

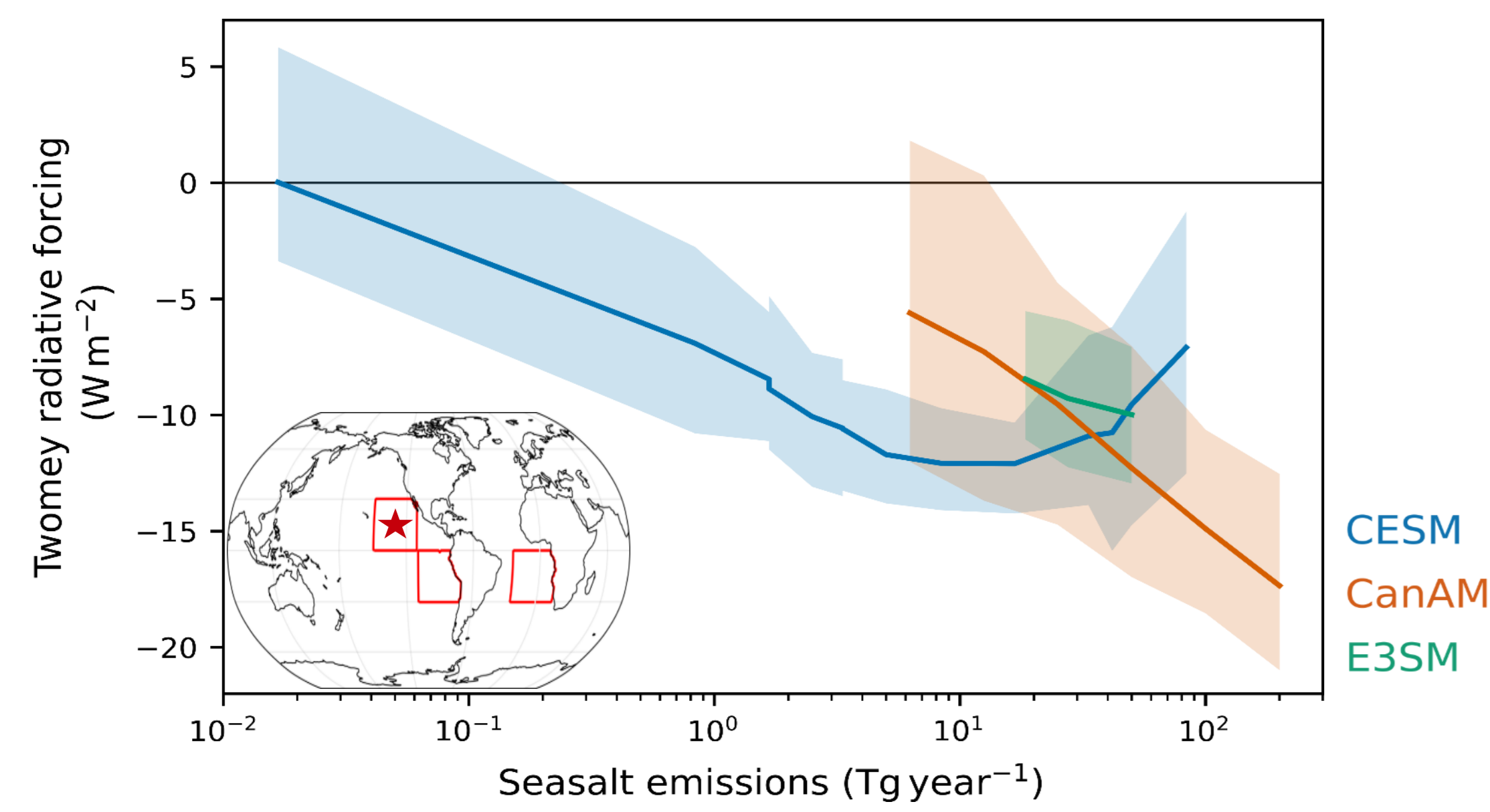
The Impact of Aerosol Size on the Efficacy of Marine Cloud Brightening

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1 INTRODUCTION

Simulations with different global Earth System Models (ESMs) produce widely differing shortwave cloud radiative effects when clouds are seeded by seasalt aerosol in three subtropical regions (figure below). Here we show that the differences in three of the global models (CESM2, E3SMv2, and CanAM5.1-PAM) can be explained by **distinct factors associated with biases and uncertainties in specific turbulence and microphysics parameterizations.**



