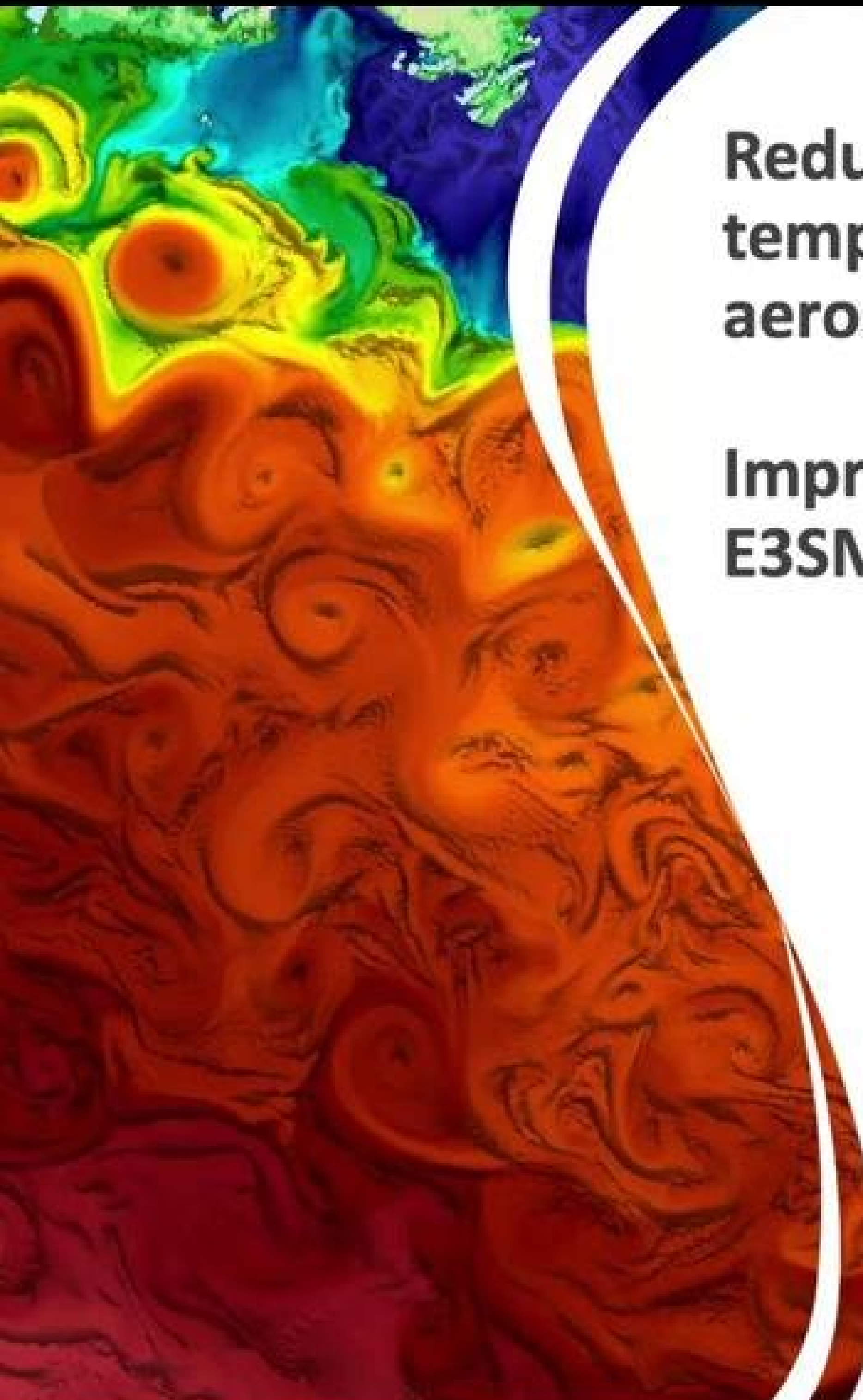


Reducing biases in the simulated historical temperature record through calibration of aerosol and cloud processes:

Improvements to the aerosol forcing in E3SMv3

E3SM Aerosol Working Group (June 2022 - Nov 2023)

Susannah Burrows (Aerosol Working Group lead)

Cloud microphysics: Jiwen Fan, Yunpeng Shan

Aerosol: Mingxuan Wu, Hailong Wang

Aerosol-cloud interactions: Naser Mahfouz, Johannes Mülmenstädt

Shaocheng Xie, Chris Terai and the E3SM Atmosphere Group

Chris Golaz, Wuyin Lin, Xue Zheng, Kai Zhang, and the E3SM Coupled Group

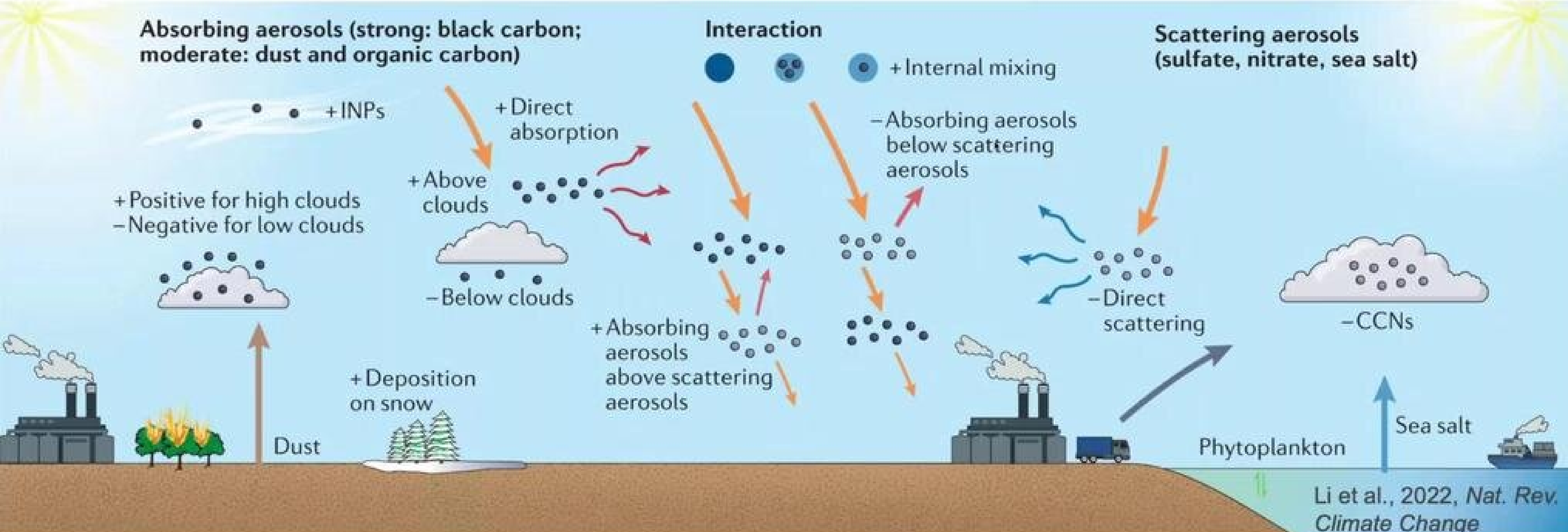
E3SM Energy Exascale Earth System Model

ERF = “Effective Radiative Forcing”

- ERF_{ari} = “direct” effects from aerosol-radiation interactions
- ERF_{aci} = “indirect” effects from aerosol-cloud interactions

ERF_{aer} = difference in net top-of-atmosphere radiative downward flux between two simulations, one with present-day (PD) and one with pre-industrial (PI) aerosol emissions.

- Sea surface temperature fixed
- Includes adjustments (temperatures, water vapor and clouds)

