A Quantitative Framework for Establishing the Value of Existing and Hypothetical Observations on Earth System Model (ESM) Projection Envelopes

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Acknowledgements:
Marcus van Lier-Walqui, Ann Fridlind, Greg Cesana, Gavin Schmidt, Qingyuan Yang, Max Kelley, Andy Ackerman, Kaitlyn Loftus, Jingbo Wu, & many other modeling/obs community colleagues

National Aeronautics and Space Administration
Goddard Institute for Space Studies

obs4MIPs
Observations for Model Intercomparisons Project

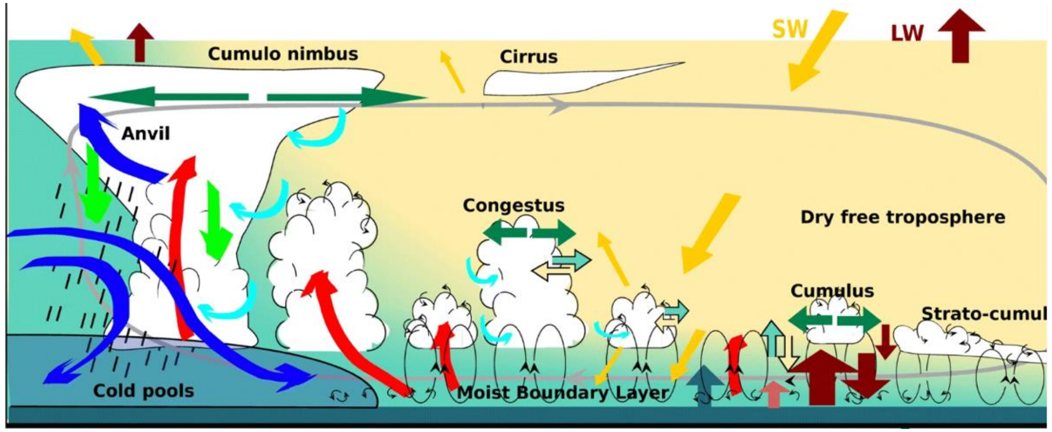
NSF

LEAP

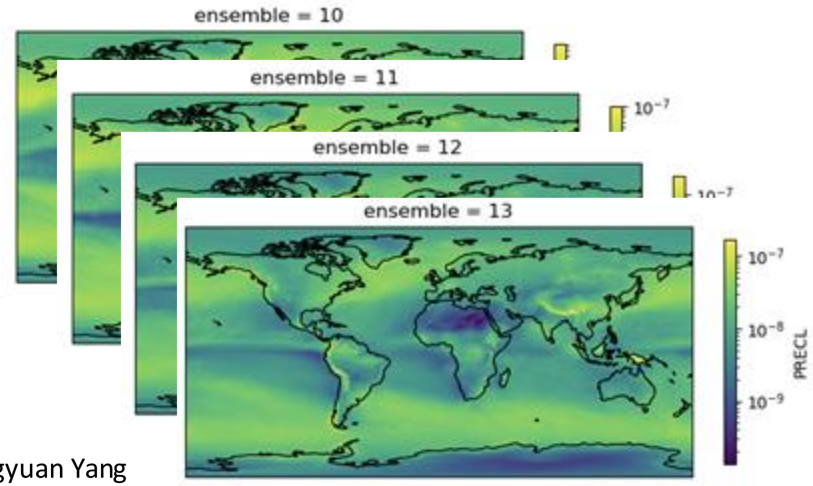
CESAS Meeting, Modeling Panel Event, 28 Oct 2025

A Climate Model (Atmosphere) PPE

- Survey the parameterizations representing the various atmospheric processes/structures.
- Select the equations used to describe the processes, and perturb their parameters (coefficients/constants) simultaneously.
- Which parameters? Probably not Coriolis parameter ‘f’, nor gravity ‘g’).



Rio et al. 2019



From Qingyuan Yang

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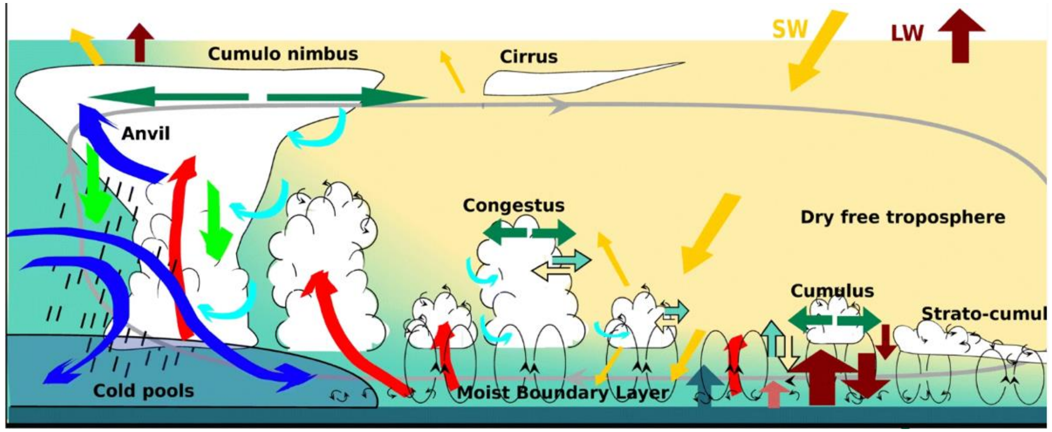


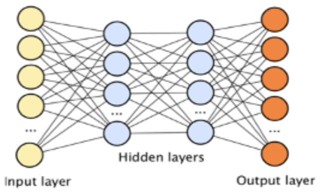
2019

Example equations (thunderstorm vigor, raindrops):

$$\frac{dw}{dt} = \boxed{g}\left(\frac{\theta'}{\bar{\theta}} - \frac{q_c}{\rho} - \frac{q_r}{\rho}\right) - \text{Pressure Perturbation Term} - \text{Drag}$$

$$P_{ACCR} = \boxed{A}\, q_c^{\boxed{\alpha}}\, q_r^{\boxed{\beta}}$$

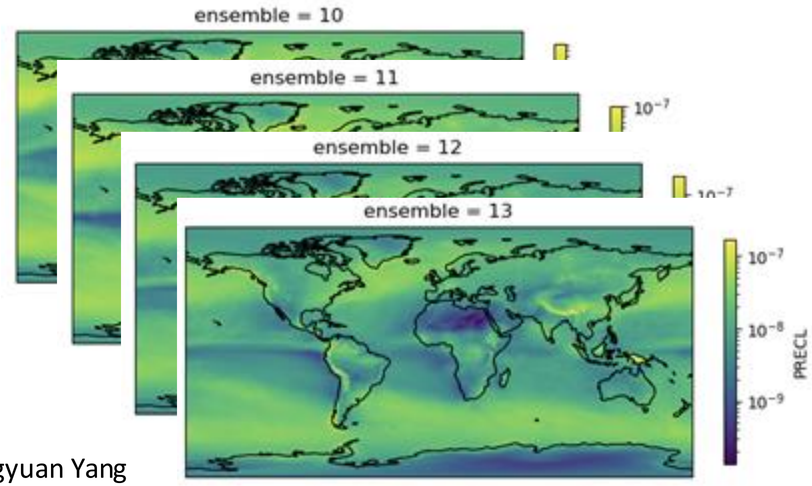
Inputs:
T, Qv
Cloud
properties



Outputs:
Other cloud
Properties,
T, Qv

. . . . .

