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On the Links Between Ice Nucleation, Cloud Phase, and Climate Sensitivity in CESM2

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Key Points:

- Ice nucleation representation is only found to sizably affect total cloud feedback when allowed to promote biased global mean cloud phase
- Community Earth System Model 2's strongly positive cloud feedback is consistent with realistic mixed-phase cloud representation despite a known model issue
- Simulated relationships among ice nucleation, cloud phase, and feedback strength are partly set by mid-level and tropical high clouds

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Ice nucleation in mixed-phase clouds has been identified as a critical factor in projections of future climate. Here we explore how this process influences climate sensitivity using the Community Earth System Model 2 (CESM2). We find that ice nucleation affects simulated cloud feedbacks over most regions and levels of the troposphere, not just extratropical low clouds. However, with present-day global mean cloud phase adjusted to replicate satellite retrievals, similar total cloud feedback is attained whether ice nucleation is simulated as aerosol-sensitive, insensitive, or absent. These model experiments all result in a strongly positive total cloud feedback, as in the default CESM2. A microphysics update from CESM1 to CESM2 had substantially weakened ice nucleation, due partly to a model issue. Our findings indicate that this update reduced global cloud phase bias, with CESM2's high climate sensitivity reflecting improved mixed-phase cloud representation.

Plain Language Summary

Simulations of Earth's climate have revealed that the extent of greenhouse gas warming depends on a microscopic process in cold clouds known as ice nucleation. Problematically, this process is poorly understood and crudely represented in projections of future climate. Here we assess why ice nucleation affects Earth's projected future temperature, and estimate the sensitivity to different simulated representations of this process. We find that ice nucleation influences warming through feedback mechanisms in clouds in all regions and heights of the troposphere that are at temperatures where either ice crystals or liquid droplets may exist. The primary link between ice nucleation and warming is revealed to be the role this process has in setting the global mean ratio of ice to liquid water within clouds. We also demonstrate that an issue that weakened ice nucleation in a widely used climate model reduced bias in this ratio. Our findings suggest that the reduced bias is responsible for this model's strong global warming projections, enhancing the possibility that such projections may be realistic.

1. Introduction

Mixed-phase clouds, which exist at temperatures where either liquid droplets or ice crystals may form (roughly −38°C–0°C), are a major source of uncertainty in climate projections (Forster et al., 2021; Storelvmo et al., 2015). These clouds are governed by complex microphysical interactions between water's three thermodynamic phases (vapor, liquid, and ice) (Korolev et al., 2017). The importance of these processes has been brought to light by a number of studies (Frey & Kay, 2018; Tan & Storelvmo, 2016; Zhu et al., 2022) that uncovered major changes to projected climate after altering mixed-phase clouds in global simulations. These studies reported strong impacts on the global mean surface air temperature change that ultimately develops following a doubling of carbon dioxide in the atmosphere, a central metric in climate science known as equilibrium climate sensitivity (ECS).

The established link between mixed-phase clouds and ECS is the *cloud phase feedback* (Mitchell et al., 1989), wherein warming ice clouds reduce global climate change by deglaciating into liquid clouds. Since cloud droplets tend to be smaller than ice crystals, deglaciation results in more exposed surface area per unit mass (i.e., optically thicker clouds), hence more reflection of sunlight and reduced ECS. This negative feedback has been most associated with near-surface clouds at high latitudes, especially over the Southern Ocean. Climate model estimates of

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ECS have likely overestimated this feedback, implying underestimated global warming (Tan et al., 2016). This is linked to a deficiency of cloud liquid relative to total cloud condensate (supercooled liquid fraction, or SLF) in these models compared to satellite retrievals (Komurcu et al., 2014), leaving simulated clouds with excessive ability to deglaciate with warming. Effort to correct this bias has been proposed as a major reason that an unprecedented proportion of contemporary climate models have high (>4.5°C) climate sensitivity (Zelinka et al., 2020).

Multiple realizations of microphysical processes may result in similar global mean SLF (Tan et al., 2016). It is unknown which microphysical processes most account for the present-day proportion of ice, and to what degree each process will affect ECS by responding to warming. New ice crystals may form within mixed-phase clouds, primarily through *immersion freezing*, whereby cloud droplets freeze with the aid of embedded aerosols acting as *ice nucleating particles* (INPs) (Kanji et al., 2017). Alternatively, ice crystals may fall from overlying cirrus or be detrained from deep convective cores. Once ice crystals are present in mixed-phase clouds, the crystals may grow by depleting surrounding liquid droplets via the Wegener-Bergeron-Findeisen (WBF) vapor deposition process (Storelvmo & Tan, 2015). Frequently, the WBF process makes ice crystals grow sufficiently heavy to initiate precipitation. Figure 1a provides a simplified depiction of these ice formation processes' influences on cloud phase and occurrence.