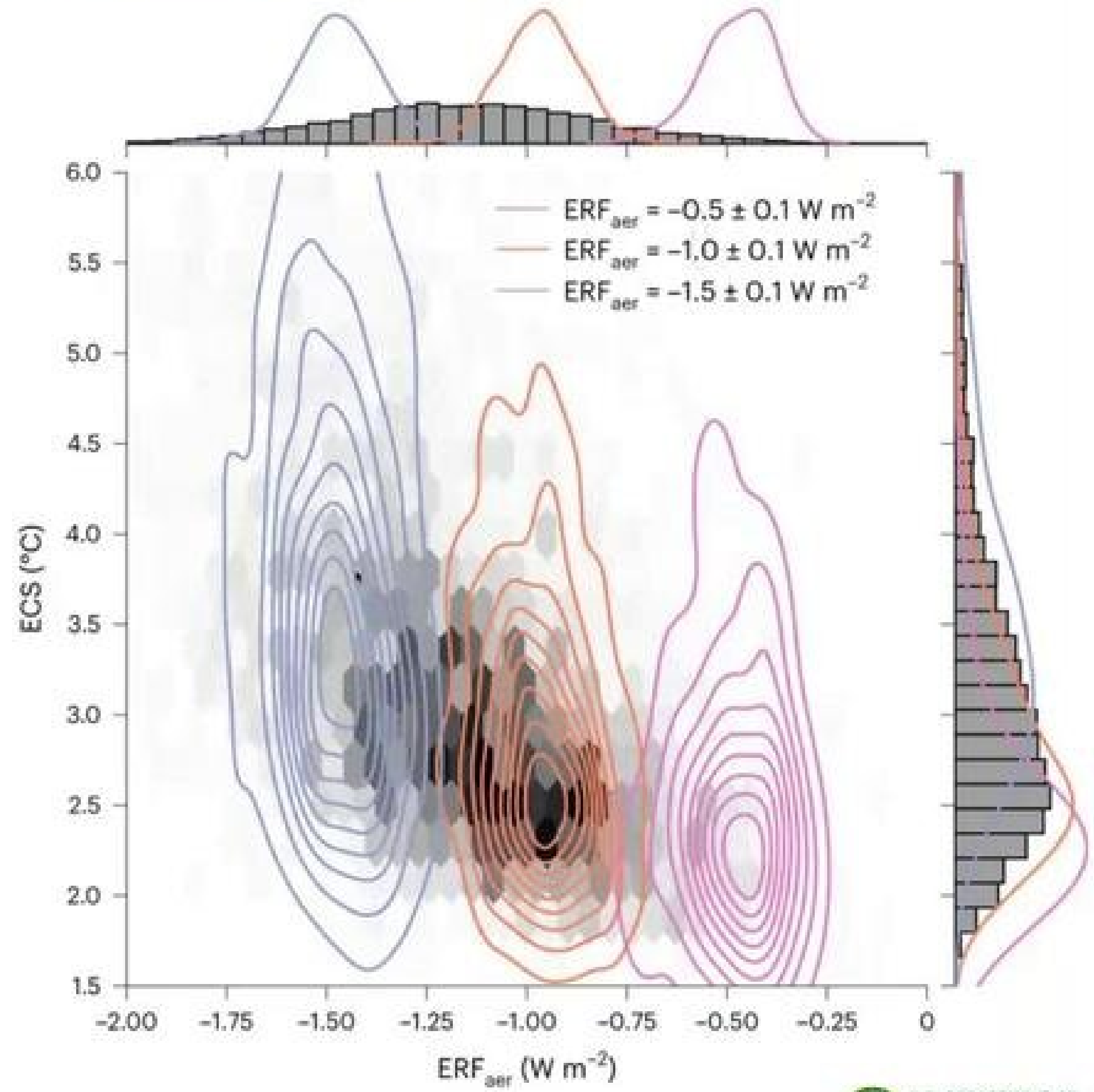


Li et al., 2022, *Nat. Rev. Climate Change*

Uncertainties in aerosol effective radiative forcing limit confidence in future climate projections

The equilibrium climate sensitivity (ECS) and the historical aerosol effective radiative forcing (ERF_{aer}) are the two main sources of uncertainty in future climate projections (for a given atmospheric composition pathway).

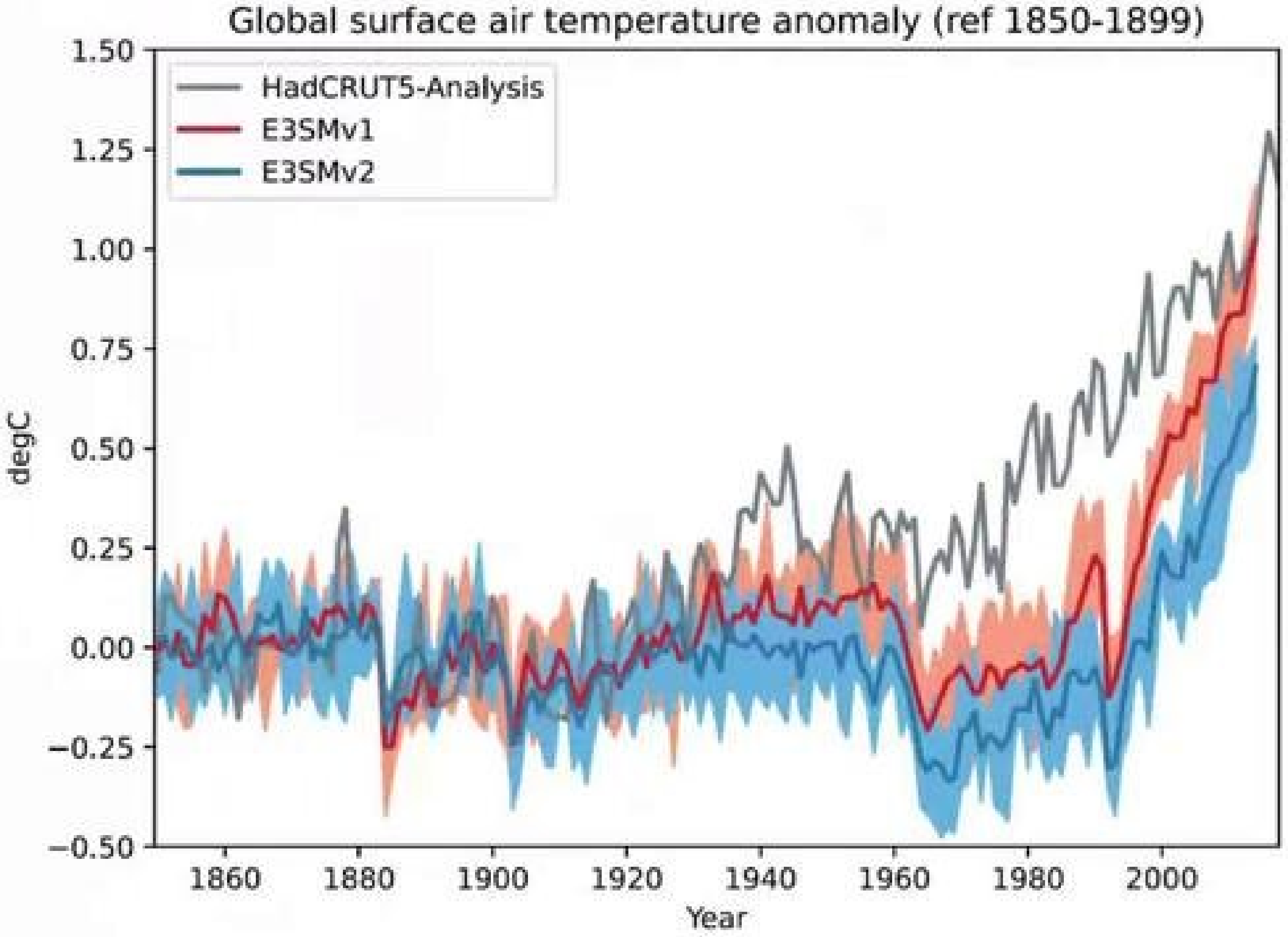
Constraints on both can be inferred from the historical temperature record, but these constraints are interdependent.



Watson-Parris and Smith,

Nature Climate Change, 2022

The problem: bias in the mid-20th century global mean temperature



Golaz et al. (2022)

Attributed to aerosol effective radiative forcing (ERF_{aer}) through single-forcing experiments (Golaz et al., 2022)

