Effective radiative forcing of anthropogenic aerosols in E3SM v1 and v2

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Contributors

V1 simulation and analysis: *Wentao Zhang, Hui Wan, Philip J. Rasch, Steven J. Ghan, Richard C. Easter, Xiangjun Shi, Yong Wang, Hailong Wang, Po-Lun Ma, Shixuan Zhang, Jian Sun, Susannah Burrows, Manish Shrivastava, Balwinder Singh, Yun Qian, Xiaohong Liu, Jean-Christophe Golaz, Qi Tang, Xue Zheng, Shaocheng Xie, Wuyin Lin, Yan Feng, Minghuai Wang, Jin-Ho Yoon, and Ruby L. Leung*

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

Motivation

- E3SMv1 has a relatively large effective aerosol forcing (**ERF_{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 ERF_{aer}** is **significantly reduced in both SW and LW** components in v2. The net change is relatively small (~$0.3Wm^{-2}$). Both the 1st and 2nd indirect ERF_{aer} magnitudes are reduced significantly.
- **SW and LW surface ERFaer changes are small**. Reduced indirect ERF_{aer} is compensated by **stronger direct ERF_{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 ERF_{aer} simulated in E3SM.
- ERF_{aer} estimates from **nudged runs** with time slice aerosol emissions are overall **consistent with** that derived from **AMIP/RFMIP** simulations.

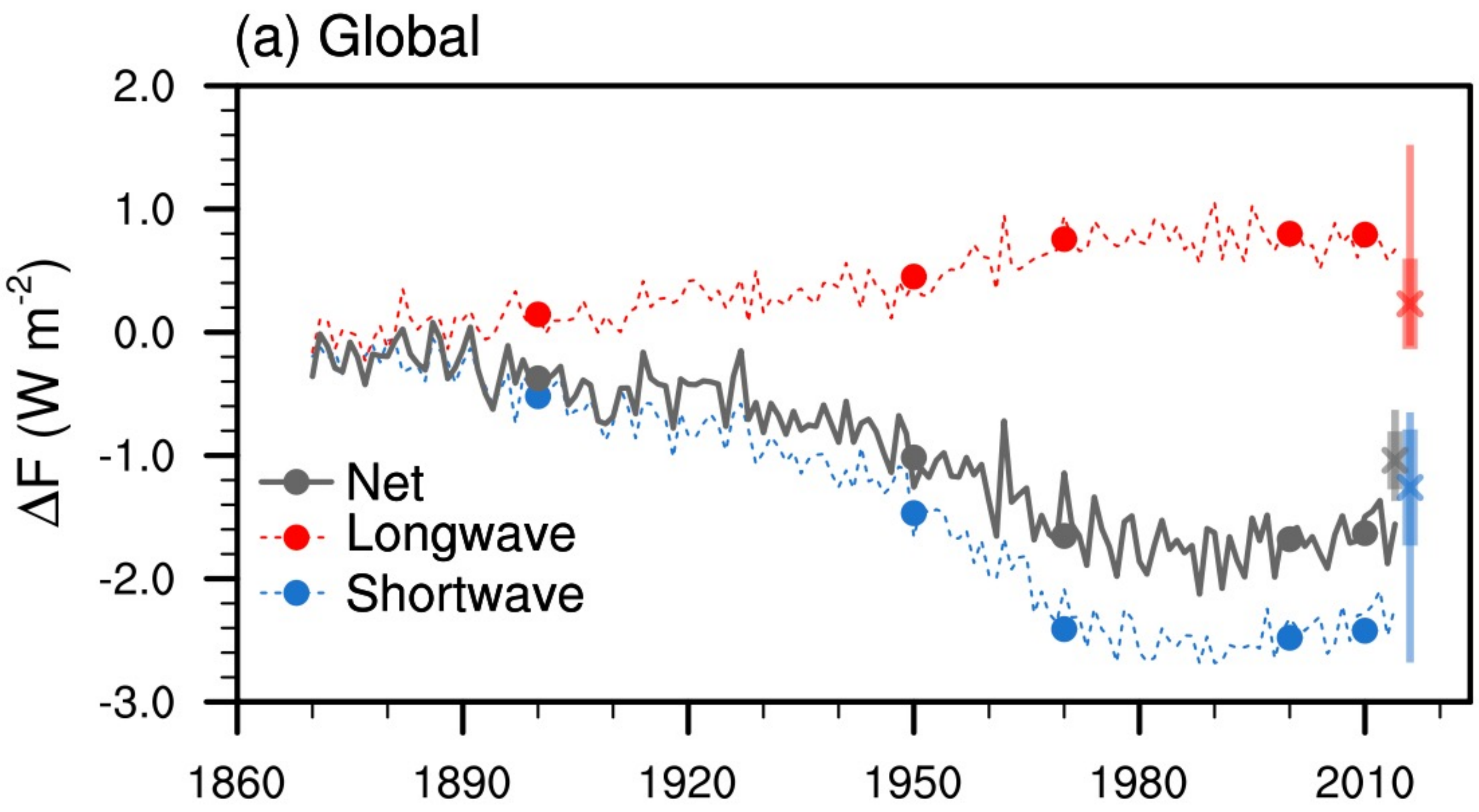
V1 simulations

- 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



Cross and vertical bars

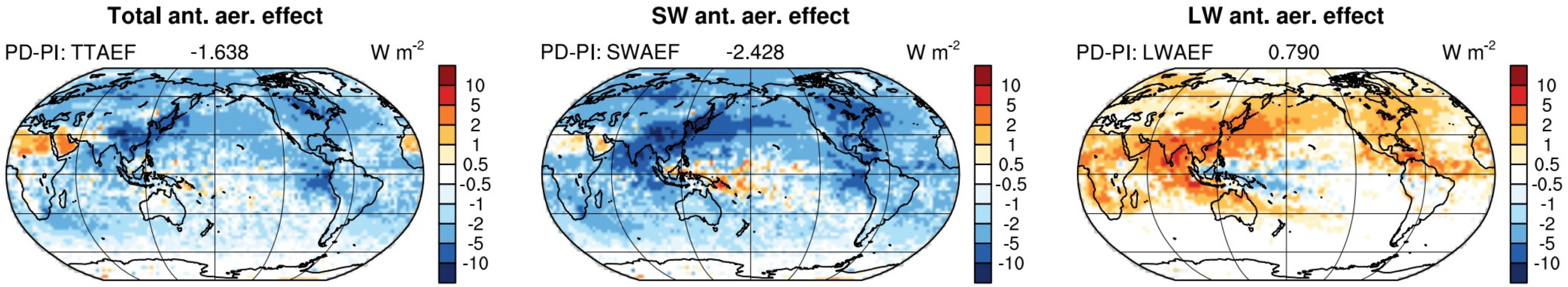
CMIP6 RFMIP model estimates from Smith et al. (2020)

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.*

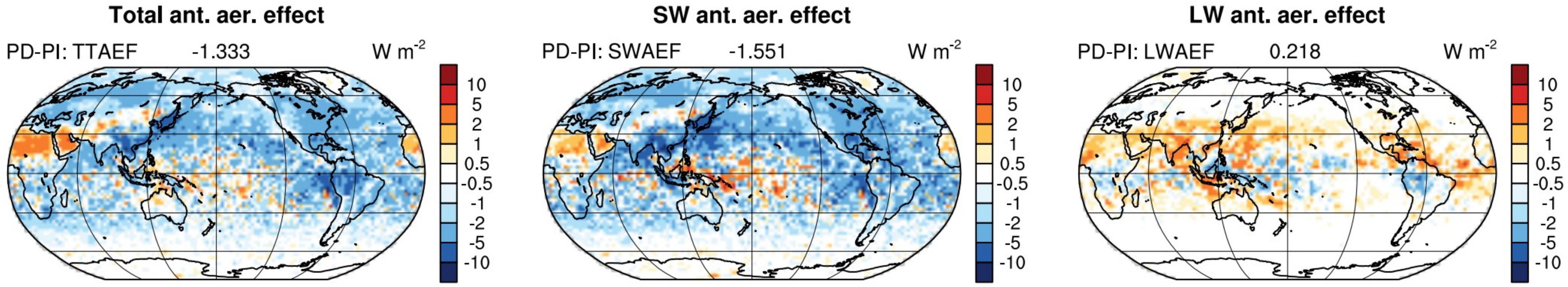
ERF$_{aer}$ at TOA

TOA ERF$_{aer}$ is significantly reduced in both SW and LW components in v2.

