Institute for Climate & Atmospheric Science
SCHOOL OF EARTH AND ENVIRONMENT

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Perturbed parameter ensembles as a way to improve models and understand system behavior

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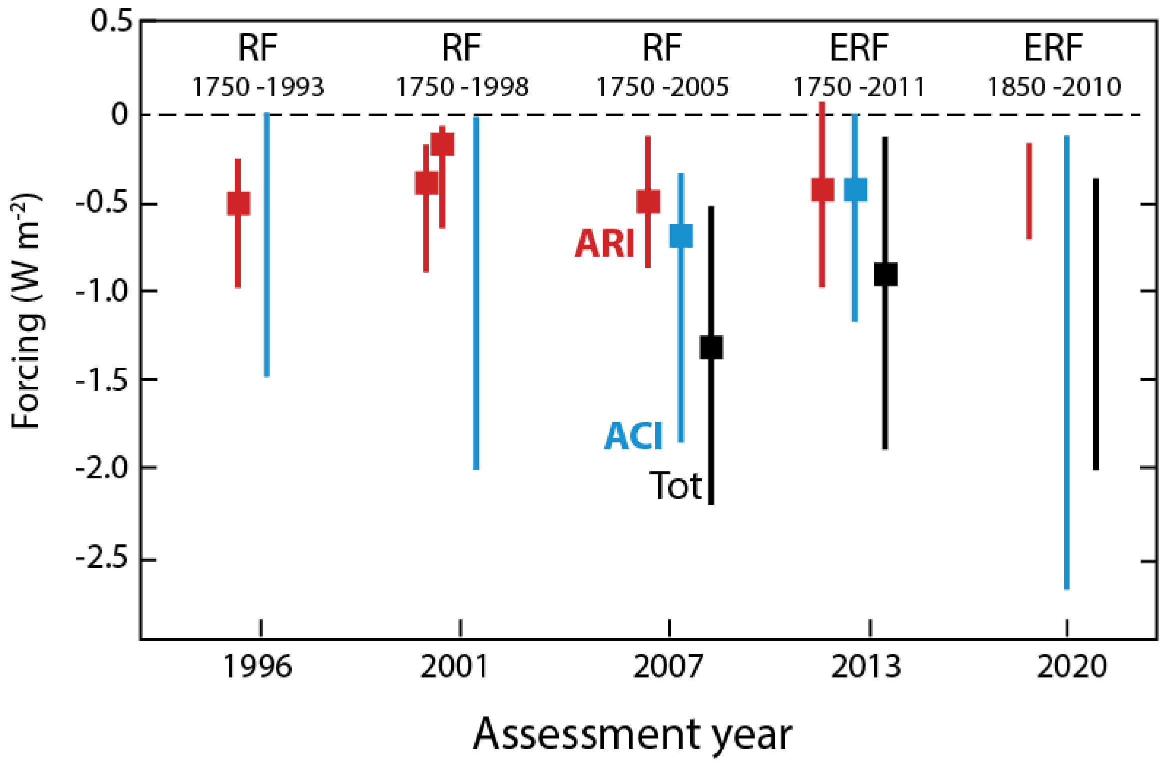
Aerosol radiative forcing uncertainty



How do we reduce uncertainty?

Constraining models – e.g., using observations to constrain dozens of uncertain model parameters

Making models better – detecting and attributing structural deficiencies

Understanding processes – e.g., how clouds respond to aerosols in an environment with many confounding factors

Carslaw (2022) Aerosols and Climate, Ch2

Approach to model development and tuning

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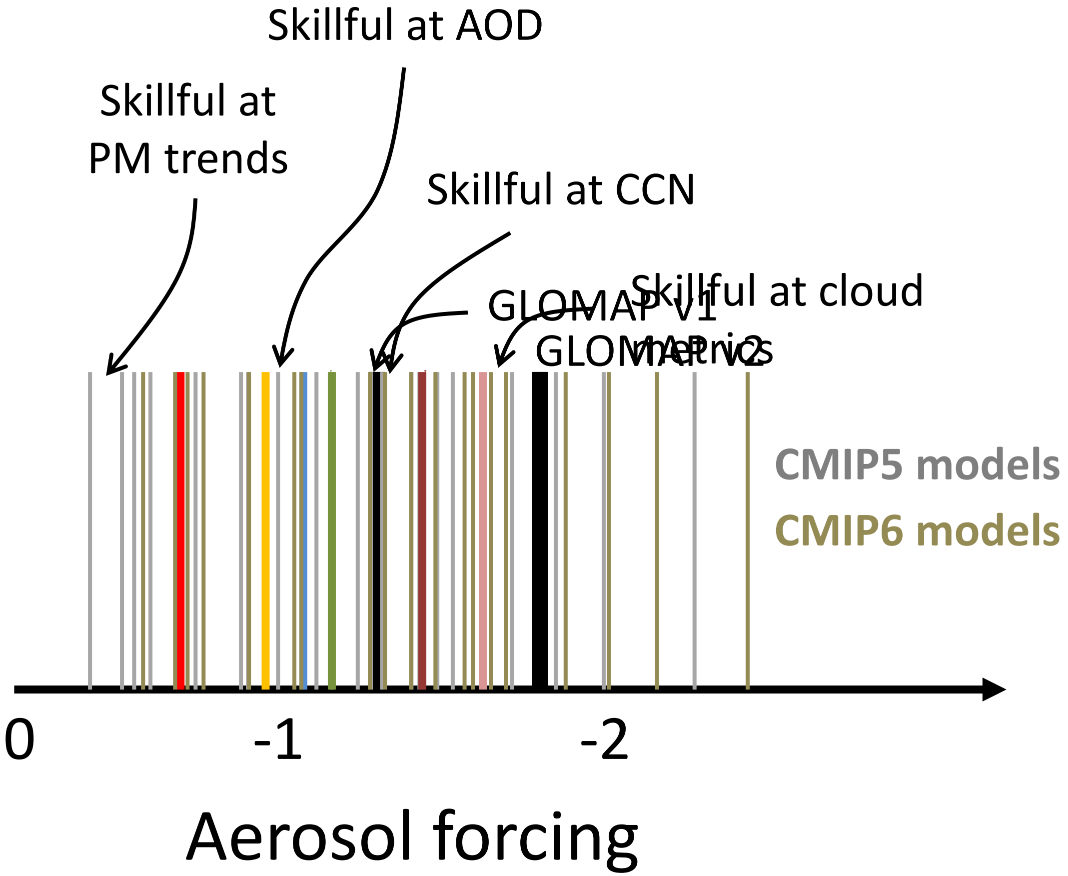

Different parameterizations (structural uncertainty)
Different parameter settings (parametric uncertainty)

A sampling problem

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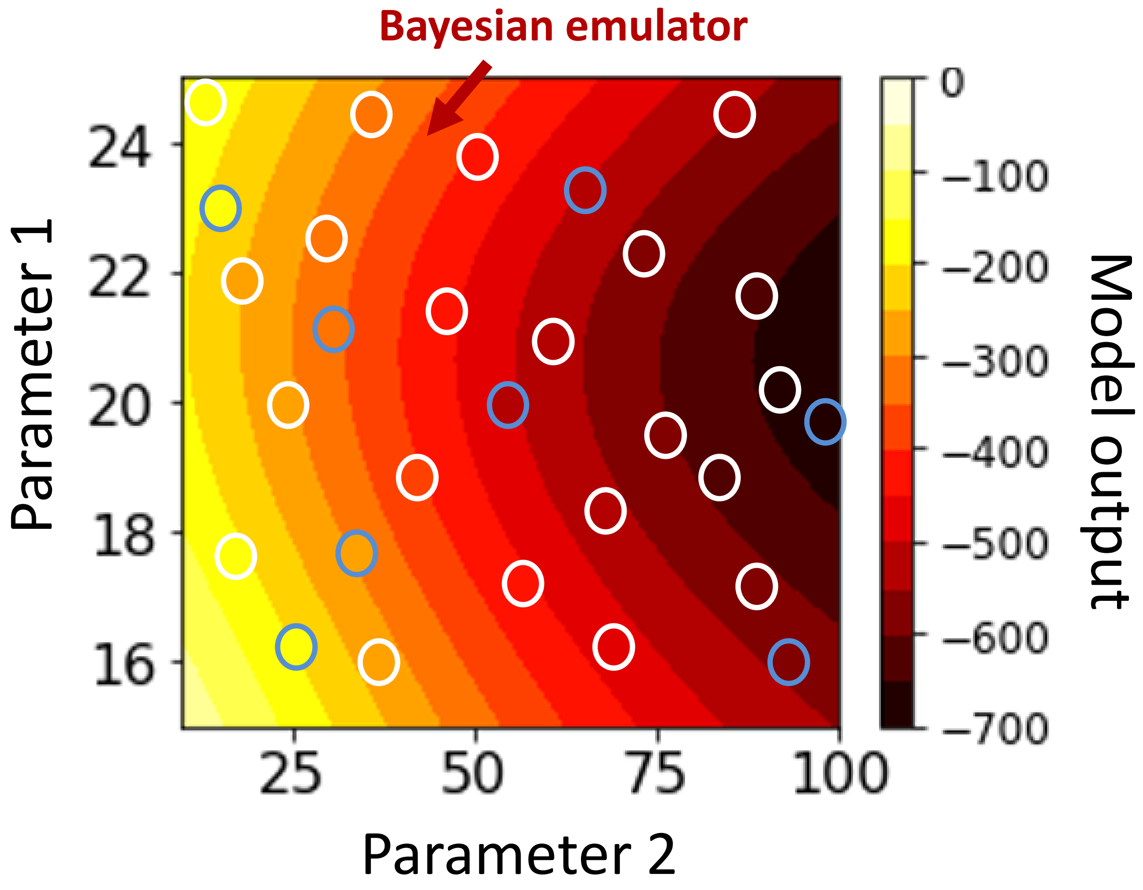
- Our models and our natural systems of interest are **controlled by many factors** (many structures, parameters and environmental conditions)

- Models are expensive to run

- We therefore usually only sample tiny parts of the 'parameter space'

Increasing the model sampling density



- A **perturbed parameter ensemble** (PPE) is a set of model simulations designed to optimally sample combinations of model inputs

- Designed to train a statistical emulator

→ Can then generate **~millions of "model variants"**

Oakley and O'Hagan, Probabilistic sensitivity analysis of complex models: A Bayesian approach, J. Roy. Stat. Soc. B (2004).