Recent publications have highlighted the influence of ice nucleation on ECS (Gettelman et al., 2019; Murray et al., 2021; Zhu et al., 2022). Ice nucleation is a complex process that continues to evolve within climate models. Laboratory experiments have consistently found ice nucleation to act strongest in environments with abundant aerosols capable of acting as INPs (Kanji et al., 2017), yet models do not typically make ice nucleation sensitive to aerosols (*aerosol-sensitive*). It has been argued that constraining ECS will necessitate a realistic treatment of aerosol-sensitive ice nucleation (Murray et al., 2021). Apparently supporting this hypothesis, ice nucleation developments in the Community Earth System Model (CESM) have been implicated in a substantial ECS shift. The CMIP6 version of this model (CESM2) featured updates over the earlier CESM1 that intended to make ice nucleation in mixed-phase clouds aerosol-sensitive. Concurrently, simulated ECS jumped from 4.0 to 5.3 K. Adding confusion, a model error identified by authors of the present study negates nearly all ice nucleation in stratiform mixed-phase clouds (explained below in Section 2, and in Shaw et al., 2022). Reversion to CESM1's ice nucleation scheme was found to undo most of the feedback difference causing the ECS jump (Gettelman et al., 2019), while correcting the error considerably lowered ECS in a reduced-resolution version of CESM2 (Zhu et al., 2022). However, an update to CESM2's microphysics that included removal of the error only weakly affected total cloud feedback relative to the CMIP6 version (Gettelman et al., 2022), and the link between ice nucleation and ECS remains poorly understood.

Here we assess how ice nucleation in mixed-phase clouds influences climate sensitivity. We evaluate cloud feedbacks in CESM2 simulations with varied realizations of ice nucleation, including both aerosol-sensitive and aerosol-independent representations. A detailed analysis reveals that feedbacks in mid-level and high clouds play an unappreciated role in INPs' influence on feedback strength. We find little influence of ice nucleation representation on cloud feedback strength as long as simulated cloud phase is kept consistent with global-scale observations. Using knowledge from our experiments, we attribute CESM2's increased climate sensitivity to reduced cloud phase bias and link this to the model's ice nucleation updates.

2. Methods

Here we perform two groups of model experiments with the CESM2 global climate model (Danabasoglu et al., 2020). The experimental setup is visualized in Figure 1b. In the first experiments (hereafter Group A), we alter simulated ice nucleation only, which results in lower SLF for schemes with stronger ice nucleation. In the second (Group B), we alter ice nucleation while adjusting the WBF process to have observed global mean cloud phase at present-day. Group B simulations hence represent distinct plausible realizations of mixed-phase clouds. Group A experiments demonstrate the role of cloud phase bias in climate projections under strong uncompensated ice nucleation, while Group B simulations enable us to test whether model ice nucleation options (e.g., strength relative to other ice sources, aerosol-sensitivity) independently affect projections. Except for the differences described herein, simulations are carried out with the CMIP6 model version at its 1.25° × 0.9° resolution. Within CESM2, microphysical processes pertaining to stratiform mixed-phase clouds—including ice nucleation and WBF—are treated by the Gettelman and Morrison (2015) microphysics scheme. The physical parameterizations in CESM2's atmospheric component, the Community Atmosphere Model version 6 (CAM6), are described