Step 1: Clear definition of the goal

Targeted range of ERF_{aer}:
-0.5 to -0.7 W/m^2

ERF_{aer} evolution in E3SM compared with benchmarks

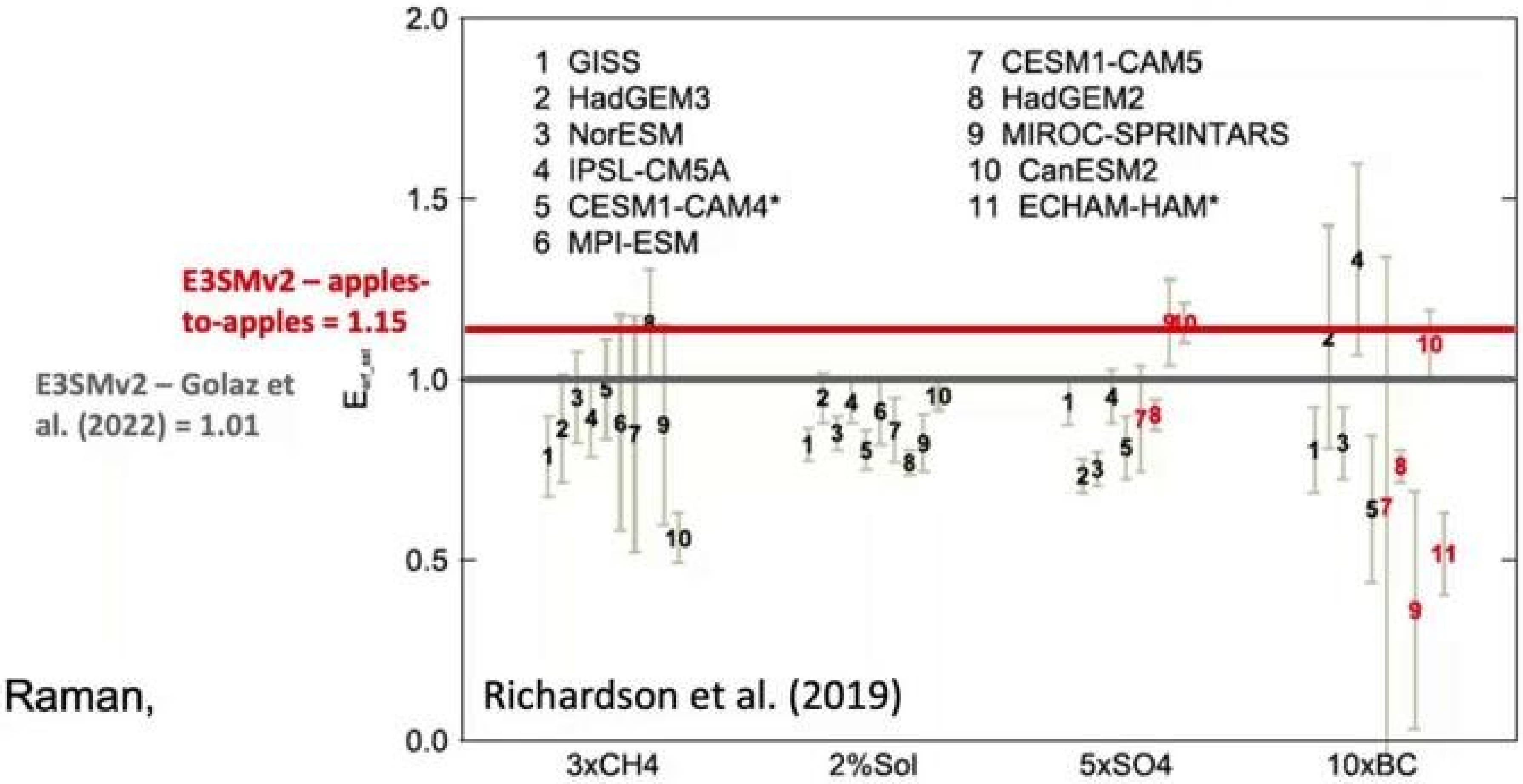
	Total Aerosol Effective Radiative Forcing (ERF_{aer}) (1850 vs PD, fixed SST)	Aerosol-radiation interactions (ERF_{ari})	Aerosol-cloud interactions (ERF_{aci})
E3SMv1 *(Zhang et al., 2022)*	**-1.64**	0.04	-1.77
E3SMv2 *(Zhang et al., in prep)*	**-1.33**	0.04	-1.51
E3SMv3 *(Burrows et al.; Xie et al.; in prep)*	**-0.71**	-0.03	-0.77
Multi-model range *(Smith et al., 2020)*	-1.01 ± 0.23 -1.37 – -0.63 (range)		
Obs. constraints *(Bellouin et al., 2020; Smith et al., 2021)*	-1.6 – -0.6 (68%) -2.0 – -0.4 (90%) -1.1 [-1.8 – -0.5]	–0.71 to –0.14 (90%)	–2.65 to –0.07 (90%)
IPCC AR6 **(1750-2011)**	-1.3 [-2.0 to -0.6]	–0.3 [-0.6 to 0.0]	–1.0 [-1.7 to -0.3]

E3SMv2 aerosol efficacy is higher than many other models; this may contribute slightly but is not a dominant effect

- E3SMv2 all-aerosol efficacy of ~1.15 is within, but at the high end of the range of PDRMIP models

Johannes Mülmenstädt, Aishwarya Raman, Susannah Burrows

Efficacy of Climate Forcings (E_{erf_sst})



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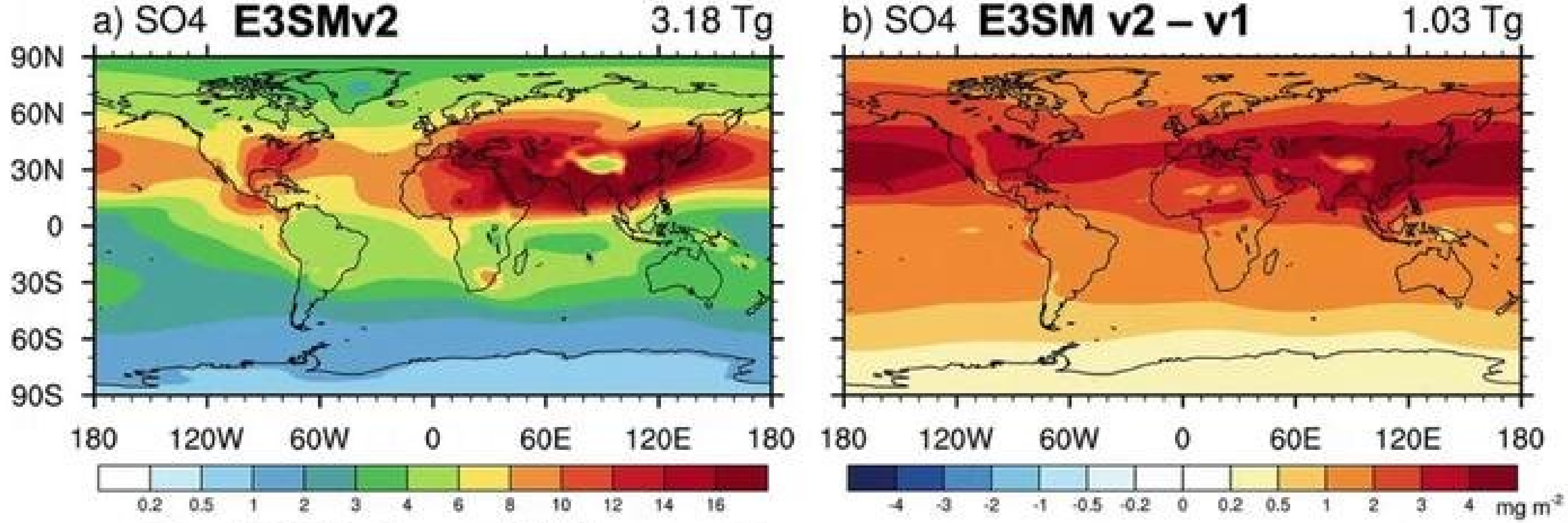
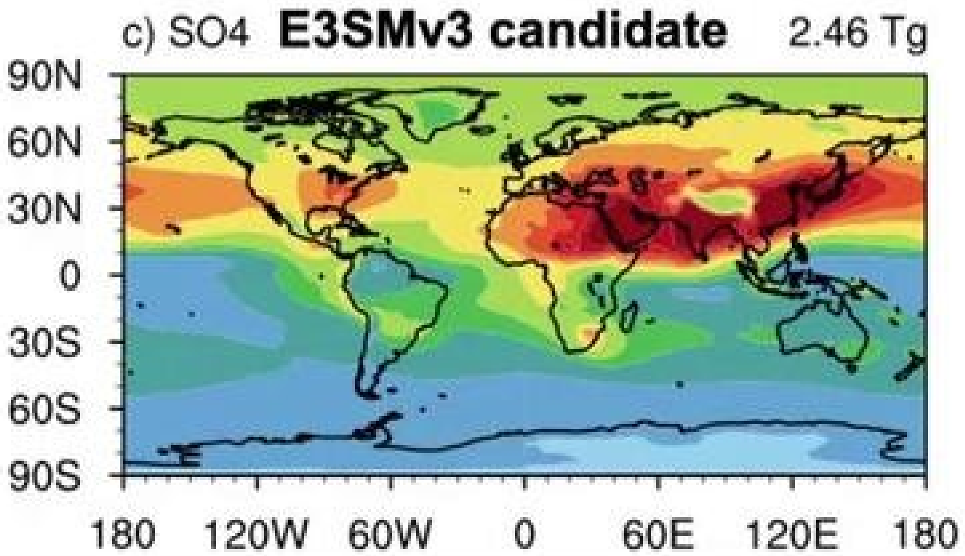
Anthropogenic aerosol burdens increased in E3SMv2 after retuning, resulting in a high bias in AOD

Sulfate aerosol column density and total burden





Model development efforts targeting wet removal significantly reduced anthropogenic aerosol burdens and thereby reduced the aerosol indirect forcing from **1.79** to **1.52 W/m²** in v3 candidates (versus 1.51 W/m² in v2).

