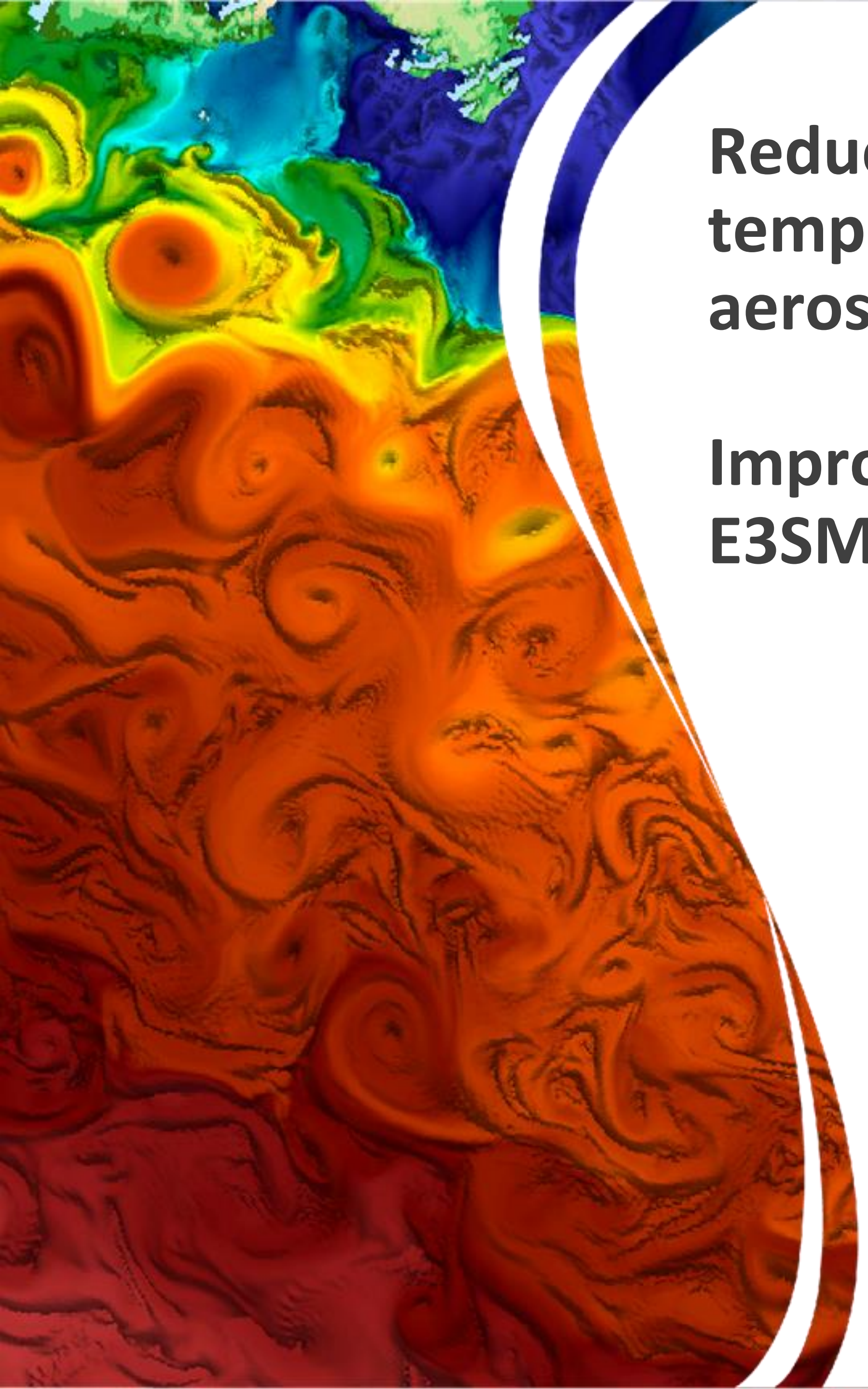


Reducing biases in the simulated historical temperature record through calibration of aerosol and cloud processes:

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

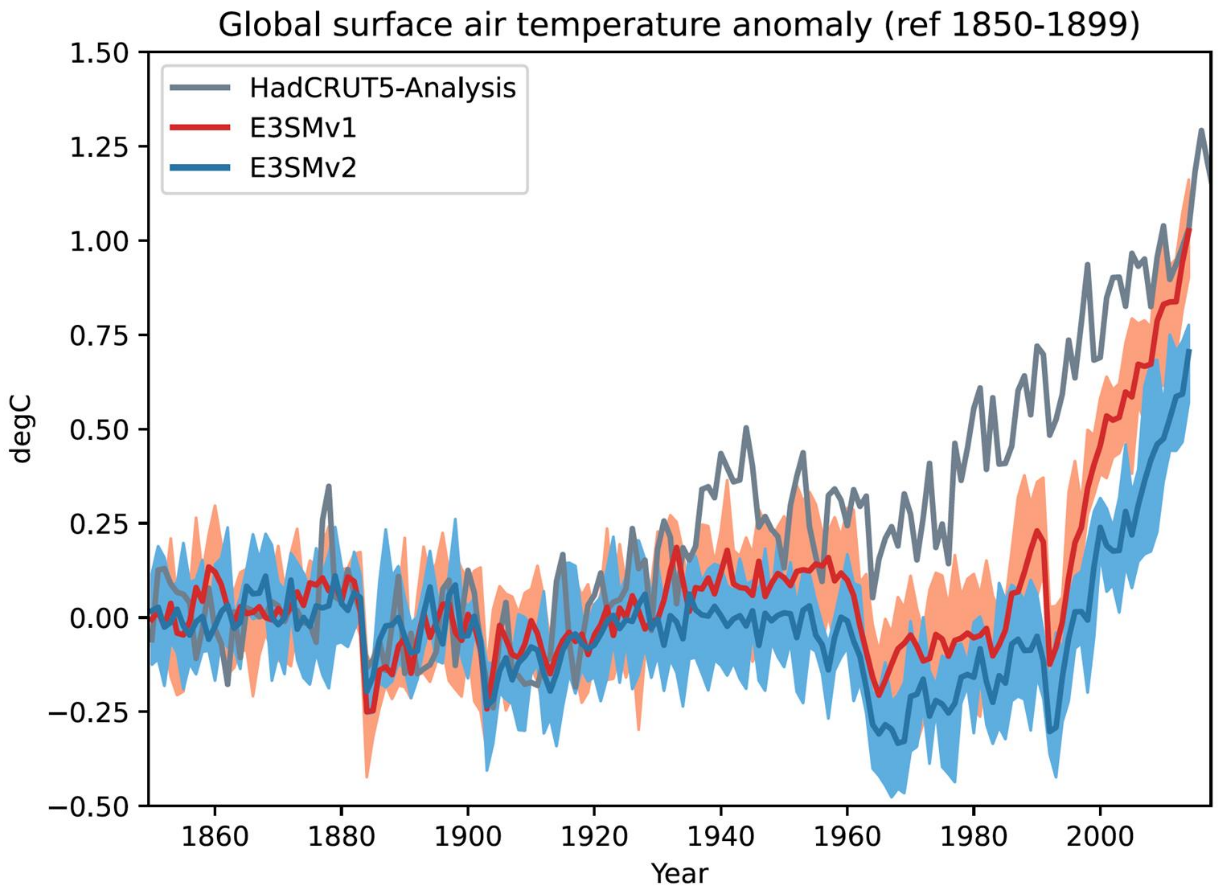
Aerosol-cloud interactions:

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

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



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}:

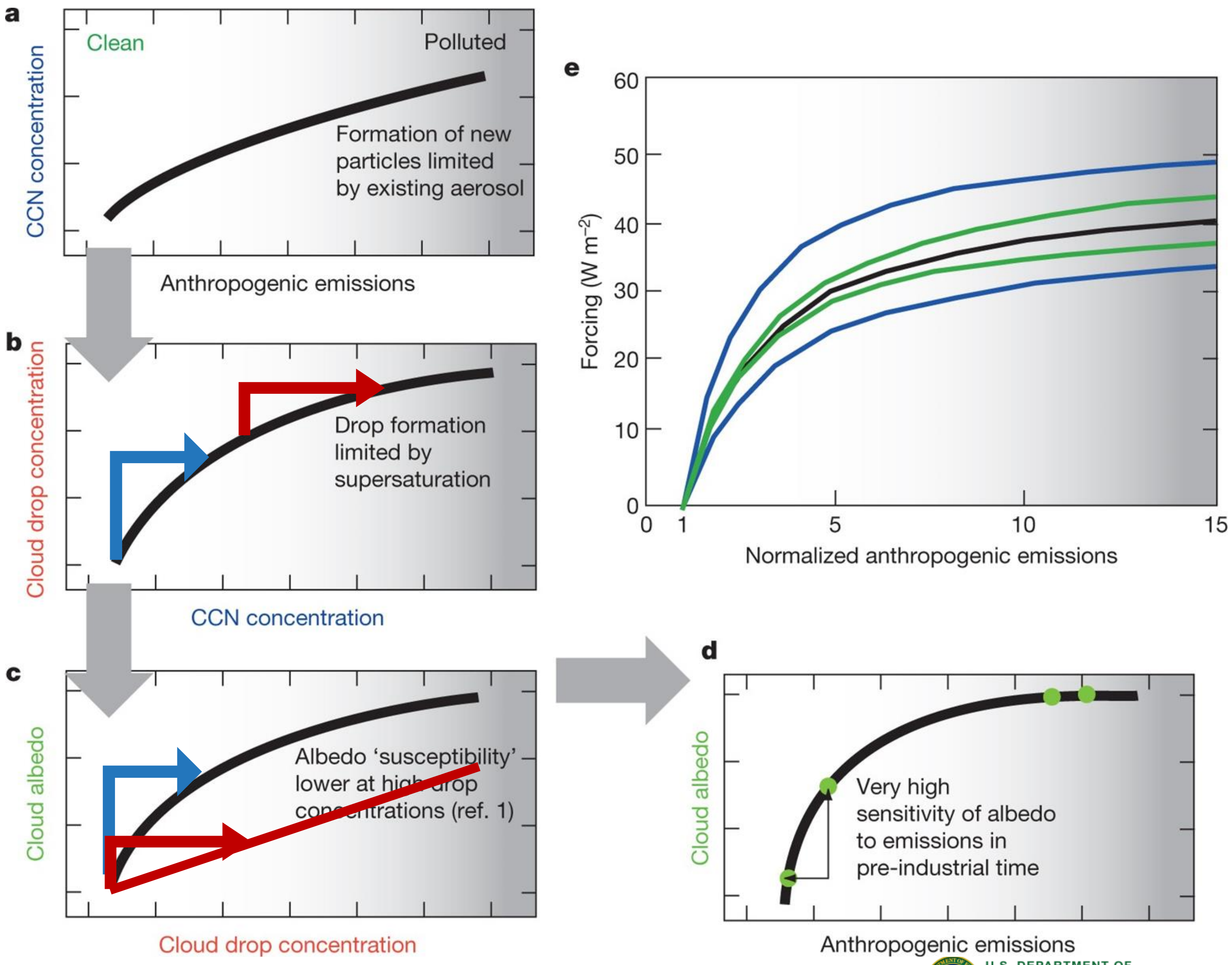
-0.5 to -0.7 W/m^2

Golaz et al. (2022)