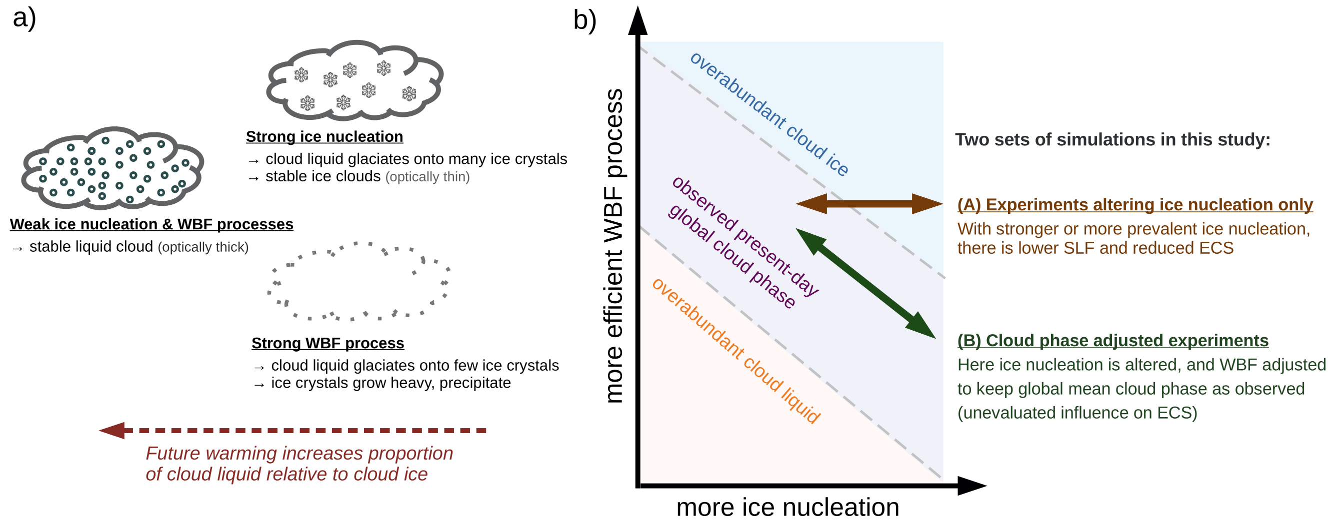

Figure 1. Ice formation processes, their links to mixed-phase cloud development and ECS, and our experimental setup. In (a), we illustrate the influences of microphysical processes on mixed-phase cloud properties and lifetime. In (b), we highlight these processes' role setting cloud phase and depict the two microphysical axes we explore in our simulation Groups A and B. Here "more ice nucleation" can involve either more INPs at concentrated locations or increased INP prevalence across locations.

in Gettelman et al. (2019). For each experiment, we ran two 10-year simulations having fixed sea surface temperatures (SSTs). One simulation has present-day climatology while the other has SSTs uniformly raised by 4°C (Cess et al., 1989). Cloud feedbacks were then evaluated using a kernel method described later in this section.

In the first set of experiments, Group A, we tested the default model (hereafter referred to as *Default*) as well as three alternative ice nucleation realizations (listed in Table 1). In CESM2, an aerosol-sensitive ice nucleation scheme (Hoose et al., 2010) is enabled by default, which includes immersion freezing along with weaker contact and deposition nucleation mechanisms. However, an overlooked limit on ice number negates the scheme's ability to produce ice number. This leaves the scheme only capable of reducing cloud droplet number and transitioning mass from droplets and vapor onto ice. For our second experiment, we correct the error to enable the Hoose scheme's direct impact on ice number (experiment *Hoose (A)*). We additionally test the model with all ice nucleation terms in mixed-phase clouds set to zero (*No INPs (A)*) and with the aerosol-independent strong ice nucleation source of CESM1 (Meyers et al., 1992, hereafter *Meyers (A)*).

For the SLF-constrained experiments (Group B), ice nucleation is again varied but we negate differences in present-day global cloud phase. Specifically, in all present-day simulations we adjust the WBF process to bring global mean SLF within ±1°C of the −20°C isotherm to that observed by the CALIOP satellite instrument (Tan et al., 2016). SLF in the +4°K simulations is free to shift in response to temperature. This method is based on the two SLF-constrained experiments in Tan et al. (2016). To improve SLF agreement for warmer isotherms, we reduce the proportion of ice phase detrained from convective cores as in Tan and Storelvmo (2016), here simultaneously doubling detrained liquid radius to offset impacts on cloud radiative effects. For each experiment, the WBF process is then adjusted by a constant efficiency multiplier to keep cloud phase within the observed range (see simulated cloud phase at −20°C in Table 1, with SLFs in other isotherms in Figure S1a in Supporting Information S1 and across latitudes in Figure S1b in Supporting Information S1). To ensure SLF from the model and retrievals are comparable, we use custom model output that considers only the clouds observable to CALIOP, as in Komurcu et al. (2014). We repeat experiments *No INPs (A)* and *Meyers (A)* through this methodology. The *Hoose (A)* experiment reveals that the Hoose scheme with no further modification directs an overabundance of ice crystals toward major mineral dust INP sources (i.e., Saharan and Middle-Eastern deserts) compared to DARDAR-Nice satellite retrievals (Sourdeval et al., 2018) (see experiment *Hoose (A)* in Figure S2a in Supporting Information S1). We note that ice number retrievals in mixed-phase clouds remain highly uncertain. Since Group B experiments are intended to behave plausible mixed-phase cloud representations, so we here reduce this scheme's efficiency to improve ice number spatial agreement. We simulate the Hoose scheme in two Group B experiments, having dust INPs capped to 5% and 20% of total mineral dust concentrations (*Hoose-cap1 (B)* and *Hoose-cap2 (B)*, respectively). That these experiments represent a relatively weak and strong aerosol-sensitive ice