Hundreds more



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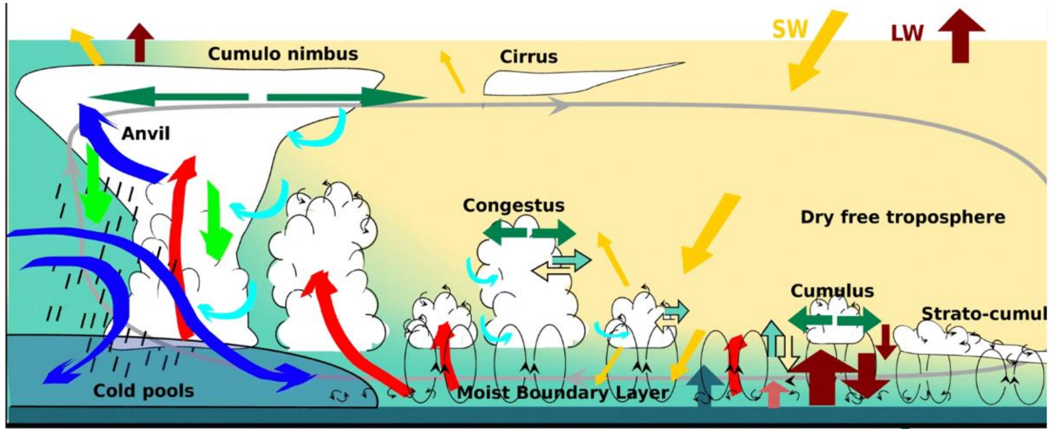

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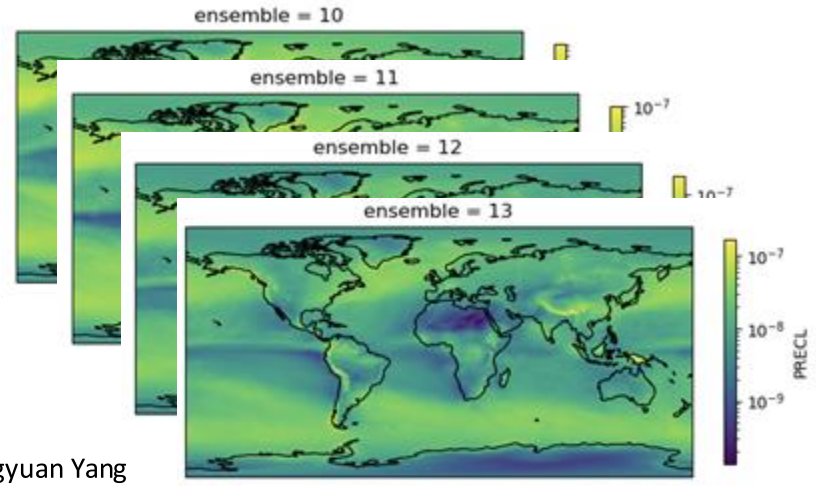
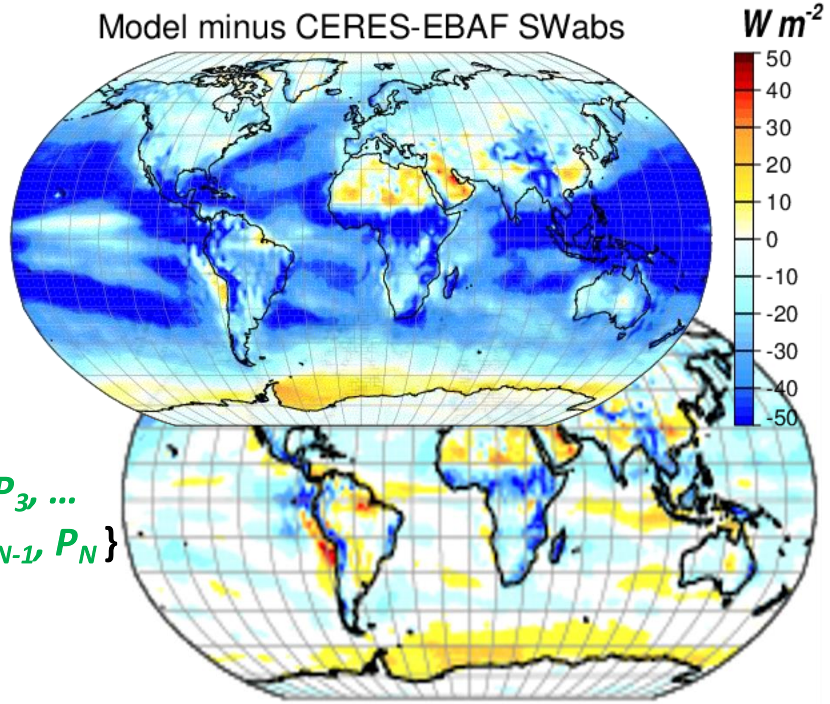


From Qingyuan Yang

Some are like Earth, some are like some exo-planet.

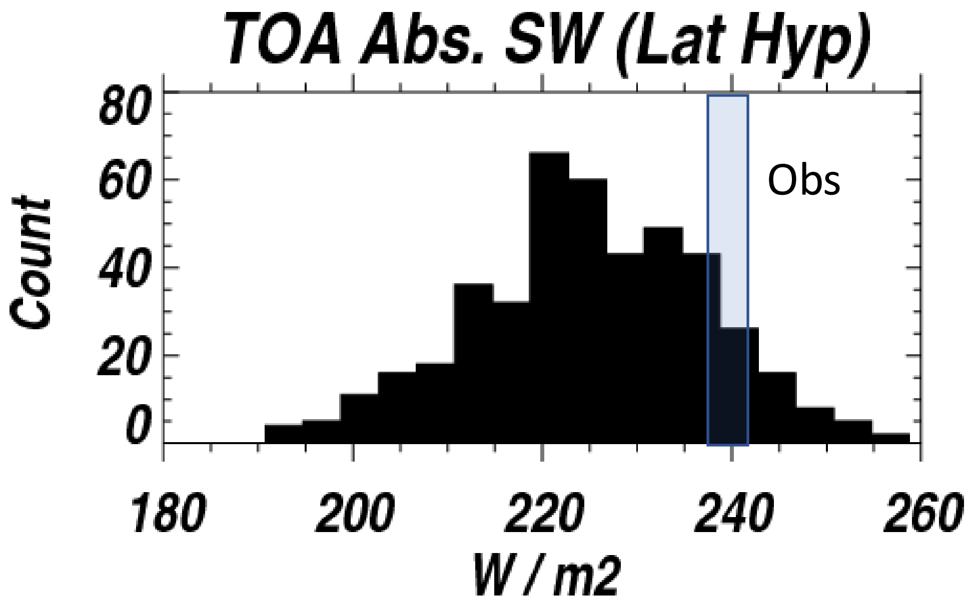
$P_{exp} = \{ P_1, P_2, P_3, \ldots P_i, \ldots P_{N-1}, P_N \}$

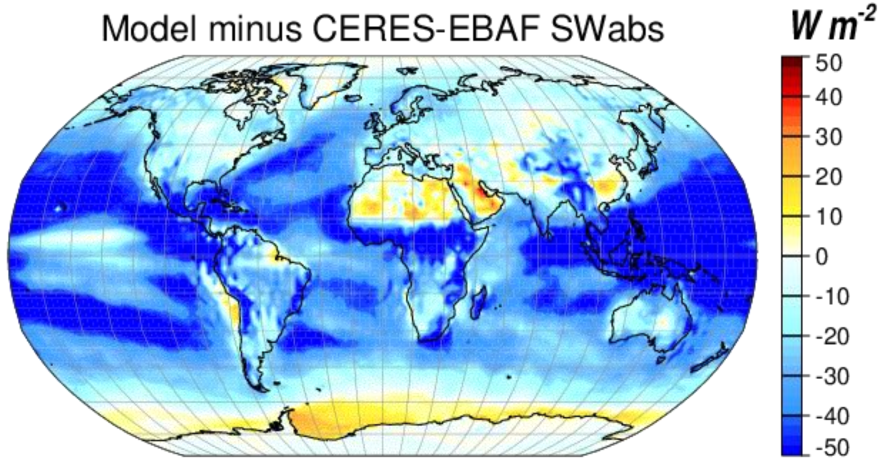


A *Somewhat-Typical* Climate Model (Atmosphere) PPE

$\boldsymbol{P_{exp}} = \{ P_1, P_2, P_3, \ldots P_i, \ldots P_{N-1}, P_N \}$

You might want to take the atmospheric PPE members (each one with a unique $\boldsymbol{P_{exp}}$ *set) and run them forward to get a prediction envelope, perform sensitivity analyses, etc. but there is a problem:* ***most*** *are not Earth-like in some way.*





Constructing a different type of PPE

- Minimum requirement: find ***all*** combinations of parameters (P_{exp}) that yield model output in agreement with the base-state climate (notwithstanding structural error).

- Expanded definition of base-state climate, if only because cloud feedbacks are state dependent. Are we underutilizing available observations?

