



Viability of mixed-phase cloud thinning with prognostic mineral dust in CESM2

Paul Farron¹, Ulrike Lohmann¹, and Diego Villanueva¹

¹Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland

Correspondence: Paul Farron (paul.farron@env.ethz.ch)

Abstract. Mixed-phase cloud thinning (MCT) has been proposed as a regional climate intervention method to offset Arctic warming by reducing the longwave cloud radiative effect of high-latitude winter clouds. While initial studies suggested that MCT could achieve meaningful Arctic cooling using idealized MCT scenarios with prescribed ice-nucleating particle (INP) concentrations, the radiative impact of a more realistic, prognostic seeding aerosol has remained largely unexplored so far. Here we evaluate the viability of MCT using prognostic mineral dust in a global climate model. We conducted a set of 16 sensitivity experiments in the Arctic during the boreal winter (Nov–Feb), varying the dust injection altitude and the seeding rate relative to a control simulation. Mineral dust seeding triggers glaciation of mixed-phase regime clouds, producing a net negative top-of-atmosphere radiative effect, that strengthens with seeding rate, driven by a competition between a positive longwave effect arising from aerosol-radiation interactions (LW ARI), a negative shortwave effect arising from aerosol-radiation interactions (SW ARI), and effects from aerosol-cloud interactions (ACI). Lower seeding altitudes retain more of the seeded dust within the target region and activate a larger fraction of it into cloud droplets, yet produce weaker cloud glaciation and thinning than high-altitude injections. Overall, these results indicate that MCT can produce a meaningful negative top-of-atmosphere radiative forcing over the target region, consistent with the surface-cooling potential suggested by earlier studies, but that both injection altitude and rate influence its efficacy and its side effects.

1 Introduction

With a current global warming above 1 °C and projections under high-emission scenarios exceeding 4 °C by the end of this century (IPCC, 2021), climate-related risks are expected to intensify (Magnan et al., 2021). Several climate tipping points are at a risk of being triggered already at 1.5 °C of warming, with potential cascading effects that could further accelerate human-driven climate change (Lenton et al., 2008; Armstrong McKay et al., 2022; Wunderling et al., 2023). This urgency motivates the exploration of solar radiation modification (SRM) strategies as a complementary approach to emission reductions for risk reduction (Lawrence et al., 2018).

While much of the literature focuses on shortwave SRM, which targets the incoming solar radiation, other methods aim to mitigate warming by enhancing the emissions of longwave radiation to space. Two cloud-based interventions of this type have been proposed: cirrus cloud thinning (CCT; Mitchell and Finnegan, 2009) and, more recently, mixed-phase cloud thinning (MCT; Villanueva et al., 2022). The effectiveness of CCT is still debated (Muri et al., 2014; Tully et al., 2022), while MCT



remains poorly constrained; in particular, it is unclear whether its net effect stays negative once the direct effect and transport of aerosols are accounted for (Villanueva et al., 2022; van Wijngaarden et al., 2024).

The physical basis of MCT relies on radiative properties of clouds at high latitudes during winter. Clouds exert a significant influence on the climate because of their ability to scatter, absorb and emit radiation. The net cloud radiative effect (CRE) results from two opposing contributions, the shortwave (SWCRE) and the longwave (LWCRE) cloud radiative effects. The SWCRE is primarily driven by the scattering and absorption of incoming solar radiation, which generally leads to a net cooling effect. In contrast, the LWCRE is governed by the scattering, absorption and re-emission of terrestrial longwave radiation, which typically results in a net warming effect (Ramanathan et al., 1989). The net CRE depends on environmental conditions; at high latitudes during the polar winter, incoming solar radiation is minimal and the SWCRE is weak. As a result, the CRE predominantly results in a warming effect, owing to the LWCRE (Shupe and Intrieri, 2004). In addition to environmental conditions, the net CRE is also influenced by various cloud properties including the cloud base and top temperatures, optical depth and phase partitioning (Matus and L'Ecuyer, 2017; Gonçalves et al., 2022).

Mixed-phase regime clouds (MPRCs) are clouds occurring at temperatures between 0 °C and -38 °C, and can be purely liquid, ice or a mixture of both. Introduction of ice-nucleating particles (INPs) into MPRCs initiates cloud glaciation, subsequently altering the cloud optical depth and lifetime, which ultimately impacts their radiative properties. Among the numerous types of INPs, mineral dust is considered one of the most effective and naturally abundant agents for triggering glaciation in MPRCs, primarily through immersion freezing (Murray et al., 2012). During glaciation, ice crystals form and grow at the expense of supercooled droplets via the Wegener–Bergeron–Findeisen process (WBF; Findeisen, 1938). Other ice-phase processes can further deplete liquid water alongside WBF such as riming and accretion (Lohmann et al., 2016). All of these processes potentially lead to precipitation and cloud thinning. Even low INP concentrations can significantly deplete the total water content (TWC) of MPRCs, reducing their optical thickness and associated heat-trapping capacity (Villanueva et al., 2022). However, high INP concentrations have also been theorized to potentially stabilize MPRCs by promoting the formation of numerous small ice crystals (Villanueva et al., 2025), which reduces the efficiency of the WBF process by increasing the competition among the ice crystals for water vapor. Since the resulting ice crystals are smaller, sedimentation is also reduced, leading to longer-lived clouds. Satellite retrievals indicate that Arctic clouds predominantly occur in the mixed-phase temperature regime (Intrieri et al., 2002), suggesting potential sensitivity to seeding with INPs.

MCT exploits this sensitivity by introducing INPs into mixed-phase clouds to trigger glaciation and subsequent cloud thinning. Previous work by Villanueva et al. (2022) demonstrated that Arctic surface cooling may be achieved through MCT in idealized simulations that prescribed in-cloud INP concentrations. However, mineral dust aerosols do not only interact with MPRCs; they also interact directly with radiation and can modify other cloud types, thereby altering the net radiative budget in potentially opposing ways (Kok et al., 2023). In this study, we extend this line of inquiry by conducting large-scale mineral dust seeding simulations with a climate model to evaluate the different radiative impacts of an MCT scenario in the Arctic during winter with prognostic aerosols. To this end, we modified the model's atmospheric component to include new sources of mineral dust aerosols and identified Arctic cloud regions exhibiting net warming. We then investigated how variations in dust concentrations affect cloud properties and the top-of-atmosphere (TOA) radiative balance.



2 Data and methods

2.1 Model description and mineral dust seeding

The climate simulations for this study were conducted using the Community Earth System Model version 2.1.5 (CESM2; Danabasoglu et al., 2020), run on a $0.9^\circ \times 1.25^\circ$ finite-volume horizontal grid with 32 vertical levels. Sea-ice conditions and sea-surface temperatures were prescribed from a climatology of the year 2000. To separate the radiative response of the seeded dust from meteorological variability, the horizontal winds were nudged towards the ERA5 reanalysis (Hersbach et al., 2020); as a consequence, potential feedbacks through circulation changes are not captured. All simulations were branched from a common 1-year spinup and subsequently run for 3 years. Aerosol microphysical processes are resolved by the four-mode Modal Aerosol Module (MAM4; Liu et al., 2016). In MAM4, aerosol species are internally mixed and represented by a lognormal size distribution divided into four modes: Aitken, accumulation, coarse and primary carbon modes. The model predicts mass mixing ratios for each aerosol species and number mixing ratios for each mode. We focused on accumulation mode particles to minimize the longwave component of aerosol-radiation interactions (ARI) while maximizing the aerosol-cloud interactions (ACI). Therefore, all seeded aerosols were treated as accumulation mode mineral dust. In MAM4, the accumulation mode aerosols have a default number median dry diameter of $0.11\ \mu\text{m}$, which can increase to $0.48\ \mu\text{m}$. The seeded aerosols are therefore radiatively active in the longwave (Kok et al., 2021). Aerosols were continuously emitted with an external aerosol source similar to continuously outgassing volcanoes (Emmons et al., 2020). By default, this forcing scheme linearly interpolates between the mid-month values of the external forcing file, which would leak seeding mass into the months surrounding the target season. To confine seeding strictly to the boreal winter season (NDJF), we implemented a step-function forcing for both the seeded mass and the associated aerosol number concentrations. The prognostic treatment ensures dust is subject to dry deposition, gravitational settling and wet removal, although potential feedbacks on sea-ice albedo due to deposition of mineral dust (Kok et al., 2023) are not represented due to prescribed sea-ice conditions. Mineral dust can moreover serve both as cloud condensation nuclei (CCN) and as INPs, although in CESM2 only coarse mode dust nucleates ice in cirrus clouds (Liu et al., 2007). Cloud microphysical processes are represented in CAM6 by the two-moment Morrison–Gettelman scheme (MG2; Gettelman and Morrison, 2015), which parameterizes ice nucleation, depositional growth, riming, autoconversion of cloud ice to snow, sedimentation and the WBF process. In CAM6, heterogeneous ice nucleation by mineral dust in supercooled droplets is parameterized based on classical nucleation theory (Hoose et al., 2010), using a probability density function of contact angles (Wang et al., 2014). Finally, mineral dust also interacts with radiation through the scattering and absorption of shortwave radiation and the absorption and emission of longwave radiation. Aerosol optical properties within each spectral interval of the RRTMG radiation scheme are parameterized in terms of wet refractive index and wet surface mode radius following Ghan and Zaveri (2007). The baseline refractive indices for mineral dust are taken from the OPAC dataset (Hess et al., 1998).

