Response to Reviewer Comments

Sea Salt Aerosols from Blowing Snow: Contributions to Radiative Forcing

Response to Reviewer 1

Major Comment 1 — Blowing snow mechanism and sensitivity tests

> *The blowing snow mechanism is not fully clear yet. For example, the salinity, how many ice crystals are produced for each snowflake, sublimation rate under sub-/super-saturations are not clear yet. This paper lacks such information for the model simulation. More importantly, it would be even better to run the sensitivity test for each parameter.*

We thank the reviewer for this comment. We have substantially expanded Sect. 2.3 to explicitly describe the key parameters of the blowing-snow SSA parameterization and their associated uncertainties. Specifically, we now state that: (1) snow salinity is prescribed using the observed frequency distribution from Weddell Sea field measurements (Frey et al., 2019), with a median of 0.06 psu and a mean of 0.92 psu; (2) one SSA particle is formed per sublimating snow particle (N = 1), following the SI_Base_A control run of Yang et al. (2019), which represents a lower bound on SSA number production. We note in discussion that Yang et al. (2019) show that N = 10–20 under the alternative moisture-diffusion mechanism also provides good agreement with observations; (3) SSA production is computed only under subsaturated conditions (RH < 100%), following the bulk sublimation flux parameterization of Déry and Yau (1999, 2001), and the sublimation rate under near-saturated conditions remains a recognized source of uncertainty. We have also added a paragraph in discussion sections (line 279 onwards) explicitly discussing the remaining uncertainties in the parameterization, covering the sublimation mechanism choice, snow salinity distribution, and blowing-snow particle size distribution.

Regarding sensitivity tests: we acknowledge this would be a valuable addition. However, a full multi-parameter sensitivity ensemble is beyond the scope of the current study, whose primary aim is to implement and evaluate the parameterization as established in Yang et al. (2019) and assess its radiative effects in EC-Earth3 for the first time. Importantly, Yang et al. (2019) already performed comprehensive sensitivity experiments for the key parameters — sublimation function, size distribution shape, snow salinity, RH, wind speed, and temperature — using the p-TOMCAT model, and Ranjithkumar et al. (2025) performed a formal Sobol sensitivity analysis. We now explicitly reference these results in Sect. 2.3. We agree that extending such sensitivity tests to a fully coupled GCM setting is an important priority and have added this to the future work discussion in the conclusions.

✓ Addressed in revised manuscript

Major Comment 2 — Contextualization with existing literature

> *The current results section is primarily descriptive rather than an in-depth analysis. The authors fail to place their findings in the context of existing literature. For*

instance, the simulated SSA AOD and its contribution to the total aerosol load should be compared with previous studies or satellite/AERONET observations.

We thank the reviewer for this valid criticism and have revised the results section throughout to place our findings in the context of existing literature.

For the MOSAiC comparison (Sect. 3.1), we now explicitly compare our correlation values (R = 0.37 baseline, R = 0.39 with blowing snow) against those reported by Ranjithkumar et al. (2025) (R = 0.23 and R = 0.28 for the old and new p-TOMCAT schemes respectively) and Gong et al. (2023) (R = 0.43 and R = 0.53 for GEOS-Chem).We discuss why TM5 shows a more modest full-year improvement, attributing this primarily to the inclusion of summer months when no blowing-snow events occur and both simulations are identical, thereby diluting the signal. We also note that Gong et al. (2023) used NP=5, whereas our implementation follows the conservative NP=1 SI_Base configuration.

For the particle size distribution comparison (Sect. 3.1, Fig. 4), we have corrected an error in the original text: TM5 in fact exhibits a slight decrease in Aitken mode particles when blowing snow is included (not an increase as previously stated). We now provide a mechanistic explanation: in TM5, the M7 scheme efficiently transfers mass via coagulation from smaller to larger modes, so newly emitted accumulation-mode SSA acts as a coagulation sink depleting Aitken-mode particles. In GEOS-ChemTOMAS, the more detailed sectional size representation allows blowing-snow SSA to populate finer size bins directly, leading to Aitken-mode enhancement. This is further consistent with Gong et al. (2023) using NP = 5, producing substantially more fine-mode particles.