    **Requires closer, two-way OBS-MODELer interaction.

    **I wonder: if mean-state was defined to include more outputs (e.g., warm rain fraction, convective rain fraction, cloud top condensate phase climatologies), how then would mean state fidelity map to projection?

- What of the obs at present? Are they truthy enough? **IF** uncertainties in products are provided, they are often not the full uncertainties. Does uncertainty matter?

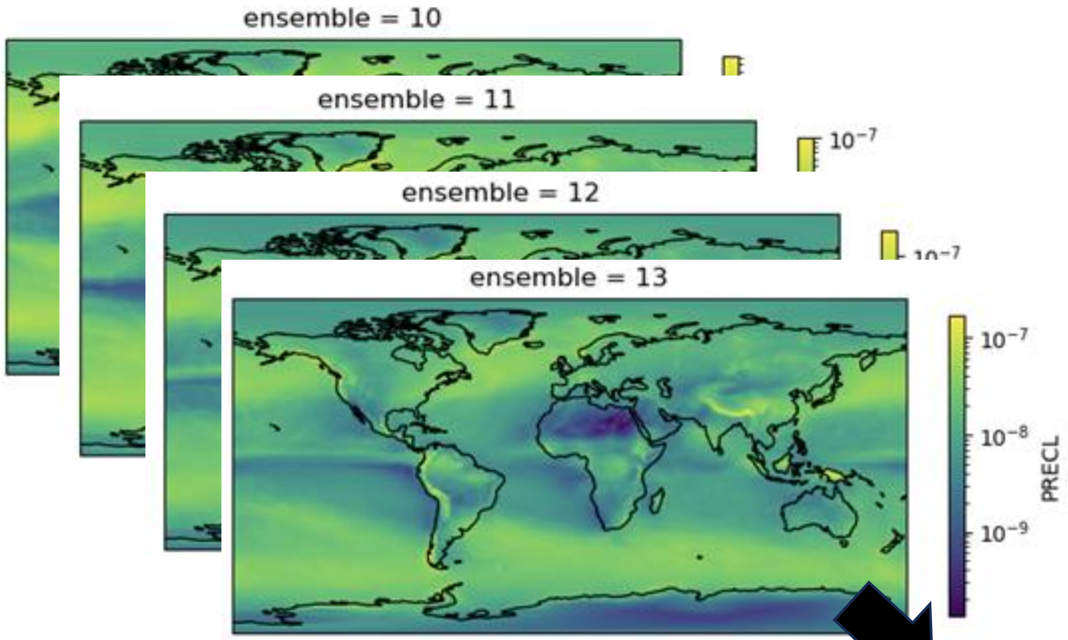
Define this PPE: "**Calibrated Physics Ensemble**", or **CPE**

Definition of "calibration" can evolve; "physics" represents the hope that we can span structure too

Elsaesser et al. (2025)

Estimate the parameters (P_{exp}) simultaneously

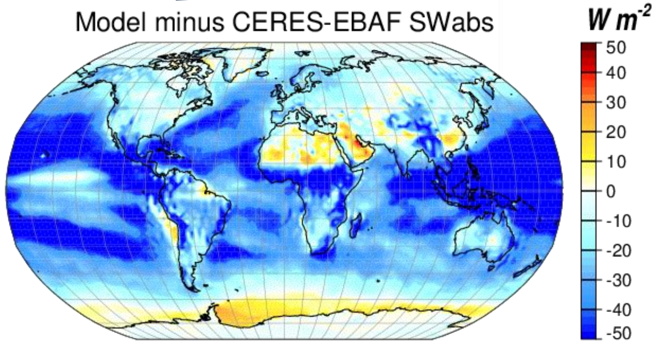
$P_{exp} = \{ P_1, P_2, P_3, \ldots P_i, \ldots P_{N-1}, P_N \}$

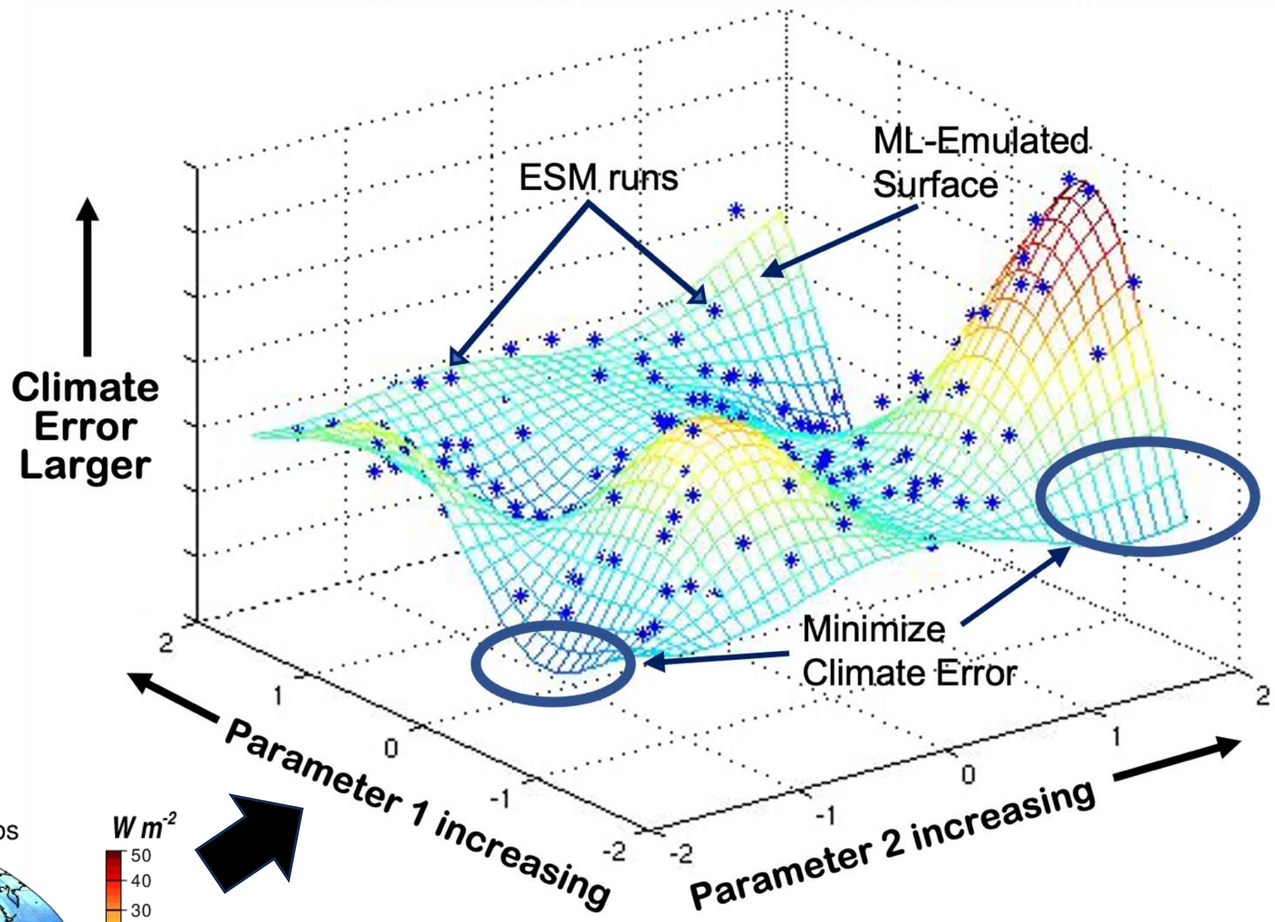


...