It is important to note that a model error in the calculation of a microphysical cloud ice limiter (*nimax*) in the default version of CESM2.1.5 was identified by Shaw et al. (2022), limiting the contribution of mineral dust to the formation of new ice crystals in mixed-phase clouds and has been shown to increase the model's equilibrium climate sensitivity (Zhu et al., 2022; McGraw



et al., 2023). However, simply removing the *nimax* limiter produces large overestimates of ice crystal number concentration, with no consensus yet on how best to address it. Potential solutions include limitations on microphysical process rates (Shaw et al., 2022), increased substepping on the microphysics (Zhu et al., 2022), or reduced number of active dust INPs (McGraw et al., 2023). Finally, the most recent Community Atmospheric Model cloud microphysical scheme includes numerous further modifications to the mixed-phase cloud processes (Gettelman et al., 2023). Given this lack of a validated alternative, we retain the default configuration of CESM2.1.5, which also permits direct comparison with the experiments proposed in the MCT-MIP (Vioni et al., 2026). By using the default configuration, we acknowledge that the risk of overseeding and stabilization of MPRCs described in Sect. 1 is likely underestimated in our simulations.

2.2 Design of the experiments

A target region where clouds exert a net positive CRE was identified using a control simulation (CTRL). Cloud radiative effects were quantified with the CRE, defined as the difference between all-sky and clear-sky radiative fluxes at TOA spatially or temporally averaged for all conditions, usually called the all-sky CRE (Ramanathan et al., 1989). We defined a domain spanning 55 °N–80 °N and 60 °W–60 °E (Fig. 1a), where the mean CRE is 20 W m⁻² during the boreal winter months (November to February; Fig. 1c). Within this spatiotemporal domain, we conducted a series of MCT experiments varying the altitude and intensity of the injection. Vertical injection layers were selected relative to the mean cloud fraction profile (Fig. 1b) at three distinct levels: boundary-layer injection (*Low*; 912–860 hPa), cloud-top injection (*Mid*; 820–763 hPa), and free-tropospheric injection (*High*; 691–609 hPa). For each altitude, cumulative, constant, homogeneous seasonal injection rates of 1, 10, 100 and 1000 Tg season⁻¹ were evaluated. Mass injected during the highest seeding rate experiments represent about half of the annual dust emission attributed to North Africa alone (~2100 Tg yr⁻¹; Kok et al., 2023). Experiments are named following the format “{injection layer}_{seeding rate}”. Additionally, combined experiments were conducted, with the same cumulative seeding rates as the single-layer experiments, but with the mass spread over all three layers simultaneously. These experiments are identified using the format “Combined_{Rate}”. In total, this design yields 16 seeding experiments (12 single-altitude and 4 combined), each compared against CTRL.

2.3 Radiative diagnostics

All radiative effects were evaluated at TOA. Radiative forcings were calculated as the difference between each seeding experiment and CTRL. To isolate the physical drivers of the radiative response, we decomposed the total effective radiative forcing of the seeded dust ($\Delta\text{ERF}_{\text{total, DIFF}}$) into two components: the instantaneous forcing due to ARI ($\Delta\text{IRF}_{\text{ari}}$) and the cloud-mediated forcing due to ACI ($\Delta\text{ERF}_{\text{aci}}$):

$$\text{ERF}_{\text{total}} = \text{IRF}_{\text{ari}} + \text{ERF}_{\text{aci}} \quad (1)$$

The ACI term encompasses indirect effects on cloud microphysics and adjustments of cloud cover to aerosol-induced heating (the semi-direct effect; Kok et al., 2023).



IRF_{ari} was calculated using an instantaneous “double-call” diagnostic method (Ghan, 2013): for every time step, radiative fluxes were calculated twice, once with the full atmospheric state (“full”) and once with the optical properties of accumulation mode mineral dust set to zero (“clean”):

$$\text{IRF}_{\text{ari}} = F_{\text{full}} - F_{\text{clean}} \quad (2)$$

130 where F_{full} and F_{clean} are the net TOA radiative fluxes [W m^{-2}].

The seeded-dust-only component of any forcing quantity X is obtained by removing the background dust effect already present in CTRL:

$$\Delta X_{\text{DIFF}} = X_{\text{SEED}} - X_{\text{CTRL}} \quad (3)$$

Assuming linearity of the radiative effects (Eq. (1)), the ACI effect of the seeded dust follows by subtracting the directly
135 diagnosed ARI effect from the total ERF:

$$\Delta \text{ERF}_{\text{aci, DIFF}} = \Delta \text{ERF}_{\text{total, DIFF}} - \Delta \text{IRF}_{\text{ari, DIFF}} \quad (4)$$

2.4 Cloud properties

We also analyzed changes in cloud properties. Clouds or cloudy grid boxes are defined as grid boxes where the total water content (TWC) exceeds a threshold value of $10^{-5} \text{ kg kg}^{-1}$ which is commonly used in the literature for cloud detection (Abel
140 et al., 2017; Huang et al., 2025). Additionally, MPRCs are defined as cloudy grid boxes where the temperature lies between -38°C and 0°C . Finally, cloud tops are defined as the highest model level where the TWC exceeded this threshold, potentially misrepresenting multilayered clouds. This simplification is acceptable for this study since the LWCRE is primarily driven by the cloud-top temperature, i.e. the highest cloud (Villanueva et al., 2022). For the spatial maps of cloud cover, a model column is considered cloudy at a given time if the TWC threshold is exceeded at any vertical level within that column; the fractional
145 cloud cover reported is the time-mean of this column indicator. Two different normalizations are used for the water-content diagnostics in Sect. 3.4: liquid water content (LWC), ice water content (IWC) and total water content (TWC) are grid-box means computed over all columns in the target region, cloudy or not, and therefore reflect the domain-mean water content. Liquid water path ($\text{LWP}_{\text{cloudy}}$) and ice water path ($\text{IWP}_{\text{cloudy}}$), when binned by cloud-top temperature, are instead averaged only over columns whose cloud top falls within the corresponding temperature bin, i.e. a cloud-conditional mean that describes
150 how the water path of the clouds that remain in that bin evolves. Forcings are reported as means over the 3 NDJF seasons with the corresponding interannual standard deviation, and their robustness is assessed relative to the magnitude of this variability.

3 Results

3.1 Dust concentrations and mass budget

This section characterizes the distribution of the dust aerosols after seeding: the resulting accumulation mode concentration
155 and activated INP profiles, and the fraction of seeded mass retained within the target region versus transported elsewhere.

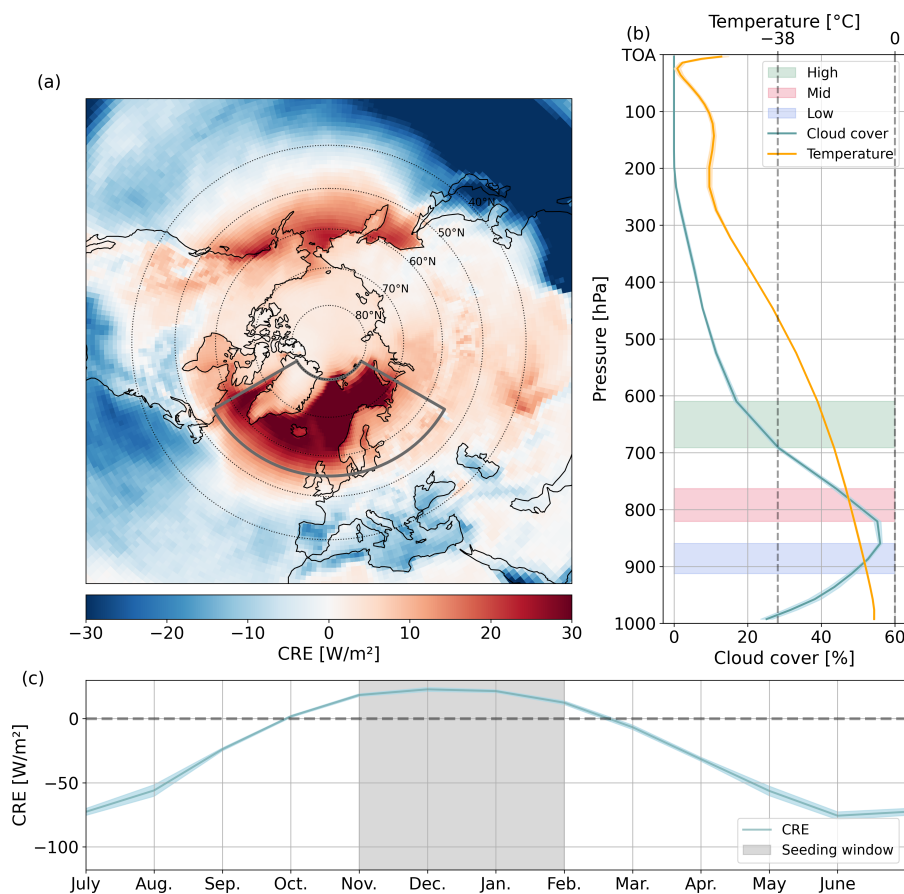


Figure 1. (a) Mean net all-sky CRE [W m^{-2}] in CTRL averaged over NDJF. The grey contour outlines the target seeding region (55°N–80°N and 60°W–60°E). (b) Vertical profile of mean cloud fraction and temperature over the target region during NDJF; colored bands indicate the three seeding injection layers. Shaded areas indicate the interannual variability. (c) Monthly averaged CRE [W m^{-2}] averaged over the target region; grey area indicates the seeding window and blue shaded areas indicate the interannual variability.