Lee et al. Emulation of a complex global aerosol model, ACP (2011)

Observational constraint using a PPE

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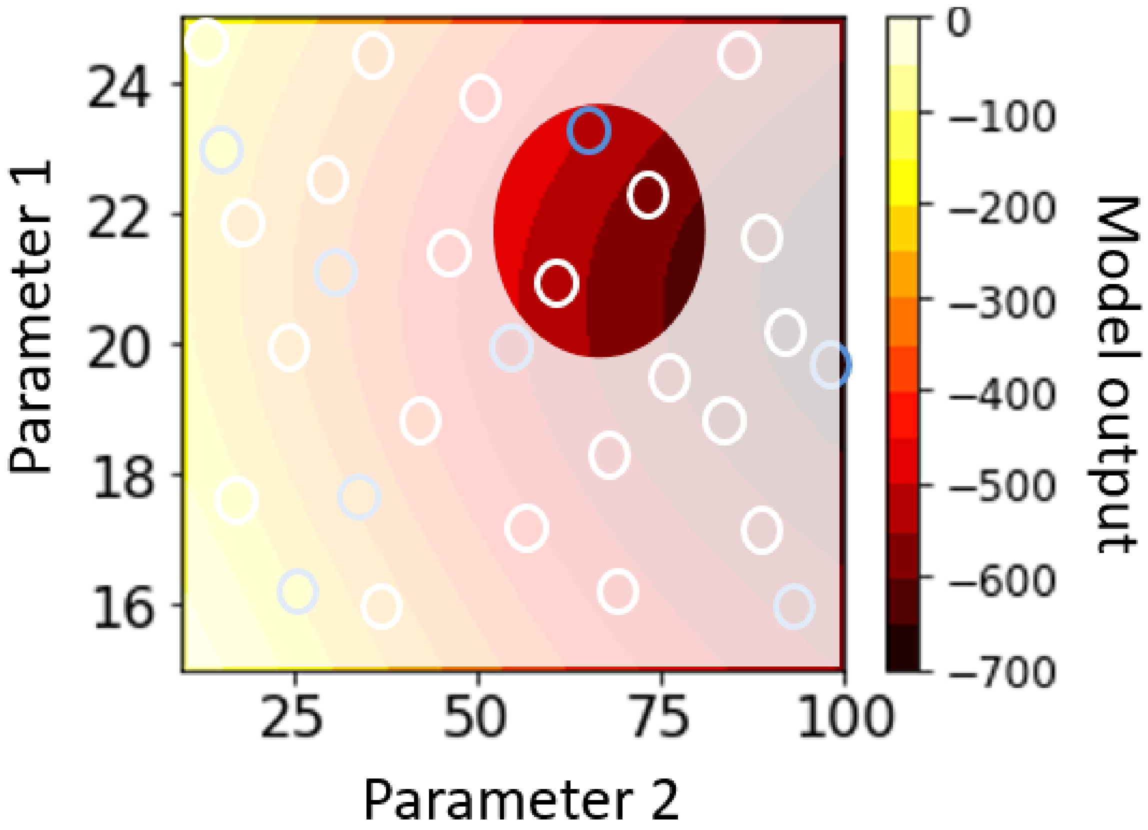

Compare PPE/emulator results against observations

→ Constrains the parameter ranges (to a joint observationally plausible range)

→ Constrains range of model outputs (e.g., reduces uncertainty in forcing)

A PPE of the HadGEM GCM with **26 aerosol-related parameters**

(emissions, aerosol processes, removal rates, chemistry, etc.)

Johnson et al. (ACP 2020)

Robust observational constraint of uncertain aerosol processes and emissions in a climate model and the effect on aerosol radiative forcing

Observations used for constraint

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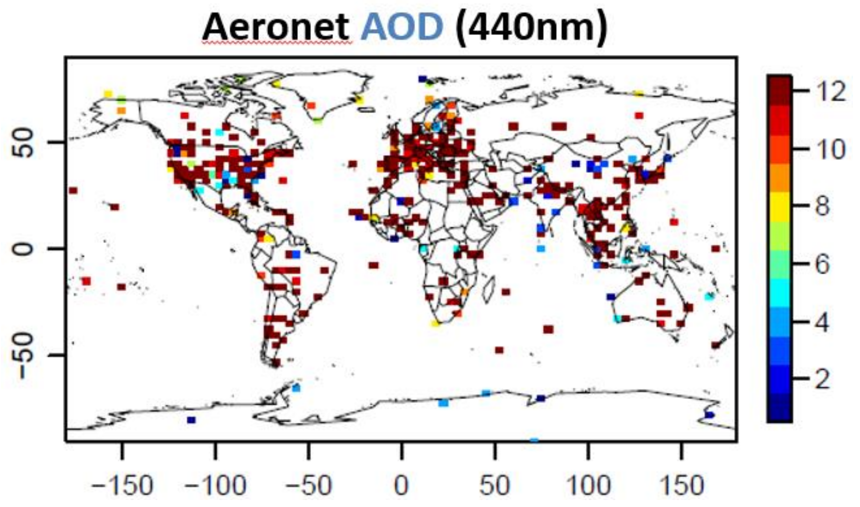
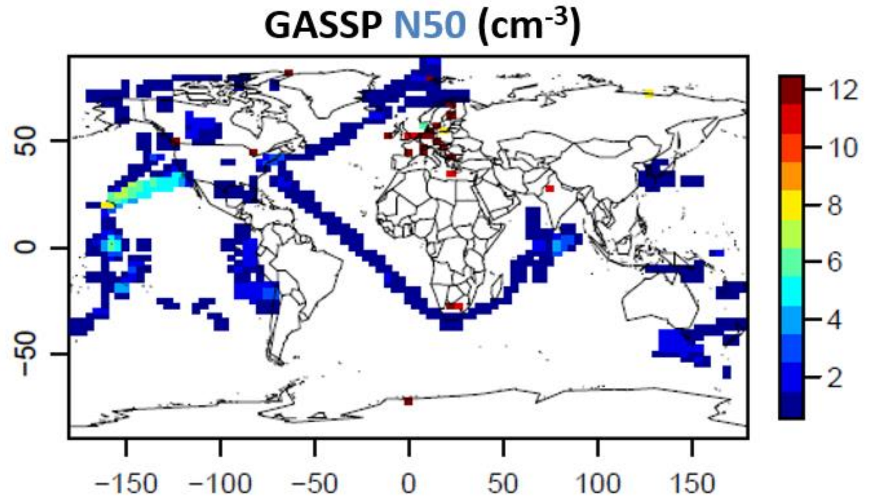




~9000 grid-point aggregated measurements of:

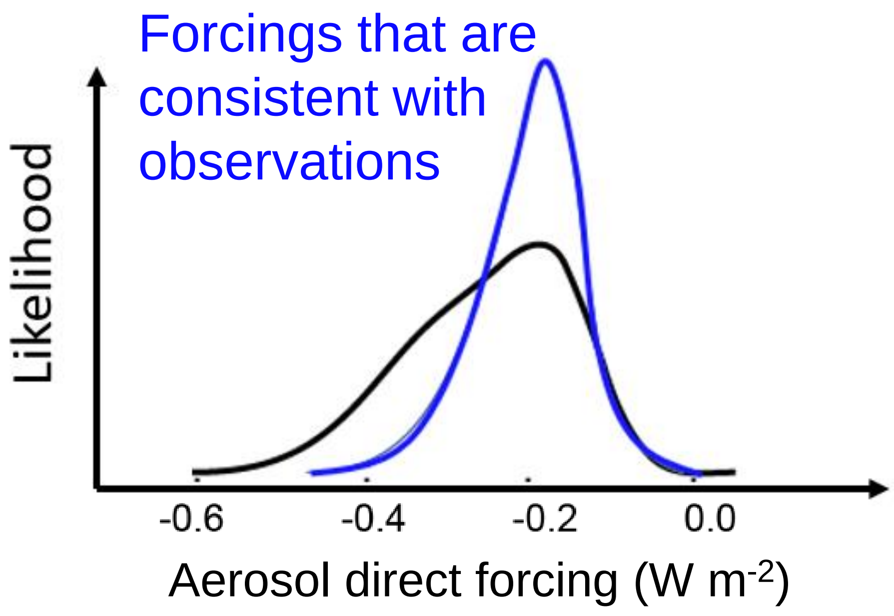
- Aerosol optical depth
- $PM_{2.5}$
- Aerosol concentration ($N_{>3nm}$)
- ~CCN concentration ($N_{>50nm}$)
- Sulphate mass
- Organic carbon mass

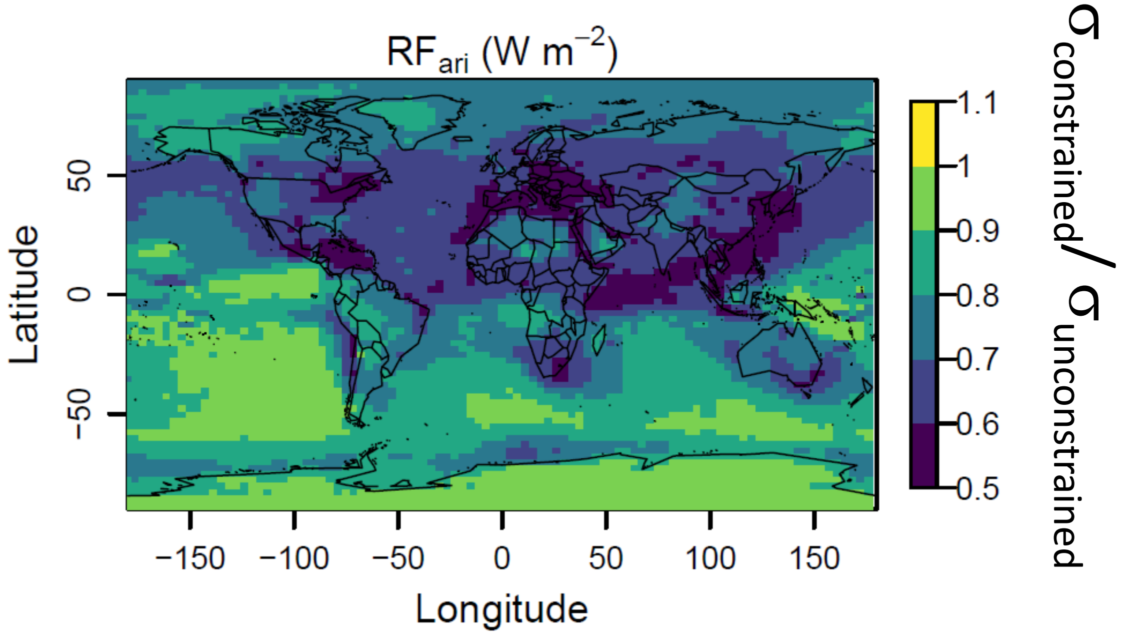
Observational constraint of aerosol forcing