Yunpeng Shan, Kai Zhang, Jiwen Fan
Also: Zhang et al. (2022)

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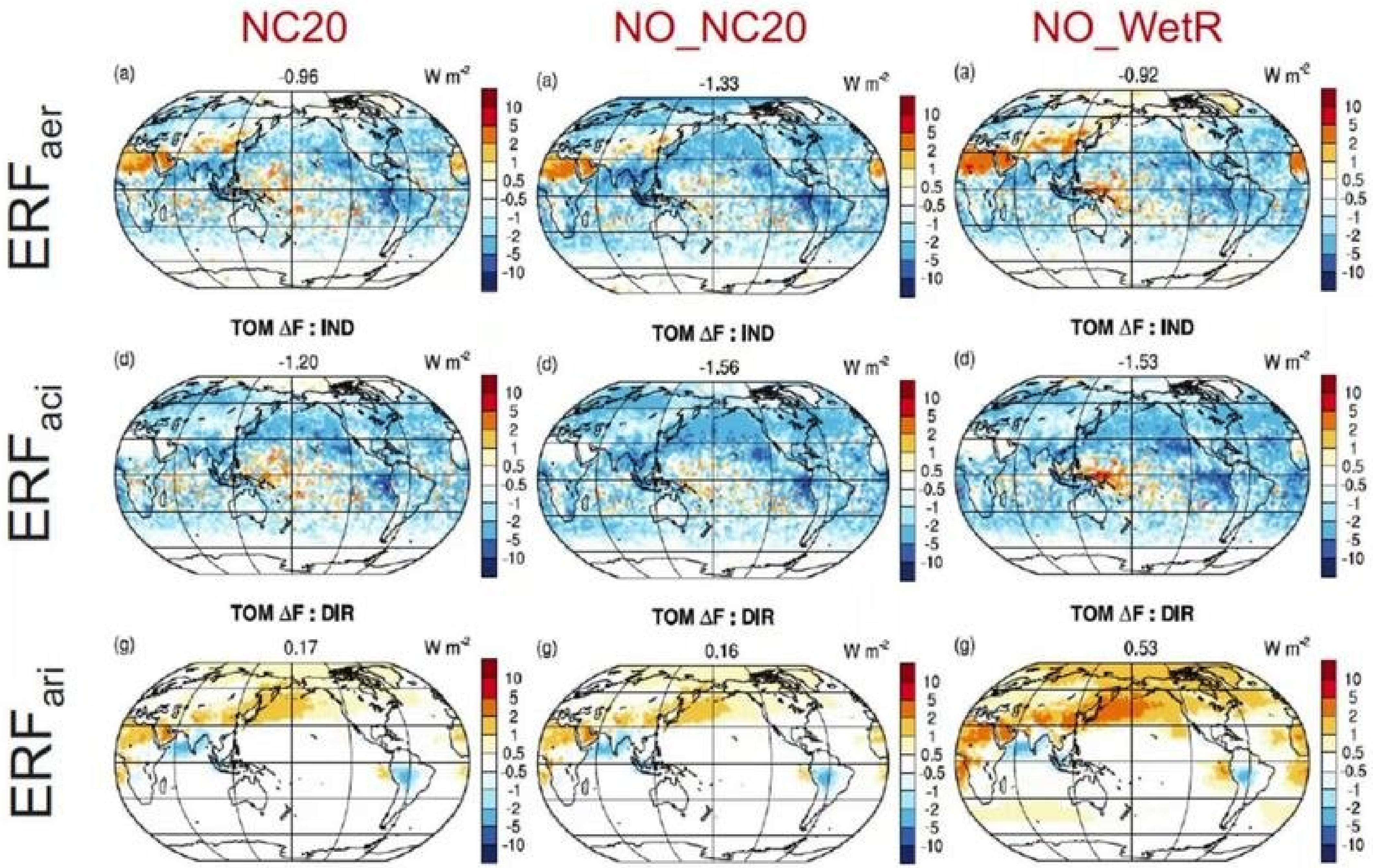
Aerosol effective radiative forcing (ERF_{aer}) at top-of-atmosphere



Yunpeng Shan,
Jiwen Fan

- minCDNC limiter strongly impacts ERF_{aci}
- Wet removal updates reduce the direct effect bias, with minor impact on overall ERF_{aer}

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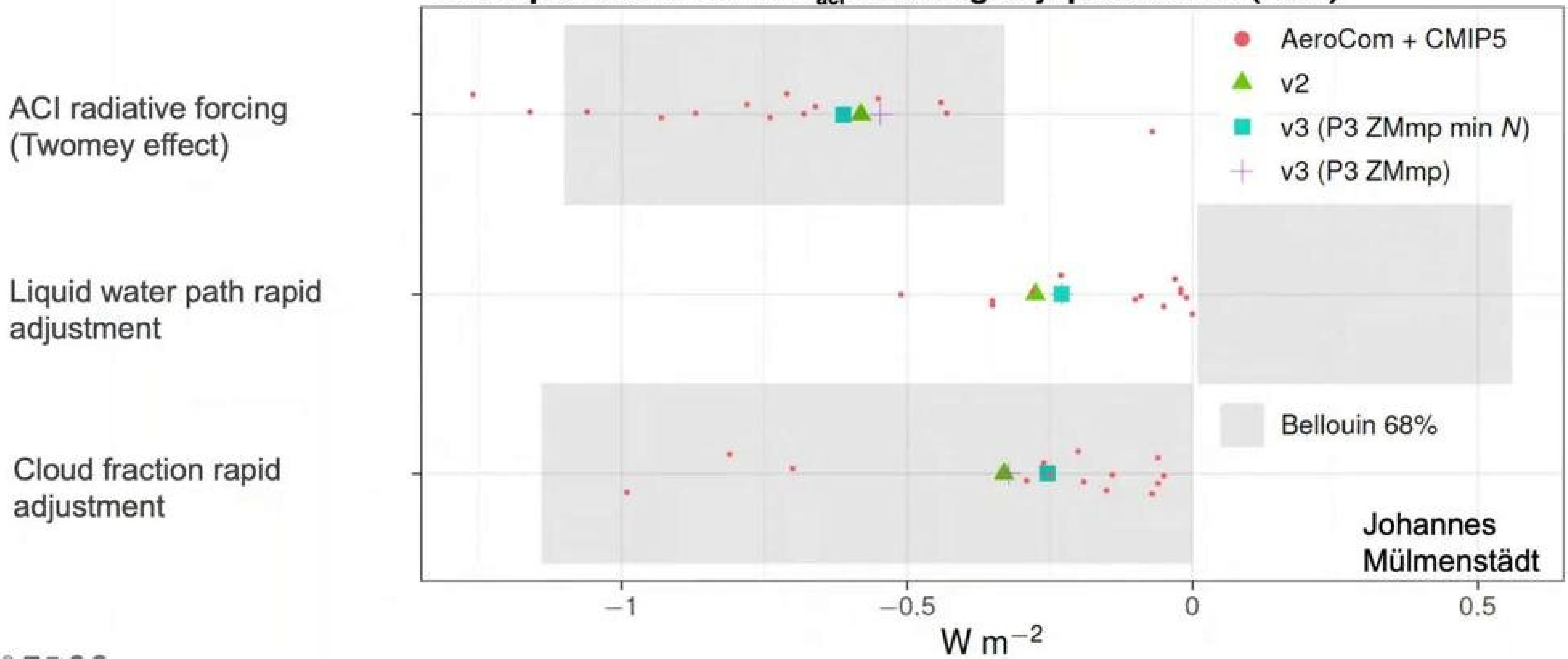
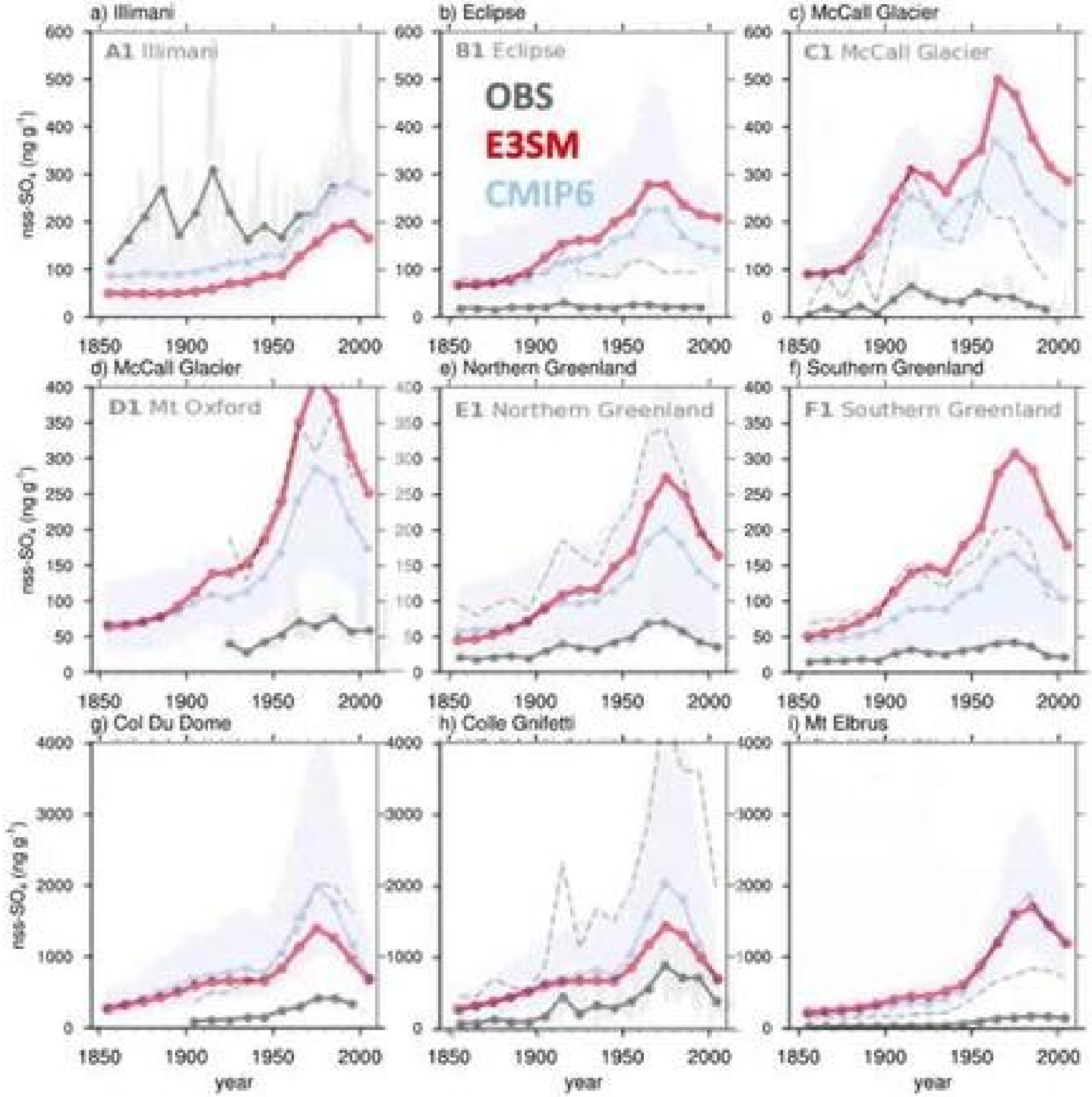
ERF$_{ACI}$ partitioning: warm cloud processes are consistent with multi-model range