V1 nudged (2010aer – 1850aer)



V2 nudged (2010aer – 1850aer)

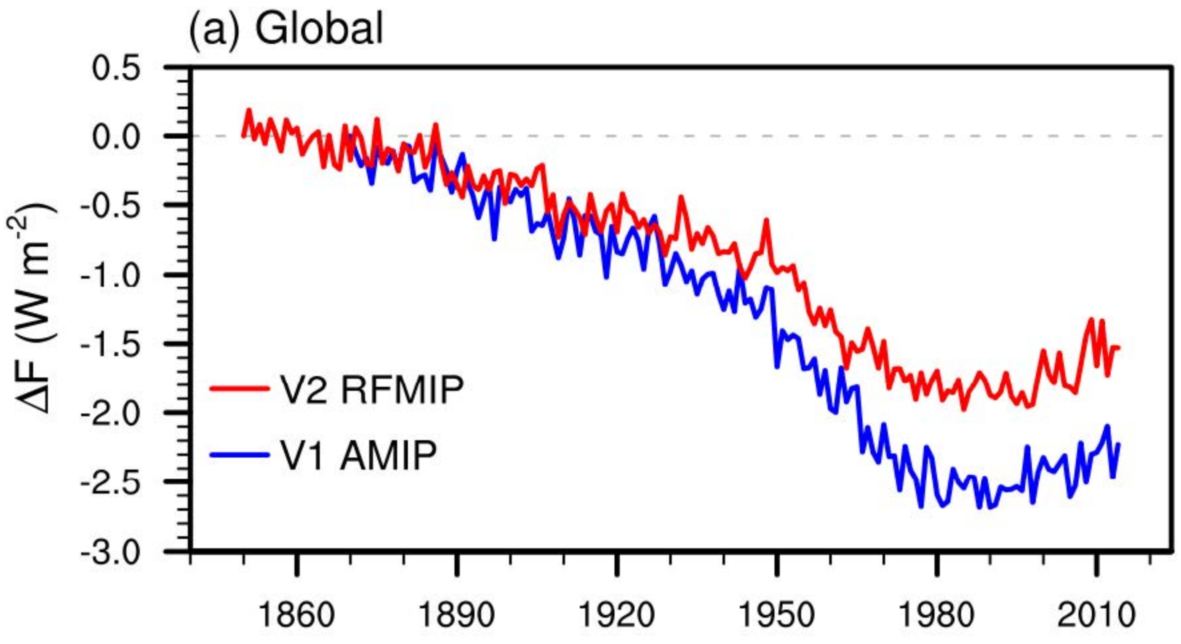


ERF$_{aer}$ at TOA

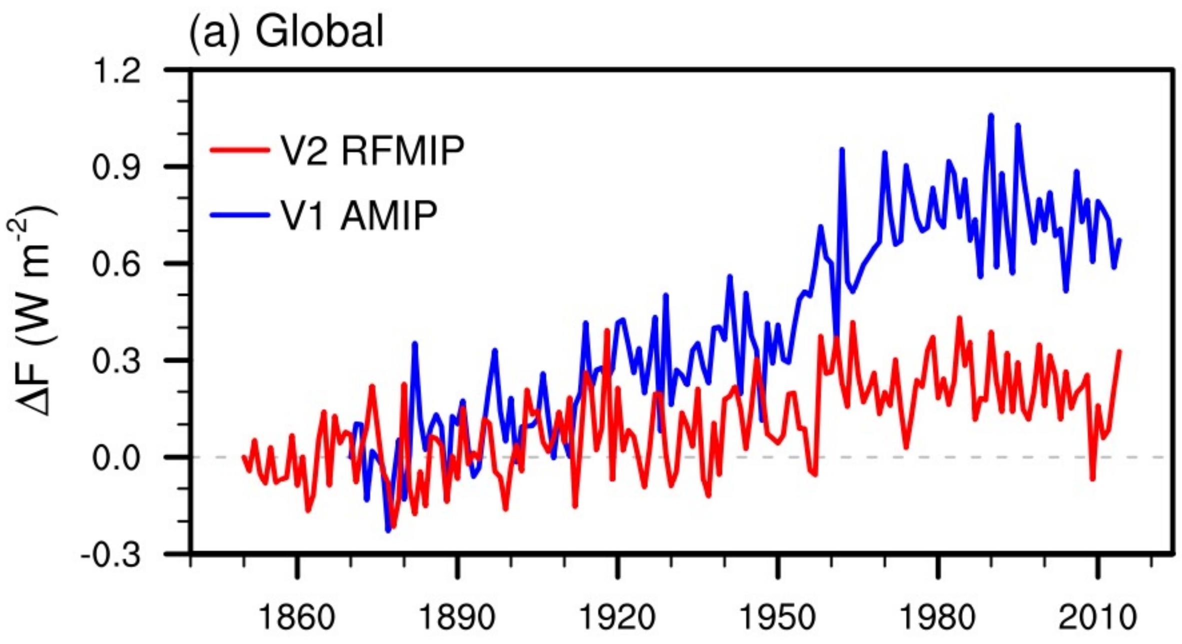
TOA ERF$_{aer}$ is significantly reduced in both SW and LW components in v2.