In all prognostic seeding experiments, the accumulation mode dust concentration increases substantially compared to CTRL, with maximal values reached in the highest seeding rate experiments. Single-layer experiments (*Low*, *Mid*, *High*; Fig.A1) each exhibit a maximum in dust concentration located at their respective injection layer altitude. Vertical profiles of dust mass concentration for the *Combined* experiments, averaged over the target region during NDJF, are presented in Fig. 2a instead: since the same cumulative mass is distributed across all three layers, the *Combined* profiles are correspondingly smoother than any single-layer case. For both *Combined* and single-layer experiments, vertical mixing is efficient enough that dust concentrations remain more elevated across the whole depth of the troposphere.

Figure 2b shows the empirical cumulative distribution function of diagnosed activated INPs for the *Combined* experiments. The number of activated INPs increases with seeding rate, in agreement with the aerosol concentration itself (Fig. 2a). However,

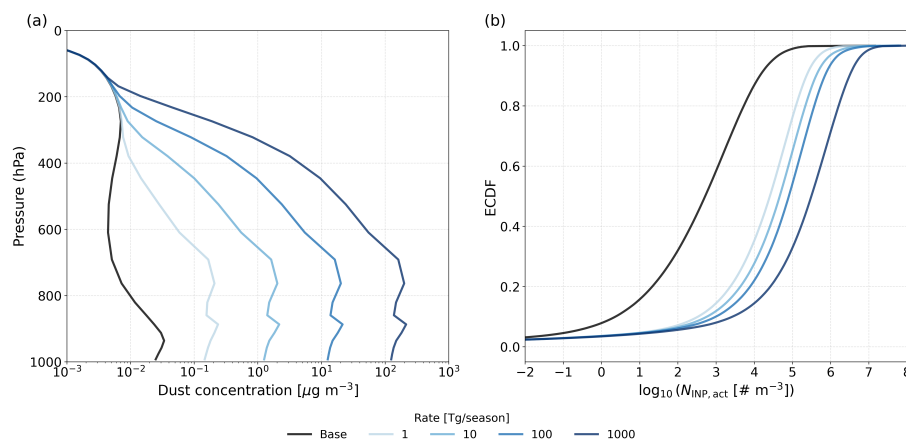


Figure 2. (a) Vertical profiles of accumulation mode dust mass concentration [$\mu\text{g m}^{-3}$] for the *Combined* experiments, averaged over the target region during NDJF. (b) Empirical cumulative distribution function (ECDF) of diagnosed activated INPs ($N_{\text{INP,act}}$) within MPRCs, for the *Combined* experiments.

as described in Sect. 2.1, each activated INP does not always lead to the formation of a new ice crystal, due to the *nimax* limiter in the default version of CESM2.1.5.

Figure 3 quantifies how the seeded dust mass is split between the target seeding region and the rest of the Northern Hemisphere, and between airborne and cloud-borne dust. All three bars in each group are expressed as a percentage of the same total steady-state atmospheric dust burden anomaly. Each altitude group averages over all four seeding rates (1, 10, 100 and 1000 Tg season^{-1}), since in-region retention versus long-range transport is governed primarily by injection altitude, not by the amount of mass injected.

Low retains substantially more dust within the target region than *High*, consistent with high altitude dust being injected above the majority of boundary-layer clouds (Sect. 3.2), leaving it subject to less wet and dry removal and thus more readily transported away from the source region. The in-region, cloud-borne bar follows the same ordering: Low altitude seeding experiments incorporate a substantially larger share of the seeded mass into cloud droplets than high altitude seeding experiments.

3.2 Decomposition of the TOA radiative forcing by seeding rate and altitude

The TOA radiative responses from the prognostic seeding experiments indicate that higher mineral dust concentrations lead to a positive LW ARI forcing, a negative SW ARI forcing and a negative ACI effect. These results are summarized in Fig. 4.

At the lowest seeding rate (1 Tg season^{-1}), ARI effects remain negligible. At higher rates (10 to 1000 Tg season^{-1}), a negative SW ARI effect emerges and strengthens with seeding rate, suggesting that scattering of incoming solar radiation becomes prevalent (Kok et al., 2023). The SW effect scales with injection altitude: at the highest seeding rate, the *High* injection produces the strongest cooling, followed by *Mid* and *Low*. The *Combined* experiment yields a response (-1.28 W m^{-2}) inter-

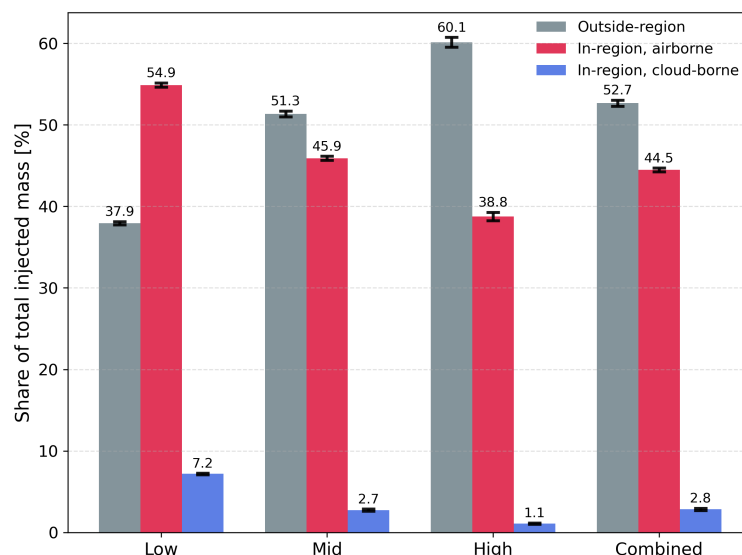


Figure 3. Dust mass budget distribution (in percent) by injection altitude: the in-region airborne, in-region cloud-borne and outside-region shares of the total steady-state atmospheric dust burden anomaly, relative to CTRL. Values are means across the three simulated years and across all four seeding rates (1, 10, 100 and 1000 Tg season⁻¹). Error bars show the standard deviation across the different seeding rates.

mediate to the *Mid* and *High* cases. In the *High* experiments, the dust is emitted above the majority of boundary-layer clouds (Fig. 1b) and is thus more exposed to incoming solar radiation.

185 The LW ARI effect only becomes substantial at the two highest seeding rates (100 and 1000 Tg season⁻¹) and remains predominantly positive. This effect increases with injection altitude, as the dust is located more and more above the clouds. Furthermore, the greater temperature differential between the surface and the *High* injection layer serves to increase the strength of the LW forcing (Kok et al., 2023). *Combined* experiments exhibit an LW ARI effect intermediate between the *Mid* and *High* cases.

190 The mean ACI effect indicates that cloud thinning strengthens with seeding rate. Notably, the *Combined* experiments exhibit ACI forcings broadly similar to the single-layer experiments, suggesting that the vertical distribution of the aerosols is a secondary factor for this component.

In summary, the net TOA forcing is a competition between a warming LW ARI effect and cooling SW ARI and ACI effects. Net cooling strengthens with seeding rate across all injection altitudes, but the balance among the three components shifts as the rate increases: at the highest seeding rate, *High* injection's large LW ARI warming term substantially erodes its net cooling (−1.85 W m⁻²), so that *Mid* and *Low* injection achieve comparable or stronger net cooling (−2.22 and −2.17 W m⁻²) despite weaker SW ARI and LW ARI effects individually.

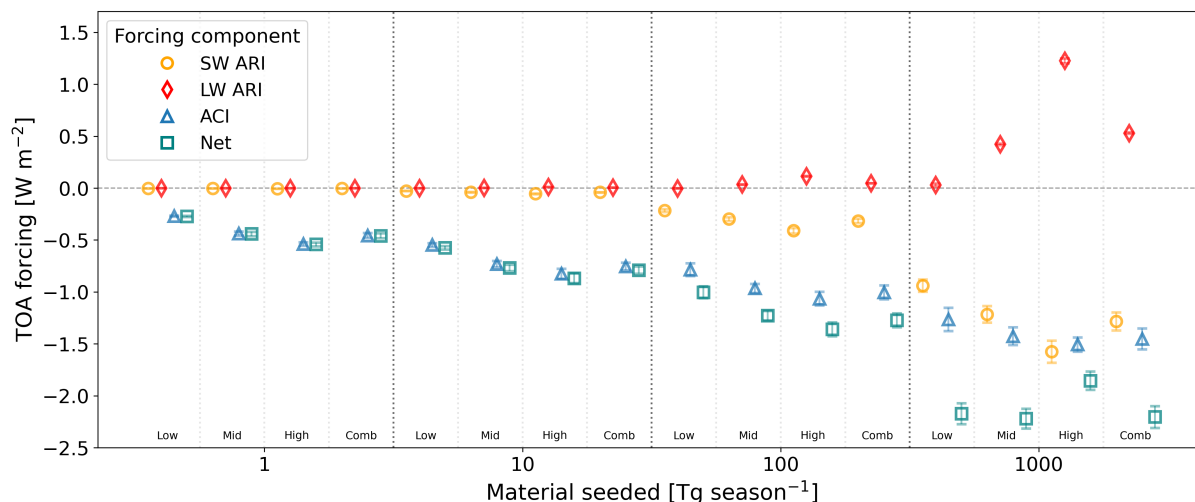


Figure 4. Decomposition of TOA radiative forcing [W m^{-2}] by seeding rate and altitude. Within each seeding-rate group, the four positions (left to right) are *Low*, *Mid*, *High* and *Combined*. Points show the 3-season mean anomaly relative to CTRL and error bars show the interannual standard deviation.