For the station comparison (Sect. 3.2), we now contextualize the overestimation at Villum and Zeppelin and underestimation at Alert. A similar Alert underprediction is reported by Ranjithkumar et al. (2025), who found p-TOMCAT underestimates sodium mass by a factor of ~3 at Alert in February, suggesting a systematic model bias. The overestimation at Villum and Zeppelin likely reflects our N = 1 lower bound and the fact that the prescribed Weddell Sea salinity distribution has a frequency-weighted mean of approximately **0.92 psu**, substantially exceeding the MOSAiC-observed Arctic snow salinities of 0.09–0.48 psu.

For the radiative forcing (Sect. 4.1), we now provide explicit values: the annual-mean net Arctic surface flux is +0.03 W m^{-2} , driven by a wintertime LW cloud effect of +0.59 W m^{-2} (range: +0.05 to +0.95 W m^{-2}). The Antarctic annual mean is −0.15 W m^{-2} (range: −0.71 to +0.08 W m^{-2}). We compare these to the +2.30 W m^{-2} of Gong et al. (2023), explaining the difference through three factors: (1) Gong et al. (2023) report a cloudy-sky-only forcing whereas our values are all-sky zonal means; (2) NP = 5 vs NP = 1; and (3) differences in model resolution and meteorological driving. Our wintertime Arctic LW cloud effect of +0.59 W m^{-2} is of comparable sign and order of magnitude to Gong et al. (2023) when these differences are accounted for.

Regarding AOD comparison: direct comparison against satellite retrievals or AERONET observations is not feasible for the polar winter conditions central to this study. AERONET sun-photometer retrievals require direct solar radiation and are therefore unavailable at latitudes poleward of 70°N during November–April when blowing-snow SSA production peaks. Satellite-based AOD retrievals face similar limitations over sea ice due to the high and spatially variable surface albedo, which prevents reliable separation of the aerosol signal from surface reflectance (Lapere et al., 2023). Instead, we evaluate our simulated SSA against in-situ particle number concentrations along the MOSAiC track and sodium mass concentrations at three Arctic ground stations, which provide a more robust constraint under polar winter conditions.

Thus, AOD validation is not pursued as blowing snow produce particles during winter when it is not practical to measure AOD..

✓ **Addressed in revised manuscript**

Major Comment 3 — Net flux sign paradox and Antarctic radiation

> *Long-term blowing snow simulations lead to cooling at both poles, yet the net flux values provided are positive (Lines 203-204). This paradox requires a detailed explanation. Is this driven by the strong negative forcing during the summer compared to the winter (Fig. S2 & S3)? The efficiency of blowing-snow-SSA production in summer versus winter needs to be explicitly shown. Furthermore, the lack of radiation simulation results for the Antarctic is a major omission.*

We thank the reviewer for identifying this apparent inconsistency and have substantially revised Sect. 4.1 to address it.

The apparent paradox is now explicitly addressed in the revised text. Using area-weighted means poleward of 60°, the annual-mean all-sky net surface radiative flux is negative in both hemispheres (Arctic: −0.06 W m^{-2}; Antarctic: −0.25 W m^{-2}), with stronger winter cooling (Arctic: −0.12 W m^{-2} in DJF; Antarctic: −0.65 W m^{-2} in JJA). We now explicitly decompose the radiative response into all-sky, clear-sky, and cloud radiative effect (CRE) components. Over the Arctic, the negative clear-sky response is partly offset by a positive longwave cloud radiative effect, which reaches +0.45 W m^{-2} in winter (+0.10 W m^{-2} annually). Over the Antarctic, the positive longwave cloud effect is outweighed by a stronger negative shortwave cloud radiative effect, resulting in a net cloud-induced cooling. We also explicitly link these hemispheric differences to the seasonal cycle of blowing-snow emissions: Arctic emissions peak during boreal winter (DJF), whereas Antarctic emissions peak during austral winter and spring (JJA–SON), with the cloud radiative response extending into the sunlit summer season. The revised manuscript also clarifies that all reported regional values are area-weighted means poleward of 60°.