V1 AMIP vs. V2 RFMIP

SW



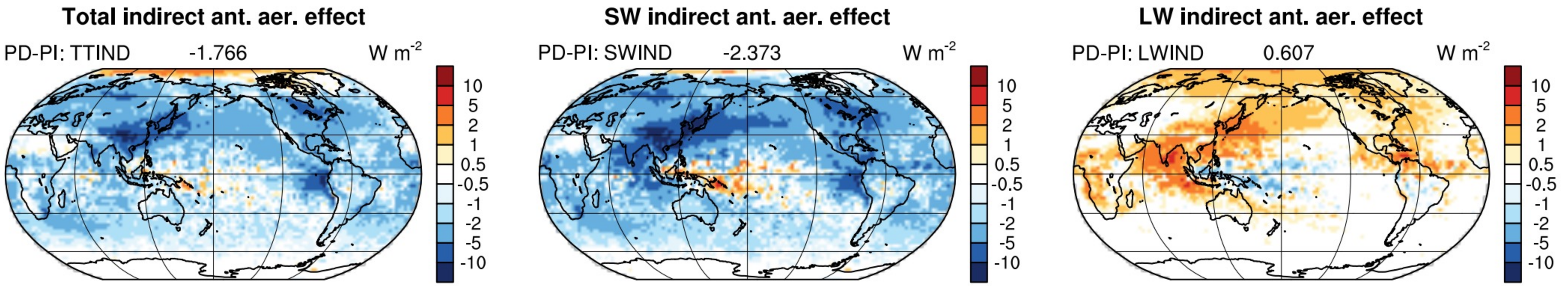
LW



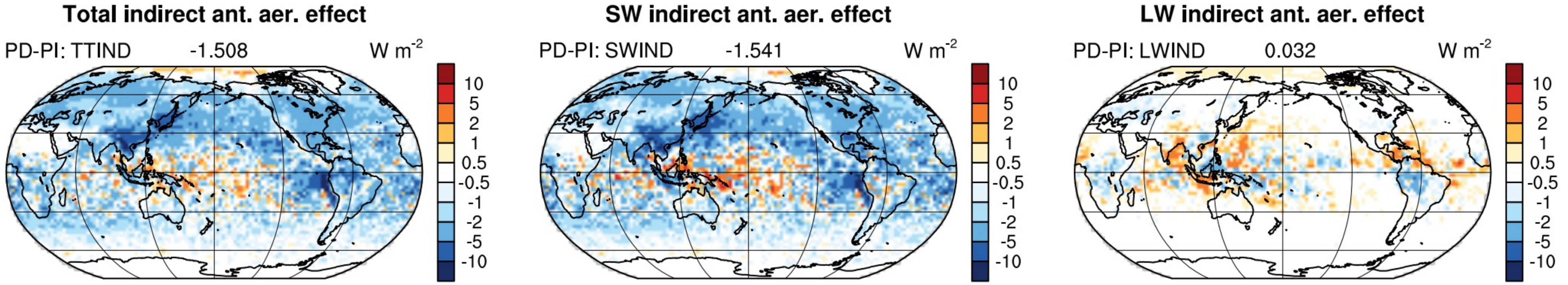
Indirect ERF_{aer} at TOA (decomposed)

The changes in ERF_{aer} are mainly caused by reduced indirect aerosol effects.

V1 nudged (2010aer – 1850aer)



V2 nudged (2010aer – 1850aer)



Important model changes that affect ERF_{aer} in v2

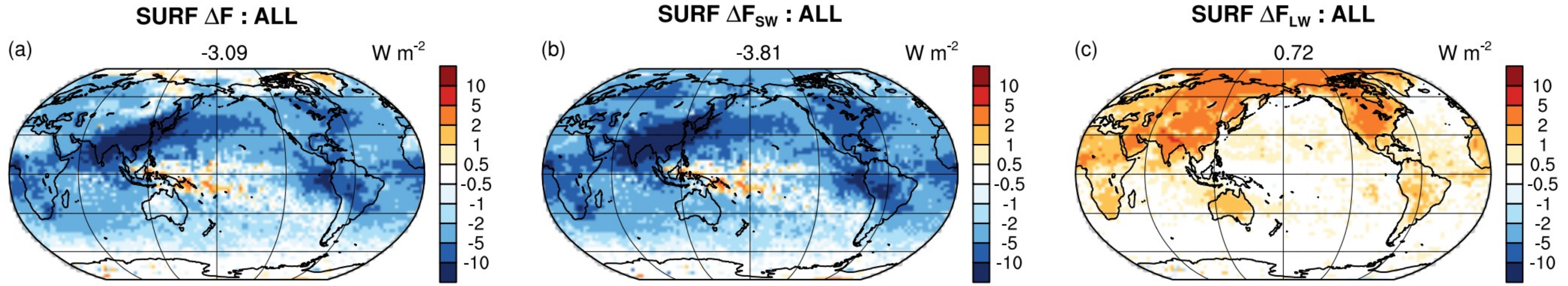
- Tuning (see Ma et al. 2022GMD and Zhang et al. 2022ACPD)
- Minimum CDNC (see slide 14)

ERF_{aer} at surface

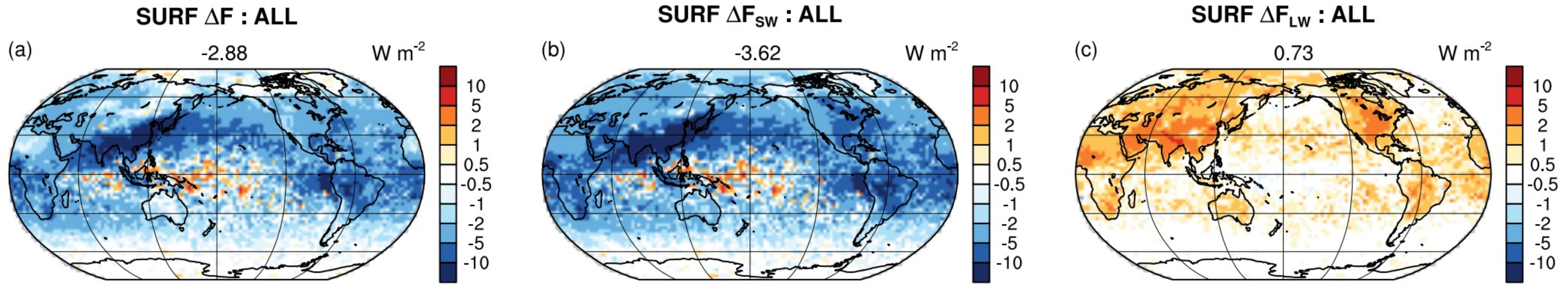
Surface SW/LW ERF_{aer} changes are small.

Reduced indirect effect is compensated by stronger direct effect (shown later).

V1 nudged (2010aer – 1850aer)



V2 nudged (2010aer – 1850aer)