Table 1
Description of Individual Model Experiments Along With the Cloud Properties Simulated in Present-Day Climate

experiment group & name		experimental setup: Ice nucleation in mixed-phase clouds	experimental setup: WBF efficiency		Present-day cloud properties: SLF at -20°C global (%)	SLF at -20°C *40-70°S* *(%)*	SLF at -20°C *15°S-15°N* *(%)*	Cloud radiative effects shortwave *(W/m²)*	Cloud radiative effects longwave *(W/m²)*	Cloud ice water path *(g/m²)*	Cloud liquid water path *(g/m²)*
Group A *altered INPs only*	*No INPs*	none	100%	↓ *more INPs*	23.7	37.5	12.6	-47.9	23.9	12.7	67.5
	Default	Hoose et al 2010 *ice number sources suppressed*	100%		21.6	34.6	11.5	-47.7	23.8	13.0	65.9
	Hoose	Hoose et al 2010 *corrected ice limit*	100%		14.7	26.8	9.6	-48.8	24.9	15.7	61.8
	Meyers	Meyers et al 1992	100%		4.3	8.3	1.9	-45.9	22.7	14.3	54.4
Group B *phase-constrained*	*No INPs*	none	100%	↓ *more INPs, weaker WBF*	31.1	48.4	18.6	-48.7	24.3	10.8	74.5
	Hoose-cap1	Hoose et al 2010 *corrected ice limit, max 5% dust*	65%		28.7	49.7	19.3	-48.2	24.2	11.7	69.5
	Hoose-cap2	Hoose et al 2010 *corrected ice limit, max 20% dust*	50%		30.3	52.0	21.7	-48.9	24.7	12.8	69.4
	Meyers	Meyers et al 1992	25%		31.3	47.6	23.6	-51.2	26.1	15.3	70.0
	observations				27–32[a]			-46[b]	28[b]	12 –140[c]	15 –102[c]

Note. In addition to the tabulated experiment differences, all Group B experiments have reduced ice phase from deep convective cores compared to Group A (see Section 2). For comparison, observational values are also shown. All values are global averages except where noted.
[a]Tan et al. (2016).
[b]Loeb et al. (2018).
[c]Jiang et al. (2012).

nucleation makes them the Group B equivalents of *Default* and *Hoose (A)*. We do not attempt to correct for disagreement between simulated and retrieved global mean ice number. Simulated ice number is lower than in retrievals at both cirrus and mixed-phase cloud isotherms (see Figure S2b in Supporting Information S1), suggesting this may relate to biases in cirrus formation and sedimentation rather than ice nucleation in mixed-phase clouds.

In order to calculate total cloud feedback and its decomposition into cloud optical depth, amount, and altitude feedback mechanisms, we use a radiative kernel method (Zelinka et al., 2012; Zelinka et al., 2012). This kernel method estimates the radiative impact of differences between two climate states among 49 cloud categories, as shown in Figure S3 in Supporting Information S1. Individual mechanisms are distinguished based on patterns of cloud changes in a warmer future. The kernel uses as input 2D cloud fractions standardized by the International Satellite Cloud Climatology Project (ISCCP) (Rossow & Schiffer, 1999), which divides clouds into 7 cloud top pressure and 7 cloud optical depth categories. A residual term exists between the total cloud feedback and sum of feedback mechanisms, which includes interactions among feedback mechanisms. We further separate feedbacks between those operating in low (cloud top pressure >680 hPa), mid-level (440–680 hPa), and high clouds (<440 hPa) through a refined decomposition method (Zelinka et al., 2016). Note that this partitioning of cloud feedbacks alters their attribution by mechanism, such that the sum of a feedback mechanism across all cloud levels is different than its unpartitioned magnitude. ISCCP cloud histograms were output from the model using the CFMIP Observation Simulator Package (Bodas-Salcedo et al., 2011).