Decomposition of SW ERF$_{aci}$ following Gryspeerdt et al. (2020)



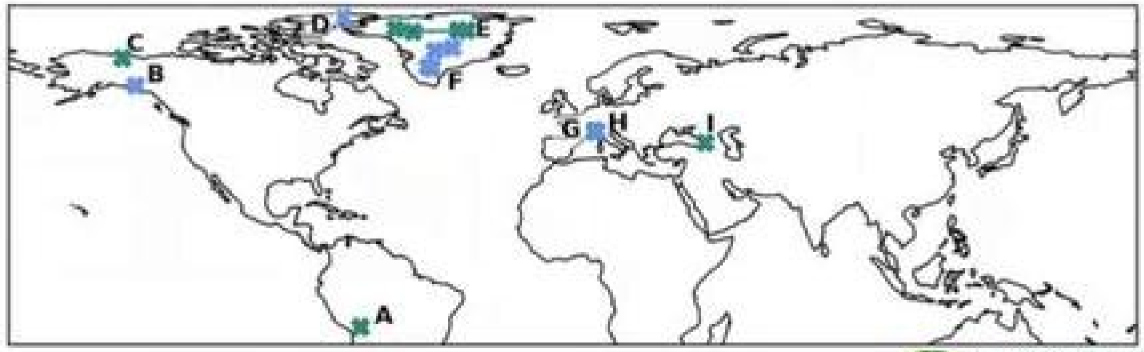
Historical evolution of sulfate aerosol agrees reasonably CMIP6 model simulations of ice core data



Obs and CMIP6 data from Moseid et al. (2022) JGR

$$conc = \frac{\sum_1^9 (wetdep + drydep)}{\sum_1^9 precip_{ice+liq}}$$

- CMIP6 models including E3SM significantly overestimate sulfate concentrations at most sites, likely in part due to unresolved topography.
- CMIP6 models including E3SM can capture the decadal trend to some extent. E3SM has similar decadal trend as CMIP6 models.



Mingxuan Wu and Hailong Wang

PRELIMINARY attribution of ERF impacts from specific model changes (Xie, et al., in prep)

Model change	Preliminary estimate of ERF_{aer} impacts from sensitivity tests ($W\ m^{-2}$)	Percentage of total change in ERF_{aer} (EAMv2 ⇒ EAMv3: +0.62 $W\ m^{-2}$)
Increase in minCDNC limiter from 10 to 20 cm^{-3}	+0.25	40%
2xDMS (with minCDNC=20 cm^{-3})	+0.12	19%
Retuning autoconversion N_d exponent from -1.4 to -1.1 *	+0.10	16%
Reduction in BC aging monolayers from 8 to 3 *	+0.08	13%
Increased hygroscopicity of POM *	+0.08	13%
Wet removal modifications *	+0.04	6%
Residual term	-0.05	-8%

Results are based on sensitivity tests with final EAMv3 or near-final (*) EAMv3 versions.

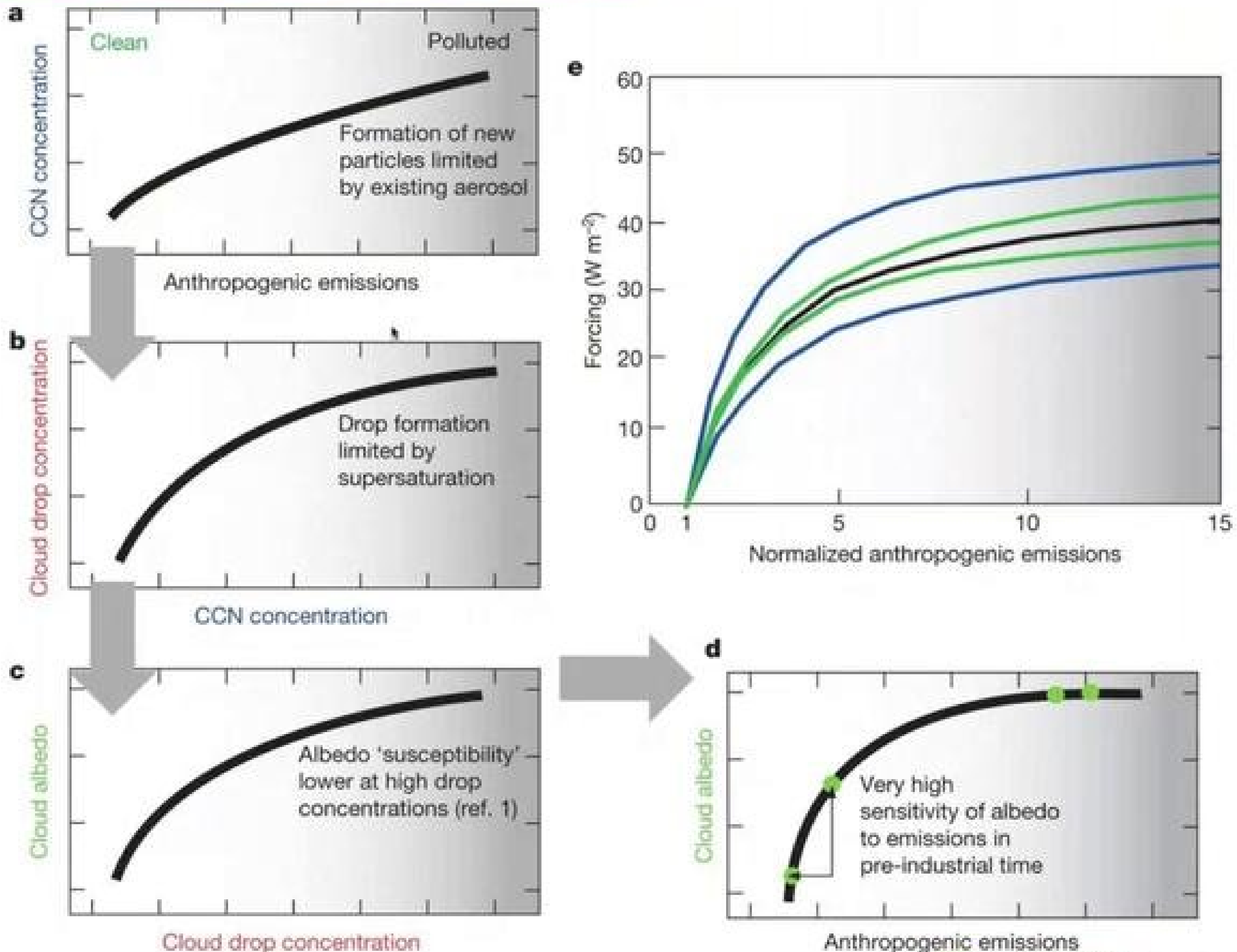
Not shown (but may be added for final publication):

- Significant, but largely offsetting changes from the update from MG2 to P3 and inclusion of convective microphysics.
- Impacts of new aerosol features. Net impact on ERFaer is small, but the new SOA feature reduces both ERF_{aci} and ERF_{ari}.

Why does increasing background N_d weaken ERF_{aci}?