Hundreds more

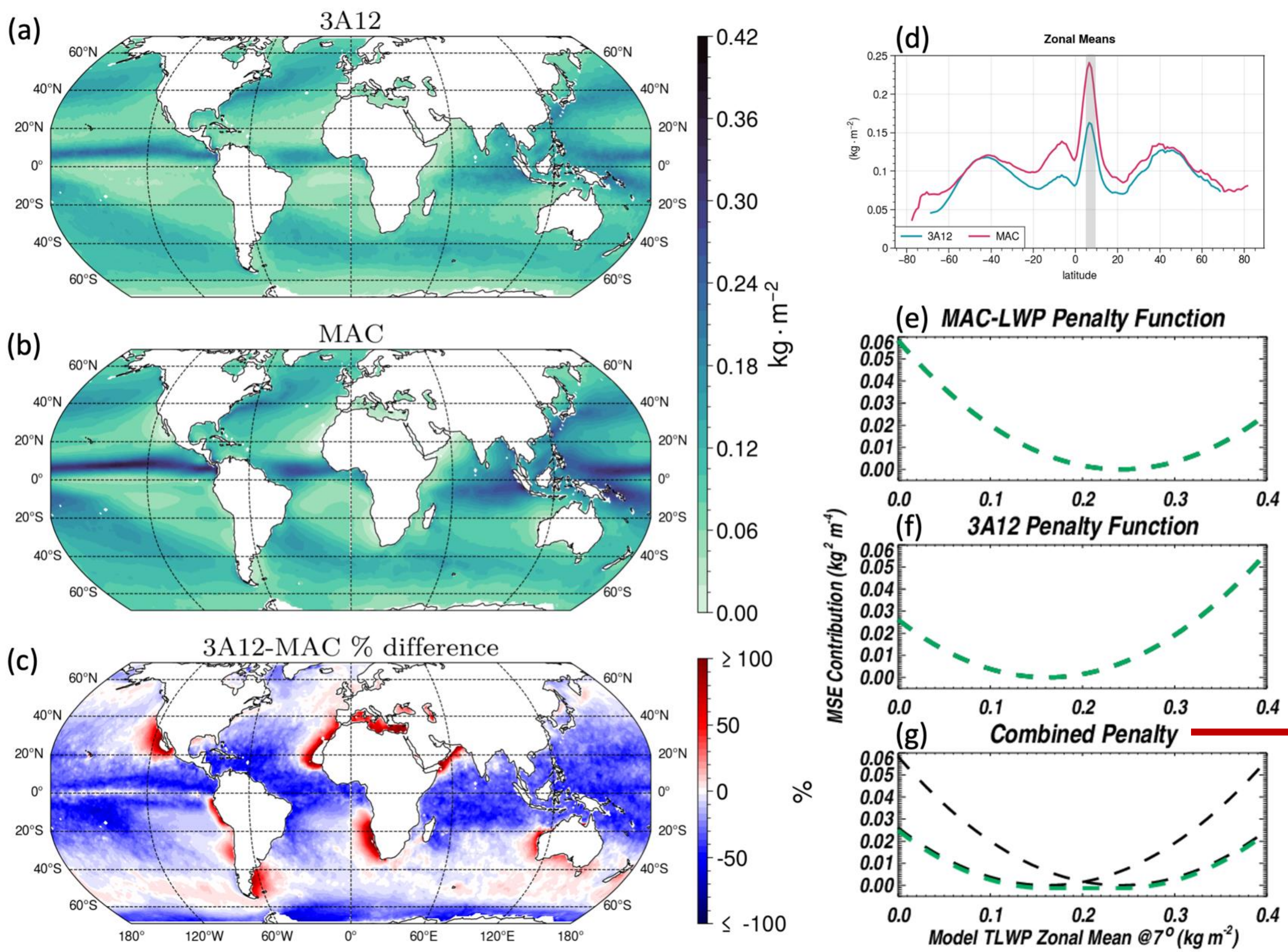
Compare all
with obs

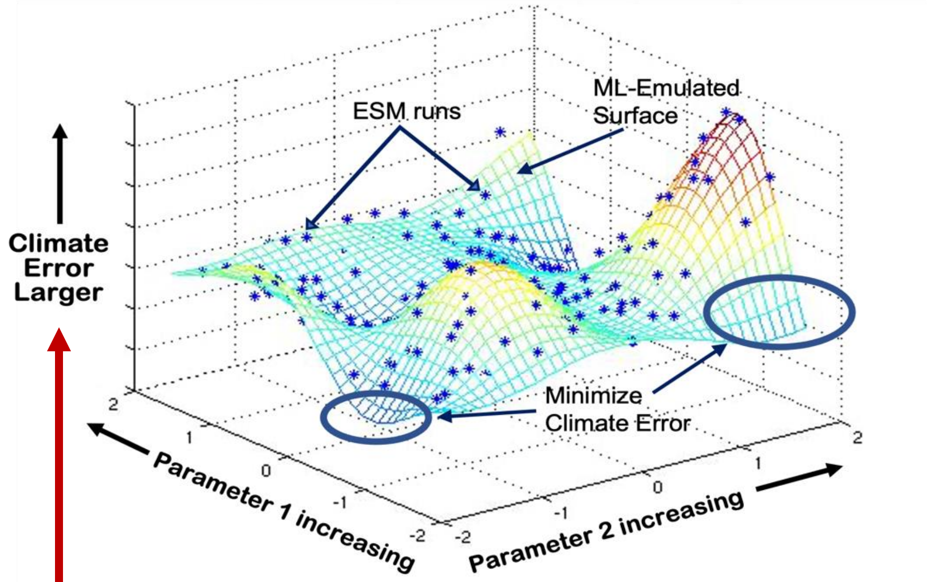




Climate Error shown as a function of 2 parameters, but really much more multi-dimensional.