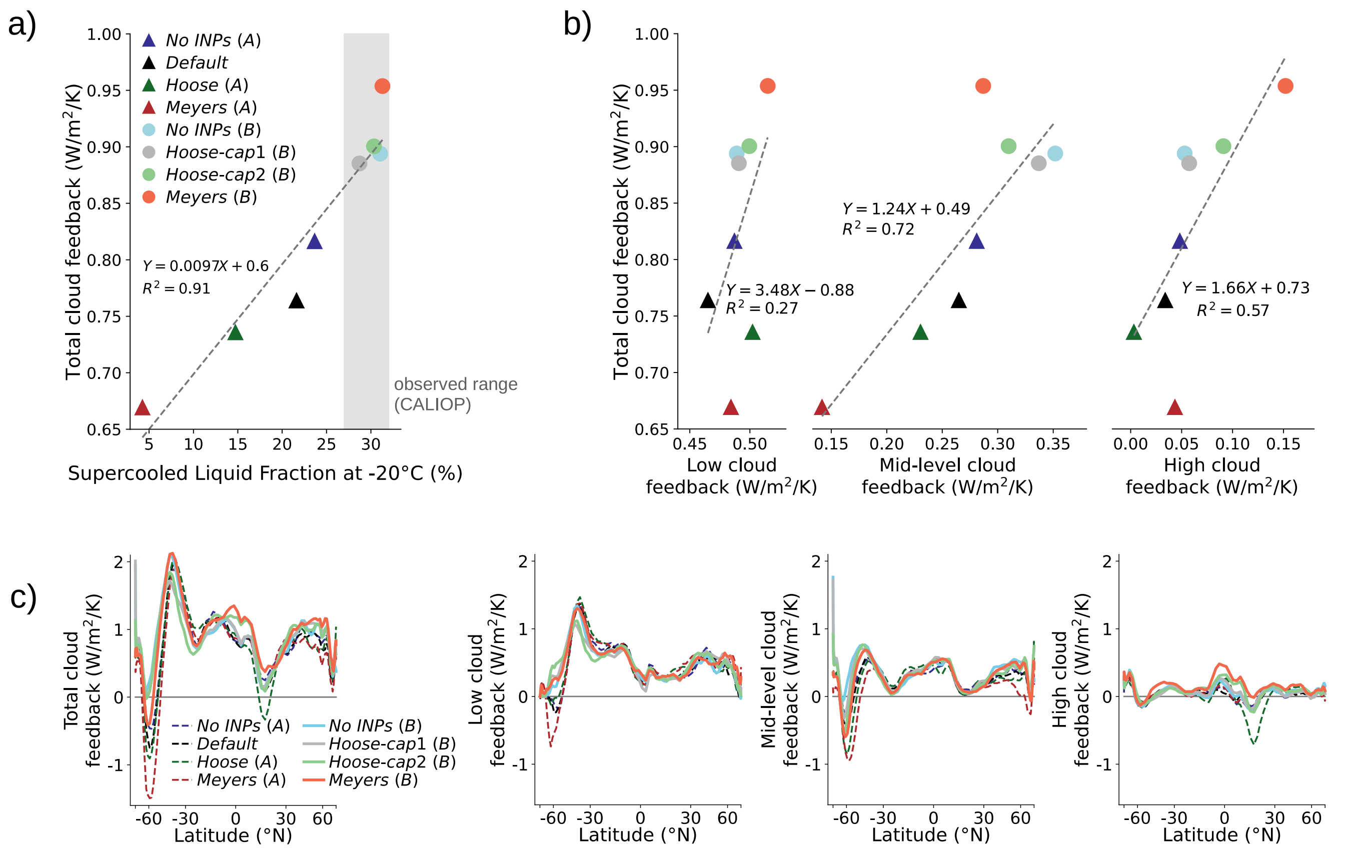

Figure 2. Relationships among cloud phase, total cloud feedback, and feedbacks grouped by cloud level and location. Shown is the relationship between simulated supercooled liquid fraction (SLF) at −20°C during present-day and cloud feedback strength (a), as well as the relationships between feedbacks operating in low, mid-level, and high clouds to their total (b). In (c), we additionally split these feedbacks by latitude band. All values in (a) and (b) are global averages. In (a), the SLF range from CALIOP satellite retrievals is shown for comparison.

3. Results

3.1. How INPs Influence Simulated Cloud Feedback Strength

In the absence of further adjustments, adding INPs reduces present-day SLF (see Group A averages in Table 1). Comparing experiments reveals a strong correlation between base state (present-day) global mean SLF and cloud feedback strength, confirming that these are heavily linked. This is presented in Figure 2a, where Group A simulations are represented as triangles. Hence, INPs' influence on global cloud phase appears to be a critical connection between ice nucleation and total cloud feedback.