Physical saturation effects in several aerosol-cloud processes lead to sublinear responses:

1. Formation of aerosols and cloud condensation nuclei (CCN) from gaseous precursors
2. Activation of CCN to form cloud droplets
3. Increases in cloud albedo with increased cloud droplet number

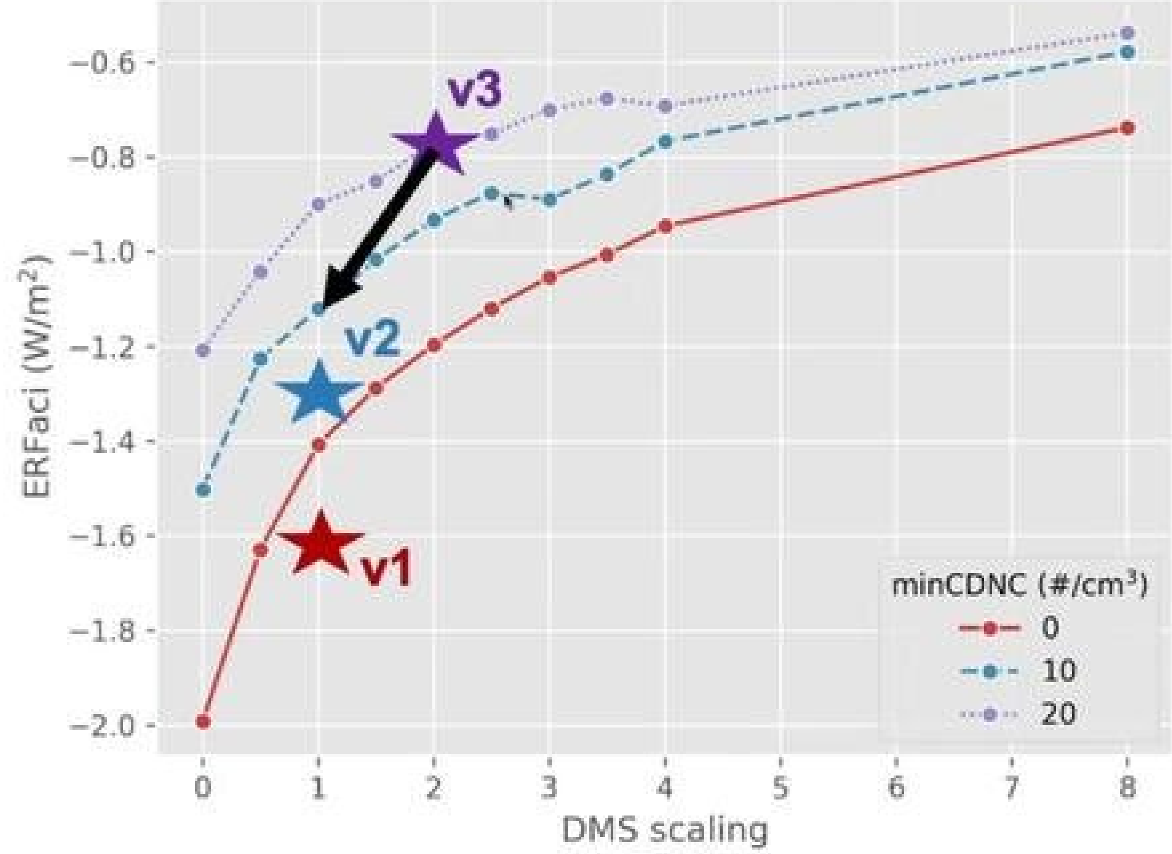


Carslaw et al. (2013)

The 80-20 rule in action:

Burrows et al. (in prep; E3SMv3 calibration)
Beydoun et al. (2023; E3SMv2 PD-PI AOD)

Large sensitivity to natural background aerosol (DMS) and min. cloud droplet number concentration (minCDNC)



✓ Enhanced aerosol and cloud processes while achieving coupled tuning targets

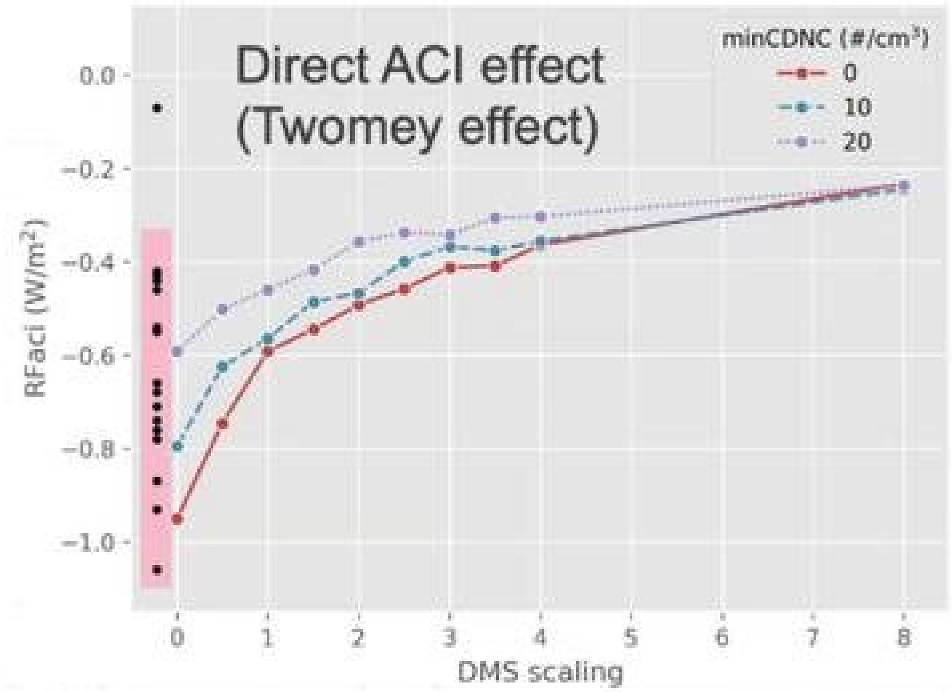
▲ Right answer for the right reasons?

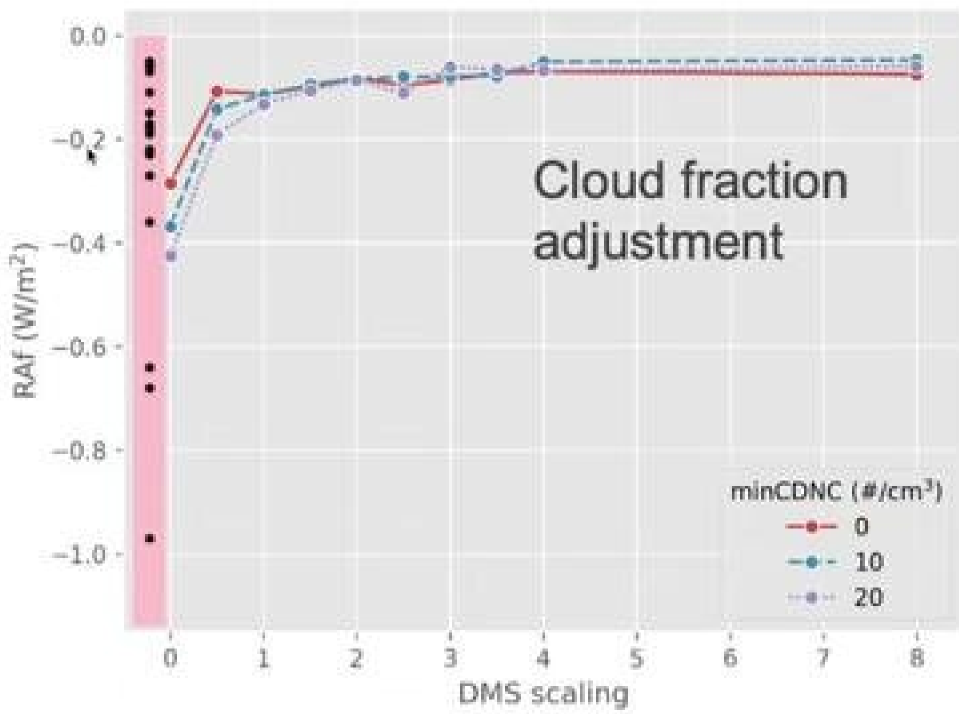
More work is needed to elucidate and address
(1) background preindustrial aerosol sources, and
(2) the structural causes of low N_d