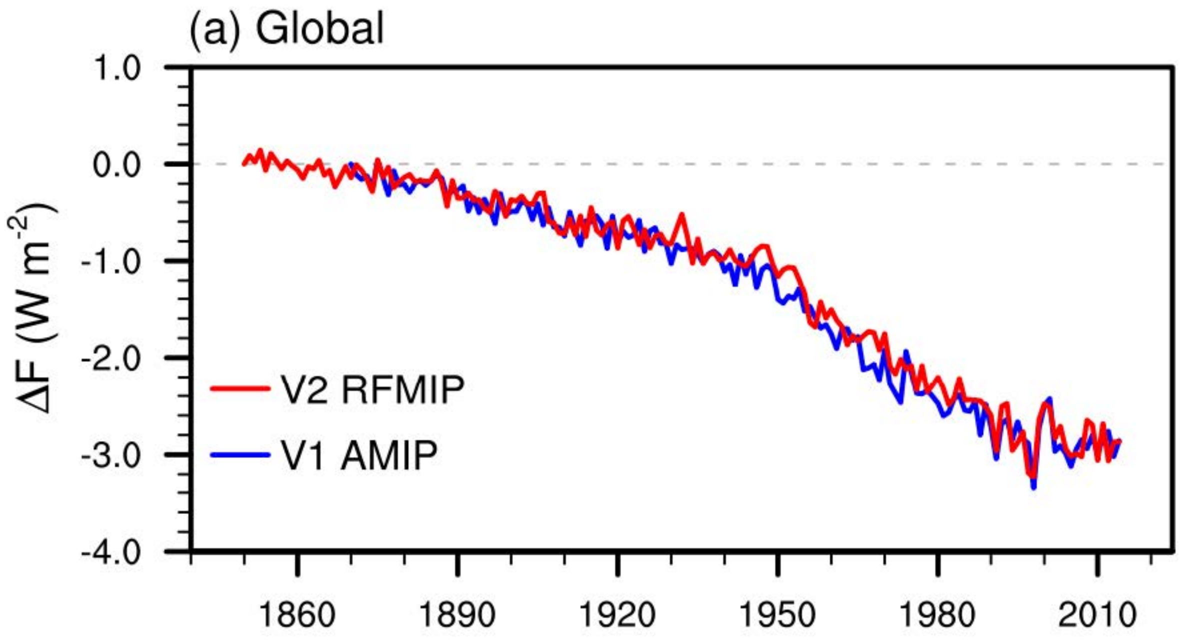
ERF_{aer} at surface

V1 AMIP vs. V2 RFMIP

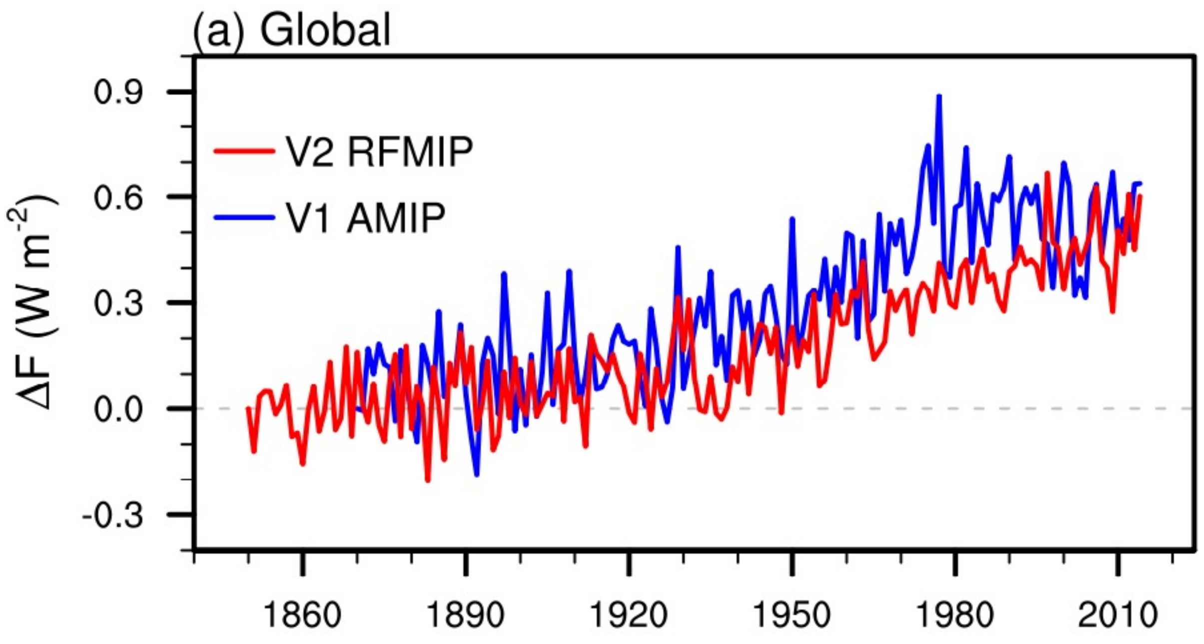
Surface SW/LW ERF_{aer} changes are small.

Reduced indirect effect is compensated by stronger direct effect (shown later).

SW



LW

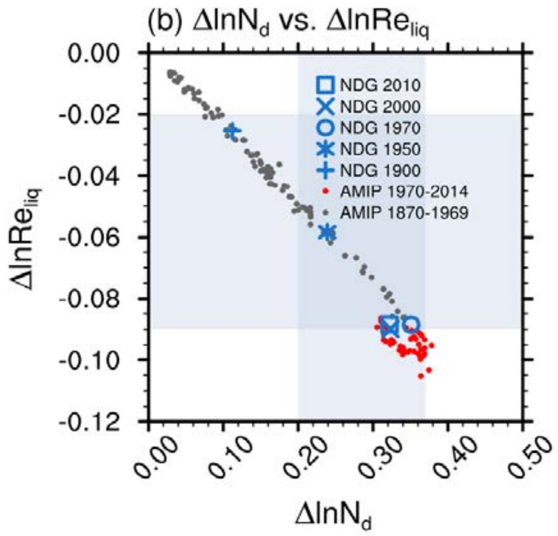


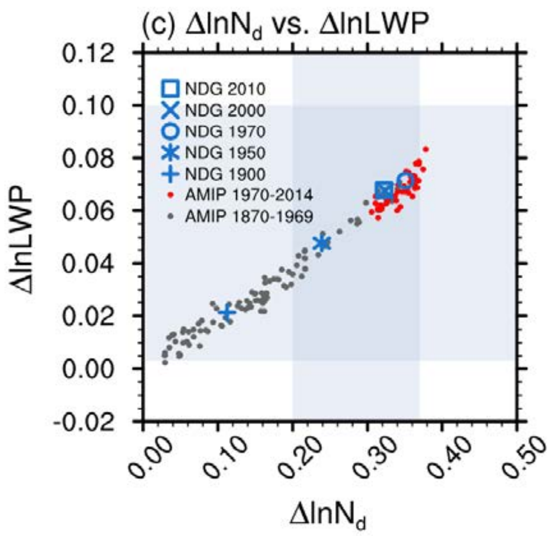
V2 vs. V1

$$\frac{d\ln \bar{R}}{d\ln \bar{E}} = \left[\frac{d\ln \bar{C}}{d\ln \bar{N}_d} + \frac{d\ln \bar{R}_c}{d\ln \bar{\tau}}\left(\frac{d\ln \bar{L}}{d\ln \bar{N}_d} - \frac{d\ln \bar{r}_e}{d\ln \bar{N}_d}\right)\right]\frac{d\ln \bar{N}_d}{d\ln \overline{CCN}}\,\frac{d\ln \overline{CCN}}{d\ln \bar{E}}.$$

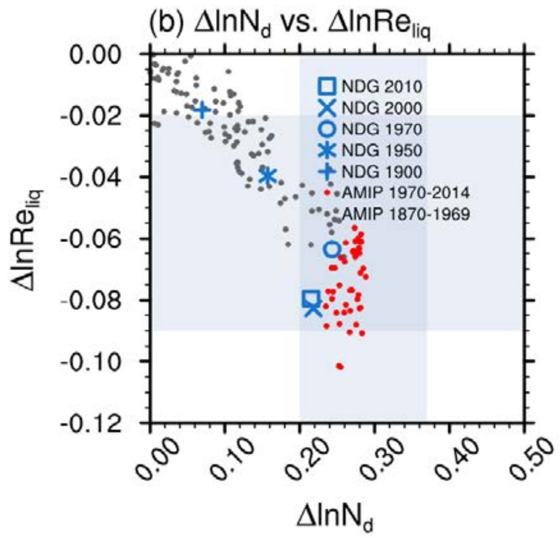
Re vs. Nd (1st) — LWP vs. Nd (2nd)

