Effective radiative forcing of anthropogenic aerosols in E3SM v1 and v2

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Contributors

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V2 simulation: Chris Golaz, Xue Zheng, Ryan Forsyth, and many others
Motivation

- E3SMv1 has a relatively large effective aerosol forcing ($\text{ERF}_{\text{aer}}$) compared to other CMIP6 models
- We need a comprehensive analysis on
  - Historical changes
  - Causal relationships
  - Forcing decomposition
  - Parameterization sensitivities
- Is V2 better?
- What is the climate response to anthropogenic aerosol effects in the coupled model?
Key points

- Compared to v1, TOA $\text{ERF}_{\text{aer}}$ is significantly reduced in both SW and LW components in v2. The net change is relatively small ($\sim 0.3 \text{Wm}^{-2}$). Both the 1$^\text{st}$ and 2$^\text{nd}$ indirect $\text{ERF}_{\text{aer}}$ magnitudes are reduced significantly.

- **SW and LW surface $\text{ERF}_{\text{aer}}$ changes are small.** Reduced indirect $\text{ERF}_{\text{aer}}$ is compensated by stronger direct $\text{ERF}_{\text{aer}}$ (mainly caused by ant. aerosol burden/AOD increase).

- **Aerosol effects** on SW/LW TOA radiative fluxes are magnified in the coupled runs.

- **Tuning, (cloud/aerosol) bug fixes, and numerical coupling errors** all have significant impacts on aerosol lifetime, AOD, and $\text{ERF}_{\text{aer}}$ simulated in E3SM.

- $\text{ERF}_{\text{aer}}$ estimates from nudged runs with time slice aerosol emissions are overall consistent with that derived from AMIP/RFMIP simulations.
V1 simulations

- E3SM atmosphere model version 1 (EAMv1) with MAM4
- Two AMIP (1870-2014) simulations:
  - one with pre-industrial (1850) aerosol emissions
  - one with transient aerosol emissions
- Nudged simulations
  - U and V nudged towards ERA-Interim reanalysis for year 2010
  - 6h relaxation time scale
  - one with pre-industrial (1850)
  - one with aerosol emissions at selected time slices (e.g., present-day 2010)
V2 simulations

- E3SM atmosphere model version 2 (EAMv2) with MAM4
- hist_aer (1850-2014):
  - RFMIP with fixed SST (from coupled simulations) with transient aerosol emissions
  - coupled simulations with transient aerosol emissions
- piCtrl:
  - RFMIP (50y) with fixed SST and 1850 forcings (including aerosol emissions)
  - coupled simulations (500y) with 1850 forcings (including aerosol emissions)
- Nudged simulations
Effective aerosol forcing in E3SMv1

AMIP simulation results (lines) are averaged from 3 ensemble members. Nudged simulations with specified emissions for a certain year (1900, 1950, 1970, 2000, and 2010) are shown as dots.
\( \text{ERF}_{\text{aer}} \) at TOA

TOA \( \text{ERF}_{\text{aer}} \) is significantly reduced in both SW and LW components in v2.

**V1 nudged (2010aer – 1850aer)**

- **Total ant. aer. effect**
  - PD PI: TTAEF = -1.838 W m\(^{-2}\)
- **SW ant. aer. effect**
  - PD PI: SWAEO = -2.128 W m\(^{-2}\)
- **LW ant. aer. effect**
  - PD PI: LWAEO = 0.790 W m\(^{-2}\)

**V2 nudged (2010aer – 1850aer)**

- **Total ant. aer. effect**
  - PD PI: TTAEF = -1.333 W m\(^{-2}\)
- **SW ant. aer. effect**
  - PD PI: SWAEO = -1.551 W m\(^{-2}\)
- **LW ant. aer. effect**
  - PD PI: LWAEO = 0.218 W m\(^{-2}\)
ERF_{aer} at TOA

V1 AMIP vs. V2 RFMIP

TOA ERF_{aer} is significantly reduced in both SW and LW components in v2.
Indirect $\text{ERF}_{\text{aer}}$ at TOA (decomposed)

The changes in $\text{ERF}_{\text{aer}}$ are mainly caused by reduced indirect aerosol effects.

**V1 nuded (2010aer – 1850aer)**

- **Total indirect ant. aer. effect**
  - PD-PI: TTIND: 1.766 W m$^{-2}$

- **SW indirect ant. aer. effect**
  - PD-PI: SWIND: 2.973 W m$^{-2}$

- **LW indirect ant. aer. effect**
  - PD-PI: LWIND: 0.607 W m$^{-2}$

**V2 nuded (2010aer – 1850aer)**

- **Total indirect ant. aer. effect**
  - PD-PI: TTIND: -1.508 W m$^{-2}$

- **SW indirect ant. aer. effect**
  - PD-PI: SWIND: -1.541 W m$^{-2}$

- **LW indirect ant. aer. effect**
  - PD-PI: LWIND: 0.032 W m$^{-2}$

Important model changes that affect $\text{ERF}_{\text{aer}}$ in v2
- Tuning (see Ma et al. 2022GMD and Zhang et al. 2022ACPd)
- Minimum CDNC (see slide 14)
**ERF_{aer} at surface**

Surface SW/LW ERF_{aer} changes are small.
Reduced indirect effect is compensated by stronger direct effect (shown later).