Step 2: Clear identification of physical hypotheses

Two major approaches to reduce ERF$_{aci}$:

1. Reduce the PD-PI difference in N_d
2. Reduce the cloud albedo sensitivity to N_d



Carslaw et al. (2013)

ERF_{aer} was primarily impacted by changes to cloud microphysics, aerosol wet removal, and background CCN

	Total Aerosol Effective Radiative Forcing (ERF_{aer}) (1850 vs PD, fixed SST)	**Direct effect (ERF_{ari})**	**Indirect effect (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 ▲
E3SMv3dev (Feb 2023) (compy)	**-0.90** ✓	0.27 ✗	-1.23 ✓
E3SMv3dev (June 2023) (chrysalis)	**-1.04** ✓	0.17 ✗	-1.31 ✓
E3SMv3dev (October 2023)	**-0.78** ✓	-0.04 ✓	-0.83 ✓
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]

v2 -> v3dev (Feb):
1. New cloud microphysics (P3)
2. Increased the lower bound on droplet number
3. Reduced the droplet autoconversion exponent
4. Improved wet removal

June updates:
1. Changed machines (!)
2. Changes to aerosol-chemistry schemes with minor effects

October updates:
1. Increased background CCN (2x DMS)
2. Retuned droplet autoconversion
3. Faster BC aging; increased POM hygroscopicity

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

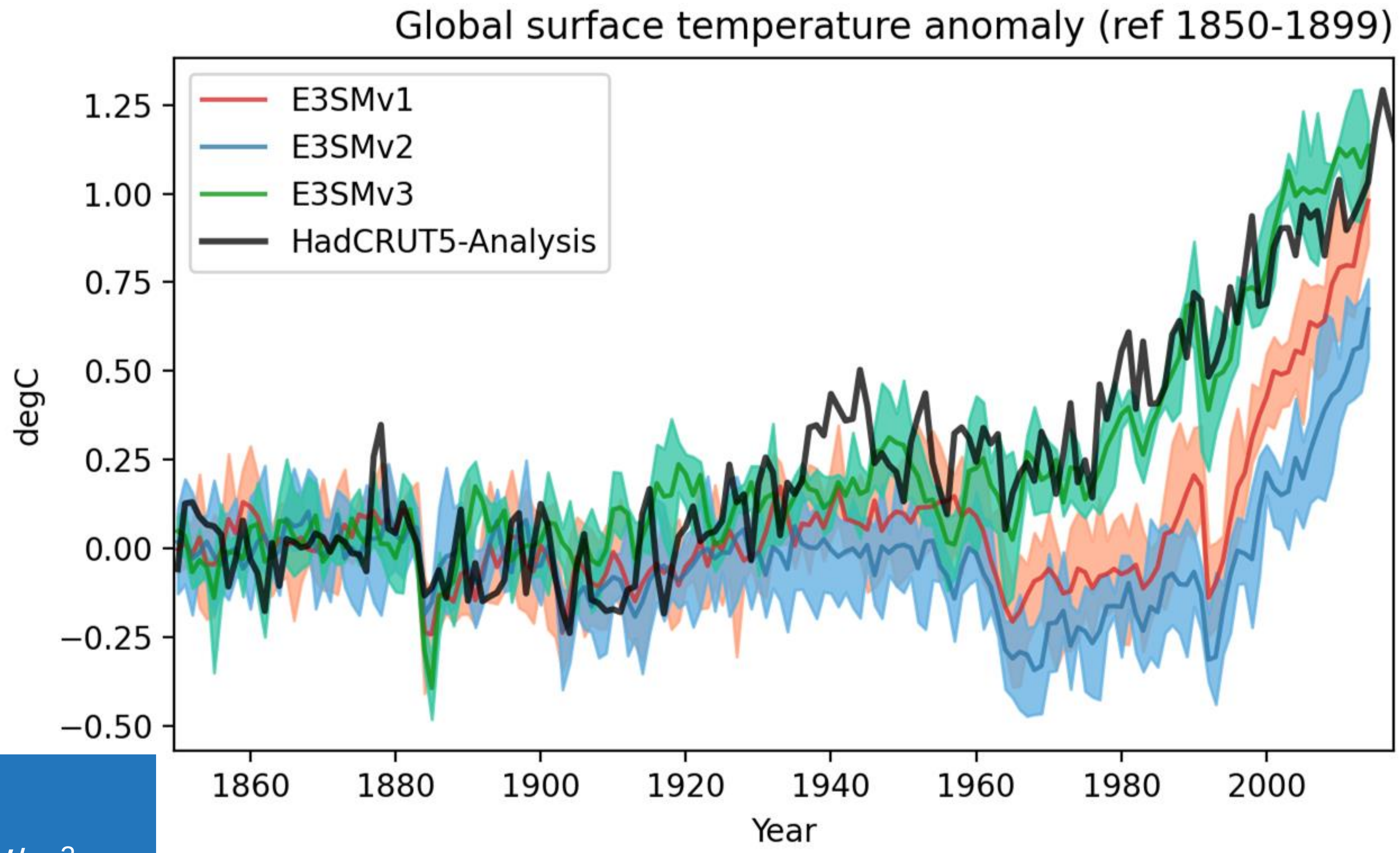


Figure courtesy of E3SM coupled group: Wuyin Lin, Xue Zheng, Chris Golaz, et al.