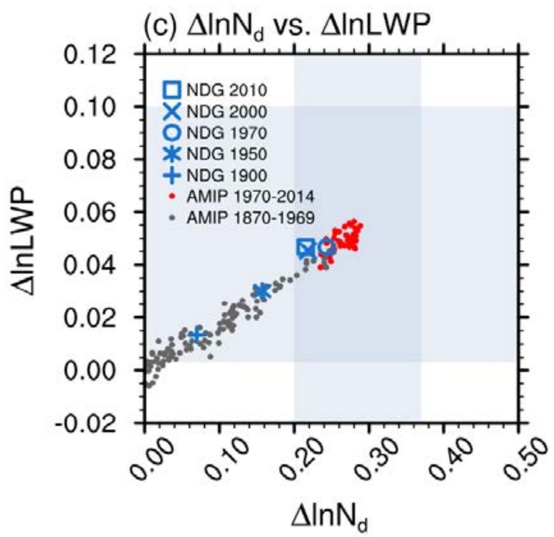
E3SMv1





E3SMv2



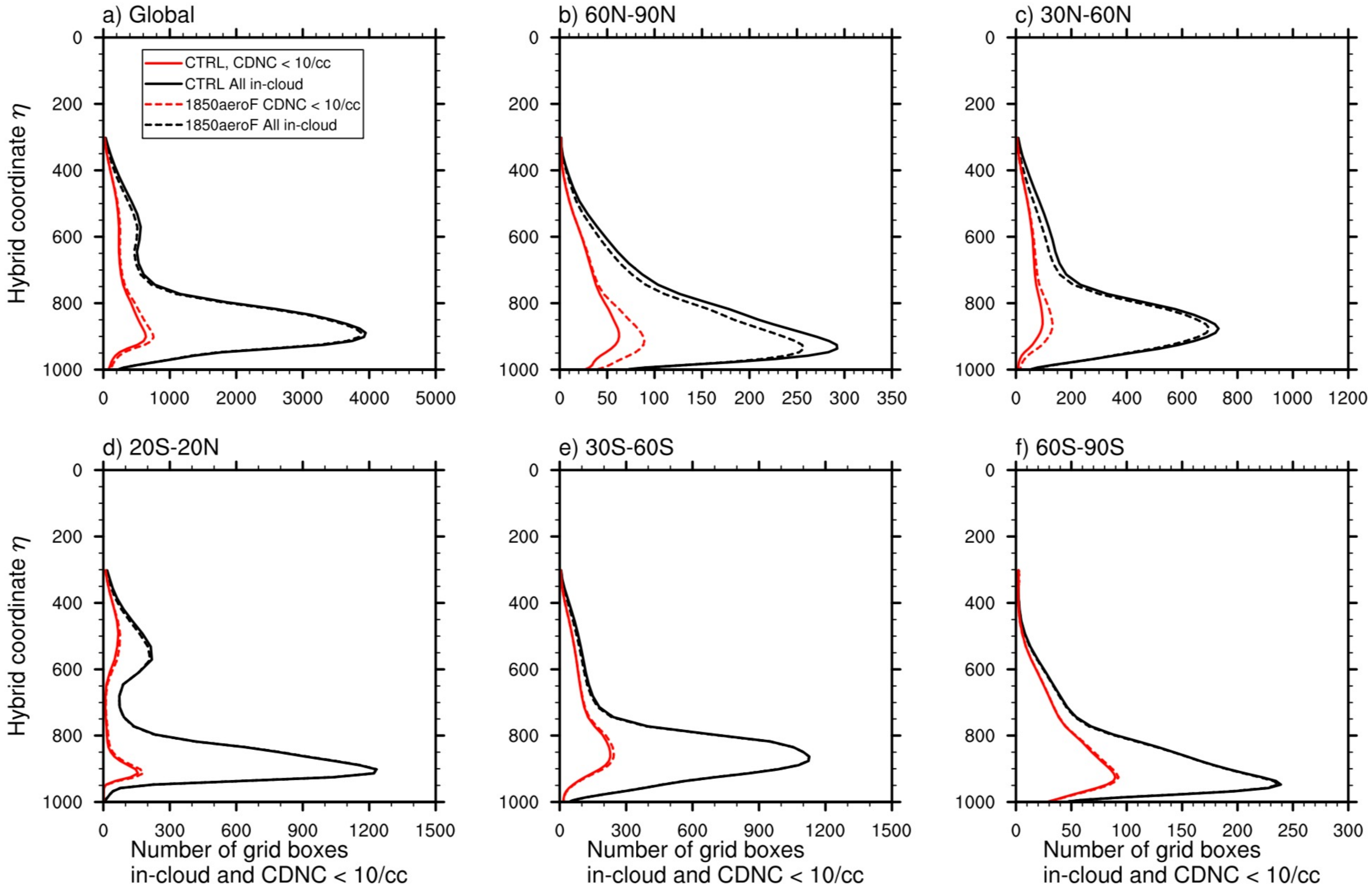


Both the 1st and 2nd indirect ERF_{aer} magnitudes are reduced significantly.

Important model changes that affect ERF_{aer} in v2

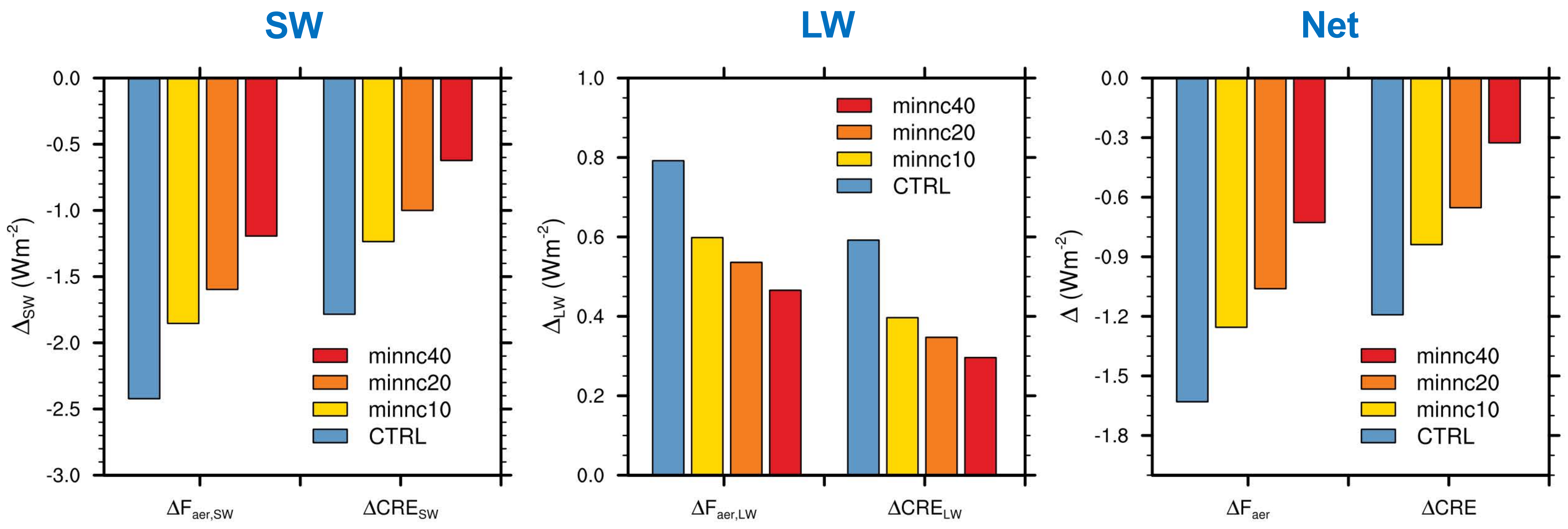
- Tuning (see Ma et al. 2022GMD and Zhang et al. 2022ACPD)
- Minimum CDNC (see slide 14)