Observations

Constrained parameter space

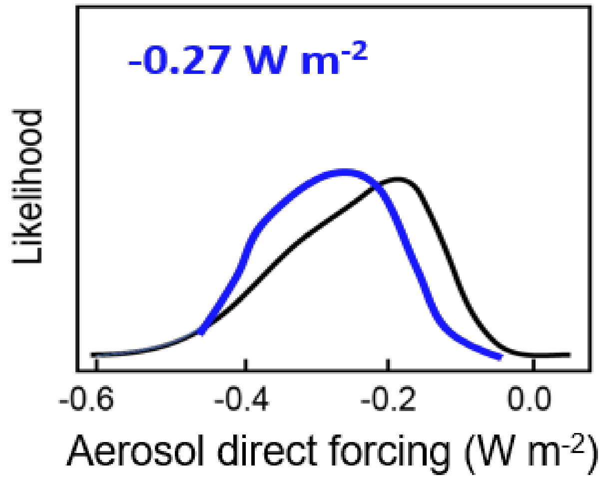
Constrained Forcing



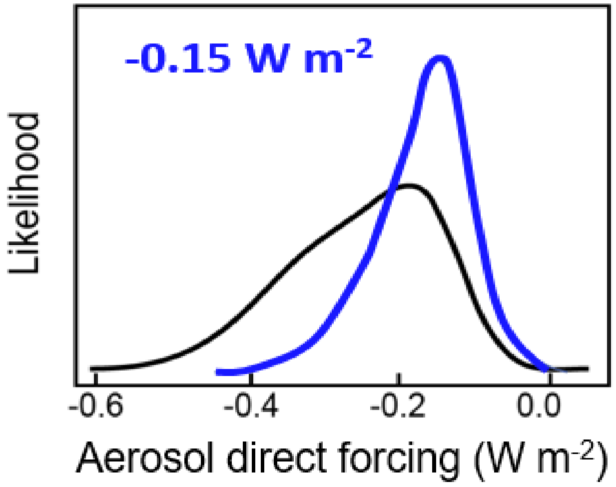


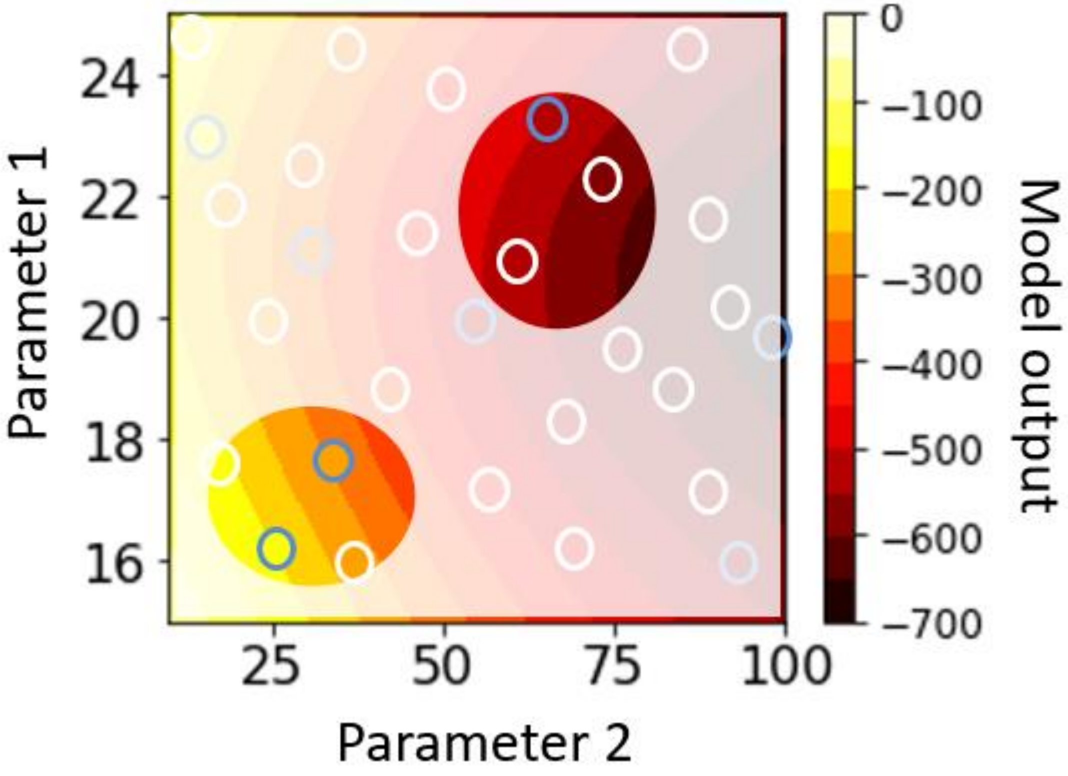
Exposure of a structural error in the aerosol model

Forcing constrained by **$PM_{2.5}$**



Forcing constrained by **Sulphate**





The model doesn't include nitrate aerosol, so constraining $PM_{2.5}$ forces sulfate to be too high

A PPE of the HadGEM GCM with **37 aerosol, cloud and physical climate parameters**

(emissions, aerosol processes, radiation, cloud processes, aerosol-cloud interaction, etc.)

Regayre et al. (ACP 2023)
Identifying climate model structural inconsistencies allows for tight constraint of aerosol radiative forcing

HadGEM PPE spread

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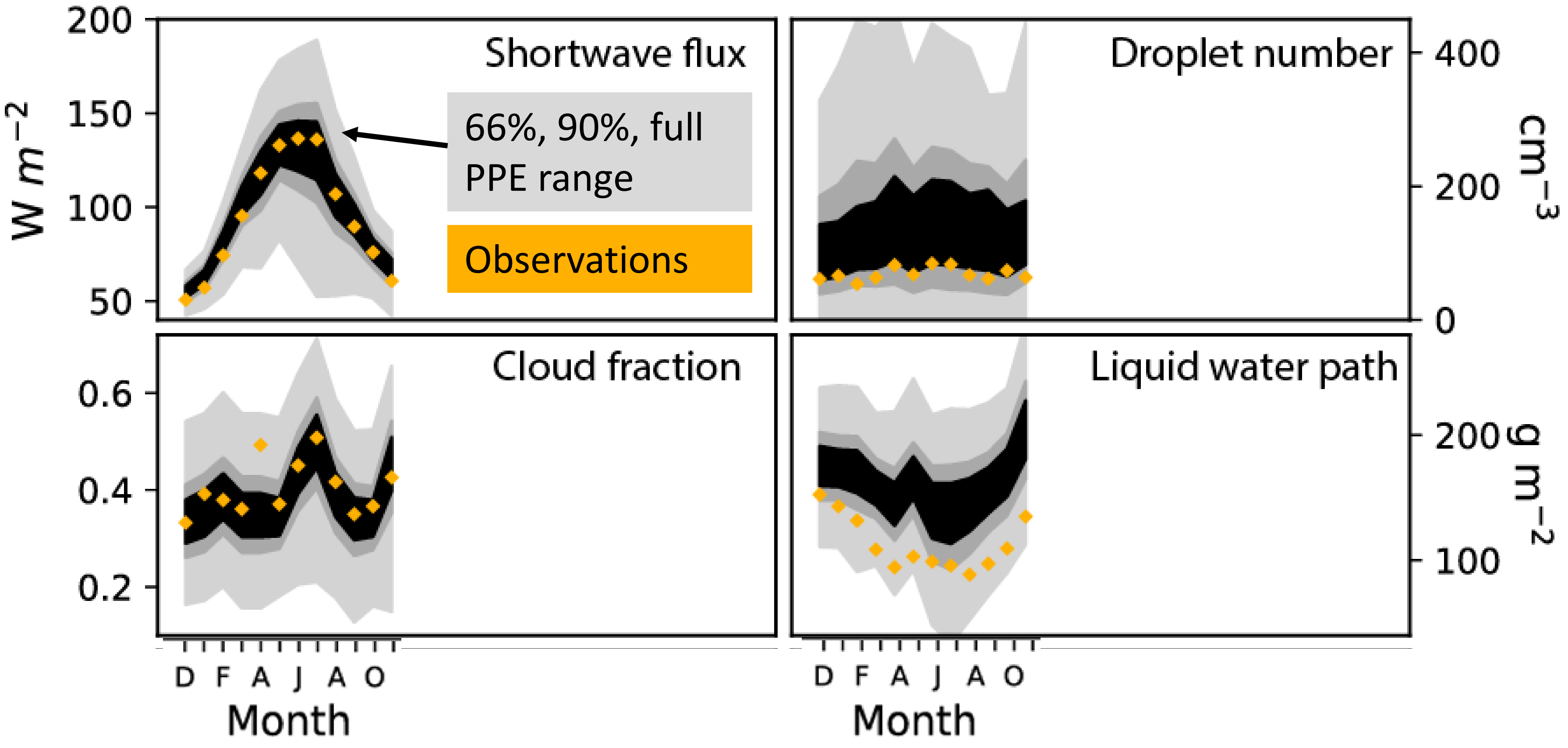