The cloud albedo can be approximated as a function of the cloud droplet concentration ratio for the seeded vs. unperturbed clouds (control simulation, CTL), $N_d/N_{d,CTL}$, assuming no cloud adjustments (Twomey effect; Wood, 2021). To assess the models we used an adiabatic cloud parcel model to simulate the “true” (benchmark) dependence of $N_d/N_{d,CTL}$ on the Cloud Condensation Nuclei (CCN) concentration (at 0.2% supersaturation) and turbulent updraft velocity in Northeast Pacific low marine clouds, based on Marine Cloud Brightening (MCB) scenarios with seasalt emissions of up to 200 Tg/year/region (Rasch et al., 2024).

2 METHODS

The **pyrcel adiabatic microphysical cloud parcel model** (Rothenberg and Wang, 2016) was extended for simulations of the “true” formation of cloud droplets from the activation of specified background and added MCB seasalt aerosols, based on Köhler theory. In addition, a simple **offline model of the different N_d parameterizations from the three global models** (see next section) was used.

The simulations with pyrcel and the offline model were initialized using specified monthly data from multi-year long global model simulations for present-day sea surface temperatures. Specifically, the specified aerosol size distributions were taken from below the base of the marine boundary layer clouds in the Northeast Pacific (15°N, 130°W). The specified monthly turbulent cloud updraft velocities in pyrcel were taken from the adjacent layer above.

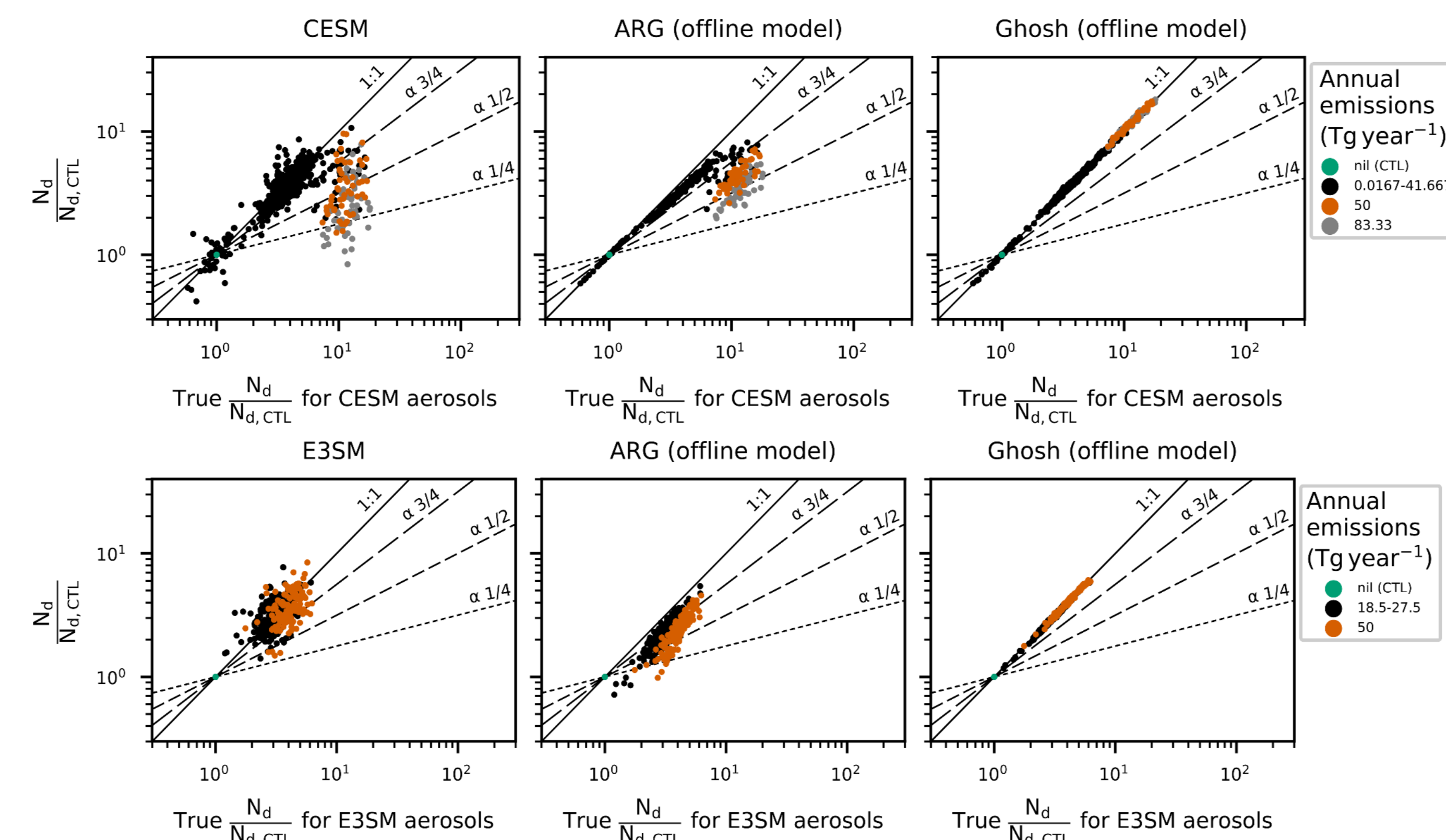
- **CESM2:** Community Earth System Model version 2.1 with the Community Atmosphere Model version 6 (CAM6) and the Modal Aerosol Model 4 (MAM4)
- **E3SMv2:** Energy Exascale Earth System Model version 2.0 with Energy Atmosphere Model version 2 (EAMv2) and the Modal Aerosol Model 4 (MAM4)
- **CanAM5.1-PAM:** Canadian Atmosphere Model version 5.1 with the Piecewise Lognormal Aerosol Model (PAM)