We now break down the mechanisms driving ice nucleation's impact on total cloud feedback using a refined radiative kernel decomposition (see Section 2). Contrary to the usual focus of cloud phase studies (e.g., Tan et al., 2016), differences in cloud feedback cannot be explained merely by simulated impacts on low clouds. In fact, among our CESM2 simulations of varied ice nucleation representation, most differences in total cloud feedback can be attributed to mid-level and high clouds. This is shown in Figure 2b. Group A experiments with strong ice nucleation (*Meyers (A)* and *Hoose (A)*, represented as red and green triangles, respectively) have the lowest total cloud feedback strengths yet unremarkable low cloud feedbacks. Though influence of mixed-phase microphysics on feedbacks in high clouds has not previously been examined, the isotherms where immersion-mode ice nucleation acts strongest (within −40°C to −20°C) are typically above 440 hPa in low latitudes (see Figure S4 in Supporting Information S1). This also explains why a portion of the feedback differences across Group A experiments takes place in the tropics and sub-tropics (see Figure 2c). We note that cloud top pressures adjust to a warmer climate (Hartmann & Larson, 2002), which could complicate attribution by level if cloud tops shift across the assessed pressure groups.

We next isolate the specific feedback mechanisms responsible for differences among Group A experiments. Our interpretations are described in the remainder of this subsection and summarized in Figure 3. First, these

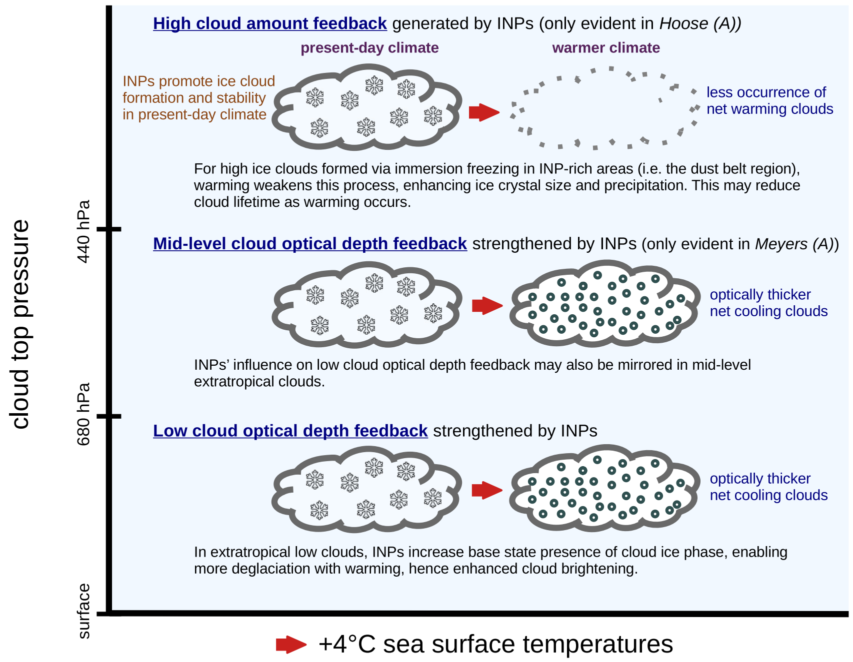

Figure 3. Simulated influences of INPs on cloud feedback strength, showing mechanisms apparent in Group A experiments. Note that we do not here depict INP influences on low and mid-latitude cloud amount feedbacks, which canceled between the two levels and hence showed only weak influence on total cloud feedback.

experiments verify the result of Tan et al. (2016) that reduced SLF causes strengthened negative cloud optical depth feedback in low clouds. This is in evident in Figure S5 in Supporting Information S1, where the red bars in the second row show low cloud optical depth feedback is substantially more negative in both *Hoose (A)* and *Meyers (A)* than in *No INPs (A)*. Unlike the earlier study, our Group A experiments alter SLF solely through INPs. We further find that associated feedback differences can operate not just in low clouds but also in mid-level clouds. The *Meyers (A)* experiment with its ubiquitous ice nucleation hence exhibits a negative mid-level cloud optical depth feedback less apparent in the other Group A experiments (compare red bars in the third row of Figure S5 in Supporting Information S1), especially over the Southern Ocean region (see Figure S6 in Supporting Information S1). Cloud amount feedbacks further shift the attribution of INP impacts from low to mid-level extra-tropical cloud feedbacks, though these cancel in total (see Text S1a in Supporting Information S1 for interpretation). Mid-level cloud sensitivities are evident in the ISCCP cloud type histograms output by the model. Looking at the influence of INP differences on base state cloud properties (Figure S7 in Supporting Information S1) and feedback strength (Figure S9 in Supporting Information S1), cloud optical depth differences (right-to-left differences within the leftmost panel of the bottom row) are apparent in both low and mid-level clouds.