N Atlantic shallow cloud properties

Constraint of droplet number

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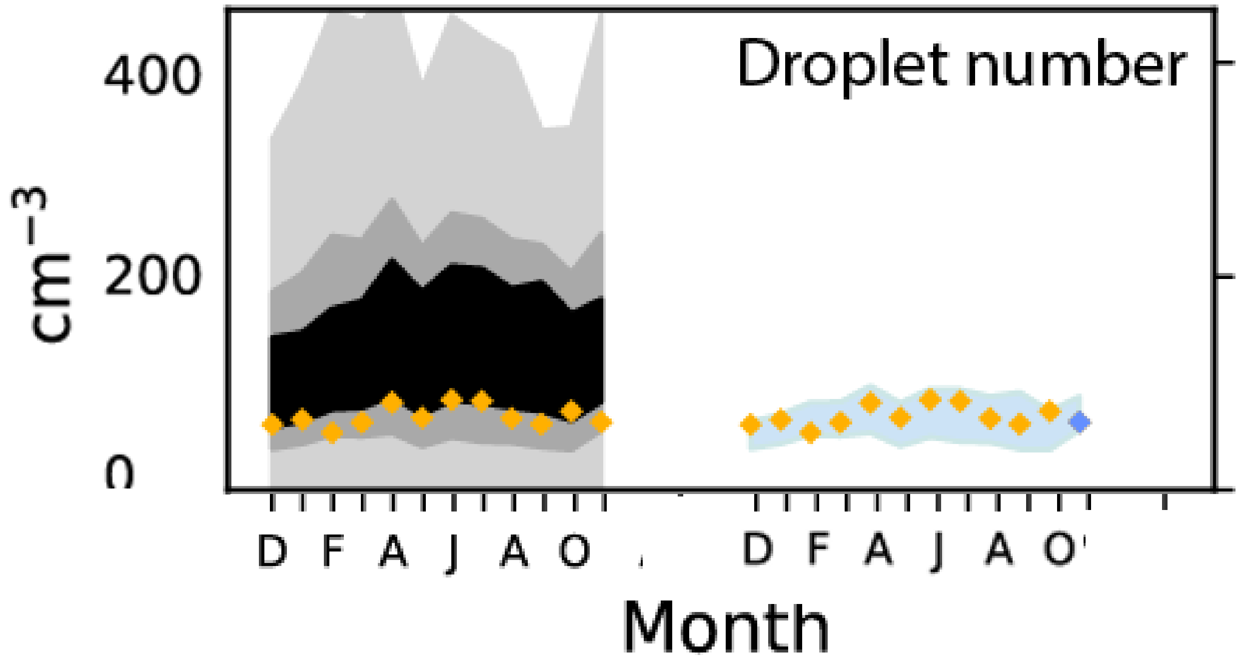
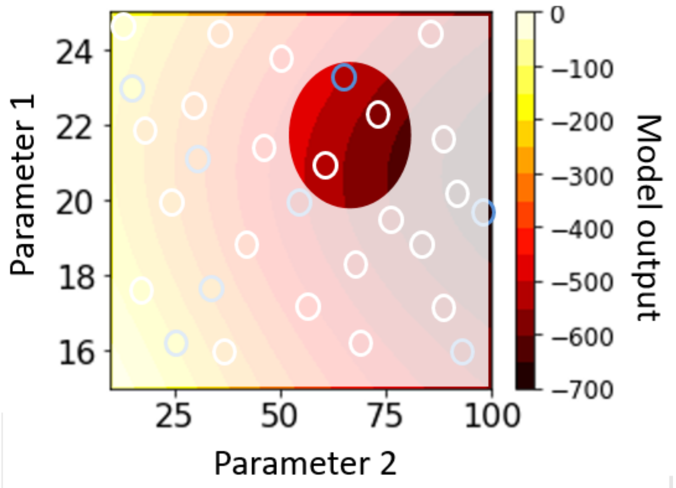
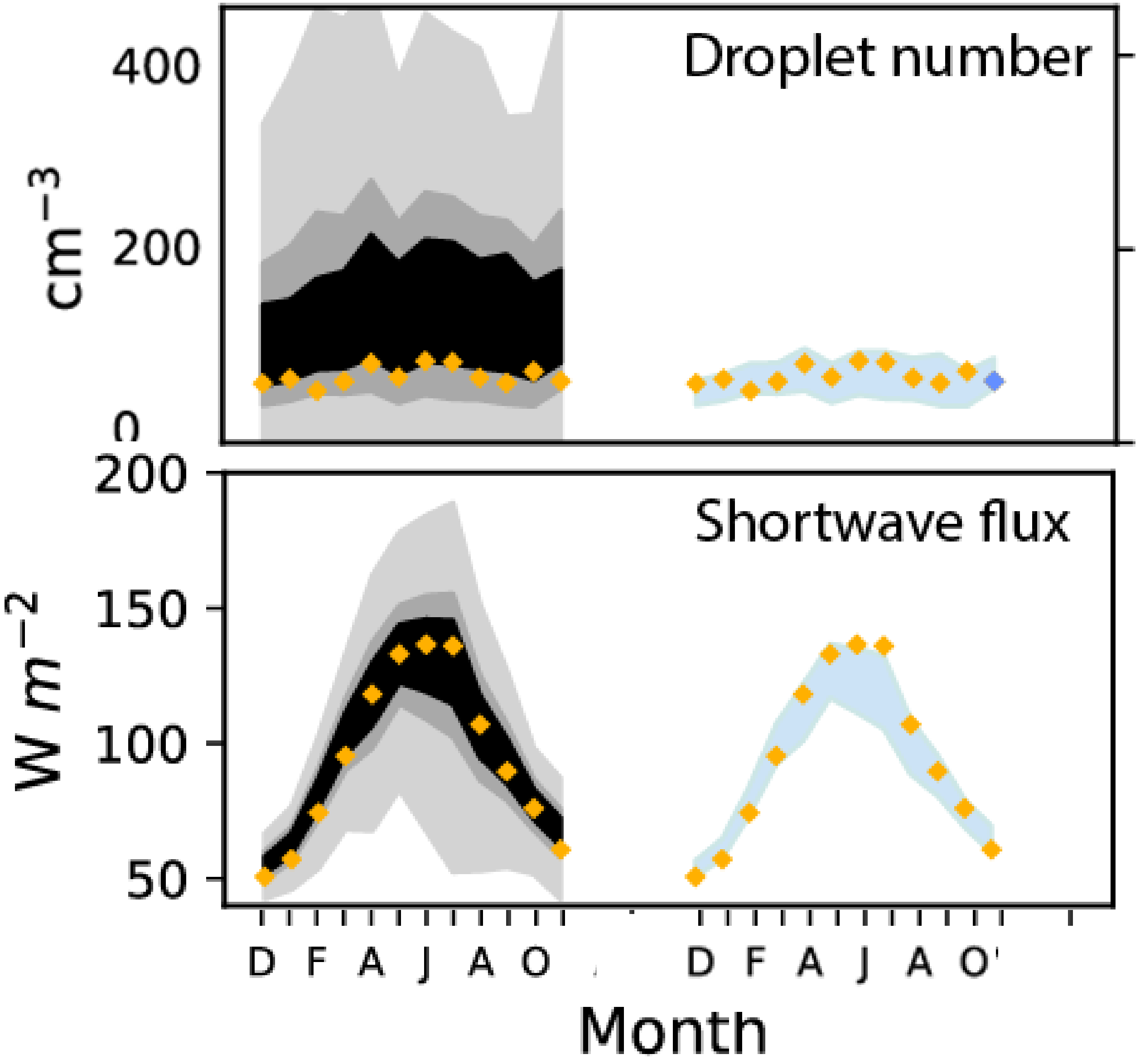


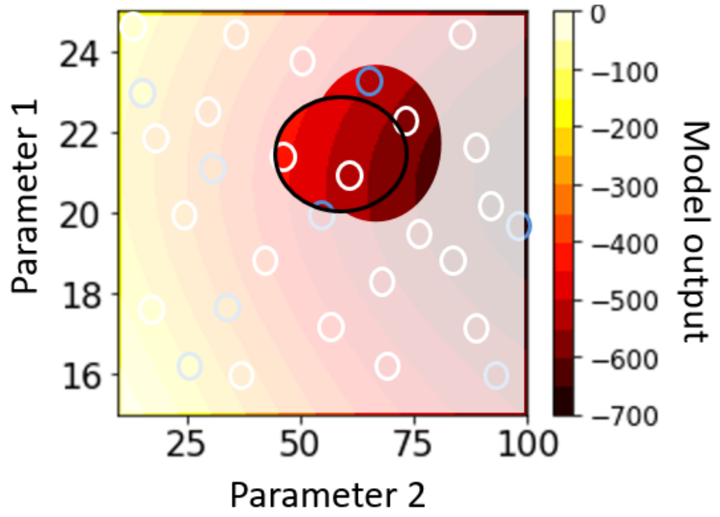
Constraining droplet number in 1 month (November) constrains all other months consistently



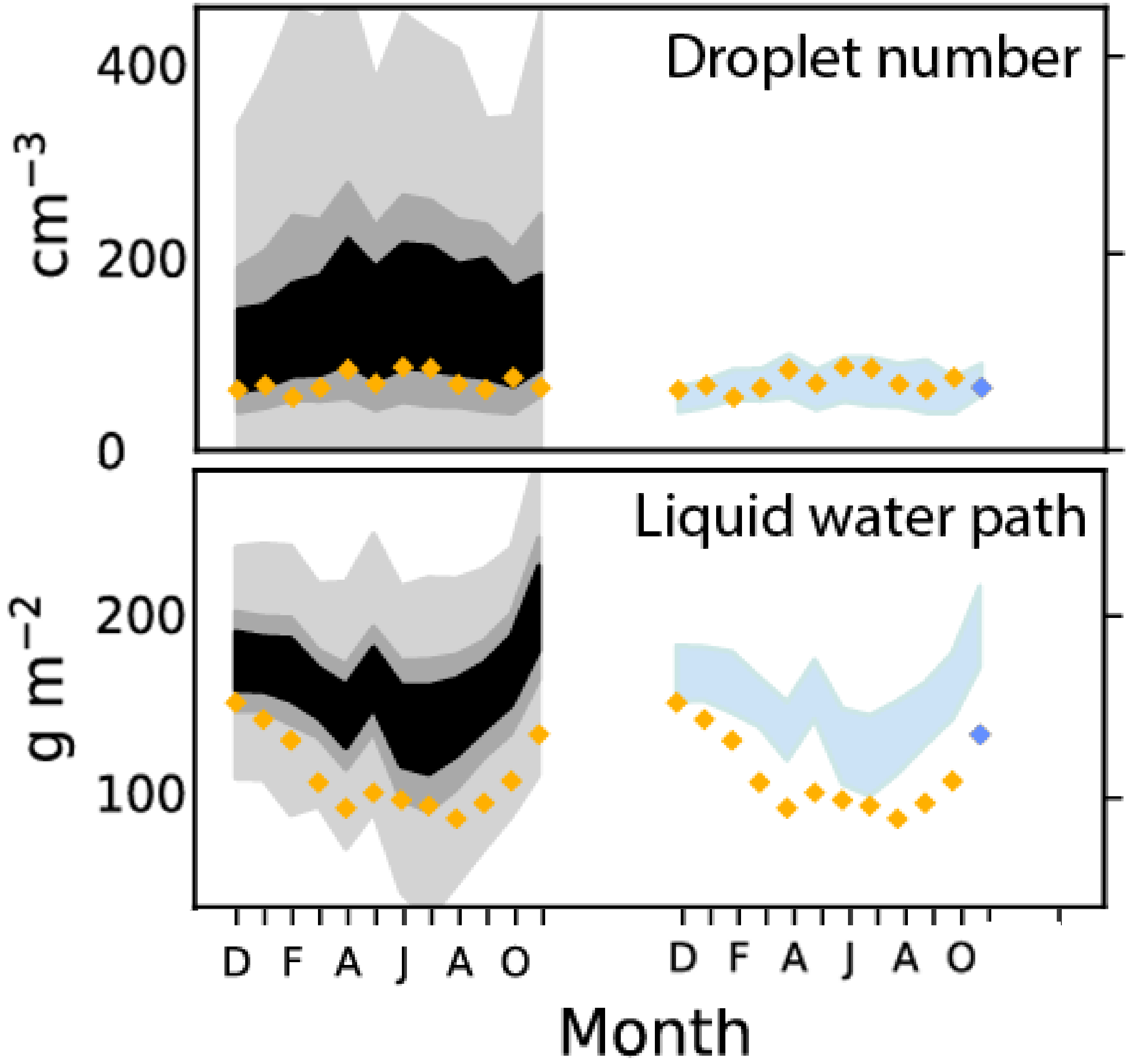
Constraint of droplet number



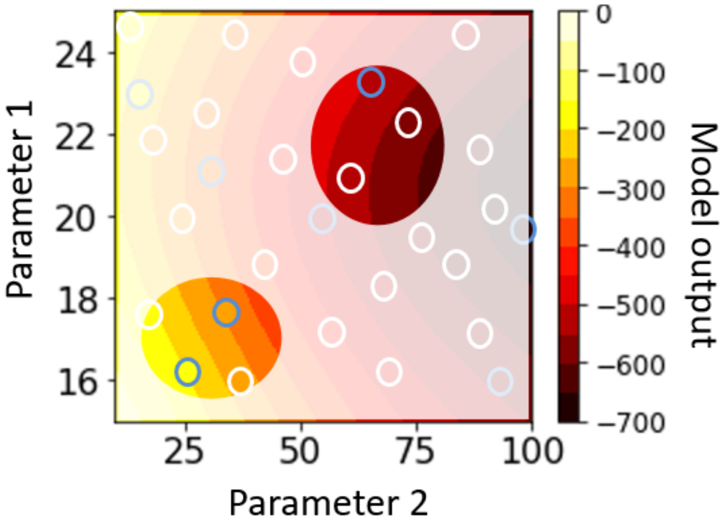
Constraining droplet number constrains **shortwave flux**