Regarding the transient Arctic cooling, this is discussed in Sect. 5. While blowing-snow SSA produces a positive wintertime longwave cloud radiative effect, this does not directly translate into a warming response in the transient coupled simulation. The radiative diagnostics presented in Sect. 4.1 isolate the surface energy perturbation associated with blowing-snow SSA, whereas the transient temperature response reflects the combined effects of cloud and clear-sky radiative changes, surface turbulent fluxes, sea-ice and ocean feedbacks, atmospheric circulation, and internal climate variability. Furthermore, the transient simulation consists of a single ensemble member, which is insufficient to robustly separate the forced response from internal variability. We therefore do not interpret the simulated Arctic cooling as a robust forced response and have explicitly added this caveat to the revised manuscript. There was also bug in calculating statistical signigicanse which is fixed in the revised manuscript.

✓ Addressed in revised manuscript

Major Comment 4 — Figure improvements

> *The figures require significant aesthetic and functional improvements. Some panels are cluttered, making them nearly unreadable. Data should be presented in a more intuitive manner (e.g., using dual axes or improved colorbar position).*

We have revised all figures as suggested. In Fig. 1, units now use proper superscripts, station markers (Villum, Zeppelin, Alert) have been added to panel (a), panel labels are standardized to (a), (b), (c), (d), and the colorbar size has been reduced. In Figs. 2 and 3, we have improved readability by adding separate subplots to show the differences in TM5 runs, and have specified the temporal resolution of the data. In Fig. 7, the label has been corrected from '0.3 supersaturation' to '0.3% SS', and the colorbar scale has been adjusted to better highlight the contrast between the Arctic and Antarctic CCN enhancements.

✓ Addressed in revised manuscript

Major Comment 5 — Conclusions: broader implications

> *The manuscript concludes abruptly without discussing the broader implications of the work. How do these findings affect our understanding of polar climate sensitivity? What are the limitations of the current TM5 implementation, and what should be the focus of future research?*

We thank the reviewer for this comment and have substantially expanded the conclusions section to address broader implications and future research directions. The revised conclusions now include the following paragraph:

'The results of this study should be interpreted in the context of key uncertainties in the blowing-snow SSA parameterization and the inherent natural variability of the polar climate system. Nevertheless, the inclusion of blowing-snow SSA in global climate models represents an important but currently underrepresented feedback in the polar climate system. Several priorities emerge for future research. First, a multi-member ensemble of transient simulations is needed to separate the forced radiative response from internal climate variability, particularly for the Arctic temperature signal identified here. Second, systematic sensitivity experiments varying the key parameterization parameters — the number of SSA particles per sublimating snow particle, the size distribution shape parameter, and the snow salinity distribution — are required to quantify the full range of plausible climate impacts. Third, evaluation against Antarctic observations remains limited by the scarcity of in-situ aerosol measurements over Southern Ocean sea ice during winter, and expanding such observational datasets would substantially improve the model constraint. Finally, as Arctic sea ice retreats, blowing-snow SSA production will decline since it requires sea-ice-covered surfaces, potentially weakening this wintertime warming mechanism precisely when the Arctic is changing most rapidly. How the contribution of blowing-snow SSA to the polar climate system will change under future sea ice conditions therefore remains an important open question for polar climate projections.'

✓ Addressed in revised manuscript

Specific Comments

Line 38 — CMIP6 model citations

> *When mentioning specific CMIP6 models, please provide appropriate citations for the models discussed.*

We thank the reviewer for this comment. The statement at Line 38 refers to the general findings of Lapere et al. (2023), which provides a comprehensive multi-model evaluation of sea salt aerosol representation across 12 CMIP6 models. Since the sentence makes a general statement about CMIP6 model performance that is fully supported by that single citation, we feel that listing individual model references here would be redundant and would not add scientific clarity. The Lapere et al. (2023) citation already directs the reader to the full model list and their respective references. We have therefore retained the original citation structure at Line 38.