The Pareto Principle in action: Large sensitivity to natural background aerosol (DMS) and min. cloud droplet number concentration (CDNC)

Burrows et al. (in prep; E3SMv3)
Beydoun et al. (2023; E3SMv2)

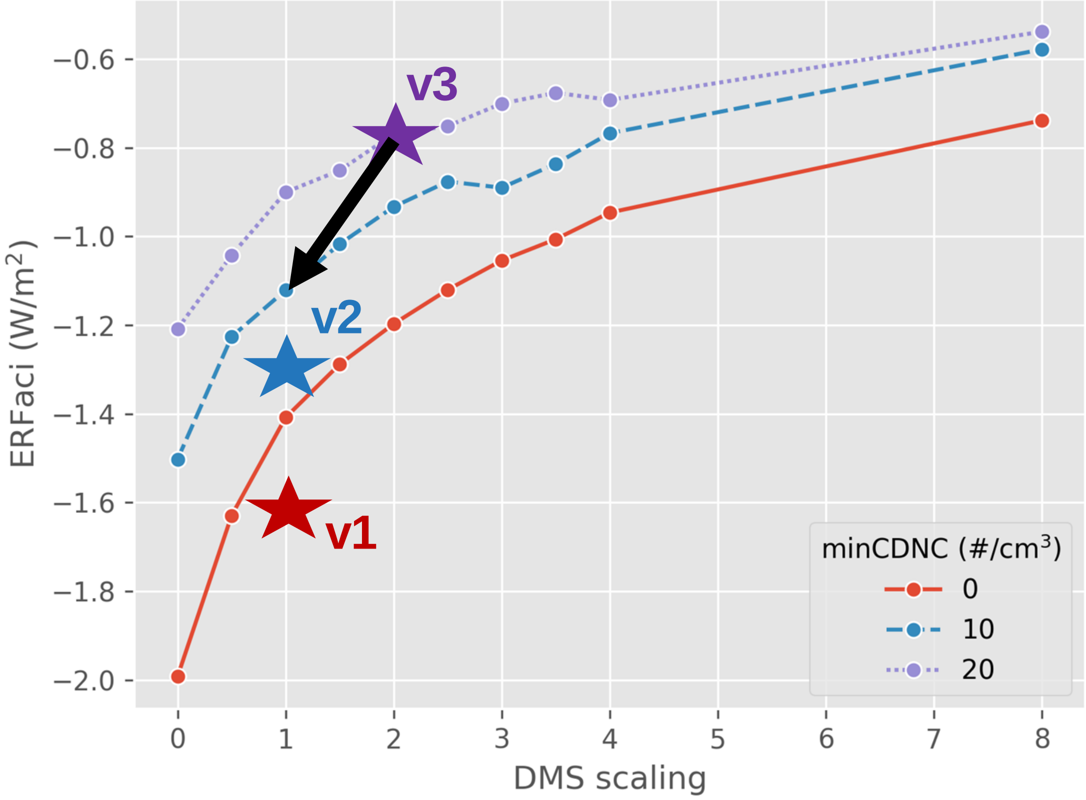


Figure courtesy of Naser Mahfouz (E3SM project)

Impacts of 2x DMS flux and minCDNC=20pcc on clouds □ ca. 80% of ΔERF_{aer} (v2□ v3)

Net effect of all other aerosol-cloud changes □ 20%

But care is needed:

- **New and updated process models requiring retuning**
- **Compensating effects from offsetting changes**
- **Right answer for the right reasons?**

Step 3: Build workflows to produce high-priority aerosol-related diagnostics and metrics

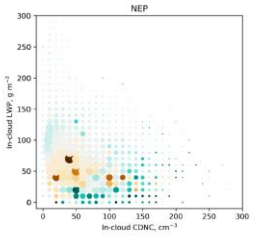
All major AWG diagnostics will ultimately be made available to the community as part of existing or new published diagnostics suites

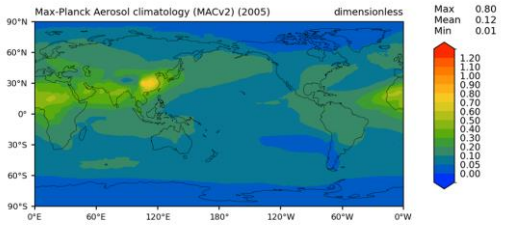
New operational/published diagnostics:

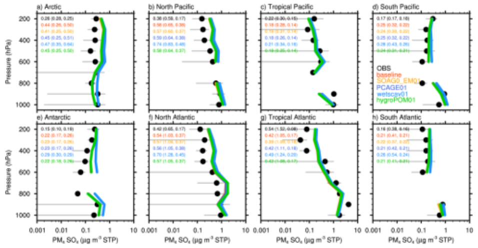
1. ARM aerosol-related diagnostics (ARM-diags)
2. Dust AOD (global mean)
3. Updated AOD climatologies
4. Anthropogenic AOD (global mean)
5. AOD and AAOD at AERONET sites (includes ARM data)
6. Global mean aerosol lifetimes, burdens, budget terms
7. T5050 (cloud phase diagnostic)
8. Historical temperature trends by hemisphere (NH, SH separately)
9. Cloud albedo susceptibility diagnostics

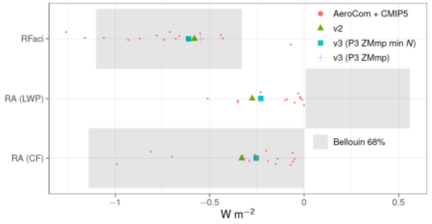
New prototype diagnostics:

1. ACI partitioning (LWP and cloud fraction adjustments)
2. Model-vs-model comparisons of multiple aerosol-related fields
3. Historical evolution of sulfate, BC aerosol versus ice core data
4. Sulfate aerosol, SO_2 gas versus surface observational networks
5. Vertical profiles versus ATom aircraft observations

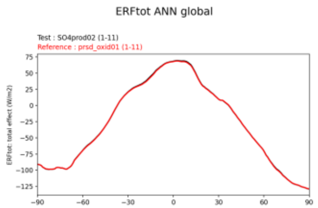


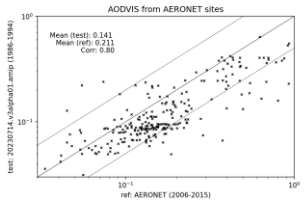


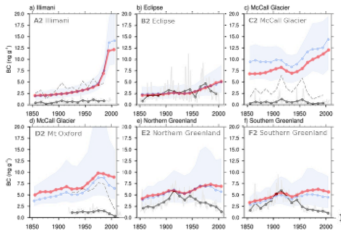


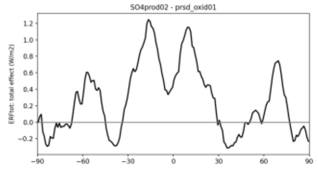


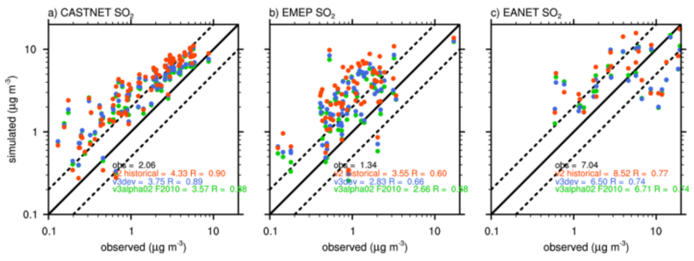
	Test	Ref
Black Carbon		
Surface Emission (Tg/yr)	7.60	0.92
Elevated Emission (Tg/yr)	1.75	1.64
Sink (Tg/yr)	9.38	2.56
Dry Deposition (Tg/yr)	3.20	0.82
Wet Deposition (Tg/yr)	6.19	1.74
Burden (Tg)	0.19	0.06
Lifetime (Days)	7.57	7.98
Dust		
Surface Emission (Tg/yr)	2632.93	2699.25
Elevated Emission (Tg/yr)	0.00	0.00

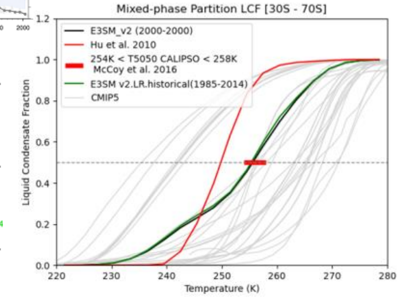










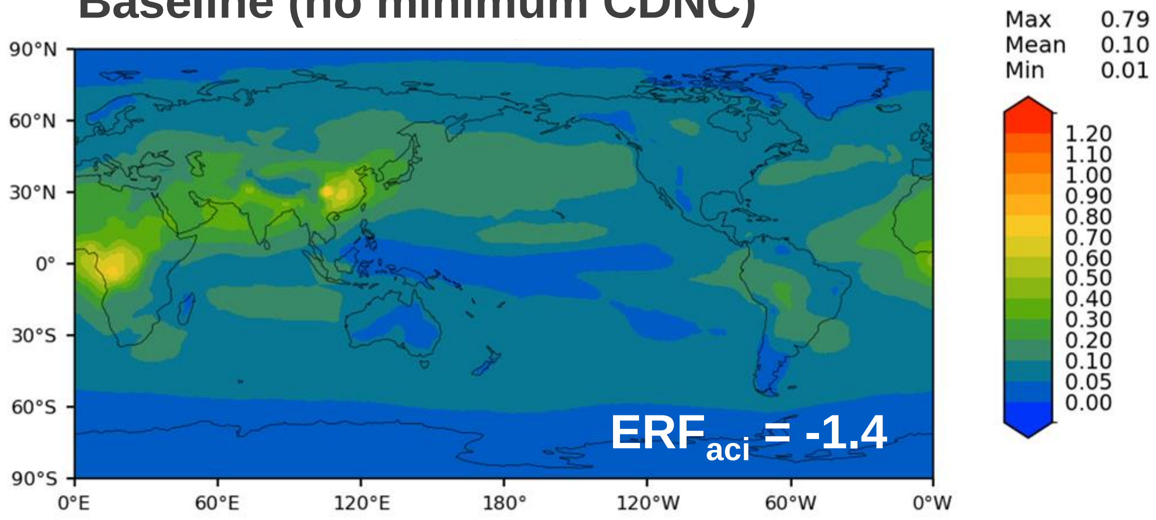


Contributors: Mingxuan Wu, Naser Mahfouz, Chengzhu “Jill” Zhang, Johannes Mülmenstädt, Susannah Burrows, Yuying Zhang, Yan Feng, Jiwen Fan, Kai Zhang, Hailong Wang, Ryan Forsyth, Charlie Zender, and others

Having the right diagnostics is essential: DMS and minimum CDNC have minimal impact on Aerosol Optical Depth (AOD) despite large impacts on ERF_{aci}