Constraint of droplet number



Constraining droplet number causes a large bias in **liquid water path**



Hints about structural errors

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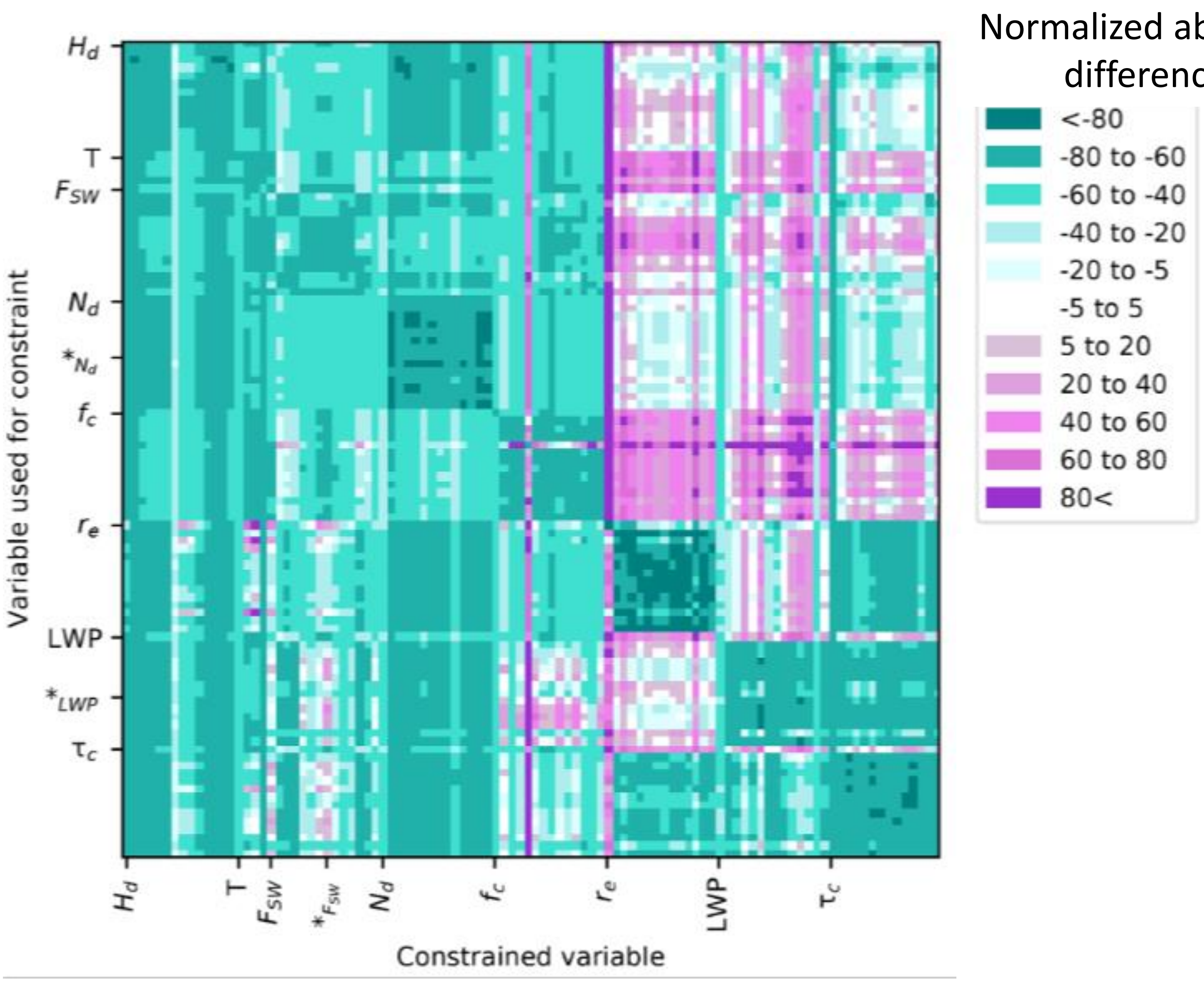
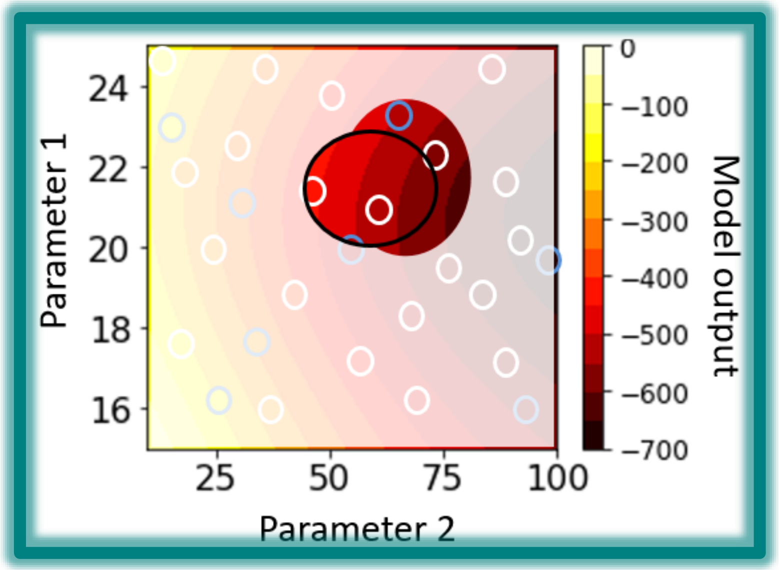
- Liquid water path and droplet number are inconsistent (constraining one creates a bias in the other)

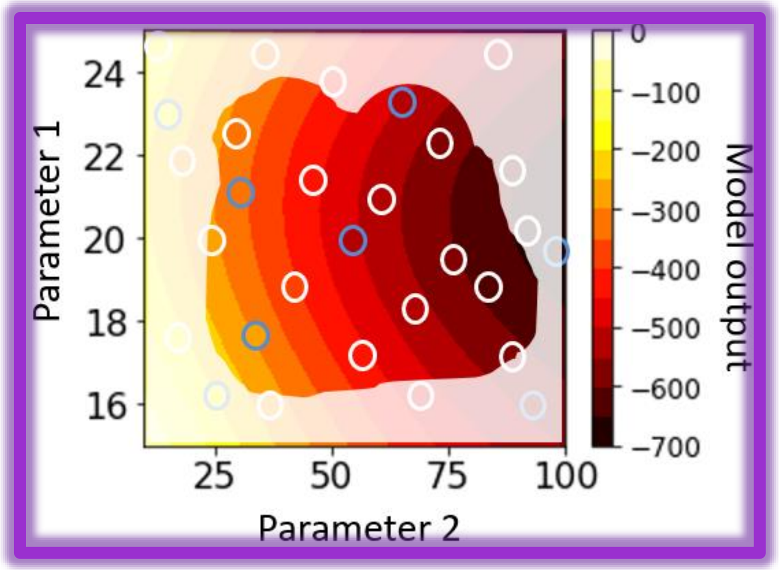
Why?

- The model has single-moment cloud microphysics
- Removal of cloud water (LWP) doesn't affect droplet number