✓ Addressed in revised manuscript

Line 53 — 2019–2020 period applicability

> *Please clarify if the '2019-2020' period applies to both study locations or if there was a time distinction between the Arctic and Antarctic datasets.*

We thank the reviewer for this clarification request. The 2019–2020 period applies to both the Arctic and Antarctic TM5 simulations. However, observational comparisons are only available for the Arctic, where MOSAiC campaign data and three ground station records (Zeppelin, Alert, Villum) provide direct evaluation benchmarks. No equivalent Antarctic in-situ observations are available for this period, and the Antarctic results are therefore presented as model-only estimates. We have revised Line 53 to make this distinction explicit, now reading: 'We also investigate how much SSA is generated from blowing snow in the years 2019–2020 in both the Arctic and Antarctic using the TM5 chemical transport model. For the Arctic, model results are evaluated against in-situ MOSAiC campaign data and monitoring stations at Zeppelin, Alert and Villum. For the Antarctic, no equivalent in-situ observations are available for this period, and the model results are therefore assessed in the context of the simulated emission patterns and seasonal cycles alone.'

✓ Addressed in revised manuscript

Line 131 — Low correlation improvement

> *The correlation improvement here is relatively low. Please elaborate on the physical or numerical reasons behind this discrepancy, or can we only show the correlation during the blowing snow events?*

We have added the November–April restricted correlation to the revised Sect. 3.1. Restricting to the blowing-snow season (N = 143 daily values) gives R = 0.59 (baseline) and R = 0.63 (with blowing snow), a more substantial improvement than the full-year values of R = 0.37 and R = 0.39, which are diluted by summer months when both simulations are identical and no blowing-snow events occur. The physical reasons for the remaining modest improvement are also discussed in the revised text: our conservative NP = 1 assumption (versus NP = 5 in Gong et al., 2023) produces fewer fine-mode particles, and TM5's M7 coagulation scheme depletes Aitken-mode particles rather than enhancing them, partially offsetting the accumulation-mode enhancement in total particle number space.

✓ Addressed in revised manuscript

Line 143 & Figure 4 — Aitken mode text error

> *The description and the figure show a different conclusion: TM5 exhibits a slight decrease in Aitken mode particles when considering blowing snow instead of increasing.*

This error has been corrected in the revised manuscript. The text now correctly states that TM5 exhibits a slight decrease in Aitken mode particles when blowing snow is included, consistent with Fig. 4 and Fig. 6a. A mechanistic explanation has been added (see Major Comment 2 response above).

✓ Addressed in revised manuscript

Response to Reviewer 2

Major Comment 1 — Aitken mode absence as model limitation

> *The absence of Aitken-mode aerosol in the model outputs should be clearly discussed and highlighted as a model limitation in reproducing Aitken-mode SSAs to avoid misleading. Since these particles significantly affect clouds and radiation, this limitation needs to be addressed when interpreting the model's results and its climate feedbacks.*

The reviewer is correct. We have added the following two paragraphs to the revised manuscript to explicitly flag this as a model limitation.

Added to Sect. 3.1: 'It should be noted that TM5's M7 scheme does not produce a net increase in Aitken-mode SSA from blowing snow — in contrast to GEOS-Chem-TOMAS and the observations of Gong et al. (2023), who identified abundant fine-mode sea salt (diameter below 300 nm) as the primary driver of CCN enhancement during blowing-snow events. This represents a model limitation: the CCN and cloud radiative effects estimated in this study are based primarily on accumulation-mode SSA, and the absence of Aitken-mode SSA production in TM5 means that our CCN enhancements and associated longwave forcing likely represent a lower bound on the true climate impact.'

Added to Sect. 4.1 before the CCN paragraph: 'The CCN enhancements discussed below should be interpreted with the caveat that TM5's M7 scheme suppresses rather than enhances Aitken-mode particles in response to blowing-snow SSA emissions (Sect. 3.1).