Key: Climate Error Computation is Aware of Obs. Discrepancies

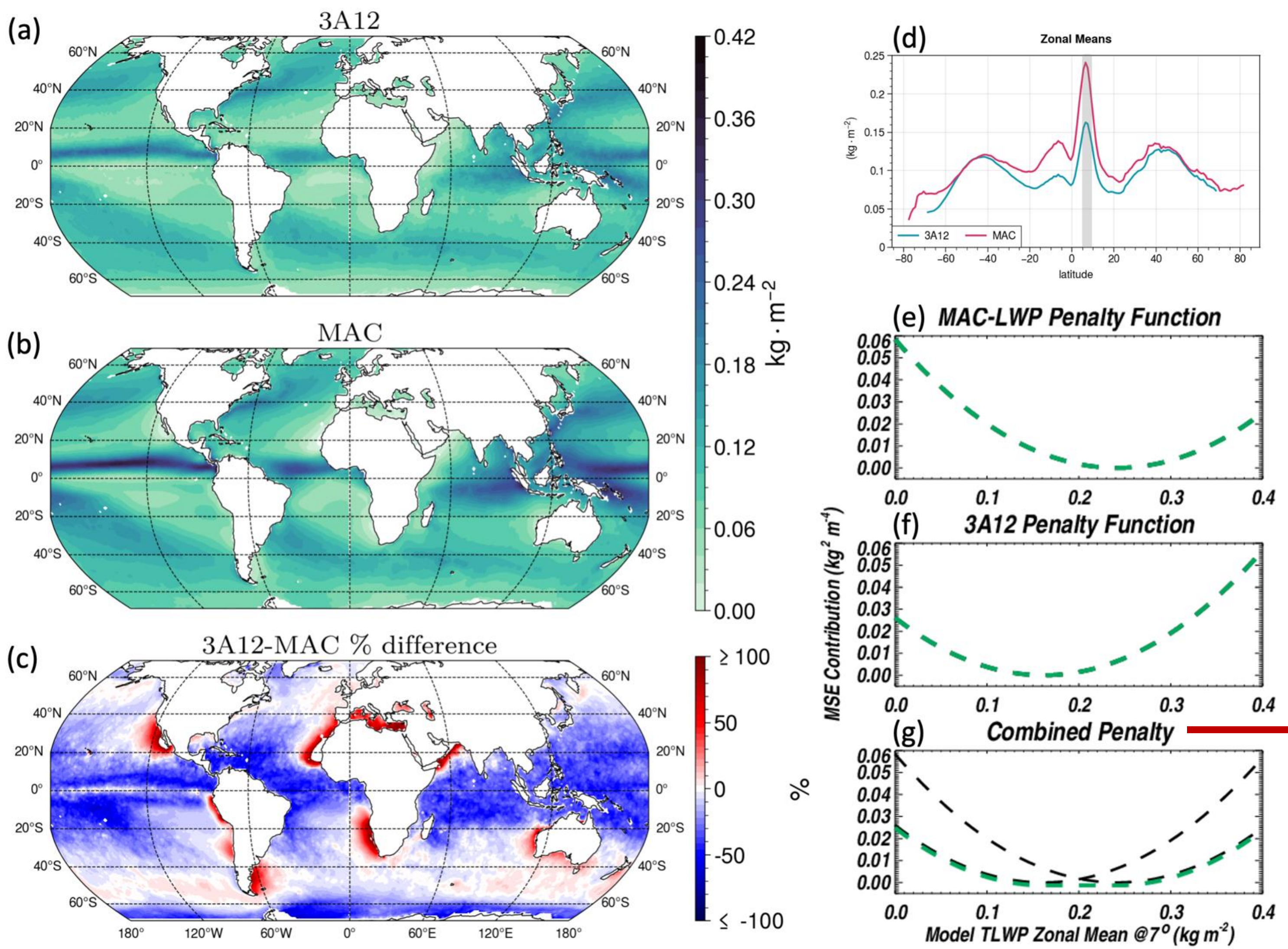


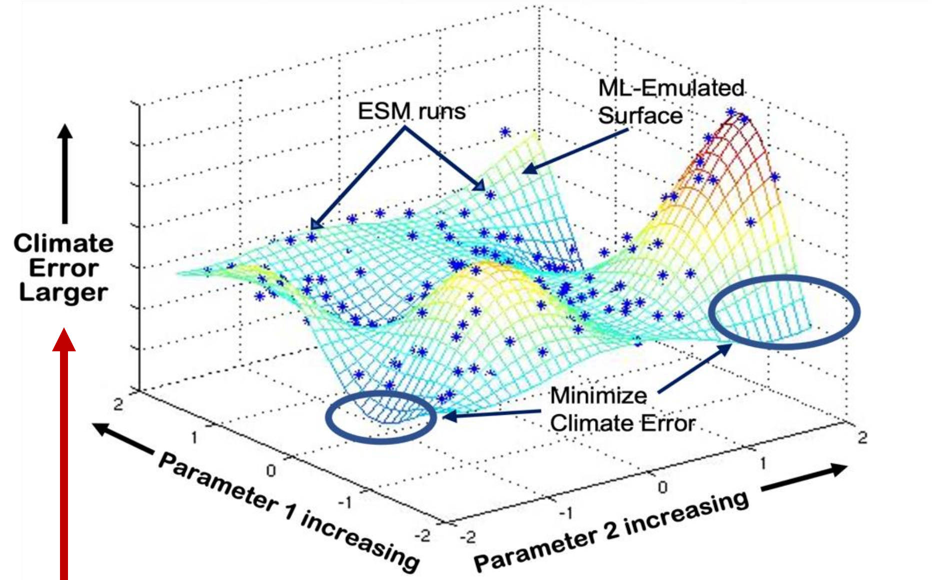


Example to LEFT of larger obs. uncertainties: liquid water path from satellites. Discrepancies are quantitatively accounted for in the model penalty (i.e., climate error) functions.

In this way, we account for systematic obs error in the emulation stage, not estimation stage.

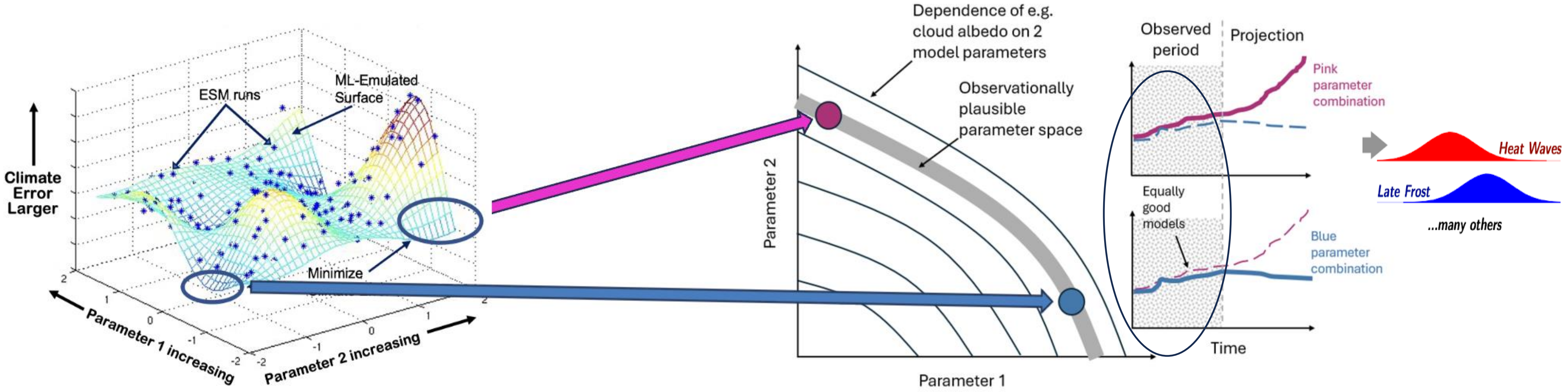
Key: Climate Error Computation is Aware of Obs. Discrepancies





Metrics (36 in total)	Data Source
Radiation (Longwave [LW], Shortwave [SW])	CERES-EBAF
Cloud Radiative Forcing (LWcrf, SWcrf)	CERES-EBAF
Column Water Vapor (CWV)	*Obs4MIPS RSS, G-VAP
Specific Humidity profiles (qv)	*Obs4MIPS AIRS, MLS
Temperature profiles (T)	*Obs4MIPS AIRS, MLS, GNSS-RO
Total Liquid Water Path (TLWP)	*MAC-LWP, GPM/TRMM
Total Ice Water Path (TIWP)	*CloudSat, MODIS
Total Precipitation (Pr)	*GPCP, GPM/TRMM
Convective Precipitation (Prc)	GPM/TRMM
Total Cloud Cover (TCC)	CloudSat/CALIPSO, ISCCP
Low (Shallow Cu, StratoCu) Cloud Cover	CloudSat/CALIPSO
Cloudtop Droplet Number Concentration (CDNC)	*MODIS (Bennartz, Grosvenor)
Surface Wind (W)	*WindSat, QuikSCAT
Liquid-to-ice transition Temperature/Height	CALIPSO

Ensemble members with small ‘climate errors’ are stored & placed in a ‘calibrated physics ensemble’ (CPE) (calibration = model output looks like satellite data).



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Using Machine Learning to Generate a GISS ModelE Calibrated Physics Ensemble (CPE)

Gregory S. Elsaesser, Marcus van Lier-Walqui, Qingyuan Yang, Maxwell Kelley, Andrew S. Ackerman, Ann M. Fridlind, Gregory V. Cesana, Gavin A. Schmidt, Jingbo Wu, Ali Behrangi ... See all authors

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Abstract | Discussion | Metrics

17 Sep 2025

Status: this preprint is open for discussion and under review for Atmospheric Chemistry and Physics (ACP).

Opinion: The importance and future development of perturbed parameter ensembles in climate and atmospheric science

Ken S. Carslaw, Leighton A. Regayre, Ulrike Proske, Andrew Gettelman, David M. H. Sexton, Yun Qian, Lauren Marshall, Oliver Wild, Marcus van Lier-Walqui, Annika Oertel, Saloua Peatier, Ben Yang, Jill S. Johnson, Sihan Li, Daniel T. McCoy, Benjamin M. Sanderson, Christina J. Williamson, Gregory S. Elsaesser, Kuniko Yamazaki, and Ben B. B. Booth