We also find evidence of an unexplored negative high cloud amount feedback generated by ice nucleation's temperature sensitivity (see blue bar in Figure S5's second row in Supporting Information S1). This is only present in the *Hoose (A)* simulation and specifically over the dust-INP-rich northern subtropics. *Hoose (A)* features the strongest aerosol-sensitive ice nucleation among all experiments, with INPs highly concentrated around the *dust belt* that includes North African and Middle Eastern deserts. This creates greater regional present-day high cloud occurrence than in any other experiment (see second to last row of Figure S7 in Supporting Information S1). The heavily concentrated INPs hence appear to locally stabilize ice cloud occurrence more than they diminish liquid cloud occurrence. Warming reduces these clouds more than in other experiments (compare central columns of Figure S9 in Supporting Information S1), which may result from these clouds precipitating out as ice nucleation becomes physically weaker at warmer temperatures, resulting in fewer, heavier ice crystals. This can result in shorter lifetime by this mechanism. Though high clouds may have net cooling or warming base states depending on optical thickness (see Figure S3 in Supporting Information S1), the net warming clouds appear to dominate this feedback mechanism. This would explain why enhanced reduction of these high clouds (evident in Figure S9 in Supporting Information S1, middle column, third row) leads to a *negative* feedback in *Hoose (A)* not present in the other experiments (see the green dashed line in Figure 2c, rightmost panel, and also Figure S6 in Supporting Information S1).

The described INP influences unique to *Hoose (A)* and *Meyers (A)* act in the same direction as INPs' influence on feedback strength in low clouds. Taken together, these indicate that non-low clouds perpetuate INPs' ability to reduce total cloud feedback, regardless of whether ice nucleation is represented as aerosol-sensitive. Overall, our simulations reveal INP influence on cloud feedback strength to operate through more mechanisms and cloud types than have previously been considered.

3.2. Weak Influence of Ice Nucleation Representation When Negating Present-Day Cloud Phase Differences

Now we turn to the influence of ice nucleation on cloud feedbacks in experiments with present-day global mean cloud phase set to the same amount in all INP representations (Group B experiments). Feedback differences are noticeably more modest than Group A experiments in all cloud top pressure groupings (compare circles to triangles in Figures 2a and 2b). This result establishes ice nucleation's influence on cloud total feedback as principally operating through its role setting base state global cloud phase. Contrarily, ice nucleation's roles setting (a) the spatial distribution of present-day cloud phase and (b) the sensitivity of cloud phase to warming are not here found to create sizable differences in total cloud feedback among experiments. A more in depth decomposition reveals that the WBF adjustment we use to negate INPs' influence on global cloud phase causes distinct cloud feedback changes that tend to offset each other, rendering total cloud feedback similar among Group B experiments (see Texts S1b–S1d in Supporting Information S1).

Whether ice nucleation is simulated as aerosol-sensitive or aerosol-independent is found to have only weak influence on feedback strength in these experiments. A key aim for modeling this process as aerosol-sensitive is to represent impacts of Southern Ocean INP-scarcity on regional cloud phase and its associated globally consequential feedback (Murray et al., 2021). Surprisingly, in our simulations SLF over the Southern Ocean is much higher than in most regions even with no INPs (see No I*NPs (B)* in Table 1 and Figure S1b in Supporting Information S1). This appears to be because ice crystal sources from cirrus and convective detrainment are similarly lacking in this region. As explained in Section 2, strong aerosol-sensitive ice nucleation appears incompatible with satellite retrievals. Hence ice nucleation within stratiform mixed-phase clouds may be modest relative to other ice crystal sources, limiting the influence of its aerosol-sensitivity.

3.3. Impact of Ice Nucleation Error in CESM2

Due to the ice nucleation error in CESM2, the default model (*Default* experiment here) has a relatively weak—yet not inconsequential—ice nucleation process. Consequently, the default cloud properties (see Table 1) and cloud feedbacks (see Figure 2) are between those with no INPs (*No INPs (A)*) and with the error corrected (*Hoose (A)*). By comparison, the intended aerosol-sensitive ice nucleation scheme would have resulted in more heavily biased SLF (see Figure 2a and Figure S1a in Supporting Information S1) and ice number spatial pattern (see Section 2).