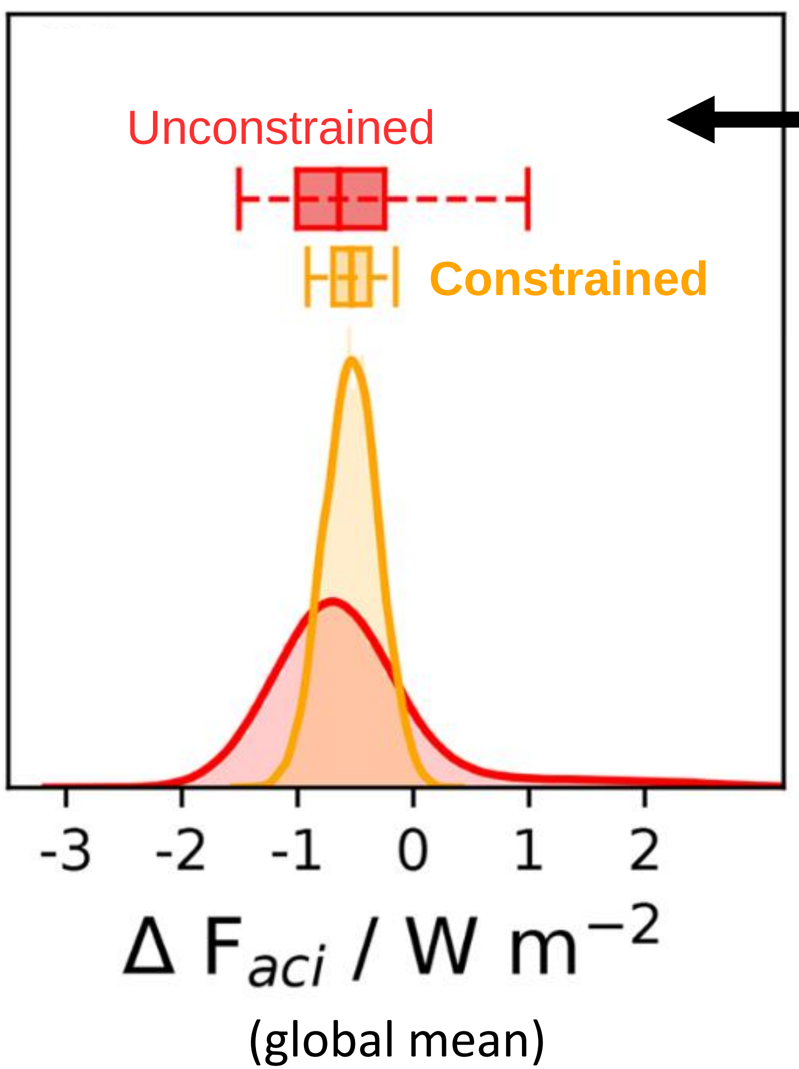
Testing all pairs of variables







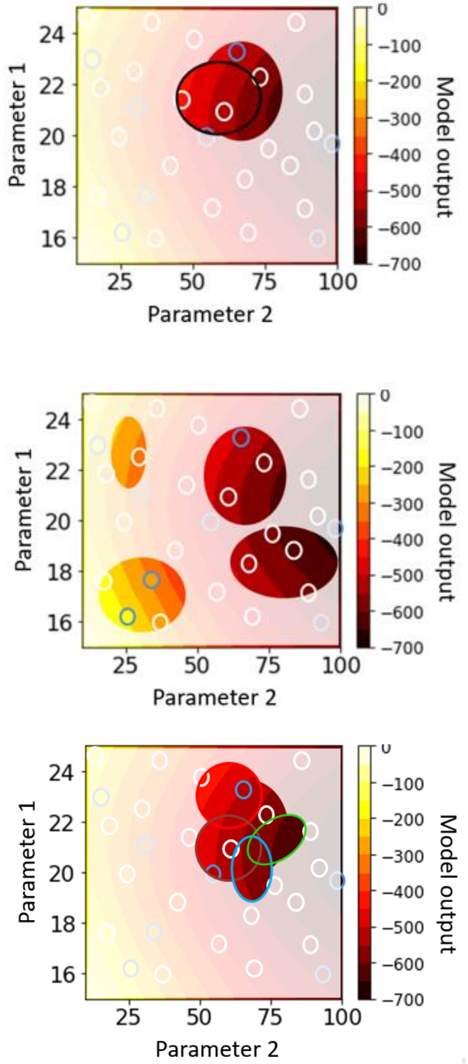
Constraint of aerosol forcing



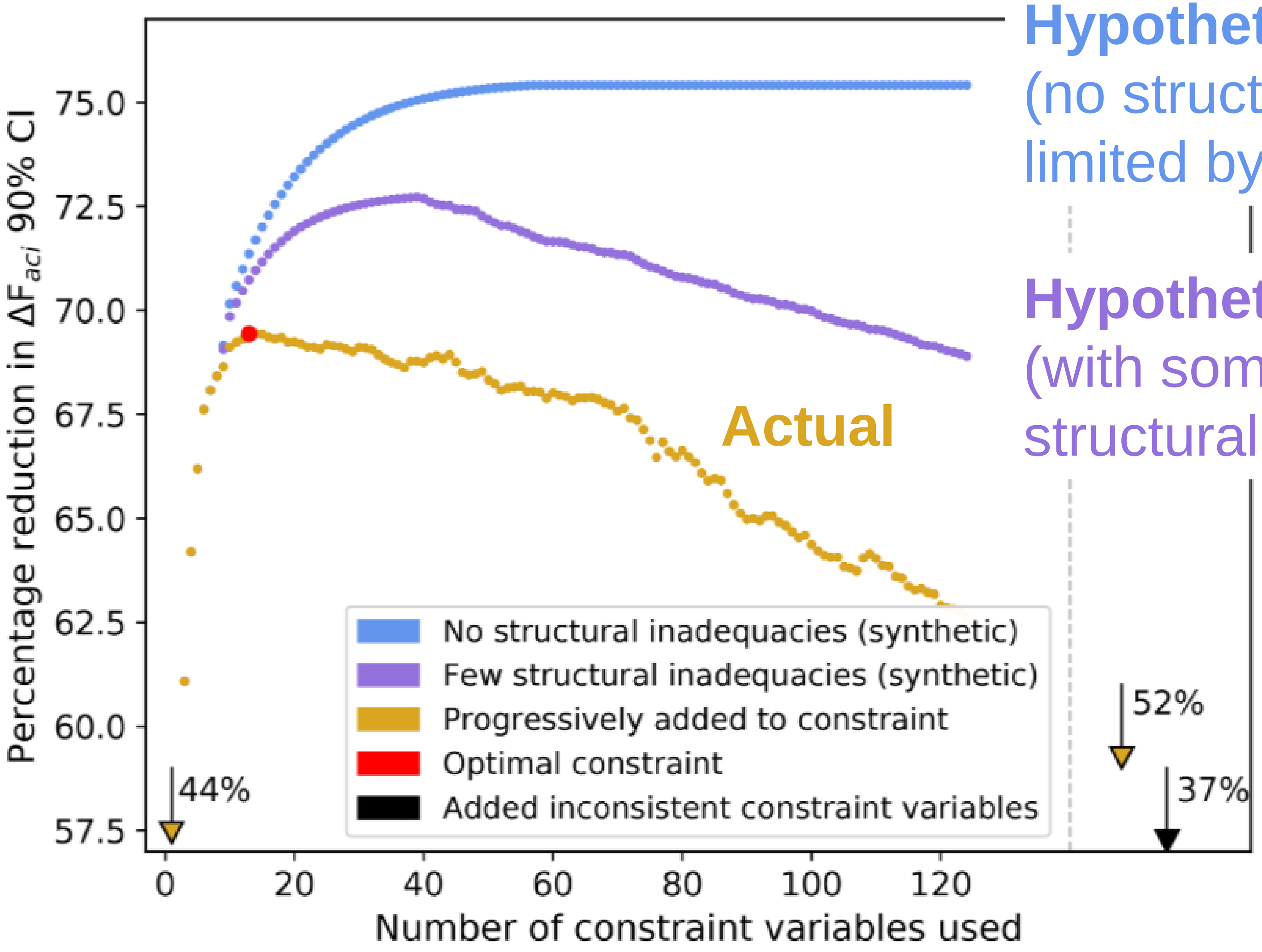
This is the forcing constraint when we use the most consistent set of observations

Adding more (less consistent) observations weakens the constraint

Tighter constraint? Find ways to eliminate the inconsistencies



Potential for improved constraint



Hypothetical
(no structural deficiencies, limited by obs. uncertainty)

Hypothetical
(with some remaining structural deficiencies)

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Visualizing cloud behavior

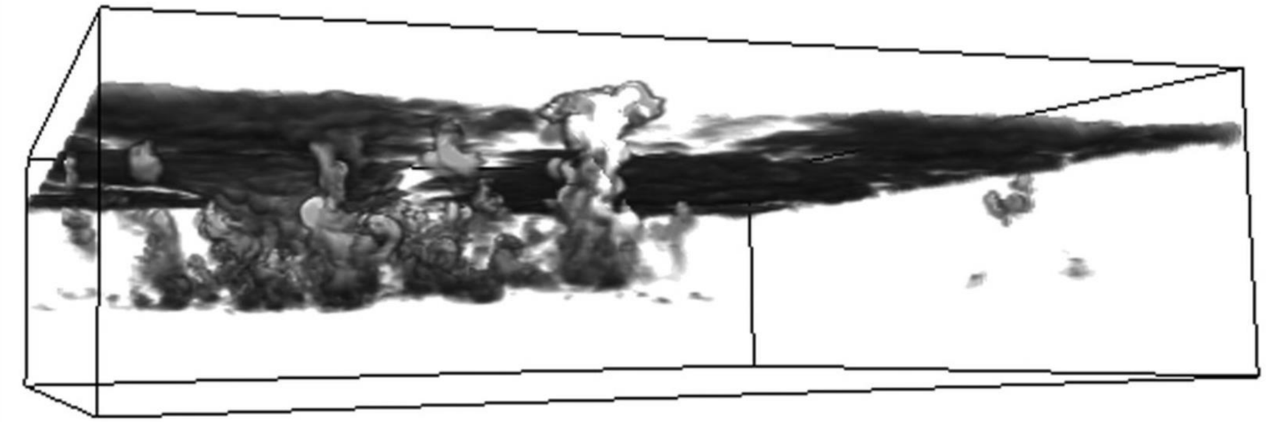
A PPE of stratocumulus to cumulus transition using the MONC large eddy 2-moment cloud microphysics model

Approach to process understanding

Sandu and Stevens (2011)

On the Factors Modulating the Stratocumulus to Cumulus Transitions

	Simulation	Domain	$\overline{CC}_{0-48h}$ (%)	$\overline{MaxCF}_{3^{rd} night}$ (%)	ΔA (%)
Reference	REF	Reference	94	83	51
Δ SST	CST-SST	Small	99	98	20
Δ droplet number	PP	Reference	86	40	72
Δ divergence	DIV	Reference	94	88	38
Δ LW radiation	RAD	Small	90	64	68
Δ stability	SLOW	Reference	97	87	44
	FAST	Reference	91	33	81
Δ inversion strength	DTH	Small	75	57	54
Δ inversion humidity	DTHQT	Small	95	94	26



Can use PPEs to understand how multiple cloud-controlling factors affect cloud behavior

6-parameter large eddy cloud PPE

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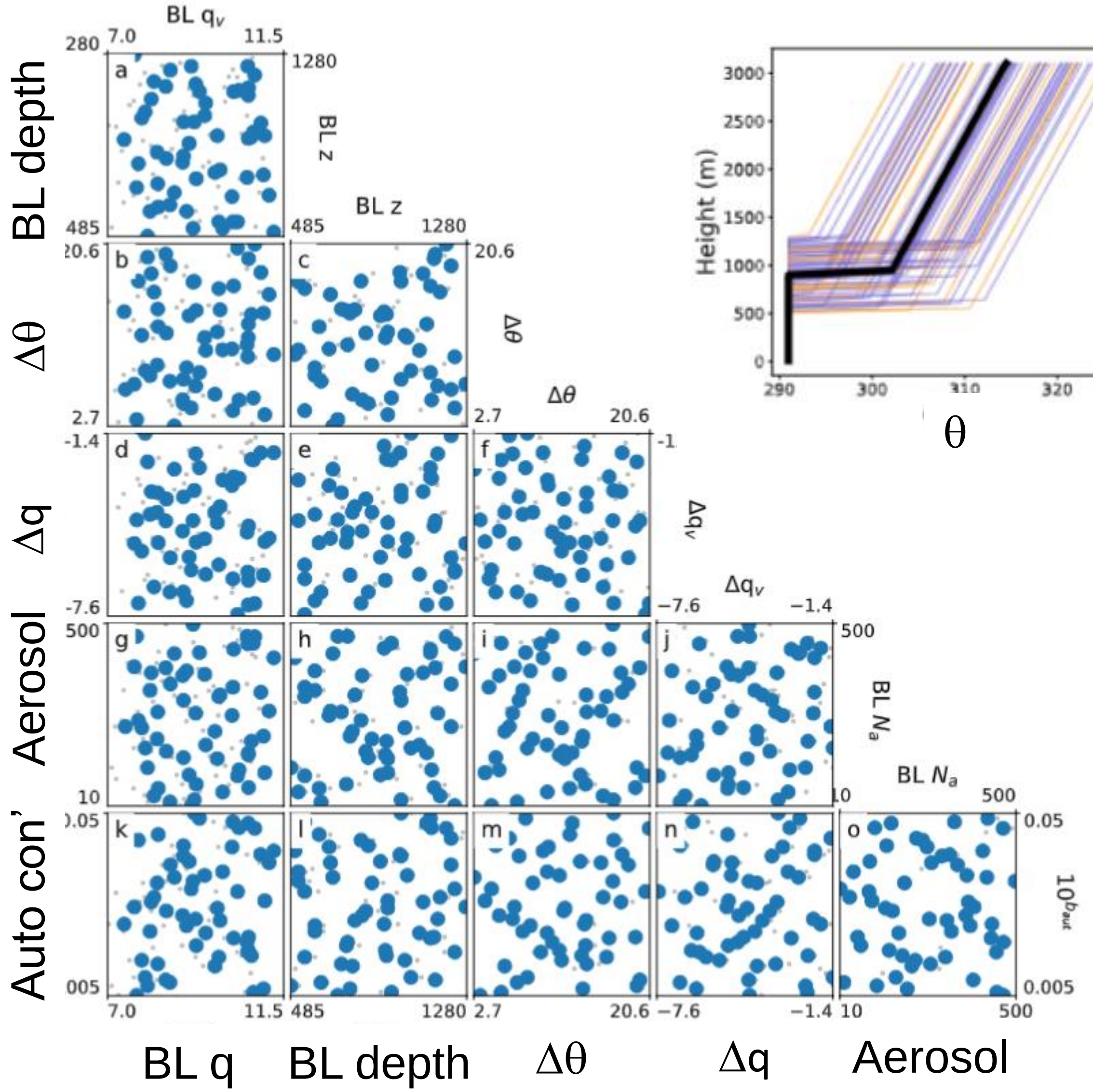