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Short summary

A major challenge in climate science is reducing projection uncertainty despite advances in...
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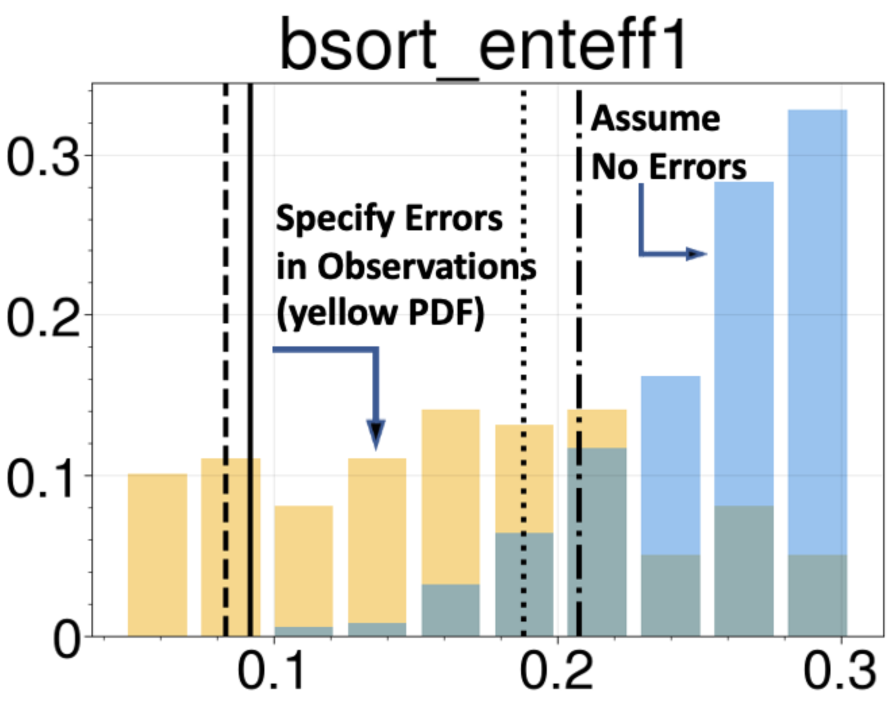
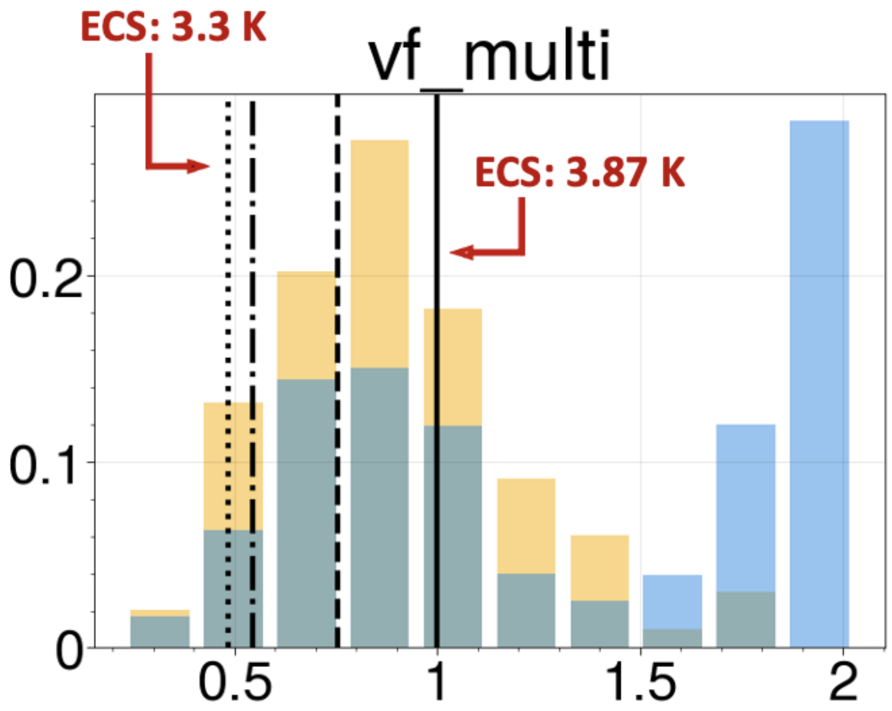
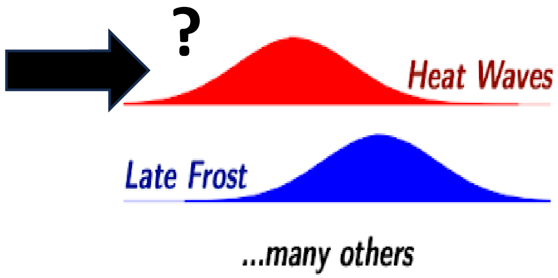
Did inclusion of observational product discrepancy matter in the estimation (or ‘retrieval’) of ESM physics parameter $\boldsymbol{P_{exp}}$ vectors?





Remember previous slide!

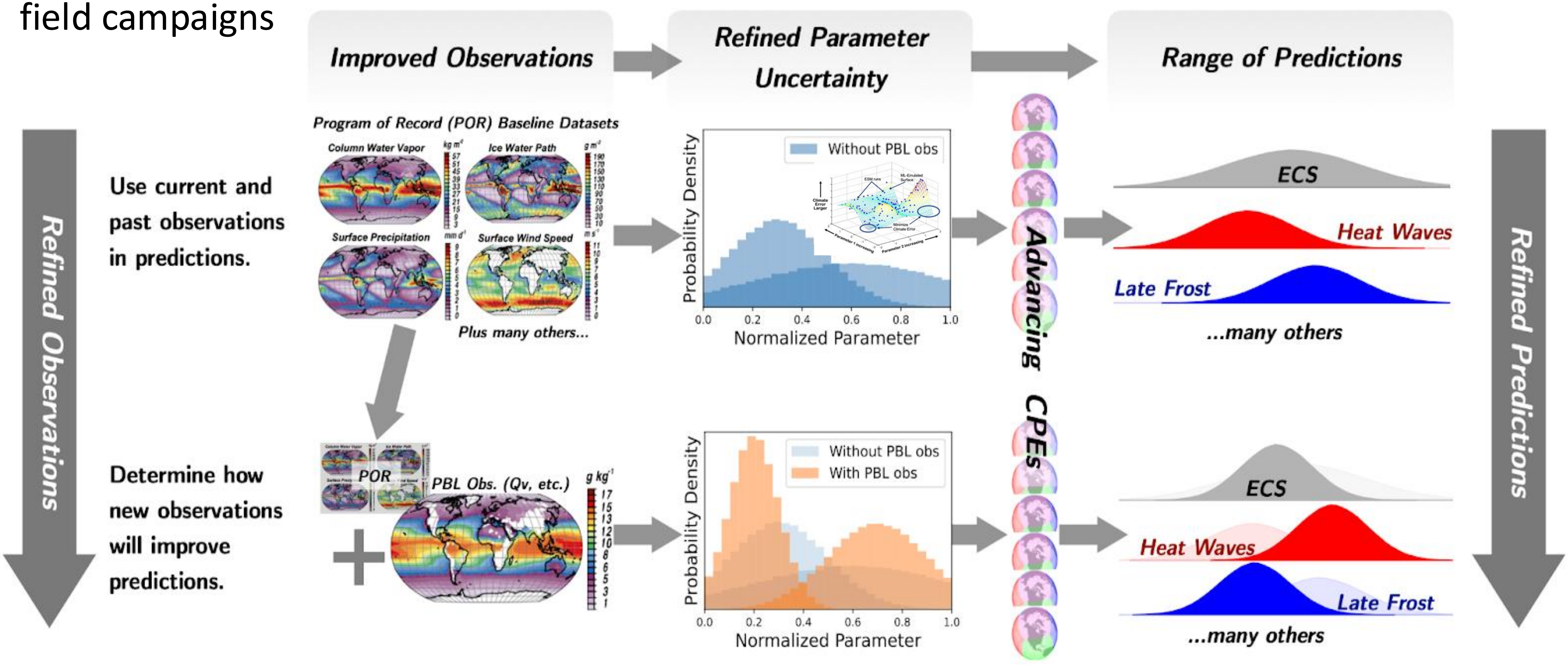


Sometimes specified observational error matters a lot!
(and thus, this impacts the projection envelope).

