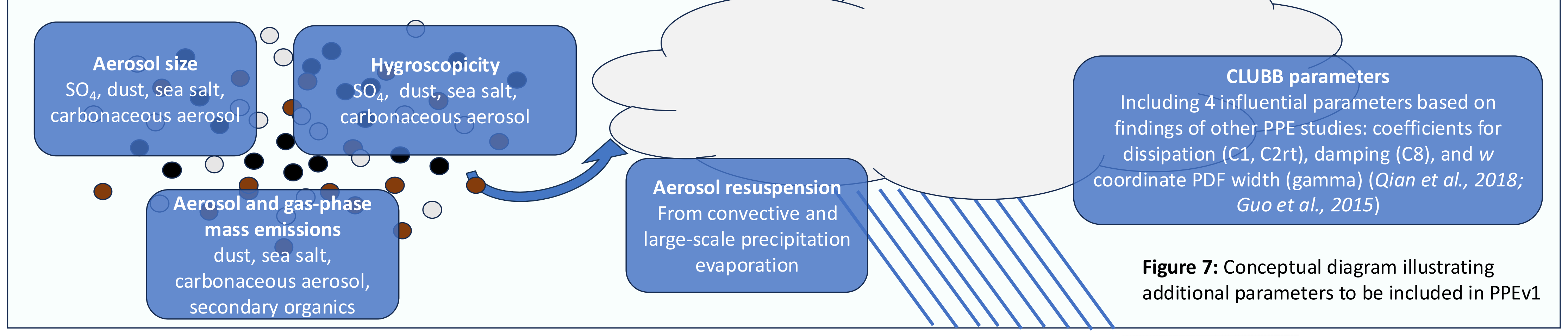
q_l: liquid water mixing ratio
ρ_a: air density
z_{base} and z_{top}: the cloud base and cloud top heights, respectively

Gustafson, WI, AM Vogelmann, X Cheng, S Endo, B Krishna, Z Li, T Toto, and H Xiao. 2017. Description of the LASSO Alpha 2 Release. U.S. Department of Energy. DOE/SC-ARM-TR-199. https://doi.org/10.2172/1376727

Figure 6: Preliminary comparison of LWP and cloud droplet number (N_d) for MODIS and LASSO Alpha2 data over the SGP region. See description panel for information on the LASSO dataset.

VII. Aerosol focused PPE (PPEv1)

- Plans to target aerosol and their role as cloud condensation nuclei (CCN) in a follow-on PPE (PPEv1).
- The focus will be emission of the major aerosol species that affect cloud in the ARM sites (e.g., carbonaceous aerosol, sulfate, sea salt, and dust), aerosol resuspension, aerosol size, and species aerosol hygroscopicity.
- These additional parameters will make up the majority of PPEv1 parameter space, which will include the aerosol, microphysical, and convective parameters mentioned above. It will also include additional turbulence parameters from the Cloud Layers Unified By Binormals (CLUBB) model



Aerosol size
SO_4, dust, sea salt, carbonaceous aerosol

Hygroscopicity
SO_4, dust, sea salt, carbonaceous aerosol

Aerosol and gas-phase mass emissions
dust, sea salt, carbonaceous aerosol, secondary organics

Aerosol resuspension
From convective and large-scale precipitation evaporation

CLUBB parameters
Including 4 influential parameters based on findings of other PPE studies: coefficients for dissipation (C1, C2rt), damping (C8), and *w* coordinate PDF width (gamma) (*Qian et al., 2018; Guo et al., 2015*)

Figure 7: Conceptual diagram illustrating additional parameters to be included in PPEv1

References
- Milbrandt et al., 2021 (10.1175/JAS-D-20-0084.1)
- Zhang and McFarlane, 1995 (10.1080/07055900.1995.9649539)
- Liu et al., 2012 (10.5194/gmd-5-709-2012)
- Song et al., 2024 (10.1029/2024GL108663)
- Bellouin et al., 2020 (10.1029/2019RG000660)
- Gryspeerdt et al., 2019 (10.5194/acp-19-5331-2019)
- Gustafson, et al., 2017 (10.2172/1376727)
- Guo et al., 2015 (10.1002/2014MS000405)
- Qian et al., 2018 (10.1029/2018JD028927)

← See QR code for more information on PROCEED