Burrows et al. (in prep); Figures courtesy of Naser Mahfouz

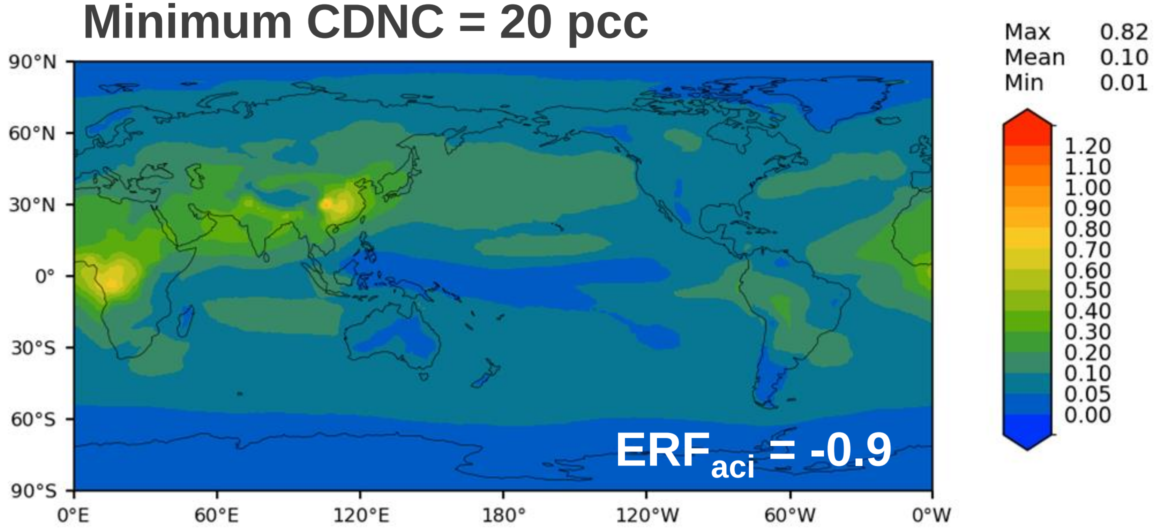
Baseline (no minimum CDNC)



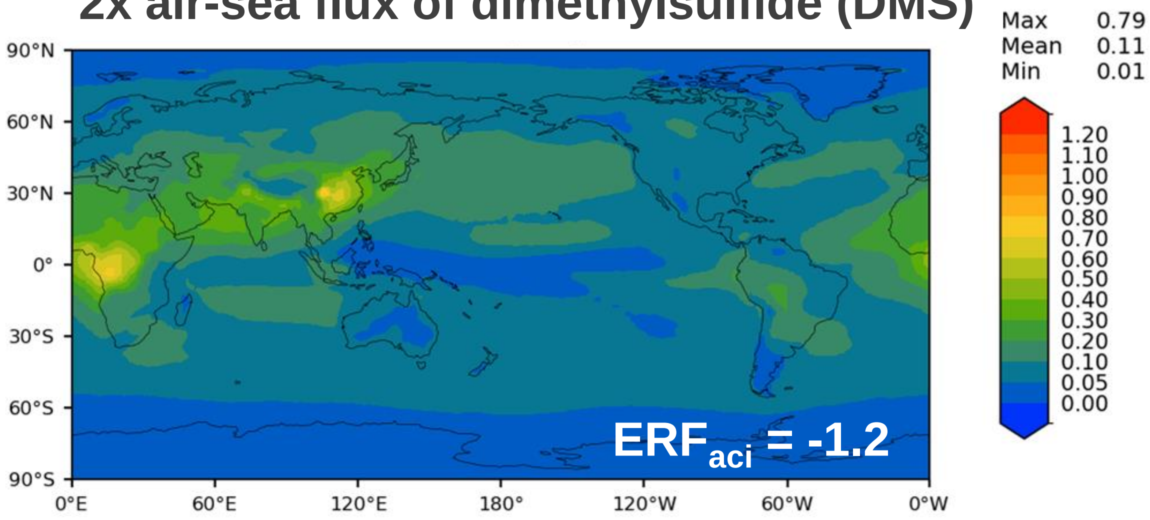
Improved observational constraints are required

- Top-down constraints (e.g., satellite-observed CDNC; McCoy, Burrows, et al., 2015)
- In situ observations (e.g., SOCRATES, ARM CAPE-K Southern Ocean campaigns)
- Integration into standard E3SM diagnostic tools

Minimum CDNC = 20 pcc



2x air-sea flux of dimethylsulfide (DMS)



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

- A strong and committed team examining the issues from multiple perspectives
  - Single working group lead (coordinate & prioritize)
  - Contributions from process experts (clouds, aerosol, aerosol-cloud interactions)
- 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

E3SM Energy Exascale Earth System Model

ARM User Executive Committee (UEC) survey:

How can ARM measurements be more useful for global models, especially E3SM?

Seeking broad community input!

- **Modelers and observationalists**
- **Broad reach – beyond current ARM user community**
- **Aerosol / ACI focus, but other topics are also welcomed**

ARM User Executive Committee

Enhancing Communication - Modeling/E3SM Subgroup

Susannah Burrows **Co-chair** Pacific Northwest National Laboratory	**Scott Collis** Argonne National Laboratory	**Erika Roesler** **Co-chair** Sandia National Laboratories	**Yunpeng Shan** Pacific Northwest National Laboratory	**Yunyan Zhang** **Co-chair** Lawrence Livermore National Laboratory	**Youtong Zheng** University of Houston