3.3 Spatial and temporal variability of TOA forcing

Building on the domain-averaged forcings in Sect. 3.2, this section examines how the TOA forcing varies spatially across the target region and temporally within the NDJF season. The spatial patterns of TOA forcing were analyzed by mapping the total TOA forcing and its components across the target region during NDJF for the *Combined* experiment at the highest seeding rate (1000 Tg season^{-1}).

The ACI effect (Fig. 5a) is negative across most of the target region, with the strongest cooling over the Barents Sea; a localized warming signal, on the order of 1 W m^{-2} , is observed over part of Greenland, likely related to frequent wintertime temperature inversions in this region (Shahi et al., 2020). Cloudy gridpoints over Greenland are on average slightly warmer than the surface during NDJF in CTRL, consistent with an inversion, which can locally alter the sign of the cloud radiative response to thinning. The SW ARI effect (Fig. 5b) is negative throughout almost the entire domain and intensifies toward the southeastern part of the target region, due to the stronger incoming solar radiation at lower latitudes within the NDJF season. The LW ARI effect (Fig. 5c) is positive across the entire domain except for Greenland, where the inversion leads to a slight negative LW ARI effect. As a result, the net TOA forcing (Fig. 5d) is negative across nearly the whole target region, with the strongest net cooling over the south of the seeding area, where both the SW ARI and ACI effects are negative.

The TOA forcing of the *Combined* experiments was further decomposed into its monthly components to examine the temporal structure of the response within the NDJF season (Fig. 6). At the two lowest seeding rates (1 and 10 Tg season^{-1}), the SW ARI and LW ARI effects both remain close to zero throughout the season, and the response is dominated by the ACI effect. At the two highest seeding rates (100 and 1000 Tg season^{-1}), the SW ARI effect becomes clearly negative and varies

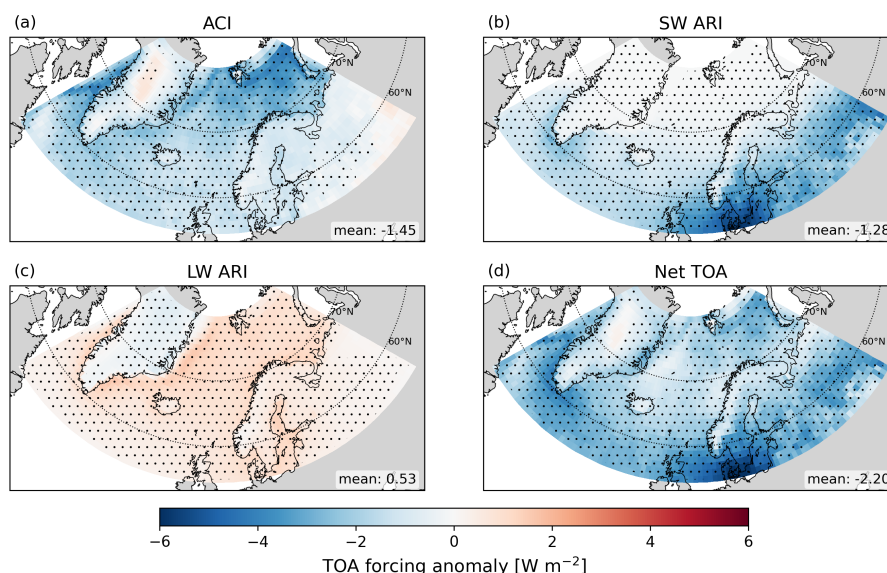


Figure 5. Map of TOA forcing anomaly [W m^{-2}] for the *Combined* experiment at the highest seeding rate ($1000 \text{ Tg season}^{-1}$) compared to CTRL during NDJF, decomposed into (a) ACI effect, (b) SW ARI effect, (c) LW ARI effect and (d) net TOA effect. Stippled grid cells indicate where the 3-season mean anomaly exceeds two standard deviations of its interannual variability. The inset value in each panel gives the area-weighted domain mean.

over the season, with the strongest cooling in November and February and weaker cooling in December and January; in line with the stronger incoming solar radiation during the shoulder months of the NDJF window. The LW ARI effect, by contrast, shows comparatively little monthly variability at any seeding rate, remaining close to 0.5 W m^{-2} throughout the season at the highest rate. The ACI effect is negative in every month and at every rate, and is consistently more negative in December and January than in November and February. This seasonal pattern is coherent with the seasonal cycle of the CRE itself (Fig. 1c): in December and January, the SWCRE is negligible and thinning the cloud deck acts to reduce the LWCRE, producing a net cooling. During November and February, incoming solar radiation increases and cloud thinning also reduces the shortwave radiation reflected back to space by the cloud deck, which is a warming contribution that increasingly offsets the LW-driven cooling, weakening the net ACI effect.

225 3.4 Cloud microphysical response

This section examines the microphysical mechanisms behind the ACI forcing: the vertical structure of the glaciation response, its sensitivity to seeding rate and its sensitivity to injection altitude. Figure 7 shows vertical profiles of cloud property anomalies for four quantities, LWC, IWC, TWC and cloud fraction on pressure levels, and liquid and ice water path ($\text{LWP}_{\text{cloudy}}$ and $\text{IWP}_{\text{cloudy}}$) binned by cloud-top temperature, compared between the *Combined* experiments across seeding rates (Fig. 7a-d) and across injection altitudes at the highest seeding rate (Fig. 7e-h). As introduced in Sect. 2.4, cloud properties computed on

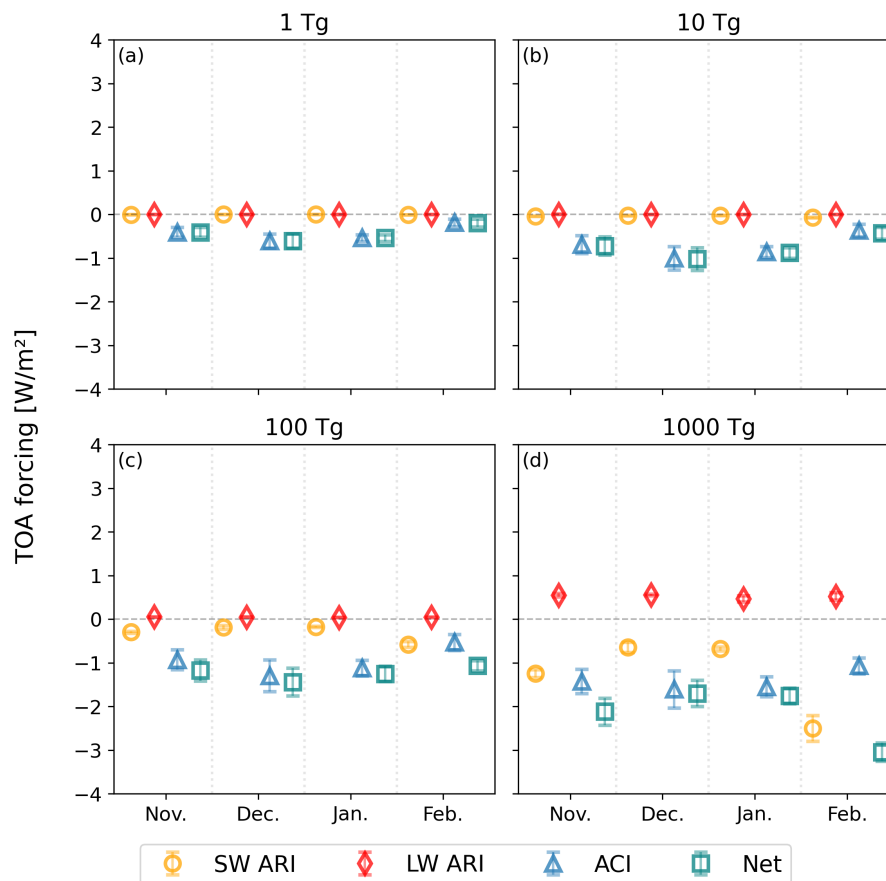


Figure 6. Monthly decomposition of TOA forcing [W m^{-2}] for the *Combined* experiments compared to CTRL, for seeding rates of (a) 1, (b) 10, (c) 100 and (d) 1000 Tg season^{-1} . Error bars show the interannual standard deviation.

cloud-top temperature bins ($\text{LWP}_{\text{cloudy}}$ and $\text{IWP}_{\text{cloudy}}$) are cloud-conditional averages. Considering the TWC threshold used to define cloudy columns, Fig. 7d and Fig. 7h show the state of the remaining clouds after seeding. The liquid and ice water content profiles (Fig. 7a) shows two distinct regimes stacked in the vertical. Between approximately 800 and 900 hPa, both LWC and IWC decrease. Below 900 hPa, the profile exhibits a signal corroborating cloud glaciation. This vertical structure is consistent across all four seeding rates, with the magnitude of both signals increasing with seeding rate (Fig. 7a-d).