3 FIRST FACTOR: CLOUD DROPLET NUMBER PARAMETERIZATION BIASES

Cloud droplet number concentrations (N_d) were simulated using different parameterizations:

- **ARG:** Abdul-Razzak and Ghan (2000) parameterization; in CESM2, E3SMv2, and in the offline model
- **Ghosh:** ARG scheme with parameter adjustment (Ghosh et al., 2025); in the offline model
- **QDGE:** Quasi-steady state approximation of the droplet growth equation (Wang et al., 2022); in CanAM5.1-PAM

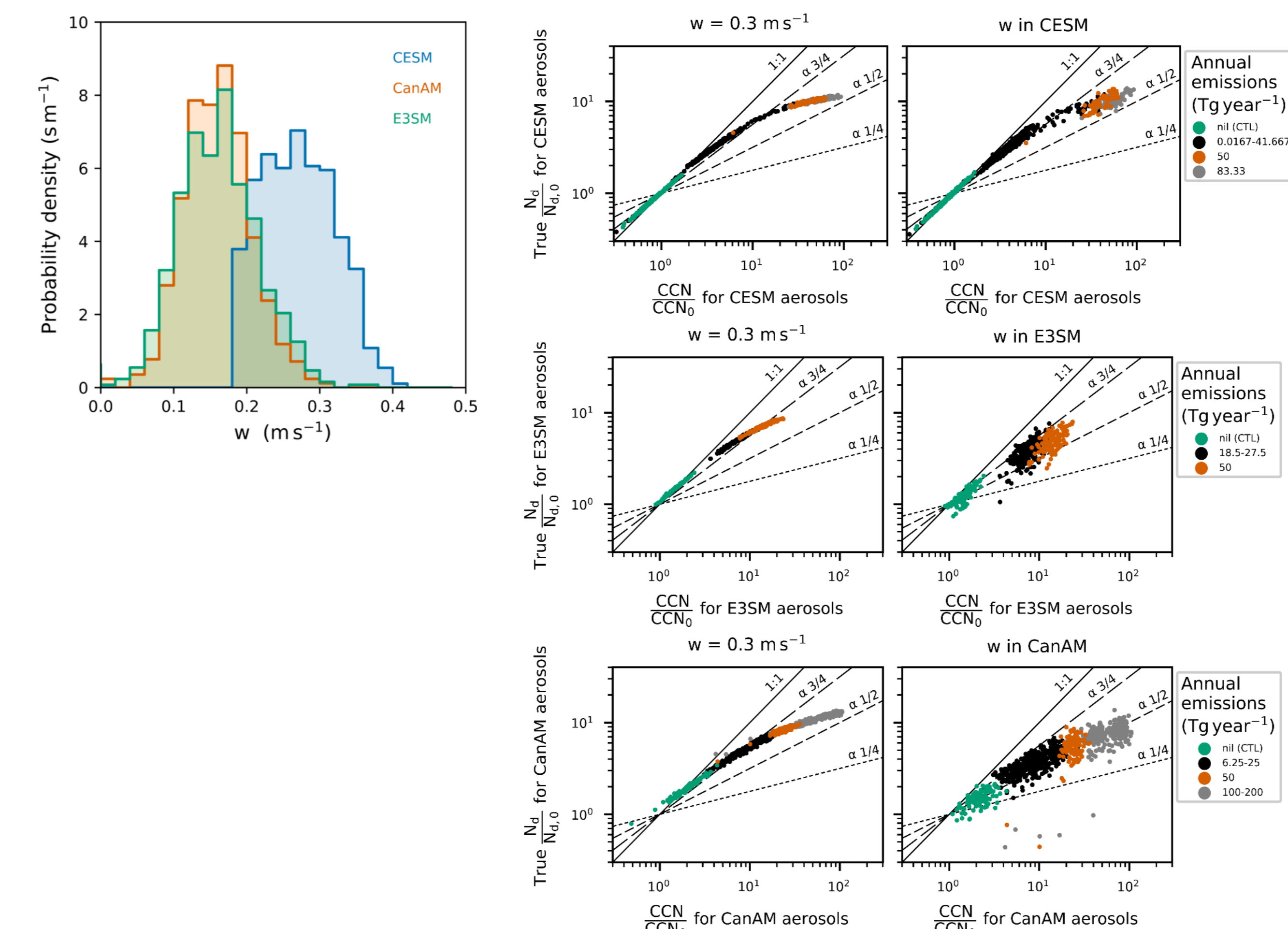
At low seasalt emissions (ca. < 50 Tg/year), simulations of $N_d/N_{d,CTL}$ in CESM2 and E3SMv2 agree well with the “true” values simulated in pyrcel, using the specified aerosol size distributions (left panel below). At higher emissions, the $N_d/N_{d,CTL}$ ratios are underestimated in CESM2, consistent with offline parcel model simulations using the ARG parameterization (middle). The parameter adjustment by Ghosh et al. (2025) fully corrects these biases (right).



4 SECOND FACTOR: BACKGROUND CCNS & TURBULENT UPDRAFTS

- Higher turbulent cloud updrafts in CESM2 than in the other models (left panel below)
- Higher CCN background concentrations in CanAM5.1-PAM control simulation than in the other models

The influences of these model-dependent factors on N_d can be assessed through 1) the use of a constant updraft velocity of 0.3 ms⁻¹ and 2) by considering the ratios $N_d/N_{d,0}$ and CCN/CCN_0 , where $N_{d,0} = CCN_0 = 100$ cm⁻³ replaces the simulated background CCN concentration. With these modifications, pyrcel produces $N_d - CCN$ relationships that are more similar to each other, for all three global model data sets (right panel).