**V1 nudge (2010aer – 1850aer)**

(a) SURF ΔF : ALL

(b) SURF ΔF_{SW} : ALL

(c) SURF ΔF_{LW} : ALL

**V2 nudge (2010aer – 1850aer)**

(a) SURF ΔF : ALL

(b) SURF ΔF_{SW} : ALL

(c) SURF ΔF_{LW} : ALL
**ERF\textsubscript{aer} at surface**

Surface SW/LW ERF\textsubscript{aer} changes are small. Reduced indirect effect is compensated by stronger direct effect (shown later).
V2 vs. V1

Re vs. Nd (1st)

LWP vs. Nd (2nd)

Both the 1st and 2nd indirect ERF_{aer} magnitudes are reduced significantly.

Important model changes that affect ERF_{aer} in v2

- Tuning (see Ma et al. 2022GMD and Zhang et al. 2022ACPD)
- Minimum CDNC (see slide 14)
Extremely low CDNC appears frequently in E3SMv1

Based on one-year average of high-frequency data
Adding a lower bound for CDNC reduces $\text{ERF}_{\text{aer}}$

In V2: $\text{CDNC}_{\text{min}} = 10 \text{ cm}^{-3}$

- If this lower bound is removed in V2, $\text{ERF}_{\text{aer}}$ is about -1.64 (vs. -1.33 in v2) Wm$^{-2}$.
- If $\text{CDNC}_{\text{min}}$ is too large, strong perturbation in LWP is observed in some regions.
Direct aerosol effect at surface (decomposed)

**E3SMv1** nudged (2010aer – 1850aer)

**E3SMv2** nudged (2010aer – 1850aer)
Larger AOD in v2 simulations

- Results are consistent with analysis done by Mingxuan and Hailong
- Recent simulations show a couple of tuning parameters play an important role
Why AOD is much larger in v2?

![Graph showing AOD and Lifetime (days) for v1 and v2](image-url)
Why AOD is much larger in v2?

**AOD**

- v1: 0.1
- v2: 0.15
- conv: tuning parameters for convection parameterization reverted to v1

**Lifetime (days)**

- v1: 5 days
- v2: 8 days
- conv: 6 days
Why AOD is much larger in v2?

A recent model development study (ICON-HAM) also reported large sensitivity of AOD simulation to convection parameterization tuning.

Salzmann et al. (2022JAMES)
Sensitivity of aerosol lifetime to other factors

Two important bugs recently identified/fixed in development branch (but still in E3SM master):

- MG2 bugfix (reported by NCAR)
- Aqueous chemistry bug (revealed during NGD P3 development)
Sensitivity of aerosol lifetime to other factors

Physics time step set to 900s (1800s by default)

- Lifetime decreases for all types of aerosols except for dust
- Similar changes seen in V1 (Wan et al., 2021GMD, 2022 in prep).
V2 versus V1 (TOA)

Aerosol effects on SW/LW TOA radiative fluxes are magnified in the coupled runs.

**SW**

- V2 Coupled
- V2 RFMIP
- V1 AMIP

**LW**

- V2 Coupled
- V2 RFMIP
- V1 AMIP
Ongoing efforts

- Further investigate why $r_{\text{eff}}$ is so sensitive to changes in Nd in E3SM/MG2.

- Fix/evaluate (important) known bugs
  - Aqueous chemistry bug (revealed during NGD P3 development)
  - MG2 bug related to ice nucleation (reported by NCAR)
  - RH used in aerosol nucleation (revealed by EAGLES computational team)

- Further analysis of the single-forcing coupled simulations

- Integrating various aerosol diagnostics tools for future model development
Key points

• Compared to v1, **TOA ERFaer** is **significantly reduced in both SW and LW** components in v2. The net change is relatively small (~0.3Wm$^{-2}$). Both the 1$^{\text{st}}$ and 2$^{\text{nd}}$ indirect ERFaer magnitudes are reduced significantly.

• **SW and LW surface ERFaer** are largely unchanged. Reduced indirect ERFaer is compensated by **stronger direct ERFaer** (mainly caused by ant. aerosol burden/AOD increase).

• **Aerosol effects** on SW/LW TOA radiative fluxes are **magnified in the coupled runs**.

• **Tuning, (cloud/aerosol) bug fixes, and numerical coupling errors** all have significant impacts on aerosol lifetime, AOD, and ERFaer simulated in E3SM.

• ERFaer estimates from **nudged runs** with time slice aerosol emissions are overall **consistent with** that derived from **AMIP/RFMIP** simulations.