Comparing across injection altitudes at the highest seeding rate (Fig. 7e-h) shows that this response is primarily governed by seeding intensity rather than injection height: *Mid*, *High* and *Combined* injection produce broadly similar LWC, IWC, TWC and cloud fraction anomalies despite their different injection altitudes. The one exception is the *Low* experiment, which produces a distinctly weaker glaciation signal than the other three configurations.

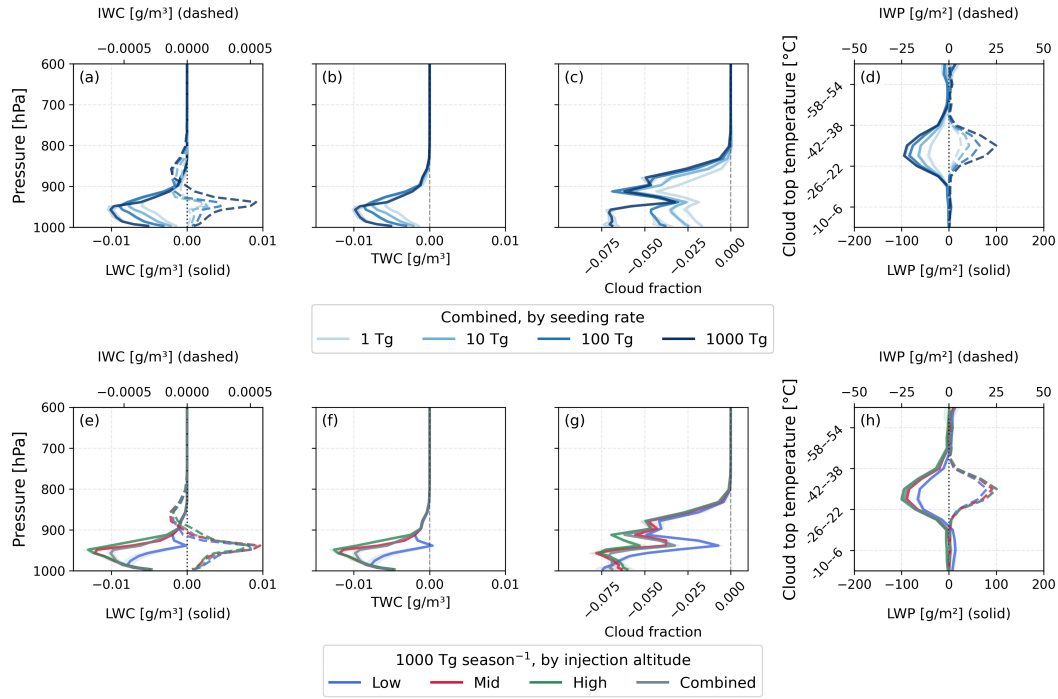


Figure 7. Vertical profiles of cloud property anomalies compared to CTRL during NDJF. Top row (a–d): *Combined* experiments across seeding rates (1, 10, 100 and 1000 Tg season^{−1}). Bottom row (e–h): *Low*, *Mid*, *High* and *Combined* injection altitudes at the highest seeding rate (1000 Tg season^{−1}). (a, e) LWC and IWC [g m^{−3}] on pressure levels. (b, f) TWC [g m^{−3}] on pressure levels. (c, g) Cloud fraction on pressure levels. (d, h) LWP_{cloudy} and IWP_{cloudy} [g m^{−3}] binned by cloud-top temperature.

240 The glaciation signal is also evident in the cloud-top temperature-binned LWP_{cloudy}, IWP_{cloudy} (Fig. 7d, h): the LWP_{cloudy} (IWP_{cloudy}) anomaly is negative (positive) between −20 °C and −38 °C, indicating the conversion of liquid water into ice and the temperature range where mineral dust is most effective as an INP in CESM2 (Wang et al., 2014).

This glaciation response is broadly consistent with direct observational evidence from outdoor glaciogenic seeding experiments: airborne and radar observations from the SNOWIE campaign showed that silver iodide seeding of supercooled orographic clouds enhanced ice crystal formation and precipitation (French et al., 2018), while drone-based seeding of super-
245 cooled stratus clouds during the CLOUDLAB campaign has directly been observed and the resulting ice nucleation and crystal growth have been subsequently quantified (Henneberger et al., 2023; Fuchs et al., 2025). These smaller scale field experiments confirm that the underlying microphysical mechanism operates in nature, although they do not inform on the response at the larger scale of the present study.

250 Figure 8 shows the spatial pattern of the total water path (TWP_{cloudy} = LWP_{cloudy} + IWP_{cloudy}) anomaly for the *Combined* experiments across seeding rates. Across most of the domain and at every seeding rate, the TWP anomaly is negative, owing to the glaciation-driven cloud thinning expected from the MCT mechanism. At the highest seeding rate (1000 Tg season^{−1}),



however, a distinct region of positive TWP anomaly (thickening) appears at the southern edge of the domain, opposite in sign to the dominant response. Decomposing this anomaly into its liquid and ice components shows that it is essentially a liquid-water phenomenon: the LWP_{cloudy} anomaly reproduces the same localized positive feature, while the IWP_{cloudy} anomaly is small and increases only weakly and more uniformly across the whole domain, showing no comparable localized signal (Fig. A2). Additionally, the ACI effect remains negative in the same region (Fig. 5a), suggesting increased cloud cover or cloud optical thickness possibly due to higher LWP. We consider three possible explanations for this feature. A stabilization of the cloud deck through the formation of numerous small ice crystals, which hinders precipitation and cloud thinning (Villanueva et al., 2025), is unlikely to be the main driver, given the liquid-only nature of the signal (Fig. A2) and the *nimax* limiter, which limits the number of ice crystals that heterogeneous nucleation can produce. A semi-direct effect, in which absorption of shortwave radiation by mineral dust warms the surrounding air and can increase cloud cover by enhancing low-level moisture convergence temperature inversions (Kok et al., 2023), cannot be ruled out either, though this mechanism typically requires dust to be present either above or below the cloud deck; since the anomaly is most pronounced for *Low*-altitude, boundary-layer injection, where dust sits mostly within and below the cloud layer itself, a semi-direct effect here would more plausibly manifest as enhanced low-level moisture convergence. Finally, this TWP increase may be due to a CCN-driven mechanism: in the warmer part of the domain, where mineral dust is less effective as an INP, we hypothesize that seeding instead acts primarily as a source of CCN, suppressing precipitation and increasing cloud optical thickness by increasing the number of cloud droplets (Twomey, 1977). This is consistent with the anomaly being most pronounced for *Low*-altitude injection (Fig. A3), which also activates the largest fraction of seeded dust into cloud-borne mass of the three injection altitudes (Sect. 3.1), and with the ACI effect remaining negative despite the LWP increase, since a CCN-driven increase in droplet number and optical thickness would be expected to cool via the LWCRE even as the liquid water path itself increases.

4 Conclusions

This study evaluated the viability of mixed-phase cloud thinning with a prognostic seeding aerosol, using mineral dust in CESM2. Three single-layer injection altitudes (*Low*, *Mid*, *High*) and a *Combined* configuration distributing the same mass across all three layers, each at four seeding rates (1, 10, 100 and 1000 Tg season⁻¹), were compared against a control simulation over the Arctic target region during 3 NDJF seasons. In all 16 experiments, seeding produced a net negative TOA radiative forcing over the target region that strengthens with seeding rate, reaching between -1.85 and -2.22 W m⁻² at the highest rate. This net forcing results from a competition between a negative ACI effect, a negative SW ARI effect that emerges from 10 Tg season⁻¹ onward, and a positive LW ARI effect that only becomes substantial at the two highest seeding rates.

The ACI cooling arises mainly because mineral dust triggers glaciation of mixed-phase clouds, thinning them and reducing their longwave warming effect. The strength of this response is broadly similar across all four injection configurations at the highest seeding rate, with only a modest decrease for *Low*: ACI cooling is -1.51 W m⁻² for *High*, -1.45 W m⁻² for *Combined*, -1.43 W m⁻² for *Mid* and -1.26 W m⁻² for *Low*. This low sensitivity to injection altitude contrasts with the dust mass budget (Fig. 3): although *Low*-altitude injection retains substantially more of the seeded dust mass within the target region,

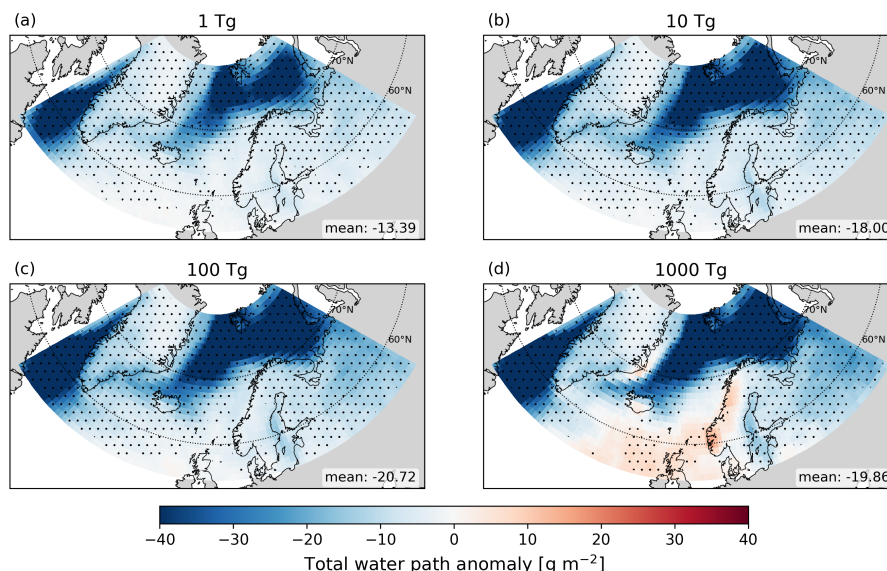


Figure 8. TWP_{cloudy} anomaly [$g\ m^{-2}$] for the *Combined* experiments compared to CTRL during NDJF, at seeding rates of (a) 1, (b) 10, (c) 100 and (d) 1000 $Tg\ season^{-1}$. Stippled grid cells indicate where the 3-season mean anomaly exceeds two standard deviations of its interannual variability. The inset value in each panel gives the area-weighted domain mean.