Extremely low CDNC appears frequently in E3SMv1



Based on one-year average of high-frequency data

Adding a lower bound for CDNC reduces ERF_{aer}

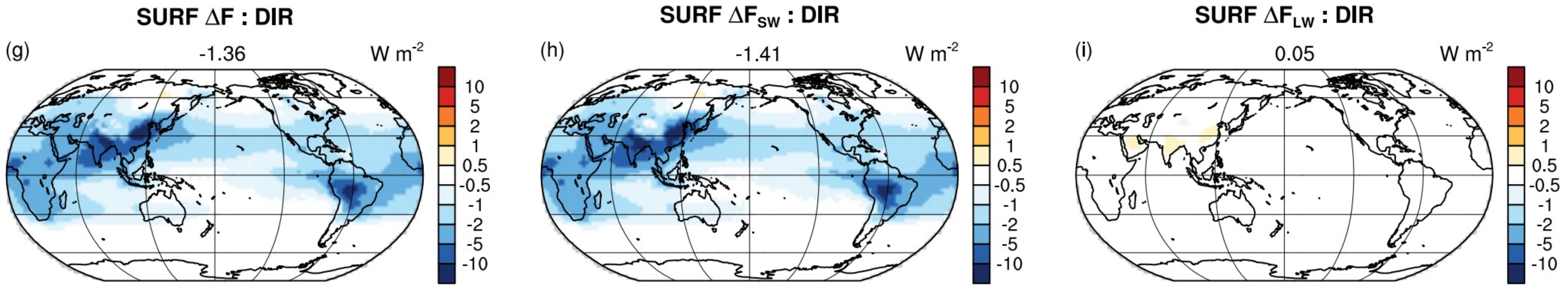


In V2: $CDNC_{min}$ = 10 cm^{-3}

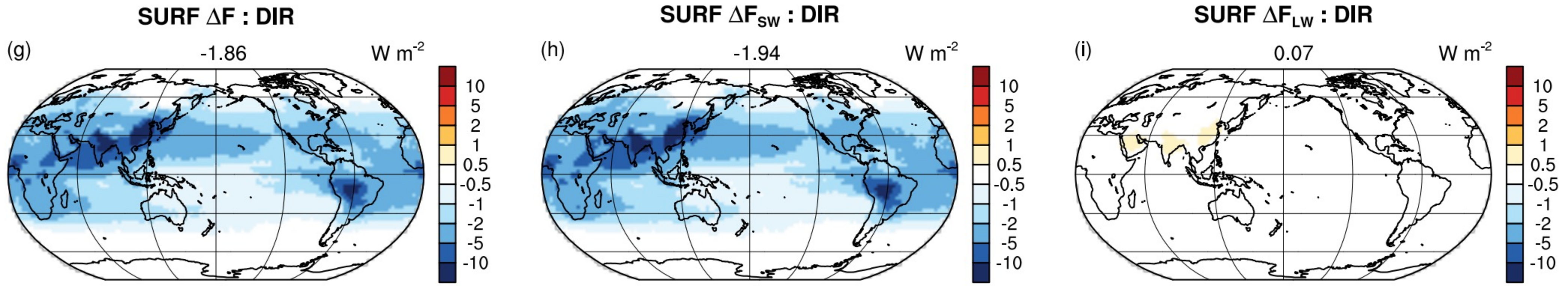
- If this lower bound is removed in V2, ERF_{aer} is about -1.64 (vs. -1.33 in v2) Wm^{-2}.
- If $CDNC_{min}$ is too large, strong perturbation in LWP is observed in some regions.

Direct aerosol effect at surface (decomposed)

E3SMv1 nudged (2010aer – 1850aer)

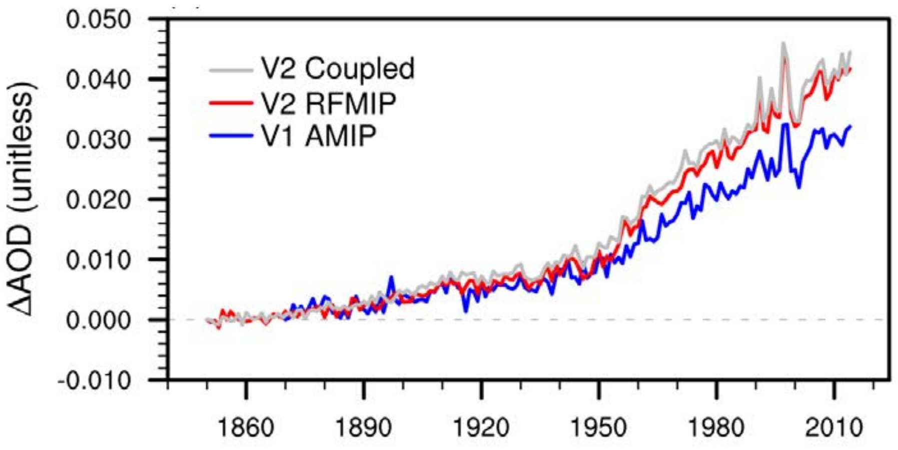


E3SMv2 nudged (2010aer – 1850aer)

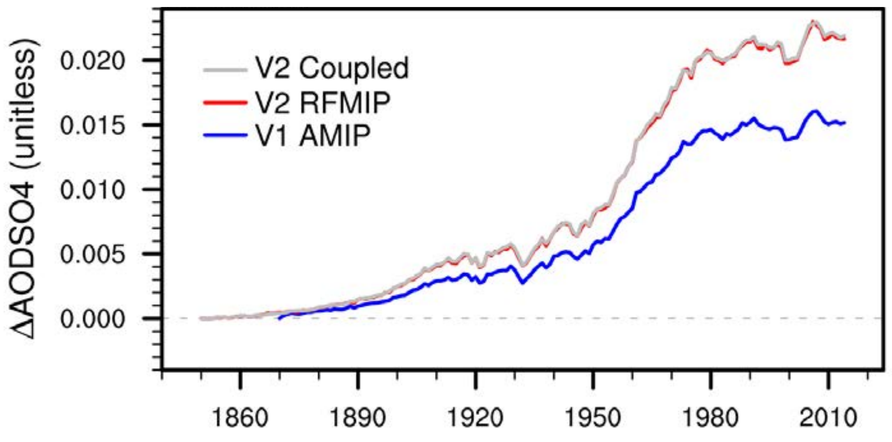


Larger AOD in v2 simulations

Ant. AOD

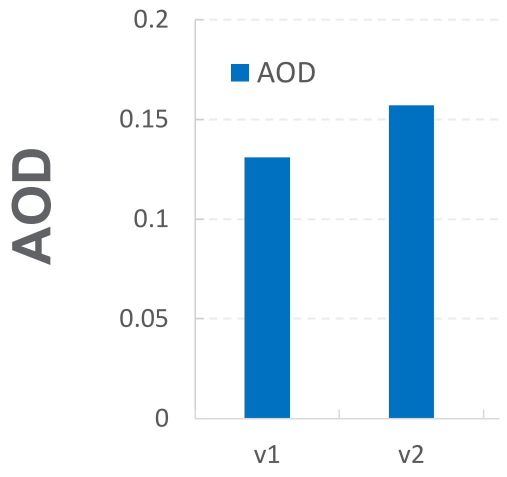


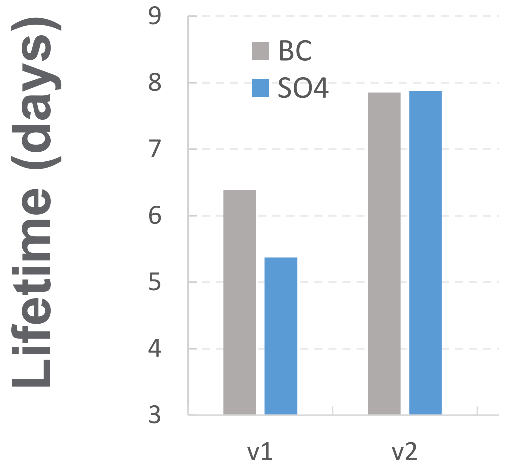
Ant. sulfate AOD



- **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?