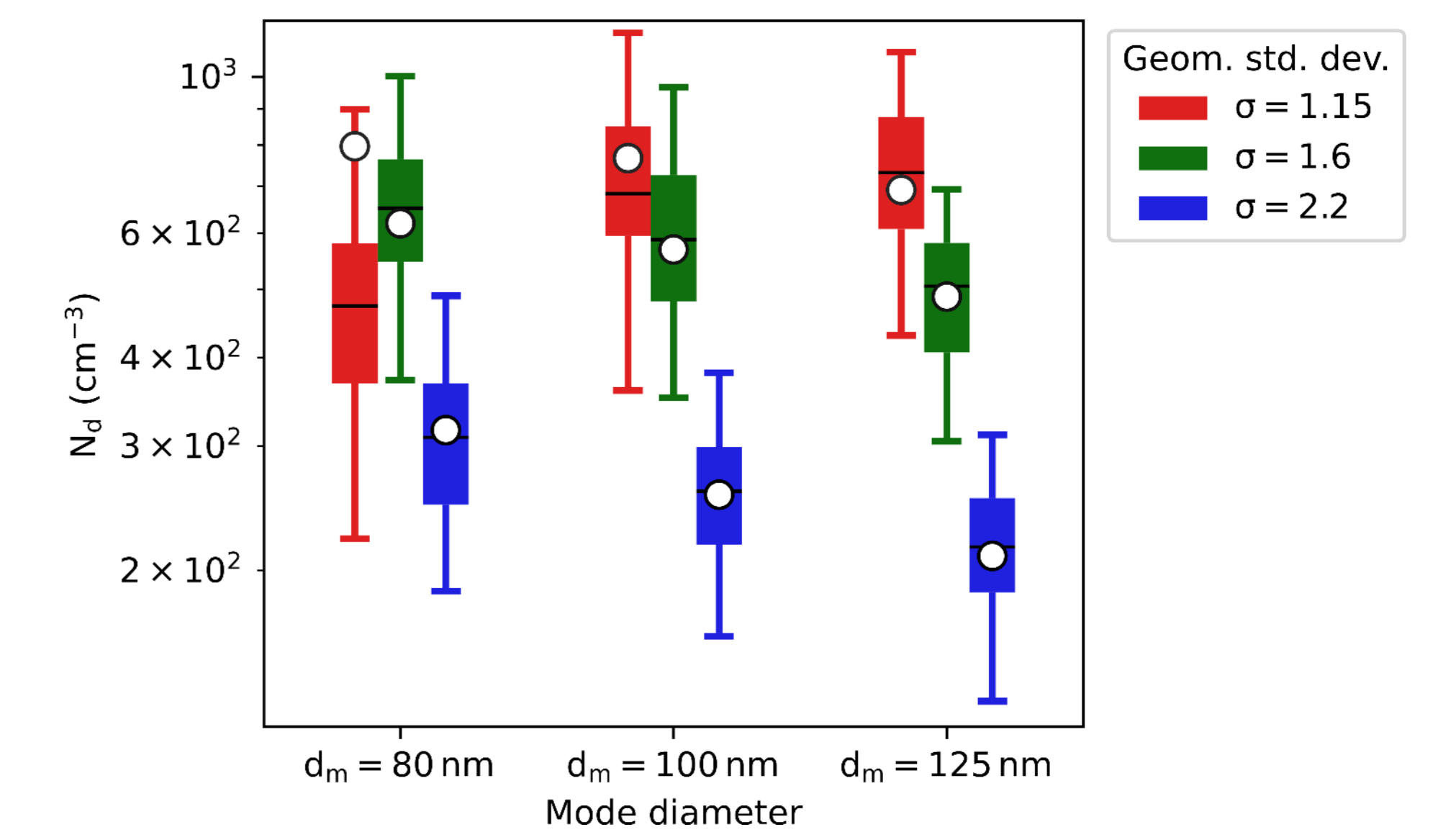


5 THIRD FACTOR: CCN CLOUD YIELD

Another factor causing differences in the simulated Twomey effects is the simulated fraction of emitted seasalt particles that contribute to the turbulent vertical flux of CCN at cloud base (CCN cloud yield). CESM2 produces higher cloud-base CCN concentrations and CCN cloud yields than the other models. There could be various causes, including longer aerosol lifetimes and less efficient export of aerosols from the boundary layer in CESM2 – further research is needed. We confirmed the importance of this factor by matching the CCN and scaling the N_d concentrations using the previously diagnosed $N_d - CCN$ relationships.

6 FOURTH FACTOR: PARTICLE SIZE

Additional simulations with CanAM5.1-PAM (bars) and pyrcel (circles) show that N_d is highly sensitive to characteristics of the specified size distribution of the emitted seasalt aerosol particles, as demonstrated by varying the distribution width (but fixing the mode diameter).



7 CONCLUSION

pyrcel successfully reproduces the simulated cloud droplet concentrations in three global models. The pyrcel simulations show that all three model have the strong potential to produce very similar MCB Twomey effects, after the correction of biases in the ARG parameterization and addressing differences in simulated updraft velocities and background CCN concentrations. It should be possible to constrain the relevant turbulence and microphysical processes through targeted observations. However, marine regions are data-sparse.

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SUMMARY: STEPS TOWARD THE DEVELOPMENT OF THREE HARMONIZED MODELS