airborne and cloud-borne combined ($\sim 62\%$ vs. $\sim 40\%$ for *High*) and converts a much larger fraction of it into cloud-borne dust ($\sim 7\%$ vs. $\sim 1\%$), this additional activated dust translates into only a slightly weaker glaciation response. The injection altitude instead mainly controls the ARI effects, which strengthen as the dust is placed higher above the clouds, so that at the highest seeding rate the large LW ARI warming of *High* injection erodes its net cooling below that of *Mid* and *Low*. In the warmer part of the domain, the seeded dust may instead increase the cloud water path, plausibly through precipitation suppression via aerosol activation or through a semi-direct radiative effect on cloud cover.

The magnitude of the cloud radiative effect change is similar to that previously found with prescribed INP concentrations (Villanueva et al., 2022), indicating that the MCT mechanism persists when the seeding aerosol is transported, removed and activated prognostically, although the ARI effects of the aerosol become significant at higher seeding rates. The simulated glaciation is also consistent with outdoor glaciogenic seeding experiments (French et al., 2018; Henneberger et al., 2023; Fuchs et al., 2025).

Several caveats affect confidence in these results. The default *nimax* limiter in CESM2.1.5 restricts the formation of new ice crystals from mineral dust, so the risk of overseeding and stabilization of MPRCs is likely underestimated. Because the horizontal winds were nudged towards ERA5, circulation feedbacks are absent, and because sea ice and sea-surface temperatures were prescribed, neither the surface temperature response nor sea-ice albedo feedbacks from dust deposition are represented.

Overall, these results indicate that MCT with a realistic, prognostic seeding aerosol can produce a meaningful negative TOA radiative forcing over the Arctic in winter, consistent with the surface-cooling potential suggested by earlier studies, but



that both injection altitude and rate influence its efficacy and its side effects. Our results point toward more spatially targeted seeding, which would keep more of the seeded mass within the intended temperature regime, and toward alternative seeding
305 agents that minimize aerosol-radiation interactions and the total mass that must be injected. Silver iodide represents a promising candidate for future study. Unlike mineral dust, it is a highly efficient ice nucleant that can trigger glaciation at much lower mass concentrations and warmer subzero temperatures (Chen et al., 2024). Beyond reducing the LW ARI warming, this higher mass-efficiency would also reduce the amount of aerosol required for effective MCT.



Appendix A

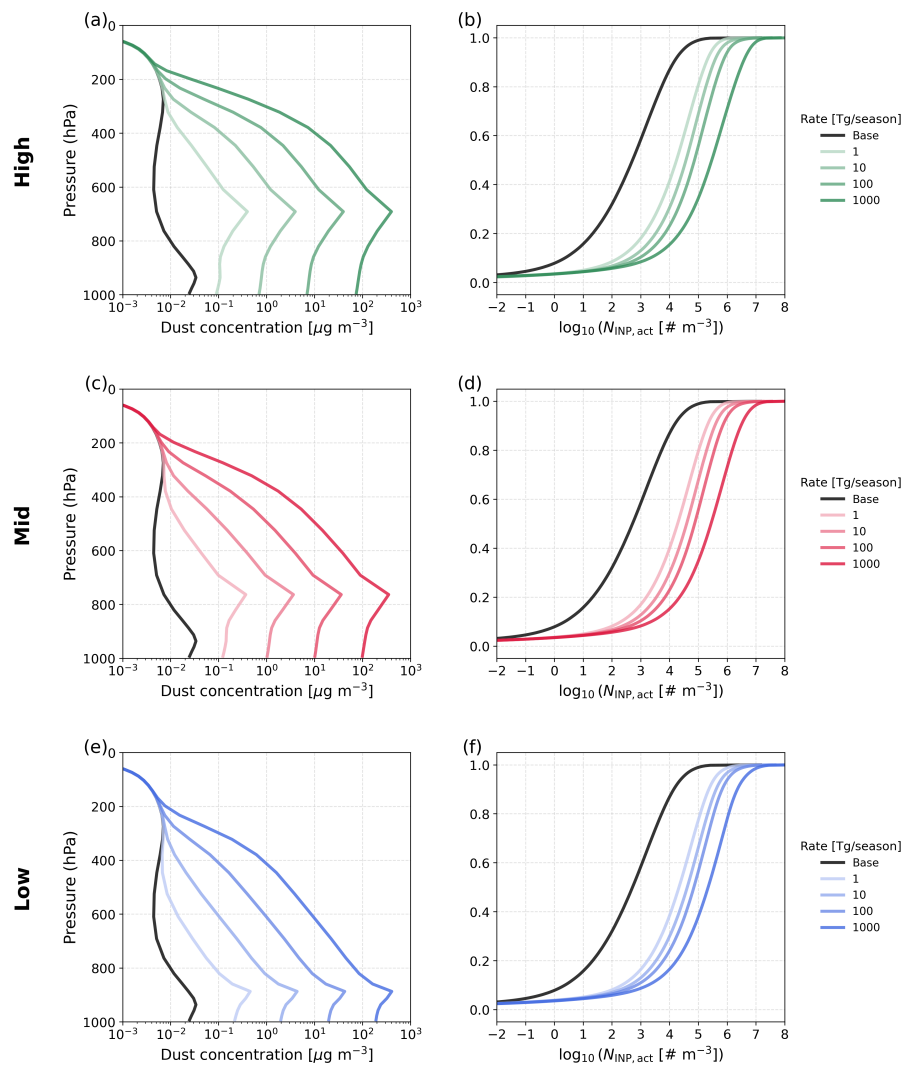


Figure A1. (a, c, e) vertical profiles of accumulation mode dust mass concentration $[\mu\text{g m}^{-3}]$ and (b, d, f) empirical cumulative distribution function (ECDF) of activated INPs ($N_{\text{INP,act}}$) within MPRCs, for the *High* (a, b), *Mid* (c, d) and *Low* (e, f) injection experiments.

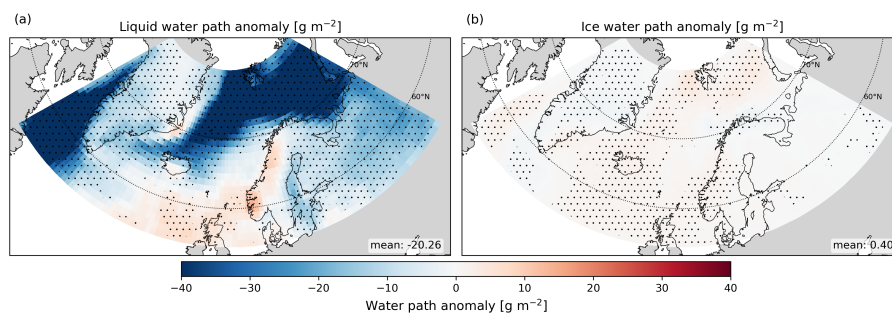


Figure A2. (a) LWP and (b) IWP anomaly [g m^{-2}] for the *Combined* experiment at the highest seeding rate ($1000 \text{ Tg season}^{-1}$) compared to CTRL during NDJF. Stippled grid cells indicate where the 3-season mean anomaly exceeds two standard deviations of its interannual variability. The inset value in each panel gives the area-weighted domain mean.

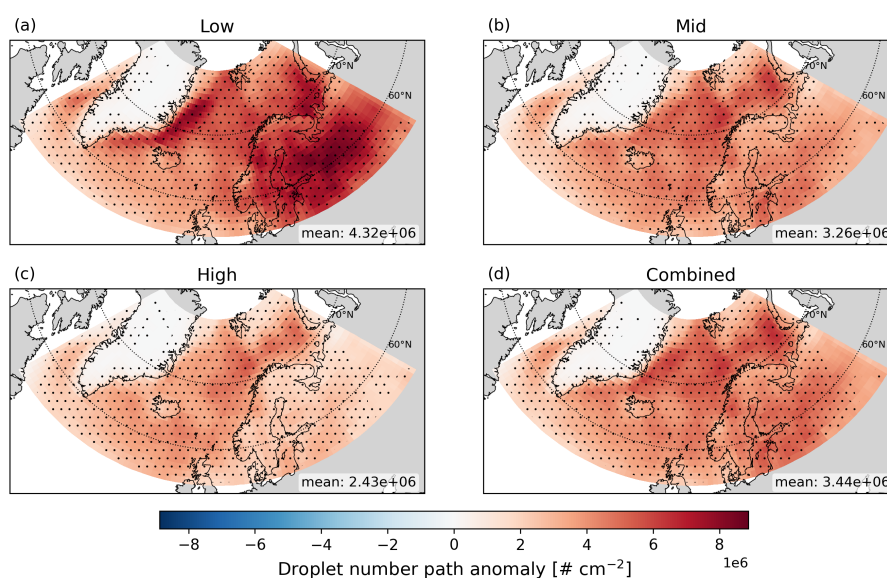


Figure A3. Droplet number path anomaly [$\# \text{ cm}^{-2}$] at the highest seeding rate ($1000 \text{ Tg season}^{-1}$) compared to CTRL during NDJF, for the (a) *Low*, (b) *Mid*, (c) *High* and (d) *Combined* injection experiments. Stippled grid cells indicate where the 3-season mean anomaly exceeds two standard deviations of its interannual variability. The inset value in each panel gives the area-weighted domain mean.