Elsaesser et al. (2025, JAMES)

Putting it all together: CPEs and ESM 'OSSEs'

Conceptual schematic for establishing value of not-yet available observations (or use of them on different timescales) in prediction constraint, and design of future satellite missions and field campaigns

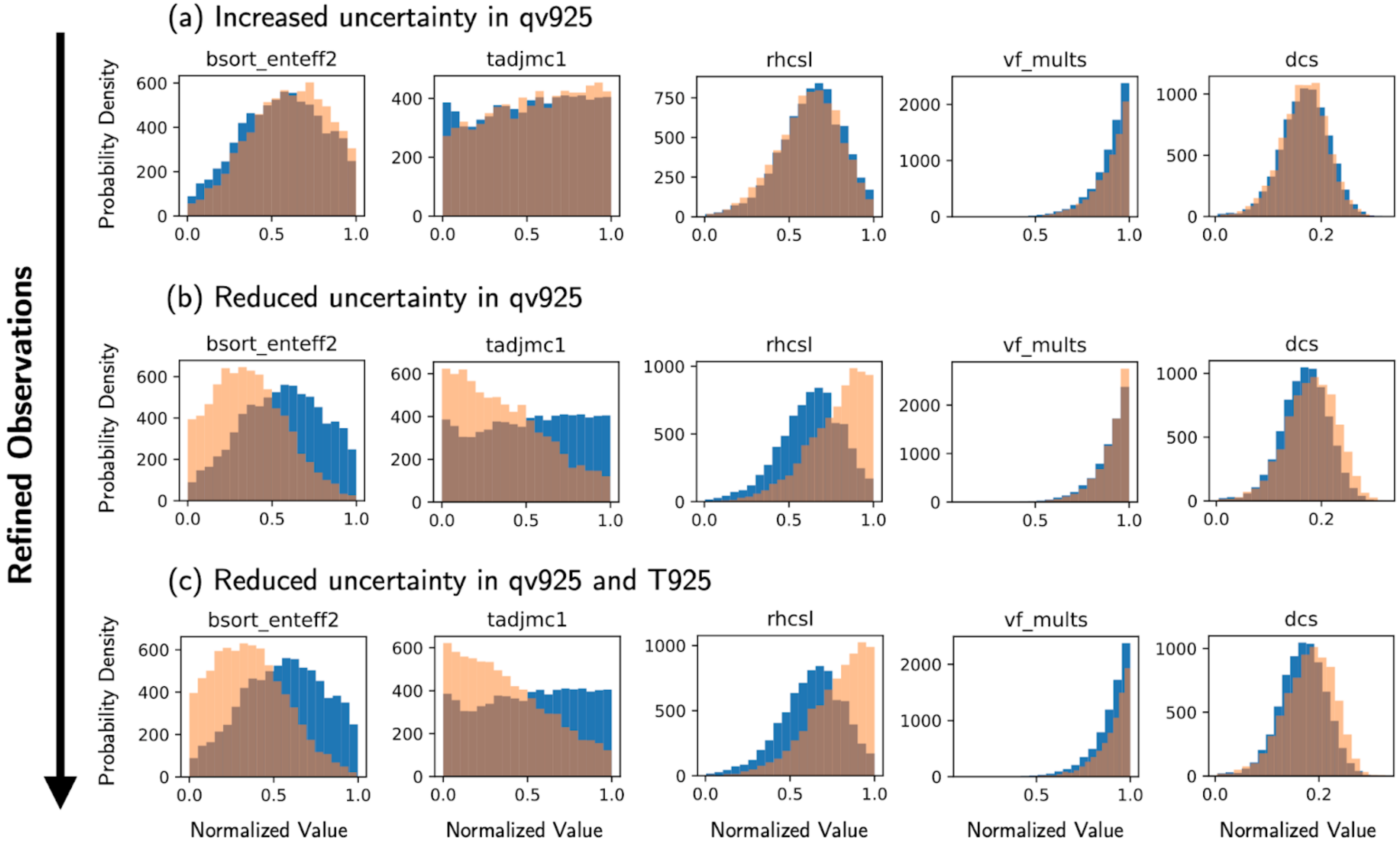


Proof of Concept on value of reducing uncertainty in AIRS retrievals (i.e., a PBL mission)

Proof of concept using planetary boundary layer water vapor and temperature (currently not well observed).

Imagine if we could improve these obs.

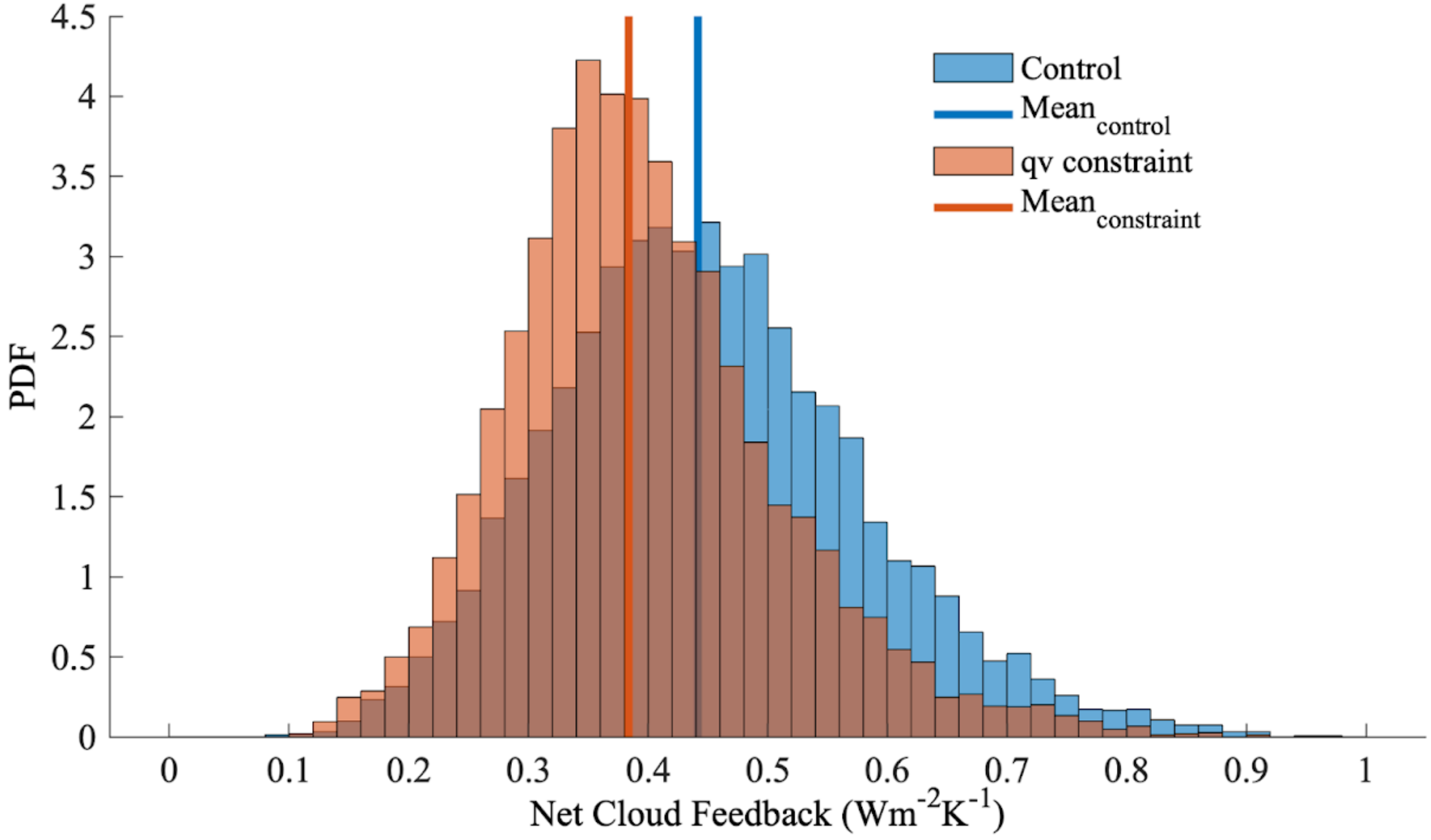
Would it even impact parameter settings and cloud feedback estimates?

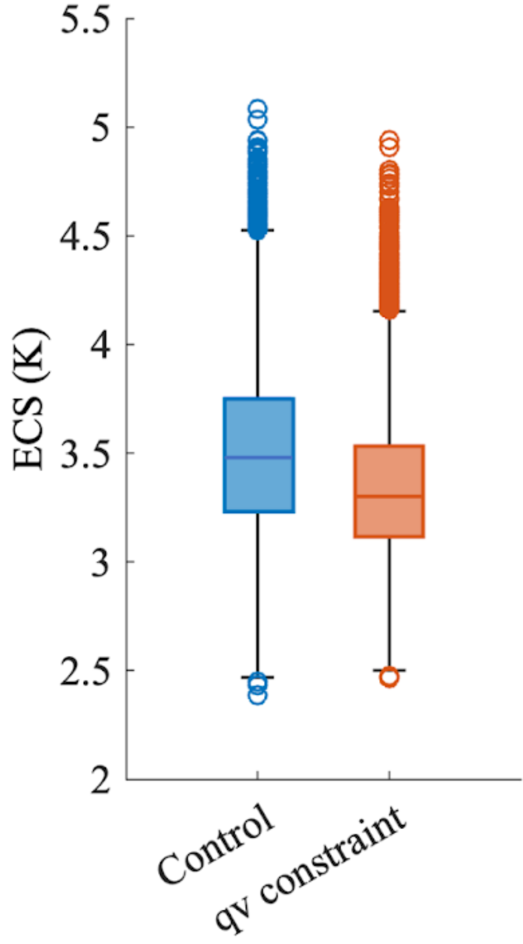


BAMS article, Fridlind, Elsaesser, van Lier-Walqui, and multi-modeling group contributions

Proof of Concept on value of reducing uncertainty in AIRS retrievals (i.e., a PBL mission)

How much constraint do we get with improved obs?