CESM2's ice nucleation scheme reduces the cloud phase bias present with the CESM1 scheme (*Meyers (A)*), while we reported above that global-scale cloud phase is the dominant link between INPs and feedback strength. These results imply that, despite the error, mixed-phase cloud influence on ECS is more realistic in CESM2 than with the earlier ice nucleation treatment. In fact, all of our observation-constrained (Group B) experiments have a total cloud feedback that is even more positive than in default CESM2. Further, we find the error to only directly affect global cloud feedback strength by +0.02 $W/m^2/K$ (comparing *Default* to *Hoose (A)*). Ice nucleation appears only capable of substantially reducing simulated ECS if represented as so strong that it generates a large bias in cloud phase. This had been the case with CESM1's ice nucleation scheme (see Tan et al., 2016) in addition to our *Meyers (A)* experiment.

4. Conclusions

Our results indicate that ice nucleation primarily influences climate sensitivity through its role setting base state global cloud phase. Simulated differences in ice nucleation strength and variability did not reveal prominent additional influences on total cloud feedback. We did not find evidence that aerosol-sensitive ice nucleation representation is critical for global climate projections. Though ice nucleation model treatment influenced simulated feedbacks over the Southern Ocean, as suggested in Murray et al. (2021), we found that aerosol-sensitive and insensitive treatments can produce similar global cloud feedback strength with simple adjustments to offset differences in present-day global mean cloud phase. It could be worth reevaluating if this result holds with more recent ice nucleation parameterizations (e.g., Ullrich et al., 2017) than the Hoose et al. (2010) scheme evaluated here. Note that we did not test for changes in INP concentrations as warming occurs. INP-climate feedbacks could alter the balance between INP-sensitive cloud feedbacks in future climate. Climate projections hence may still benefit from accurate present-day INP concentrations and accurate INP-cloud-climate interactions. Another caveat is that we did not run simulations coupled to an interactive ocean model. We hence did not directly estimate ECS, which may be affected by interactions between cloud and non-cloud feedback mechanisms (Lohmann & Neubauer, 2018).

Our findings suggest that CESM2's ice nucleation updates raised ECS primarily by correcting—partially inadvertently—much of the cloud phase bias present in CESM1 (c.f. Tan et al., 2016). Our findings are consistent with the strongly positive cloud feedbacks in a new version of CESM2's microphysics with revised ice nucleation and additional updates (Gettelman et al., 2022), which did not lead to substantial change in implied ECS. Correcting the ice limit issue in a reduced-resolution CESM2 version had reduced cloud feedback strength (Zhu et al., 2022), yet we find this does not occur in the standard-resolution model. In fact, our observationally-constrained simulations produce higher total cloud feedback than default CESM2 regardless of ice nucleation scheme. A caveat is that CESM2's ECS is already stronger than evidence suggests is likely (Sherwood et al., 2020). This apparent contradiction may relate to biases in tropical and subtropical low cloud feedbacks, which remain poorly constrained (Zelinka et al., 2020).

A unique finding of this study is that microphysical processes in mixed-phase clouds influence climate sensitivity not just through low cloud optical depth feedback, but through mechanisms operating wherever clouds exist in the temperature range where liquid-to-ice transitions occur. Our findings could motivate further research on microphysics–feedback links in mid-level and high mixed-phase clouds. Our simulations exhibit an unevaluated high cloud feedback specific to INP-rich latitudes. They also reveal feedback sensitivities to microphysical setup involving poorly constrained base state cloud properties, including cloud vertical distribution (Texts S1a and S1b in Supporting Information S1), ice water path (Text S1c in Supporting Information S1), and cloud phase spatial distribution (Text S1d in Supporting Information S1). These reflect model structural and parametric uncertainties that may warrant further examination. We note that for mid-level and high clouds to undergo sizable feedbacks might be unexpected for two reasons. First, clouds that aren't closely coupled to the surface are expected to rise as warming occurs such that they maintain minimal temperature change (Hartmann & Larson, 2002). Second, these clouds' shortwave and longwave radiative effects considerably cancel, reducing associated net feedbacks. We encourage further efforts to assess if the mechanisms newly reported here are robust across additional climate models, ice nucleation representations, and experimental setups.

Data Availability Statement

All CESM2 model output used to generate this study's figures is publicly available in a Zenodo repository (https://doi.org/10.5281/zenodo.7562342).

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