310 *Code and data availability.* The postprocessing and plotting scripts, the CESM2 model configuration, the raw monthly CESM2 output are openly available at <https://doi.org/10.5281/zenodo.23206722> (Farron et al., 2026).

Author contributions. UL and DV conceived the GLANCE project and received funding. PF and DV implemented the mineral dust seeding in CESM2. PF set up the model and performed all simulations and created the figures. All authors contributed to the interpretation of the results. PF wrote the manuscript. All authors contributed to editing and reviewing the manuscript.

315 *Competing interests.* The authors declare that they have no conflict of interest.

Acknowledgements. The authors wish to thank Simone Tilmes and Kanishk Gohil for useful comments on the model setup. We also thank Jasper Kok for providing guidance on the interpretation of the dust radiative effects.

Financial support. This research was supported by the Simons Foundation.



References

- 320 Abel, S. J., Boutle, I. A., Waite, K., Fox, S., Brown, P. R. A., Cotton, R., Lloyd, G., Choularton, T. W., and Bower, K. N.: The Role of Precipitation in Controlling the Transition from Stratocumulus to Cumulus Clouds in a Northern Hemisphere Cold-Air Outbreak, *J. Atmos. Sci.*, 74, 2293–2314, <https://doi.org/10.1175/JAS-D-16-0362.1>, 2017.
- Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., and Lenton, T. M.: Exceeding 1.5°C global warming could trigger multiple climate tipping points, *Science*, 377, eabn7950, <https://doi.org/10.1126/science.abn7950>, 2022.
- 325 Chen, J., Rösch, C., Rösch, M., Shilin, A., and Kanji, Z. A.: Critical Size of Silver Iodide Containing Glaciogenic Cloud Seeding Particles, *Geophys. Res. Lett.*, 51, e2023GL106680, <https://doi.org/10.1029/2023gl106680>, 2024.
- Danabasoglu, G., Lamarque, J. F., Bacmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., Emmons, L. K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M. M., Large, W. G., Lauritzen, P. H., Lawrence, D. M., Lenaerts, J. T., Lindsay, K., Lipscomb, W. H., Mills, M. J., Neale, R., Oleson, K. W., Otto-Bliesner, B., Phillips, A. S., Sacks, W., Tilmes, S., van Kampenhout, L., Vertenstein, M., Bertini, A., Dennis, J., Deser, C., Fischer, C., Fox-Kemper, B., Kay, J. E., Kinnison, D., Kushner, P. J., Larson, V. E., Long, M. C., Mickelson, S., Moore, J. K., Nienhouse, E., Polvani, L., Rasch, P. J., and Strand, W. G.: The Community Earth System Model Version 2 (CESM2), *J. Adv. Model. Earth Syst.*, 12, e2019MS001916, <https://doi.org/10.1029/2019MS001916>, 2020.
- 330 Emmons, L. K., Schwantes, R. H., Orlando, J. J., Tyndall, G., Kinnison, D., Lamarque, J. F., Marsh, D., Mills, M. J., Tilmes, S., Bardeen, C., Buchholz, R. R., Conley, A., Gettelman, A., Garcia, R., Simpson, I., Blake, D. R., Meinardi, S., and Pétron, G.: The Chemistry Mechanism in the Community Earth System Model Version 2 (CESM2), *J. Adv. Model. Earth Syst.*, 12, e2019MS001882, <https://doi.org/10.1029/2019MS001882>, 2020.
- Farron, P., Lohmann, U., and Villanueva, D.: Data and scripts for "Viability of mixed-phase cloud thinning with prognostic mineral dust in CESM2", Zenodo [data set], <https://doi.org/10.5281/zenodo.23206722>, 2026.
- 340 Findeisen, W.: Die kolloidmeteorologischen Vorgänge bei der Niederschlagsbildung, *Meteorol. Z.*, 55, 121–133, 1938.
- French, J. R., Friedrich, K., Tessendorf, S. A., Rauber, R. M., Geerts, B., Rasmussen, R. M., Xue, L., Kunkel, M. L., and Blestrud, D. R.: Precipitation formation from orographic cloud seeding, *Proc. Natl. Acad. Sci. U.S.A.*, 115, 1168–1173, <https://doi.org/10.1073/pnas.1716995115>, 2018.
- Fuchs, C., Ramelli, F., Miller, A. J., Omanovic, N., Spirig, R., Zhang, H., Seifert, P., Ohneiser, K., Lohmann, U., and Henneberger, J.: Quantifying Ice Crystal Growth Rates in Natural Clouds from Glaciogenic Cloud Seeding Experiments, *Atmos. Chem. Phys.*, 25, 12177–12196, <https://doi.org/10.5194/acp-25-12177-2025>, 2025.
- 345 Gettelman, A. and Morrison, H.: Advanced two-moment bulk microphysics for global models. Part I: Off-line tests and comparison with other schemes, *J. Climate*, 28, 1268–1287, <https://doi.org/10.1175/JCLI-D-14-00102.1>, 2015.
- Gettelman, A., Morrison, H., Eidhammer, T., Thayer-Calder, K., Sun, J., Forbes, R., McGraw, Z., Zhu, J., Storelvmo, T., and Dennis, J.: Importance of Ice Nucleation and Precipitation on Climate with the Parameterization of Unified Microphysics Across Scales Version 1 (PUMASv1), *Geosci. Model Dev.*, 16, 1735–1754, <https://doi.org/10.5194/gmd-16-1735-2023>, 2023.
- 350 Ghan, S. J.: Technical Note: Estimating Aerosol Effects on Cloud Radiative Forcing, *Atmos. Chem. Phys.*, 13, 9971–9974, <https://doi.org/10.5194/acp-13-9971-2013>, 2013.
- Ghan, S. J. and Zaveri, R. A.: Parameterization of Optical Properties for Hydrated Internally Mixed Aerosol, *J. Geophys. Res.-Atmos.*, 112, 2006JD007927, <https://doi.org/10.1029/2006JD007927>, 2007.



- Gonçalves, L. J., Coelho, S. M., Kubota, P. Y., and Souza, D. C.: Interaction between cloud-radiation, atmospheric dynamics and thermodynamics based on observational data from GoAmazon 2014/15 and a cloud-resolving model, *Atmos. Chem. Phys.*, 22, 15 509–15 526, <https://doi.org/10.5194/acp-22-15509-2022>, 2022.
- Henneberger, J., Ramelli, F., Spirig, R., Omanovic, N., Miller, A. J., Fuchs, C., Zhang, H., Bühl, J., Hervo, M., Kanji, Z. A., Ohneiser, K., Radenz, M., Rösch, M., Seifert, P., and Lohmann, U.: Seeding of Supercooled Low Stratus Clouds with a UAV to Study Microphysical Ice Processes: An Introduction to the CLOUDLAB Project, *Bull. Amer. Meteor. Soc.*, 104, E1962–E1979, <https://doi.org/10.1175/BAMS-D-22-0178.1>, 2023.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.-N.: The ERA5 global reanalysis, *Q. J. R. Meteorol. Soc.*, 146, 1999–2049, <https://doi.org/10.1002/qj.3803>, 2020.
- Hess, M., Koepke, P., and Schult, I.: Optical Properties of Aerosols and Clouds: The Software Package OPAC, *Bull. Amer. Meteor. Soc.*, 79, 831–844, [https://doi.org/10.1175/1520-0477\(1998\)079<0831:OPOAAC>2.0.CO;2](https://doi.org/10.1175/1520-0477(1998)079<0831:OPOAAC>2.0.CO;2), 1998.
- Hoose, C., Kristjánsson, J. E., Chen, J.-P., and Hazra, A.: A Classical-Theory-Based Parameterization of Heterogeneous Ice Nucleation by Mineral Dust, Soot, and Biological Particles in a Global Climate Model, *J. Atmos. Sci.*, 67, 2483–2503, <https://doi.org/10.1175/2010JAS3425.1>, 2010.
- Huang, X., Field, P. R., Murray, B. J., Grosvenor, D. P., van den Heuvel, F., and Carslaw, K. S.: Different Responses of Cold-Air Outbreak Clouds to Aerosol and Ice Production Depending on Cloud Temperature, *Atmos. Chem. Phys.*, 25, 11 363–11 406, <https://doi.org/10.5194/acp-25-11363-2025>, 2025.
- Intrieri, J. M., Shupe, M. D., Uttal, T., and McCarty, B. J.: An Annual Cycle of Arctic Cloud Characteristics Observed by Radar and Lidar at SHEBA, *J. Geophys. Res.-Oceans*, 107, SHE 5–1–SHE 5–15, <https://doi.org/10.1029/2000JC000423>, 2002.
- IPCC: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp., <https://doi.org/10.1017/9781009157896>, 2021.
- Kok, J. F., Adebisi, A. A., Albani, S., Balkanski, Y., Checa-Garcia, R., Chin, M., Colarco, P. R., Hamilton, D. S., Huang, Y., Ito, A., Klose, M., Leung, D. M., Li, L., Mahowald, N. M., Miller, R. L., Obiso, V., Pérez García-Pando, C., Rocha-Lima, A., Wan, J. S., and Whicker, C. A.: Improved representation of the global dust cycle using observational constraints on dust properties and abundance, *Atmos. Chem. Phys.*, 21, 8127–8167, <https://doi.org/10.5194/acp-21-8127-2021>, 2021.
- Kok, J. F., Storelvmo, T., Karydis, V. A., Adebisi, A. A., Mahowald, N. M., Evan, A. T., He, C., and Leung, D. M.: Mineral dust aerosol impacts on global climate and climate change, <https://doi.org/10.1038/s43017-022-00379-5>, 2023.
- Lawrence, M. G., Schäfer, S., Muri, H., Scott, V., Oschlies, A., Vaughan, N. E., Boucher, O., Schmidt, H., Haywood, J., and Scheffran, J.: Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals, *Nat. Commun.*, 9, 3734, <https://doi.org/10.1038/s41467-018-05938-3>, 2018.
- Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J.: Tipping Elements in the Earth’s Climate System, *Proc. Natl. Acad. Sci. U.S.A.*, 105, 1786–1793, <https://doi.org/10.1073/pnas.0705414105>, 2008.