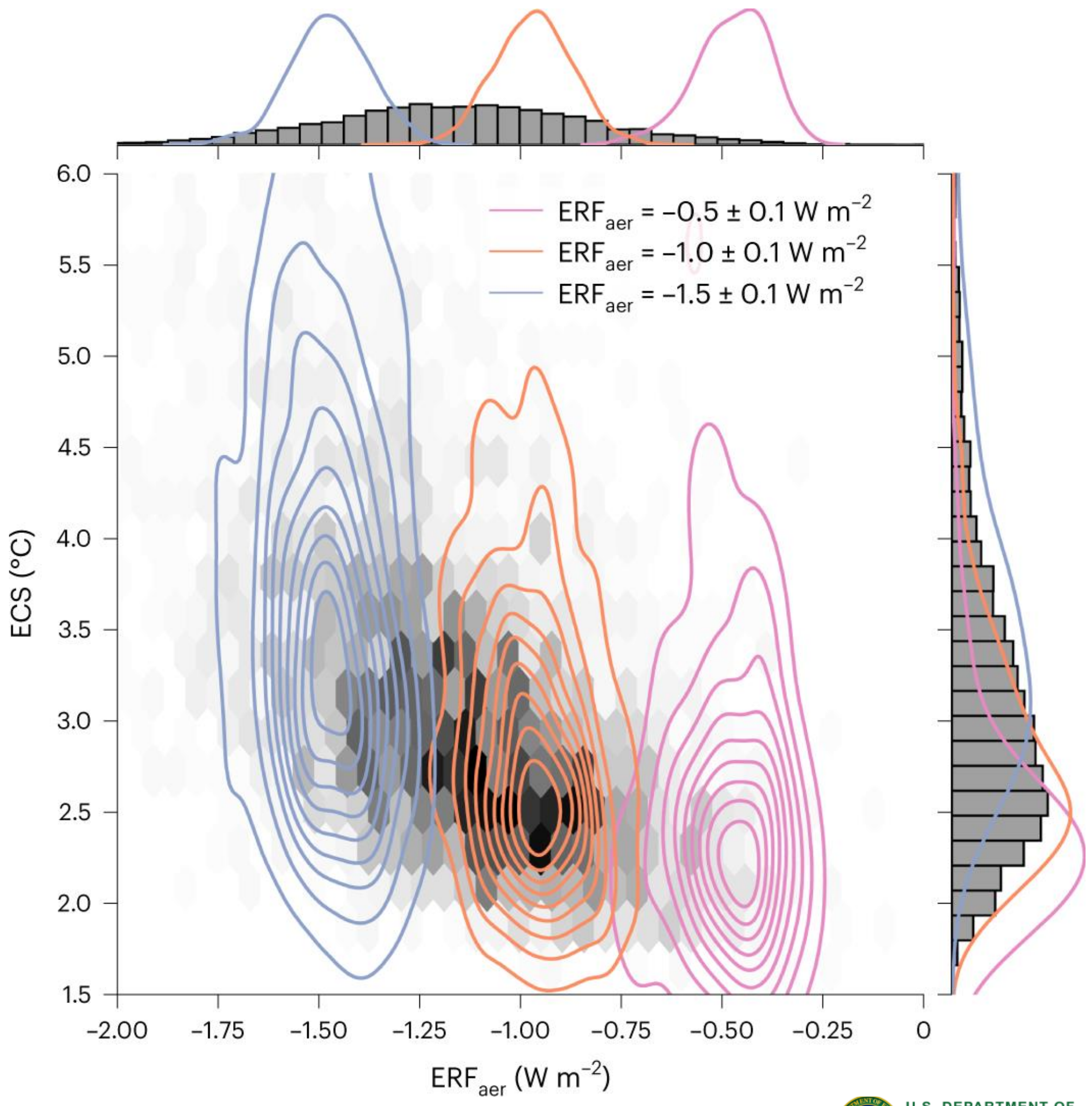
U.S. DEPARTMENT OF ENERGY

e3sm.org

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

Priority	Metric	Target	Current value	On target?
1	ERF_{aer}	ca. -0.7 W/m^2 "3rd" smoke test	-1.04 W/m^2	Likely too strong
(1)	ERF_{aci}	-1.0 [1.7 to -0.3] W/m^2 (IPCC range)	-1.31 W/m^2	Within range
(1)	ERF_{ari}	-1.0 [-0.6 to 0.0] W/m^2 (IPCC range)	0.17 W/m^2	Should be negative or near-zero
1	Aerosol burdens and life cycle diagnostics	Burdens and lifetimes within the AWG benchmark ranges.	Will be tabulated in overview papers	Most metrics are within range of other models. SOA burden is high. POM, BC lifetimes and burdens are on the high side; sulfate burden on the low side.
1	Anthropogenic AOD	~0.02-0.04	0.04	Yes
2	Global mean total AOD (PD)	0.11-0.14 Aerocom III & obs	0.13	Yes
2	Global mean total DOD	0.017-0.035 Aerocom III & obs	0.0253	Yes

Additional Tier 2 diagnostics: ACI partitioning (JM script), albedo susceptibility diagnostics (NM script), AOD at Aeronet sites, historical 20th century trend in NH and SH T, in situ surface and vertical profile measurements, T5050

Initial set of symptoms and hypotheses (Phase 2)