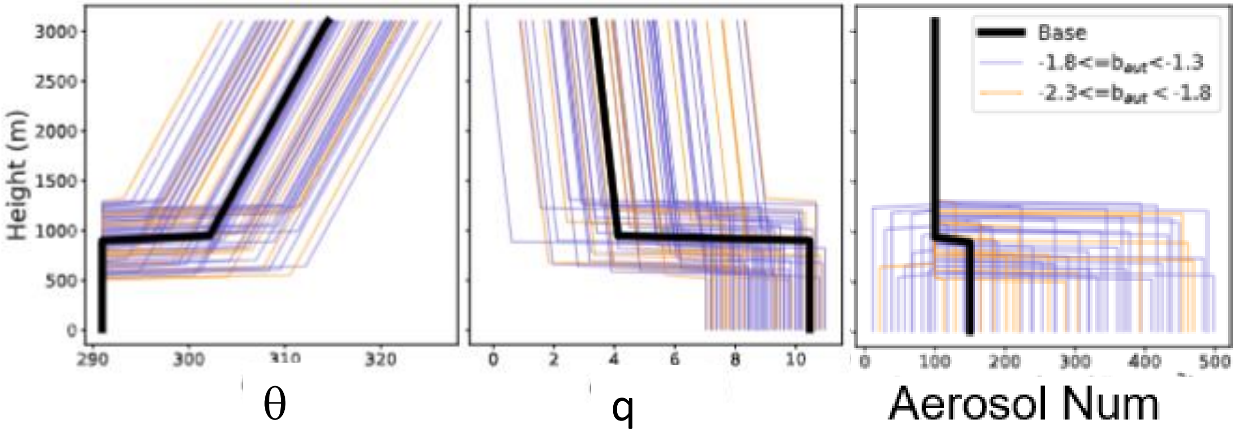

85 initial simulations

1. Boundary layer water mixing ratio
2. Boundary layer depth
3. Inversion Δθ
4. Inversion Δq
5. Aerosol concentration
6. Autoconversion (droplet→rain) rate

Evolution of one ensemble member

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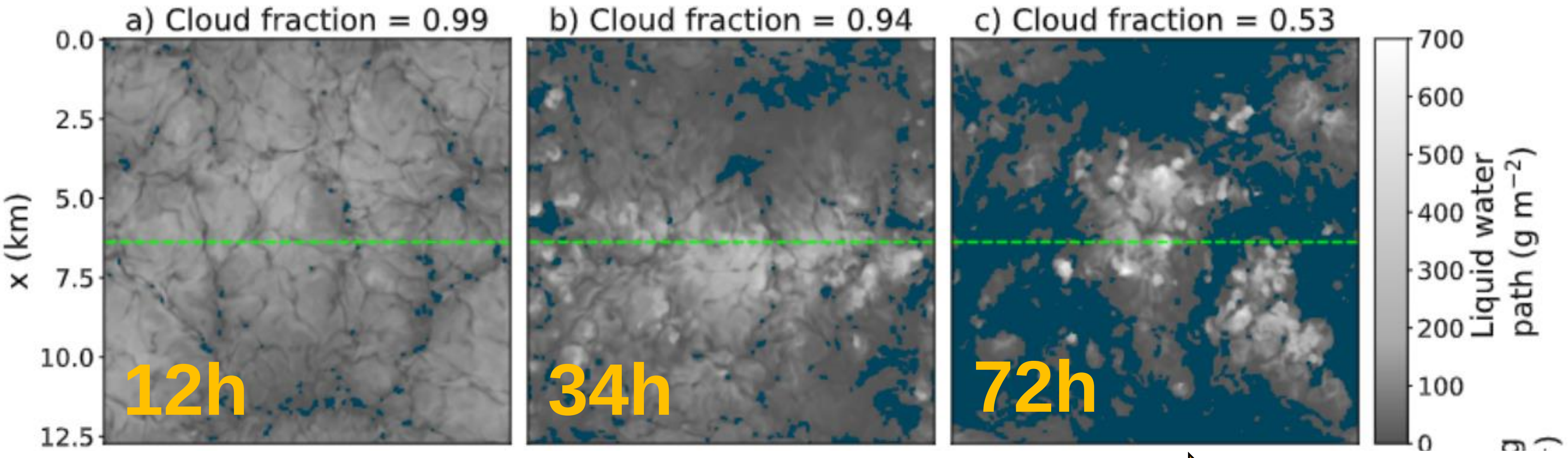

Sea surface temperatures increase 1.5 K per day

Cloud evolution across the PPE

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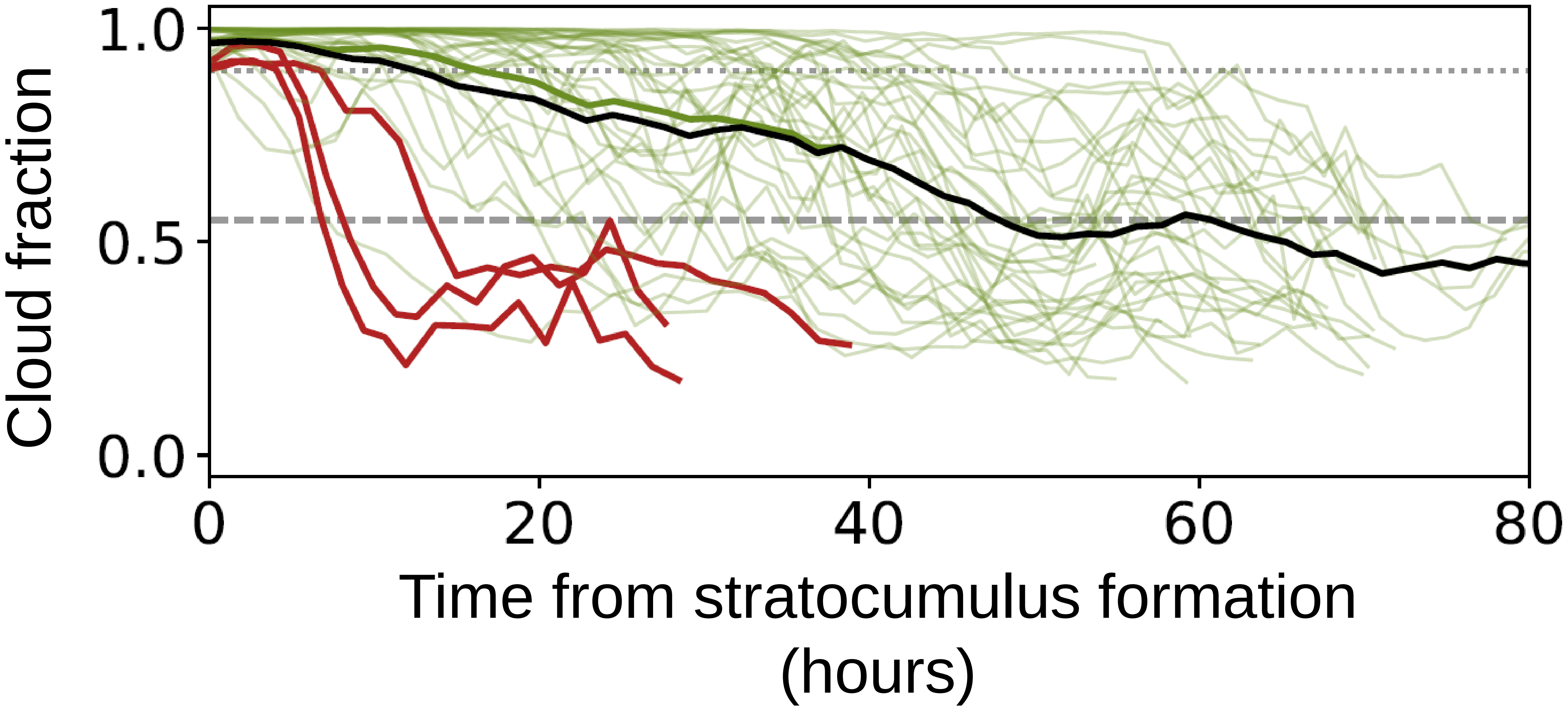

Sc to Cu transition time

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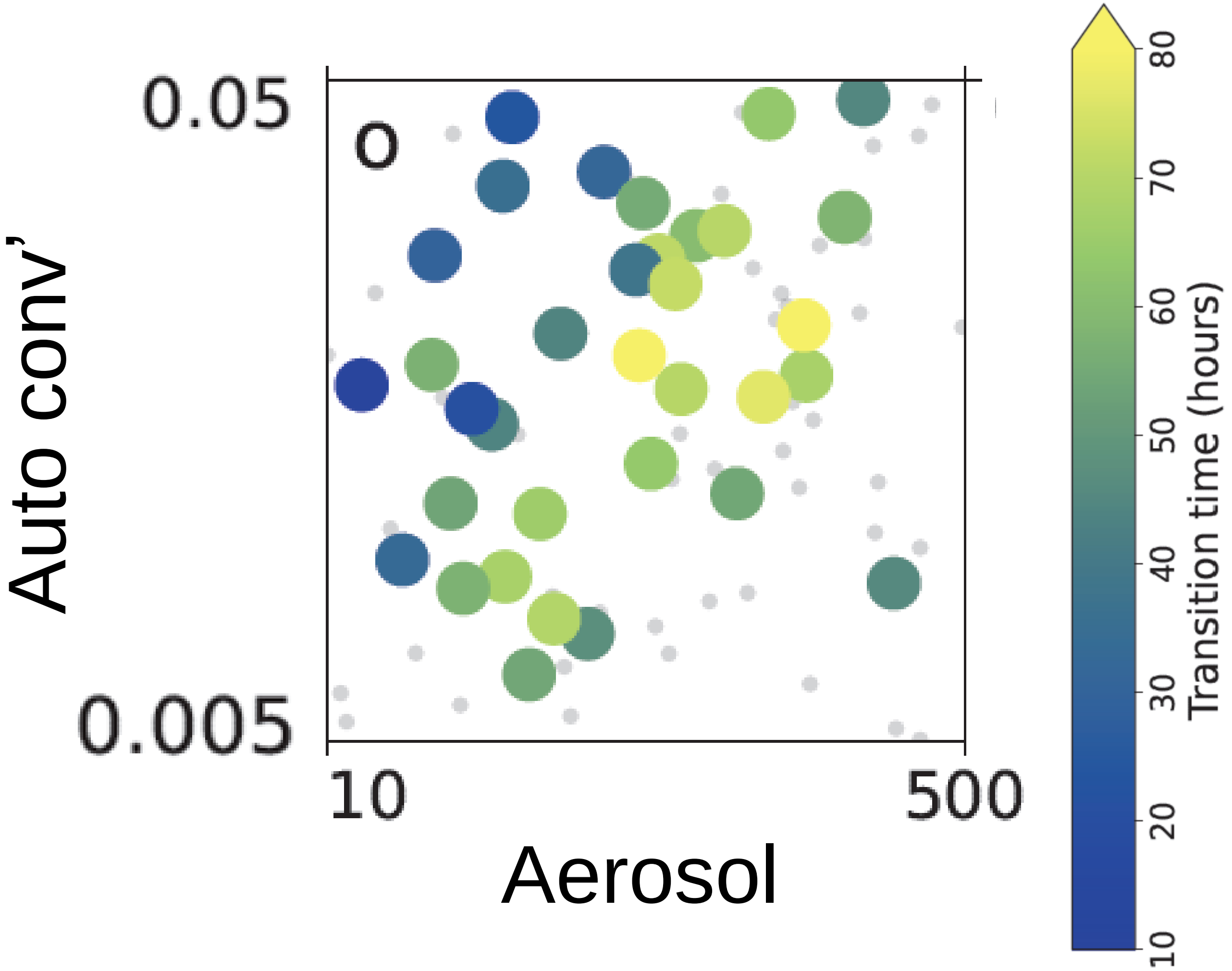