Can do this with more: use of joint rainfall and water vapor variability on hourly timescales, vertical motion in clouds, … we can now emulate most things!

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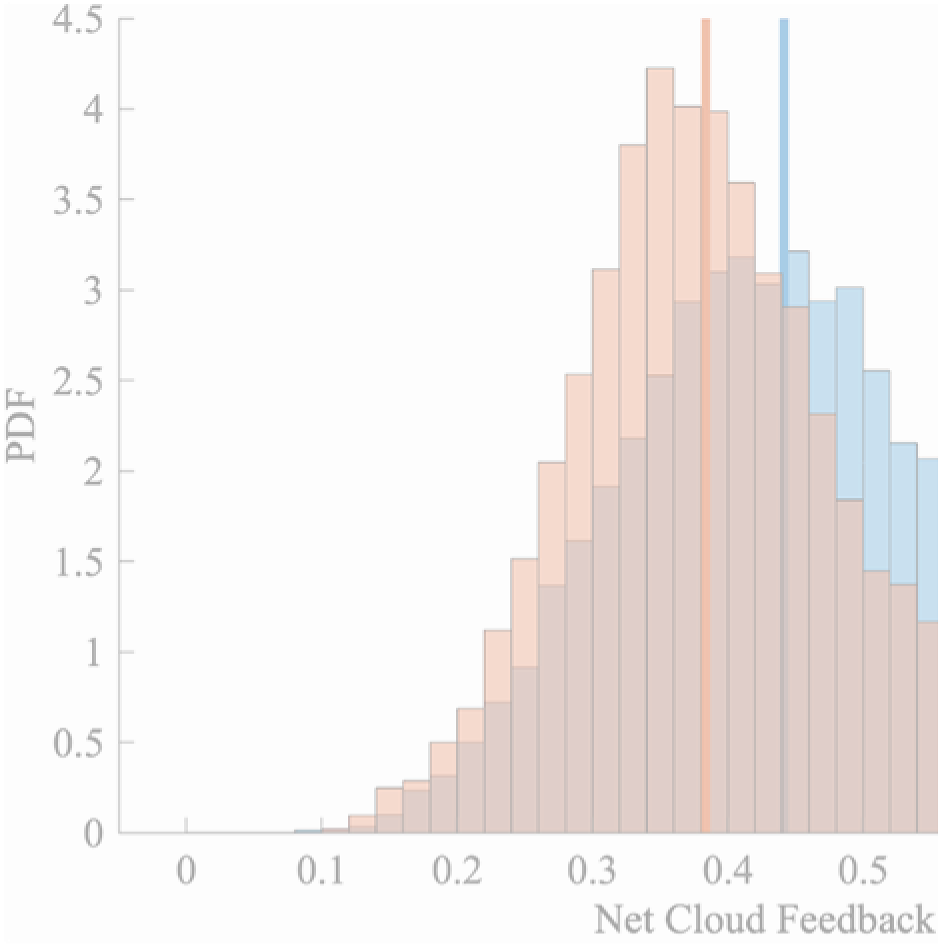

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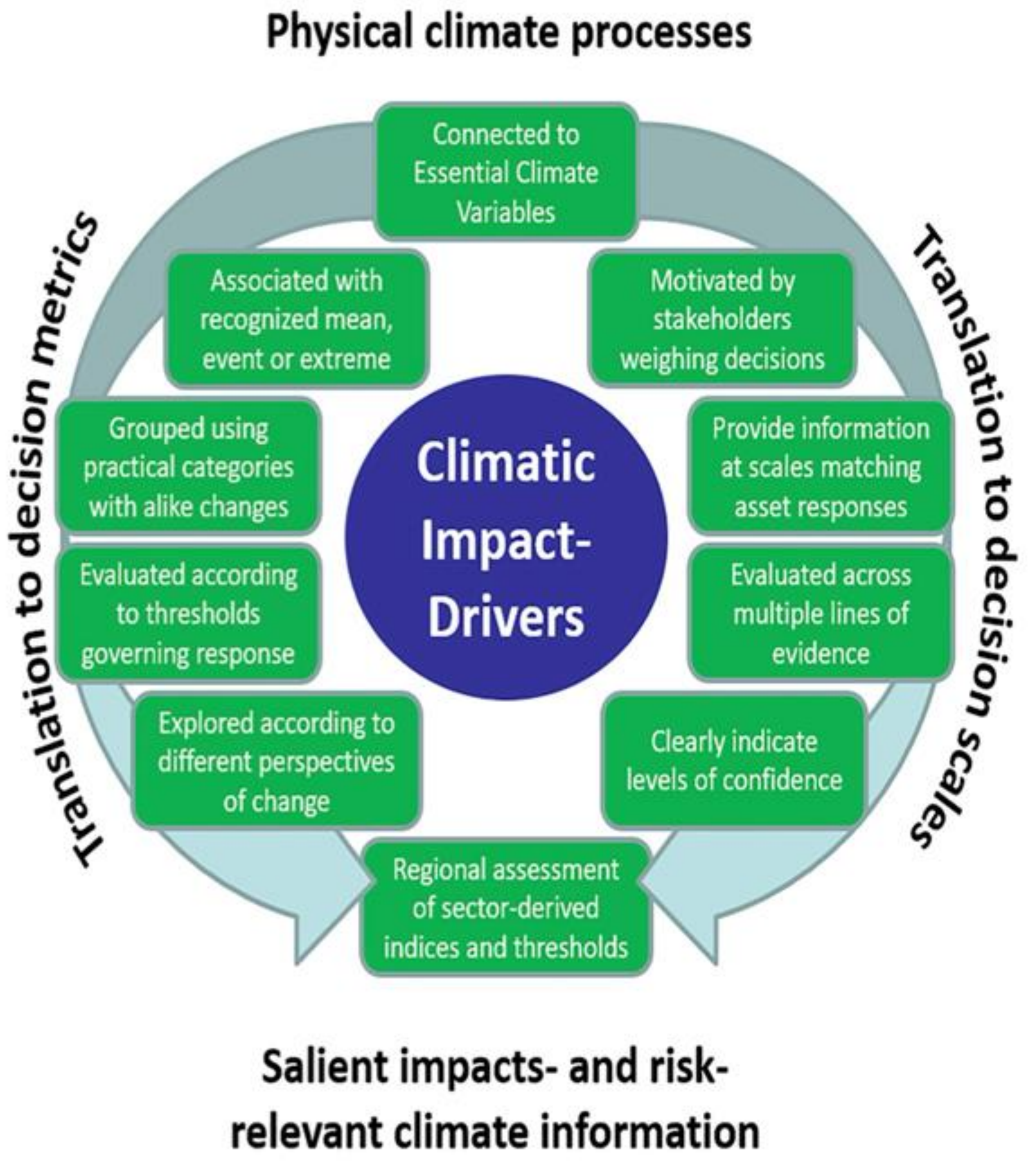

Ruane et al. 2022, *Earth's Future*

Conclusions

- ❖ With use of ML as an ESM surrogate, and a more complete (new?) use of existing obs datasets, we can establish multiple ESM calibrated physics ensembles (where each member has a projection estimate).
- ❖ This would yield a baseline at present for ESMs – then, we can run them in ‘reverse’, and find what observations+/-err change the ensemble and thus their emergent projection envelopes. “Decadal and Longer, A Climate OSSE”
- ❖ Can we uniformly establish which obs constrain similarly across ESMs?

CPE, Elsaesser et al. (2025, JAMES)

ClimateOSSE, Fridlind et al. (2025, BAMS)

Carslaw et al. (2025, ACP in rev.)