Symptom	Hypothesis	Progress and Status	Remaining TODOs and timeline
Anthropogenic aerosol burdens are too high in E3SMv2	Wet deposition lifetimes are too long	**PROPOSED FIX + diagnostics UNDER REVIEW.** Targeted developments and tunings are shown to reduce aerosol lifetimes, burdens and ERF_{aer} (Y. Shan and J. Fan), code changes have been archived in a branch on github. Aerosol-related diagnostics will be added to e3sm_diags to prevent recurrence of this issue (in progress, Jill Chengzhu Zhang).	e3sm_diags aerosol diagnostics will be completed **by Dec 30** (Infrastructure). Document simulations and analysis of wet removal code changes in Confluence **by Nov 30**. (Y. Shan, J. Fan)
Cloud droplet number concentrations are too low	Several hypotheses have been identified and are being investigated	**IN PROGRESS but temporarily on hold. P3 has been excluded as the cause of the low N_d values.** Analysis of v3 candidates is underway to isolate which subroutines cause new low-Nd values to appear, and to compare with observed frequency of occurrence of low Nd (Y. Shan and J. Fan).	Complete analysis; document simulations and analysis in Confluence. (Y. Shan, J. Fan) Currently on hold; timeline TBD.
Mid-20th century T is too cool in coupled E3SMv2	Cooling is caused by insufficient ocean heat uptake (*due to AMOC bias*)	**(1) The E3SMv1/v2 AMOC bias has been ruled out as contributor to the historical temperature bias by the v2.1 runs.** (L. Van Roeckel, C. Golaz, and coupled group) **(2) Atmosphere-only (fixed-SST) simulations are adequate to quantify the model's response to aerosol forcing in E3SM,** **(3) with the caveat that we have shown E3SM has a slightly stronger aerosol *efficacy* (climate response to aerosol normalized by GHG response) compared to many other models (the causes of which are still unknown).** Nevertheless, our quantification of the aerosol efficacy shows that **the coupled system response to aerosol is at most a modest contributor to E3SM's late-20th century cold bias**. (J. Mülmenstädt, S. Burrows, A. Raman, K. Zhang).	Documentation of simulations and analysis already performed in Confluence **by Nov 30** (A. Raman, J. Mülmenstädt, O. Garuba). No further work is planned on this topic.
	Cloud lifetime response to Nd is too strong in E3SM	**(1) E3SM's warm cloud direct ACI response (Twomey effect), cloud lifetime rapid adjustment, and cloud fraction rapid adjustment are within the multi-model range for** v2 and candidate v3 models (with P3 + ZMmp) **(2) The LWP rapid response to aerosol forcing is negative in E3SM, in contrast to observational constraints indicating it should be positive.** This bias is also present in all other CMIP models examined, so it can't explain why E3SM is an outlier in ERFaci. However, it does suggest that changes targeting the LWP rapid adjustment may be a more physically justifiable way to reduce ERFaci (J. Mülmenstädt).	Document and archive the ACI partitioning script in a github repository within the E3SM organization on github **by Nov 30**. (J. Mülmenstädt).

The Pareto Principle in action

Burrows et al. (in prep; E3SMv3)
Beydoun et al. (2023; E3SMv2)

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

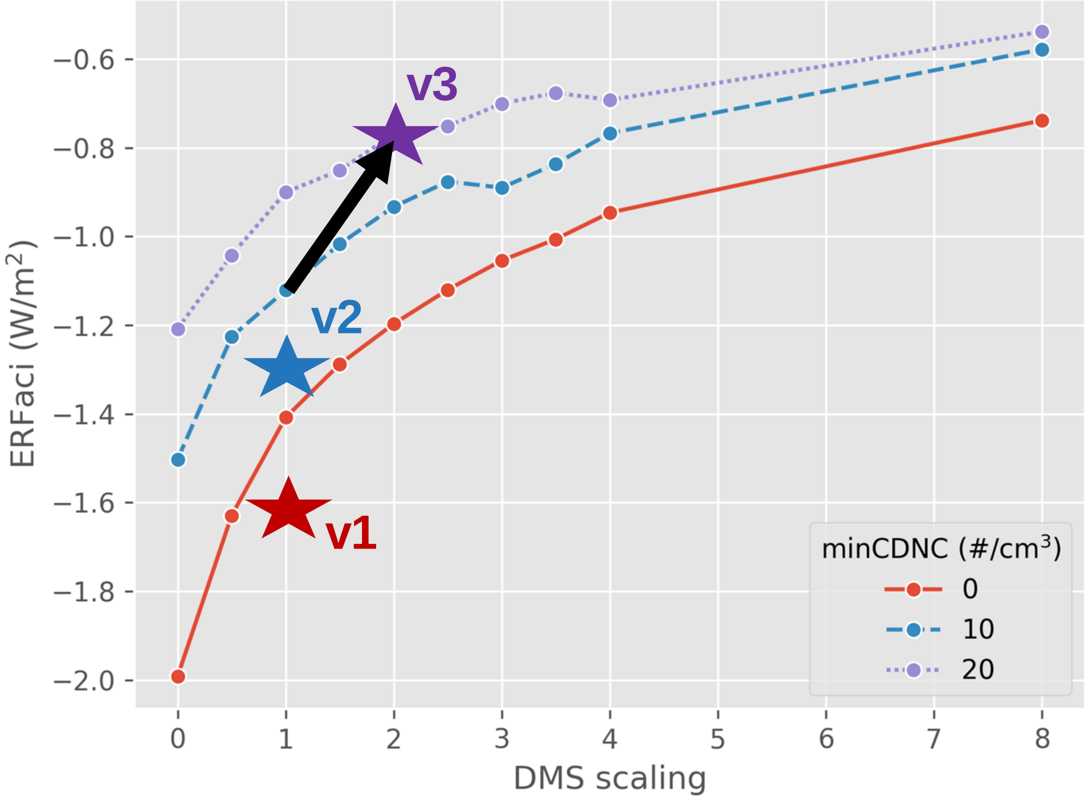


Figure courtesy of Naser Mahfouz (E3SM project)

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