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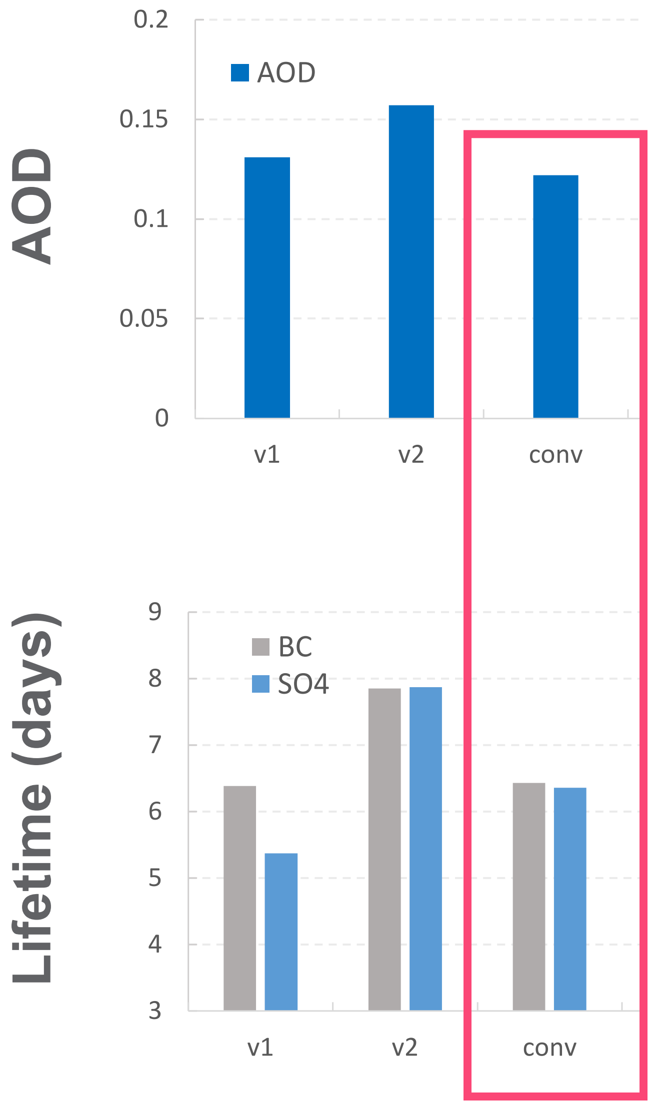
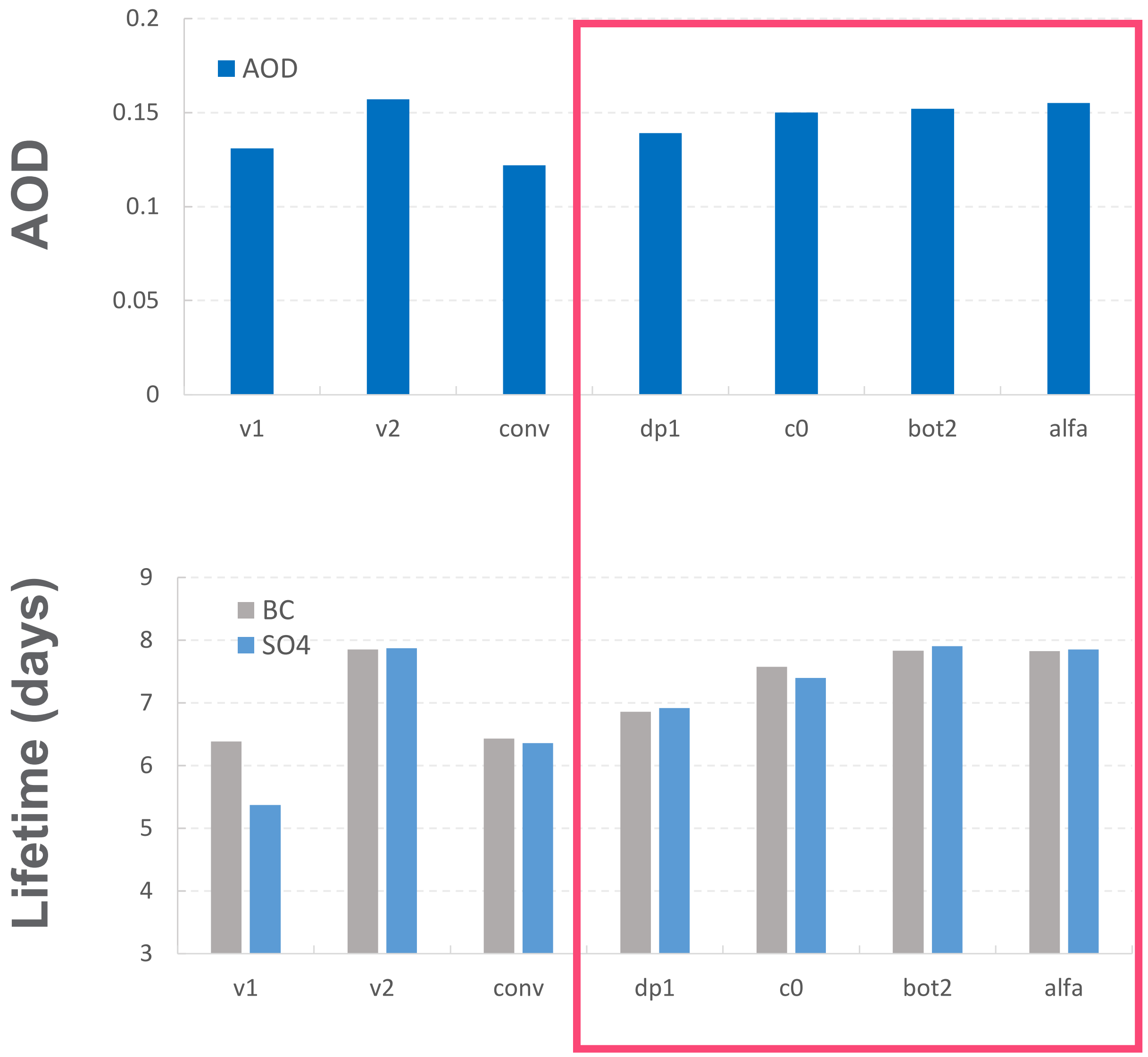


conv: tuning parameters for convection parameterization reverted to v1

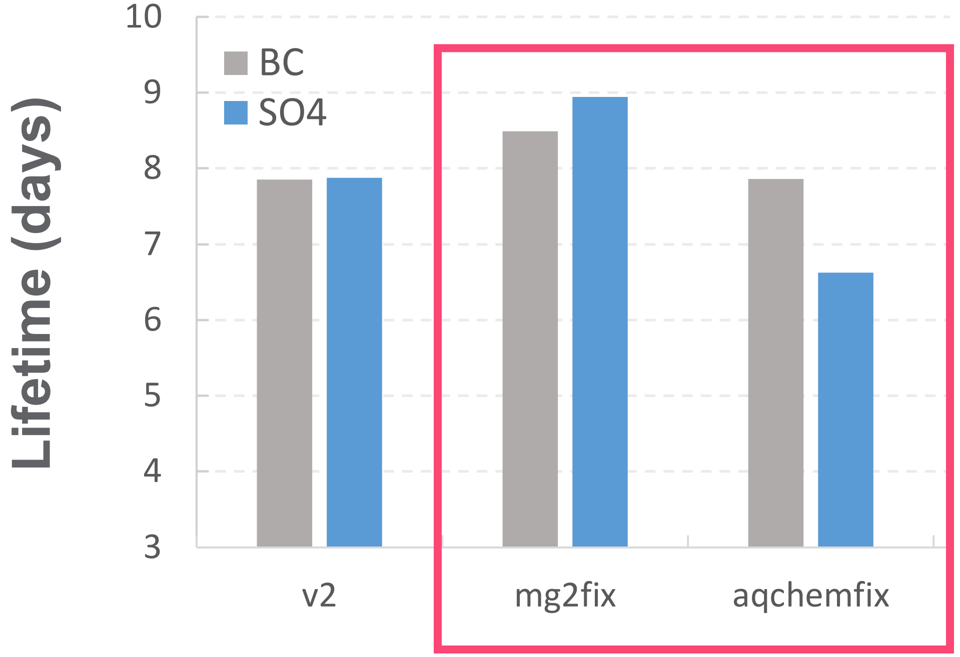
Why AOD is much larger in v2?