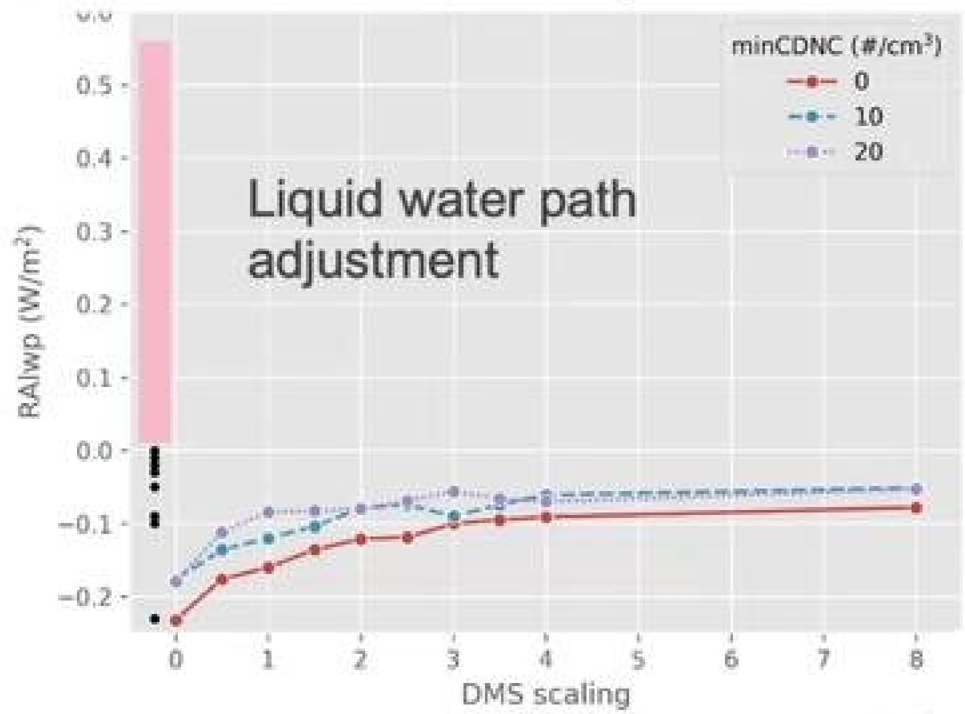
Naser Mahfouz, Johannes Mülmenstädt, Susannah Burrows

Sensitivity to DMS flux, minCDNC is driven by the Twomey effect

- At very high values of DMS scaling, Twomey effect becomes inconsistent with assessed range (pink), CMIP models (black dots).
- Cloud fraction adjustment is currently poorly constrained.
- Liquid water path adjustment remains inconsistent with the assessed range in all sensitivity cases.

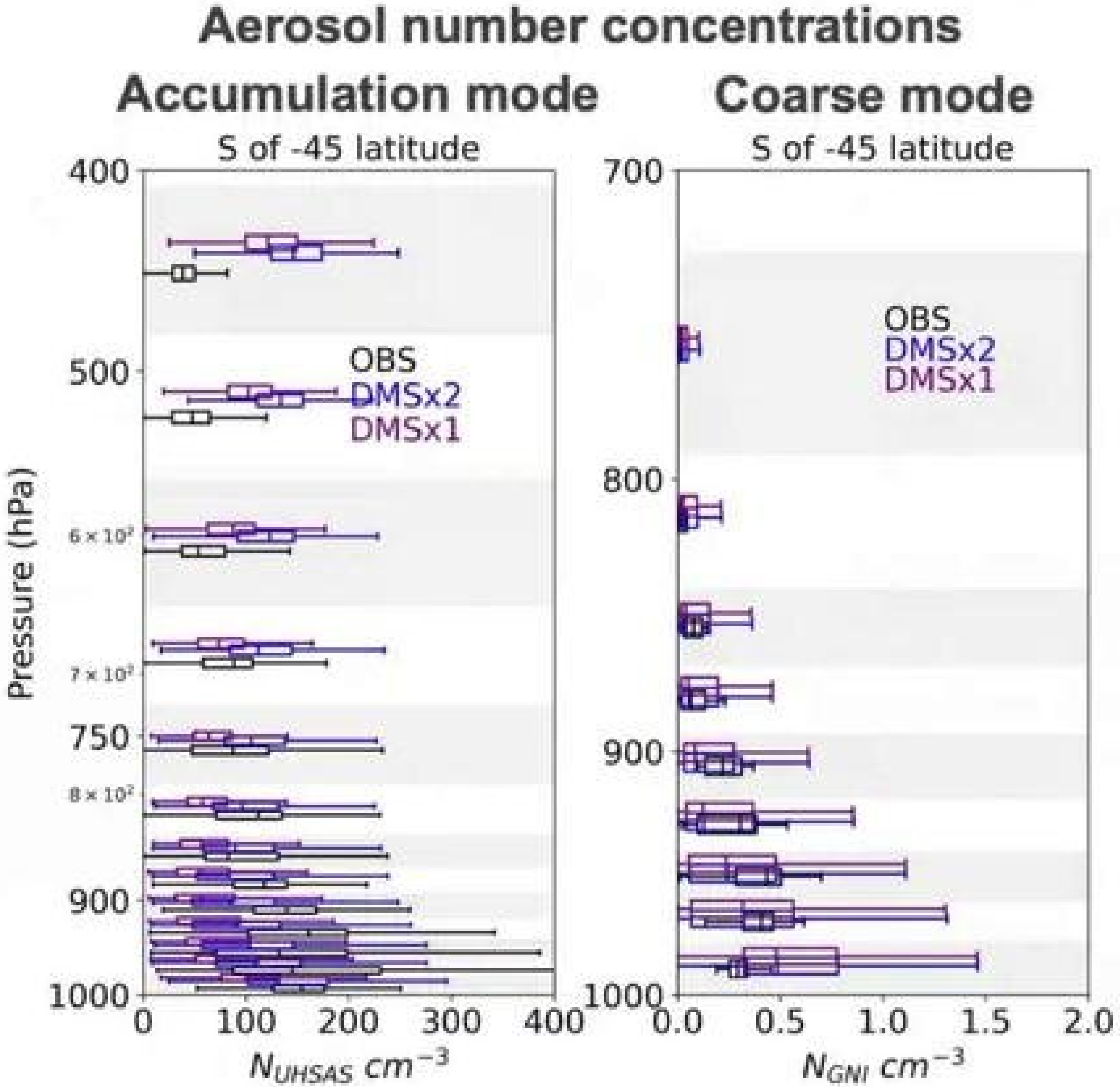






Naser Mahfouz,
Johannes Mülmenstädt,
Susannah Burrows

Benchmarking against in situ observations (SOCRATES)



2xDMS tuning improves agreement with accumulation-mode particle number concentrations in the boundary layer (up to ca. 750 hPa).

No impact on coarse-mode aerosol (as expected).

Overprediction of accumulation mode number concentrations in the UT.

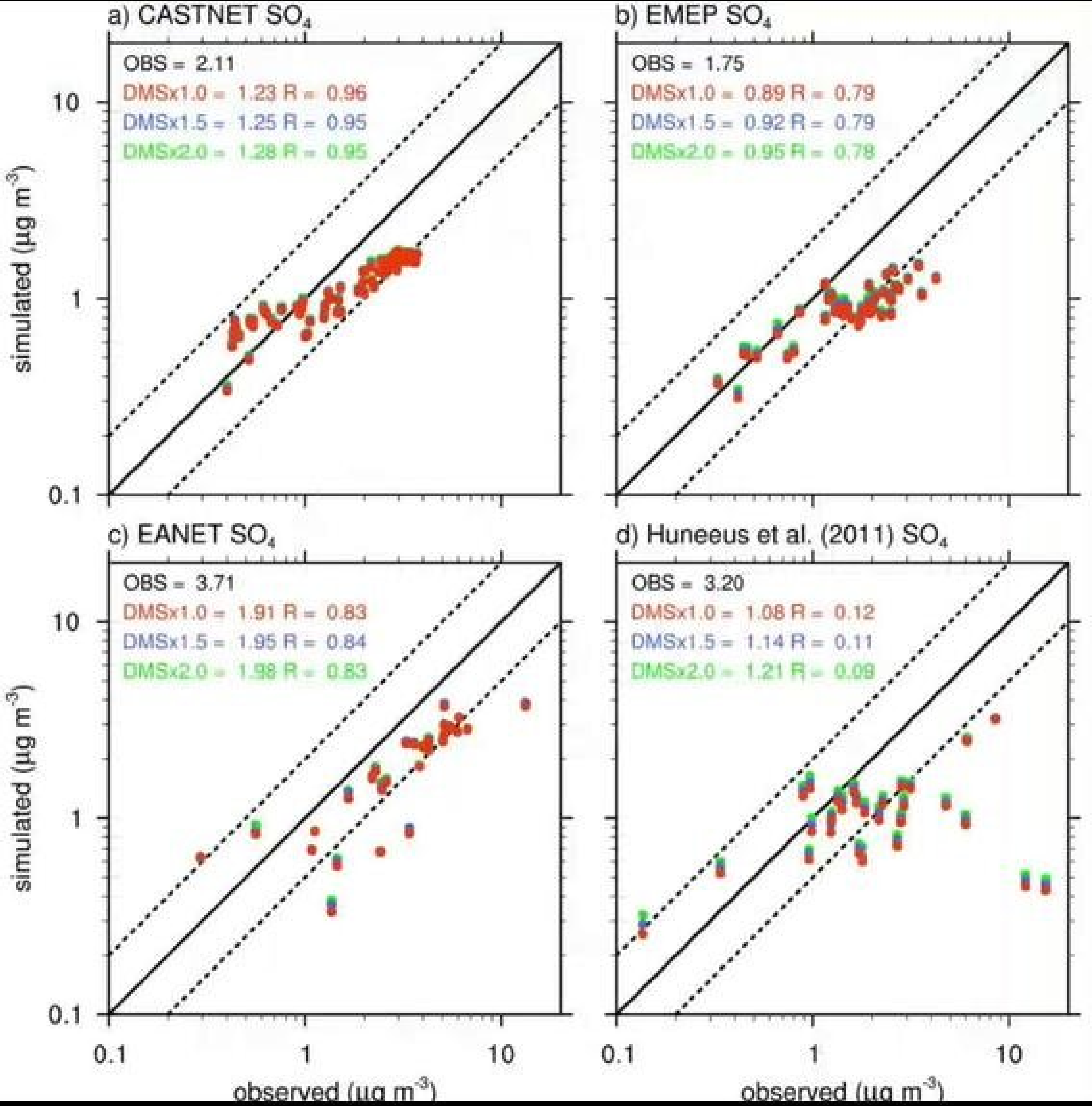
Christina McCluskey (NCAR), Qing Niu (U. Oklahoma), Naser Mahfouz, Susannah Burrows

Having the *right* (process-relevant) diagnostics is essential: Sulfate mass concentrations from ground-based networks are insensitive to 2x DMS.