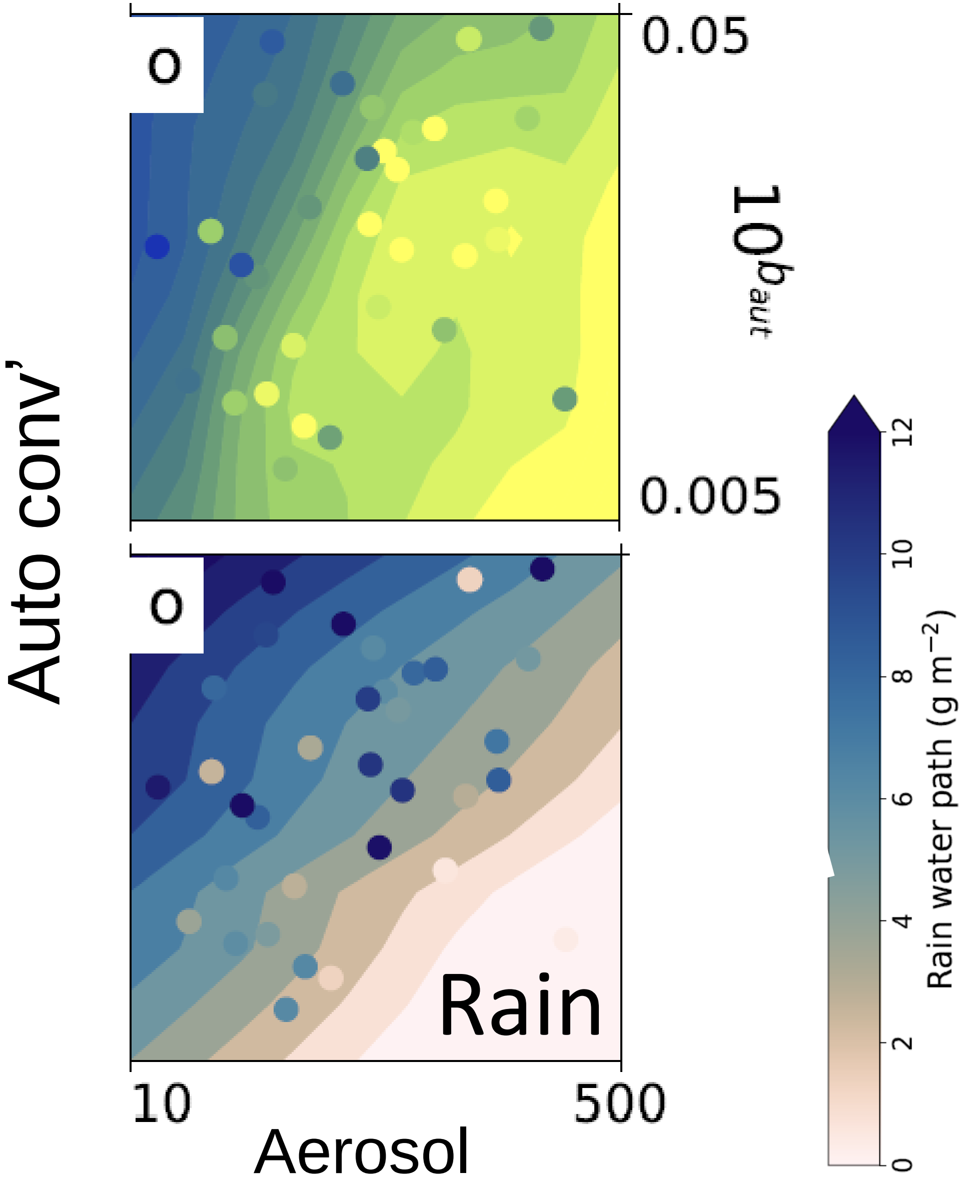

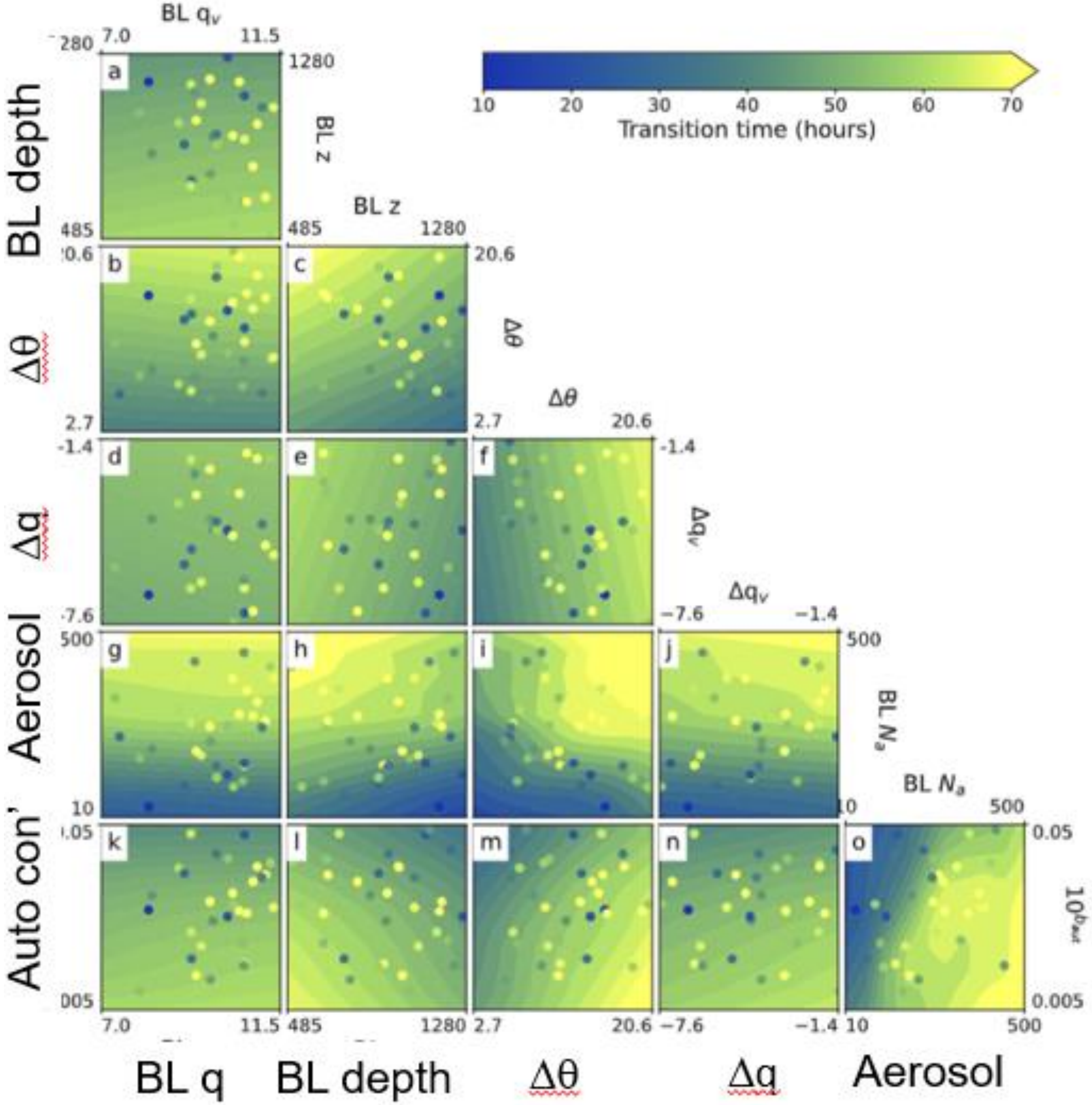
Transition time (hours)
BL depth
Δθ
Δq
Aerosol
Auto con'
BL q
BL depth
Δθ
Δq
Aerosol
BL q_v
BL z
Δθ
Δq_v
BL N_a

Summary

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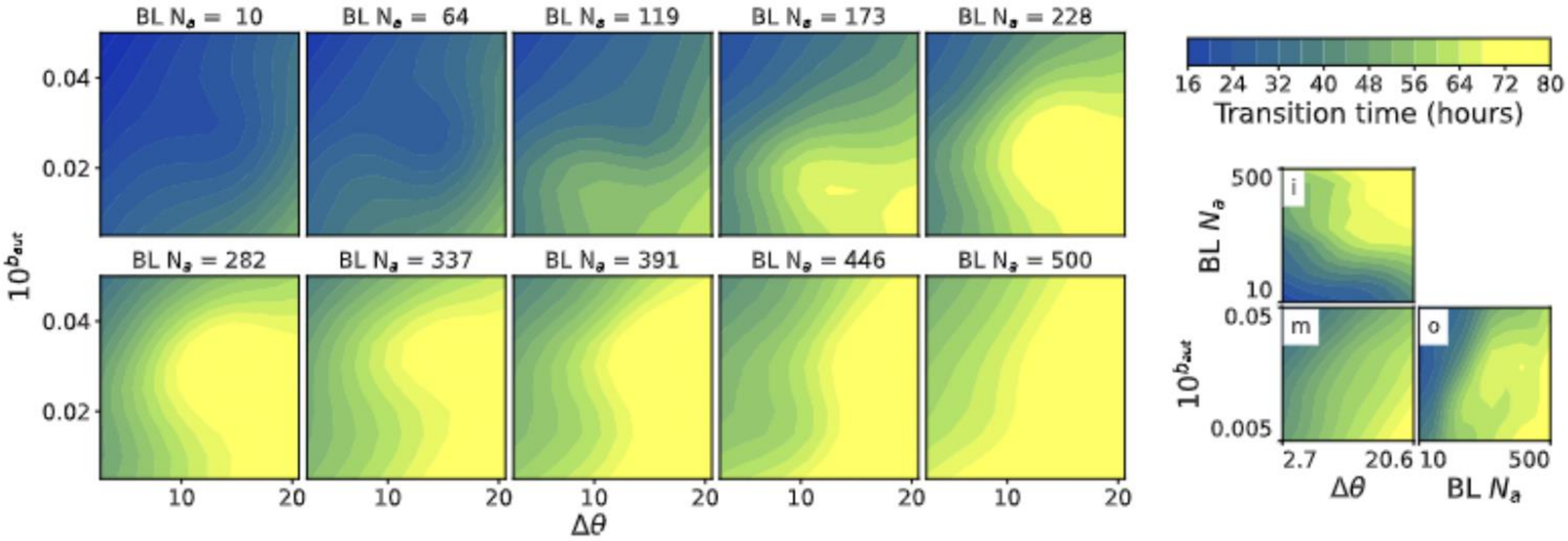
- Perturbed parameter ensembles can be used to train emulators, enabling multiple factors in models to be explored
- Provide physical insight rather than just a trained ML model
- PPEs can be analysed to expose potential structural deficiencies in models when different observations constrain the model to inconsistent regions of parameter space
  - Can apply to multiple observation types, regions and time periods
- ‘Parameters’ can also be environmental drivers – e.g., cloud controlling factors
- If interested, join the APPEAR network – Analysis of PPEs in Atmospheric Research (aerosols, chemistry, clouds, climate, meteorology from LES to ESM)



BL Na = 10
BL Na = 64
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BL Na = 391
BL Na = 446
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0.04
0.02
10^b_aut
10
20
Δθ
16 24 32 40 48 56 64 72 80
Transition time (hours)
i
m
o
500
10
BL Na
0.05
0.005
2.7
20.6