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

Salzmann et al. (2022JAMES)

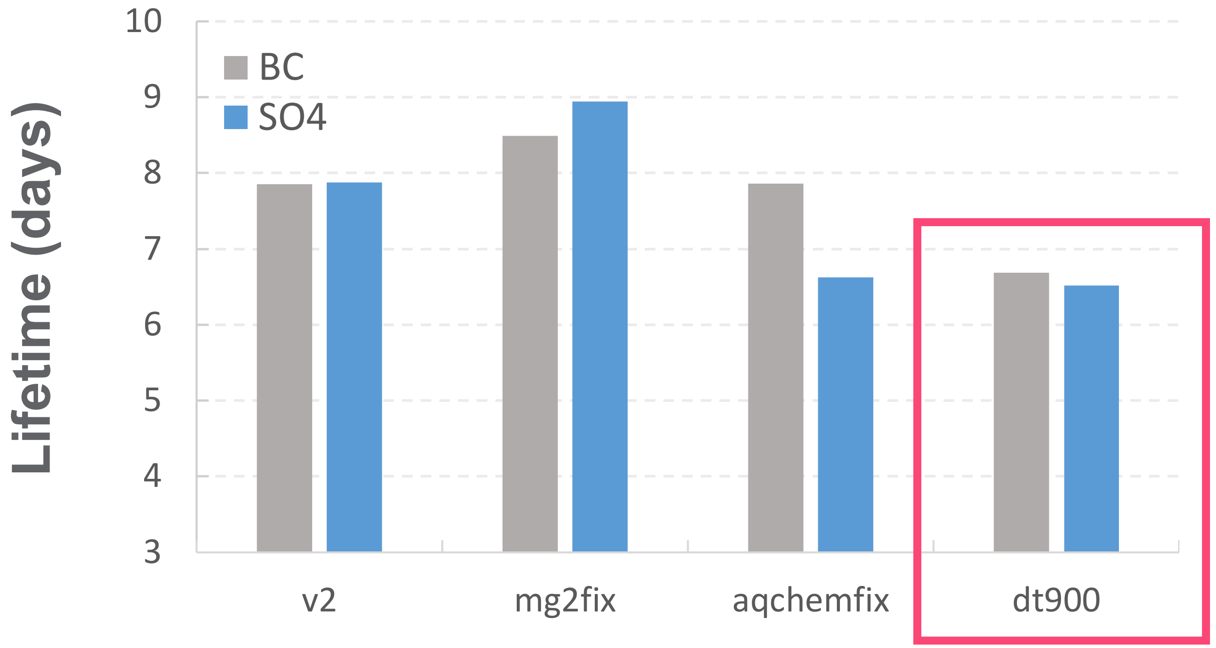
Sensitivity of aerosol lifetime to other factors



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



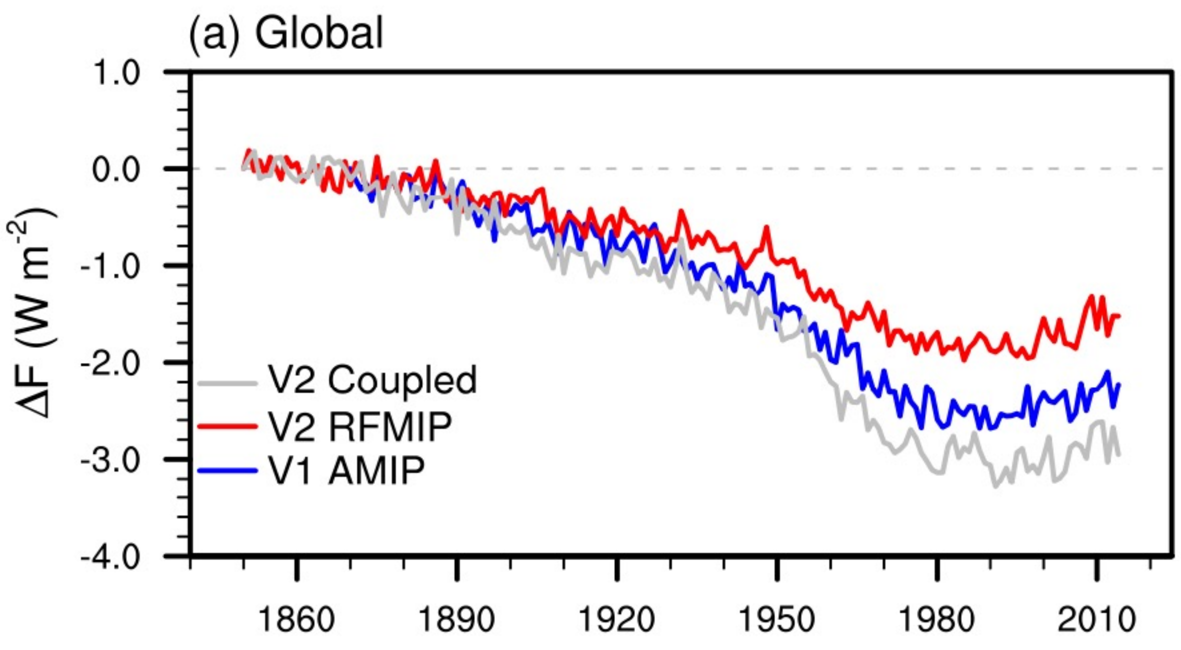
Physics time step set to 900s (1800s by default)

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

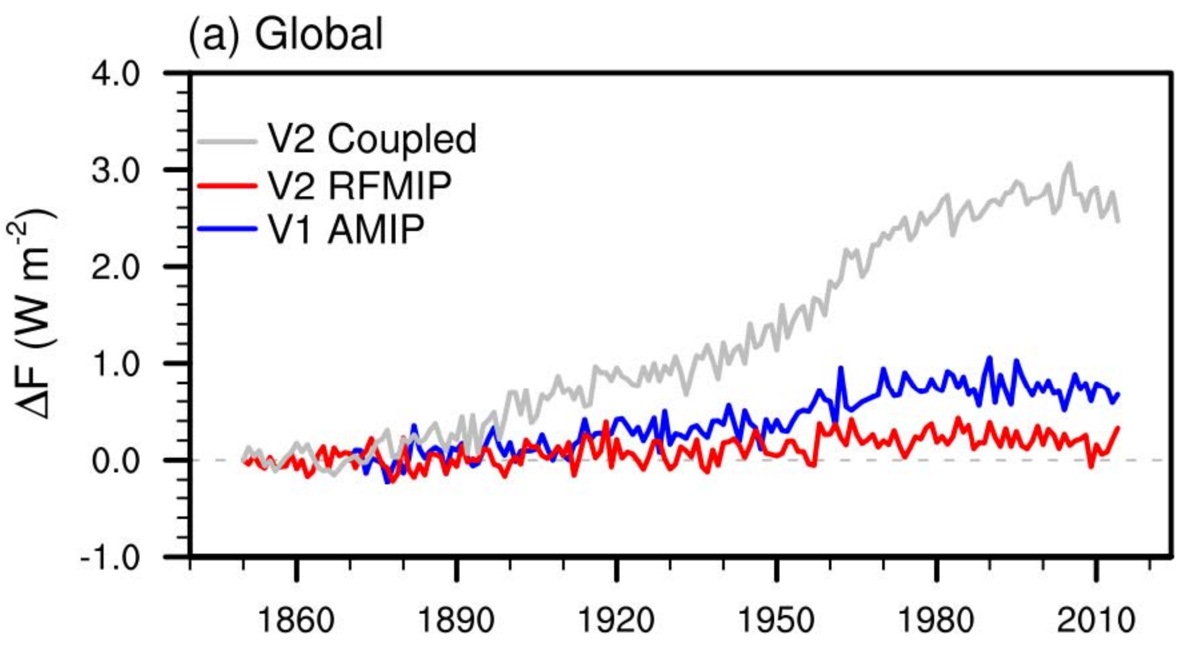
V2 versus V1 (TOA)

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

SW



LW



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Ongoing efforts

- Further investigate why r_{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 1st and 2nd 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.