- 395 Liu, X., Penner, J. E., Ghan, S. J., and Wang, M.: Inclusion of Ice Microphysics in the NCAR Community Atmospheric Model Version 3 (CAM3), *J. Climate*, pp. 4526–4547, <https://doi.org/10.1175/JCLI4264.1>, 2007.
- Liu, X., Ma, P. L., Wang, H., Tilmes, S., Singh, B., Easter, R. C., Ghan, S. J., and Rasch, P. J.: Description and evaluation of a new four-mode version of the Modal Aerosol Module (MAM4) within version 5.3 of the Community Atmosphere Model, *Geosci. Model Dev.*, 9, 505–522, <https://doi.org/10.5194/gmd-9-505-2016>, 2016.
- Lohmann, U., Lüönd, F., and Mahrt, F.: *An Introduction to Clouds*, Cambridge University Press, ISBN 9781107018228, 400 <https://doi.org/10.1017/CBO9781139087513>, 2016.
- Magnan, A. K., Pörtner, H. O., Duvat, V. K., Garschagen, M., Guinder, V. A., Zommers, Z., Hoegh-Guldberg, O., and Gattuso, J. P.: Estimating the global risk of anthropogenic climate change, *Nat. Clim. Change*, 11, 879–885, <https://doi.org/10.1038/s41558-021-01156-w>, 2021.
- Matus, A. V. and L'Ecuyer, T. S.: The role of cloud phase in Earth's radiation budget, *J. Geophys. Res.-Atmos.*, 122, 2559–2578, 405 <https://doi.org/10.1002/2016JD025951>, 2017.
- McGraw, Z., Storelvmo, T., Polvani, L. M., Hofer, S., Shaw, J. K., and Gettelman, A.: On the Links Between Ice Nucleation, Cloud Phase, and Climate Sensitivity in CESM2, *Geophys. Res. Lett.*, 50, e2023GL105 053, <https://doi.org/10.1029/2023GL105053>, 2023.
- Mitchell, D. L. and Finnegan, W.: Modification of Cirrus Clouds to Reduce Global Warming, *Environ. Res. Lett.*, 4, 045 102, <https://doi.org/10.1088/1748-9326/4/4/045102>, 2009.
- 410 Muri, H., Kristjánsson, J. E., Storelvmo, T., and Pfeffer, M. A.: The climatic effects of modifying cirrus clouds in a climate engineering framework, *J. Geophys. Res.-Atmos.*, 119, 4174–4191, <https://doi.org/10.1002/2013JD021063>, 2014.
- Murray, B. J., O'Sullivan, D., Atkinson, J. D., and Webb, M. E.: Ice Nucleation by Particles Immersed in Supercooled Cloud Droplets, *Chem. Soc. Rev.*, 41, 6519–6554, <https://doi.org/10.1039/C2CS35200A>, 2012.
- Ramanathan, V., Cess, R. D., Harrison, E. F., Minnis, P., Barkstrom, B. R., Ahmad, E., and Hartmann, D.: Cloud-Radiative Forcing and 415 Climate: Results from the Earth Radiation Budget Experiment, *Science*, 243, 57–63, <https://doi.org/10.1126/science.243.4887.57>, 1989.
- Shahi, S., Abermann, J., Heinrich, G., Prinz, R., and Schöner, W.: Regional Variability and Trends of Temperature Inversions in Greenland, *J. Climate*, 33, 9391–9407, <https://doi.org/10.1175/JCLI-D-19-0962.1>, 2020.
- Shaw, J., McGraw, Z., Bruno, O., Storelvmo, T., and Hofer, S.: Using Satellite Observations to Evaluate Model Microphysical Representation of Arctic Mixed-Phase Clouds, *Geophys. Res. Lett.*, 49, e2021GL096 191, <https://doi.org/10.1029/2021GL096191>, 2022.
- 420 Shupe, M. D. and Intrieri, J. M.: Cloud Radiative Forcing of the Arctic Surface: The Influence of Cloud Properties, Surface Albedo, and Solar Zenith Angle, *J. Climate*, 17, 616–628, [https://doi.org/10.1175/1520-0442\(2004\)017<0616:crfota>2.0.co;2](https://doi.org/10.1175/1520-0442(2004)017<0616:crfota>2.0.co;2), 2004.
- Tully, C., Neubauer, D., Omanovic, N., and Lohmann, U.: Cirrus cloud thinning using a more physically based ice microphysics scheme in the ECHAM-HAM general circulation model, *Atmos. Chem. Phys.*, 22, 11 455–11 484, <https://doi.org/10.5194/acp-22-11455-2022>, 2022.
- 425 Twomey, S.: The Influence of Pollution on the Shortwave Albedo of Clouds, *J. Atmos. Sci.*, 34, 1149–1152, [https://doi.org/10.1175/1520-0469\(1977\)034<1149:tiopot>2.0.co;2](https://doi.org/10.1175/1520-0469(1977)034<1149:tiopot>2.0.co;2), 1977.
- van Wijngaarden, A., Moore, J. C., Alftan, B., Kurvits, T., and Kullerud, L.: A survey of interventions to actively conserve the frozen North, *Climatic Change*, 177, 58, <https://doi.org/10.1007/s10584-024-03705-6>, 2024.
- Villanueva, D., Possner, A., Neubauer, D., Gasparini, B., Lohmann, U., and Tesche, M.: Mixed-phase regime cloud thinning could help 430 restore sea ice, *Environ. Res. Lett.*, 17, 114 057, <https://doi.org/10.1088/1748-9326/aca16d>, 2022.



- Villanueva, D., Stengel, M., Hoose, C., Bruno, O., Jeggle, K., Ansmann, A., and Lohmann, U.: Dust-Driven Droplet Freezing Explains Cloud-Top Phase in the Northern Extratropics, *Science*, 389, 521–525, <https://doi.org/10.1126/science.adt5354>, 2025.
- Visioni, D., Robock, A., Duffey, A., Henry, M., Hirasawa, H., Lee, W. R., Wang, C., Roberts, K., Watanabe, S., Reboita, M. S., Sugiyama, M., Kravitz, B., Haywood, J., Tilmes, S., Bonou, F. K., Chen, J., Sukhodolov, T., Vattioni, S., Jörimann, A., Villanueva, D., Vella, R., Farron, P., Bednarz, E., Niemeier, U., Golja, C., and Añel, J. A.: The Geoengineering Model Intercomparison Project (GeoMIP) Contribution to CMIP7 – Description of New Experimental Protocols and Preliminary Results, *Geosci. Model Dev.*, 19, 8469–8499, <https://doi.org/10.5194/gmd-19-8469-2026>, 2026.
- Wang, Y., Liu, X., Hoose, C., and Wang, B.: Different Contact Angle Distributions for Heterogeneous Ice Nucleation in the Community Atmospheric Model Version 5, *Atmos. Chem. Phys.*, 14, 10411–10430, <https://doi.org/10.5194/acp-14-10411-2014>, 2014.
- 435 Wunderling, N., Winkelmann, R., Rockström, J., Loriani, S., Armstrong McKay, D. I., Ritchie, P. D., Sakschewski, B., and Donges, J. F.: Global warming overshoots increase risks of climate tipping cascades in a network model, *Nat. Clim. Change*, 13, 75–82, <https://doi.org/10.1038/s41558-022-01545-9>, 2023.
- Zhu, J., Otto-Bliesner, B. L., Brady, E. C., Gettelman, A., Bacmeister, J. T., Neale, R. B., Poulsen, C. J., Shaw, J. K., McGraw, Z. S., and Kay, J. E.: LGM Paleoclimate Constraints Inform Cloud Parameterizations and Equilibrium Climate Sensitivity in CESM2, *J. Adv. Model. Earth Syst.*, 14, e2021MS002776, <https://doi.org/10.1029/2021MS002776>, 2022.
- 445