Minimal response to 2xDMS, **even at marine sites**

➔ Need operational diagnostics for Southern Ocean aerosol

Mingxuan Wu, Hailong Wang



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E3SM's simulation of the historical temperature record is significantly improved in v3 with reduced ERF_{aer}

E3SMv3.0.0 : $ERF_{aer} = -0.75\ W/m^2$

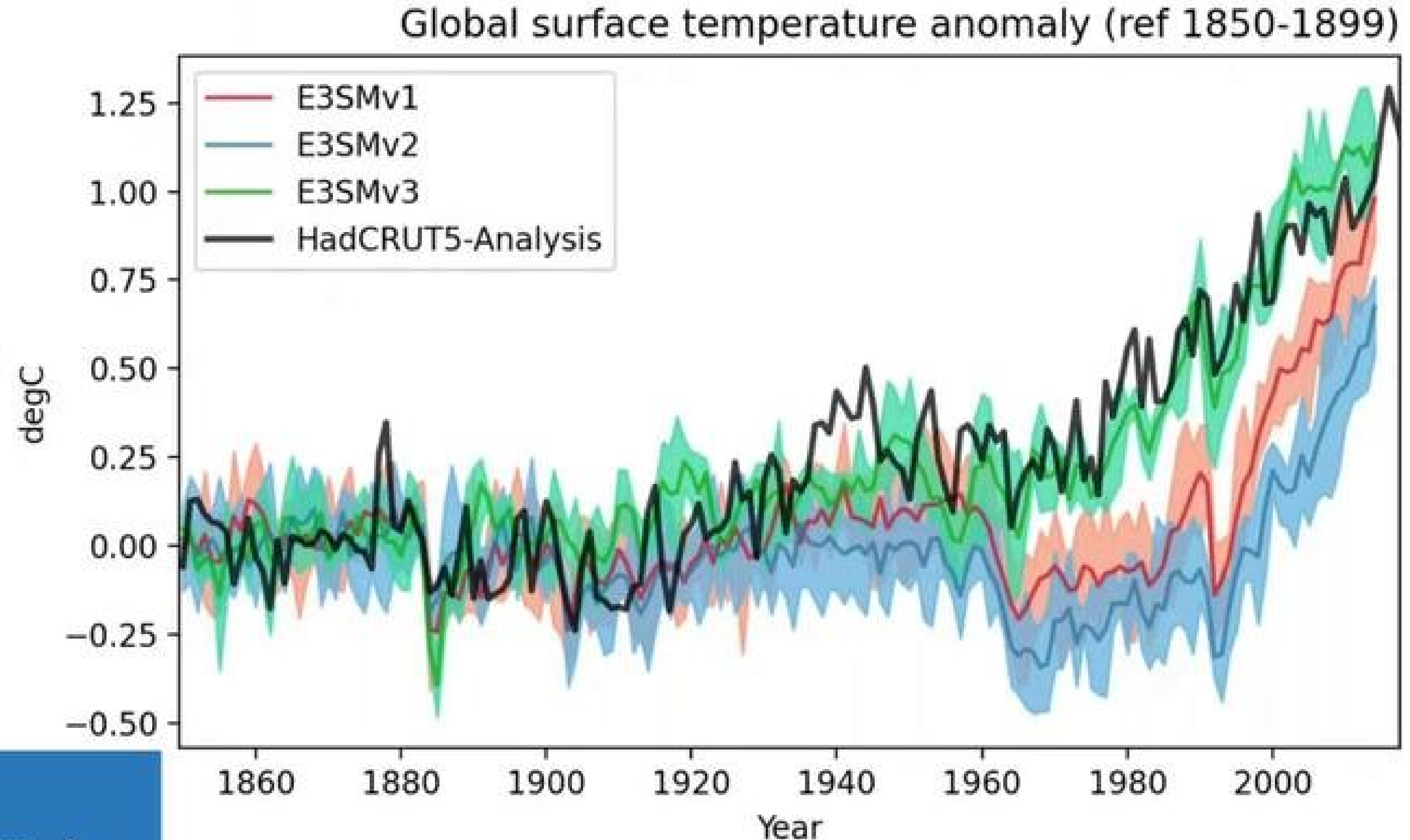

Figure courtesy of E3SM coupled group: Wuyin Lin, Xue Zheng, Chris Golaz, et al.

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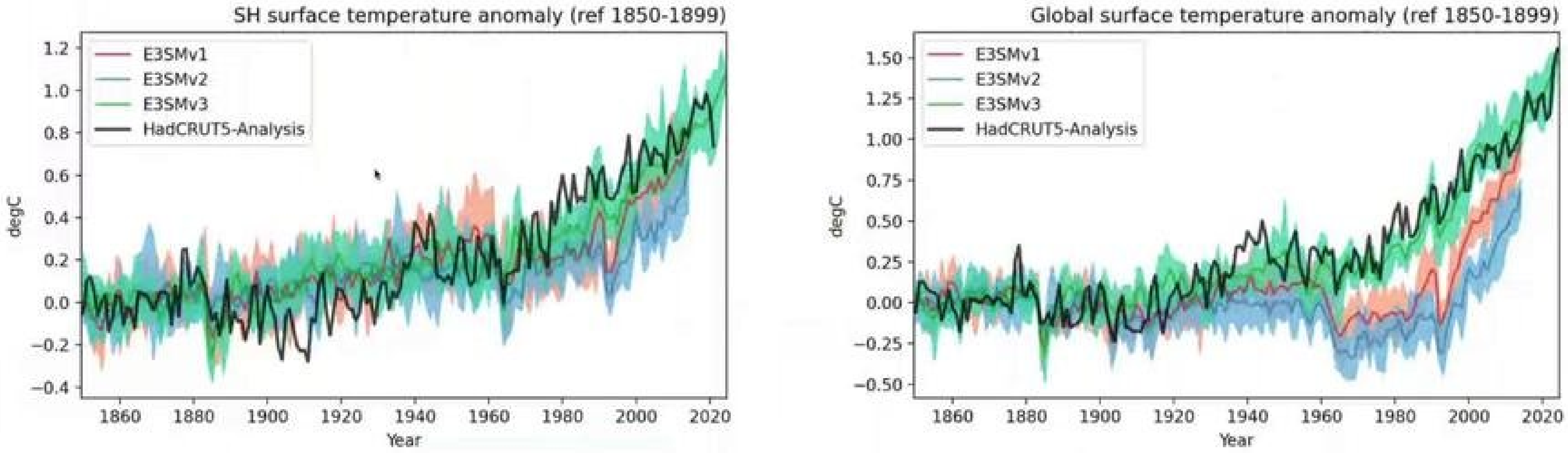
The hemispheric temperature gradient now also agrees well with the observational record



E3SMv3 ensemble extended with SSP245.

SSP245 is the medium pathway of "future" emissions, which extrapolates past and current global development into the future, with an additional radiative forcing of 4.5 W/m² by the year 2100.

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e3sm.org

Lessons for other bias reduction efforts – which strategies supported our success?

- A strong and committed team examining the issues from multiple perspectives
  - Contributions from process experts (clouds, aerosol, aerosol-cloud interactions)
  - Single working group lead (to coordinate & prioritize)
- Clear definition of the goal with objective metrics
- Coordination of priorities across groups and teams
  - Coupled group: coupled tuning priorities
  - v3 atmosphere integration team: climate mean state and variability
- Clear identification of hypotheses to explain biases
  - Pareto Principle: 20% of the effort yields 80% of the results
- Robust diagnostic tools and workflows
  - Enables rapid iteration and intercomparison of proposed solutions and hypotheses
  - Having the *right* diagnostics is essential
- More work is needed to elucidate and address
  - (1) background preindustrial aerosol sources, and
  - (2) the structural causes of low N_d