Since fine-mode sea salt particles are highly hygroscopic (Gong et al., 2023) and Arctic clouds operate in a CCN-limited regime (Mauritsen et al., 2011), the CCN increases reported here reflect primarily the accumulation-mode response and may underestimate the total CCN impact of blowing-snow SSA.'

✓ Addressed in revised manuscript

Major Comment 2 — Full-year correlation is misleading

> *The correlation comparison covers the full year. You may need to state this clearly, as there is no blowing-snow effect in summer and early autumn. It would be better to focus on the winter period, e.g., Nov/2019–Apr/2020. The same applies to your CCN comparison.*

The reviewer is correct. We now explicitly state in Sect. 3.1 that the full-year correlation (R = 0.37 to R = 0.39, N = 285) covers the entire campaign period including summer months when no blowing-snow events occur. We have added the November–April restricted correlation (R = 0.59 to R = 0.63, N = 143), which better reflects the parameterization's performance during the blowing-snow season. The same period restriction is noted for the CCN comparison (Fig. 3). See also our response to Reviewer 1, Specific Comment Line 131.

✓ Addressed in revised manuscript

Major Comment 3 — RH vs wind speed sensitivity

> *The statement that 'the blowing-snow parameterisation is most sensitive to changes in relative humidity' is incorrect. Wind speed remains the key factor governing SSA production. The impact of RH on SSA production is mediated through the BS bulk sublimation calculation.*

We thank the reviewer for this clarification. The statement in the manuscript requires nuance. The Sobol sensitivity analysis of Ranjithkumar et al. (2025) shows that when the size distribution shape parameter alpha is constrained using MOSAiC observations (alpha = 1.9–3.1), the SSA number flux is most sensitive to RH_ice, wind speed, snow age, and temperature, with RH and wind speed having similar total Sobol indices of 0.1–0.2. However, this applies specifically to the SSA number flux. For the SSA mass flux, wind speed dominates through the saltation mixing ratio term in the bulk sublimation calculation (Déry and Yau, 1999, 2001), as the reviewer correctly notes. We have revised the text to distinguish between these two cases: stating that alpha dominates overall sensitivity, and that among meteorological drivers, both RH and wind speed contribute substantially to the SSA number flux, while wind speed dominates the mass flux through the saltation term.

✓ Addressed in revised manuscript

Minor Comments

Line 7 — Capital 'S' in Simulation

> *Change capital 'S' in the word 'Simulation'.*

Corrected in the revised manuscript.

✓ Addressed in revised manuscript

Lines 26–27 — Reference for SSA quarter of Arctic aerosol

> *Add references to the statement that SSA account for more than a quarter of the Arctic aerosol number concentration. Note that the GEOS-Chem results (Gong et al., 2023) showed a much larger contribution, e.g., up to 45% in the central Arctic.*

We thank the reviewer for this suggestion. We have added a citation to Gong et al. (2023) to support the statement that SSA account for more than a quarter of Arctic aerosol number concentration, and have made the local contribution explicit: 'Model estimates show that SSA account for more than a quarter of the Arctic aerosol number concentration, and even up to 45% locally (Gong et al., 2023).' The Gong et al. (2023) estimate of ~27.6% for the region north of 70°N and up to 45% in the central Arctic during winter directly supports this statement.

✓ Addressed in revised manuscript

Line 30 — Wave breaking as SSA source

> *Note that wave breaking is an important pathway that also produces bubbles and generates sea spray directly from the open-ocean surface. Both bubble bursting and wave breaking should be considered direct sources of open-ocean SSA (de Leeuw et al. 2011).*

We thank the reviewer for this addition. Wave breaking has been added as a direct source of open-ocean SSA alongside bubble bursting in the revised manuscript. Line 30 now reads: "The primary sources of SSA in the region are bubble bursting and wave breaking over open ocean and emissions from leads in sea ice (de Leeuw et al., 2011; Lapere et al., 2024)."

✓ Addressed in revised manuscript

Lines 47–48 — GEOS-Chem vs p-TOMCAT

> *Rephrase: Gong et al.'s work used GEOS-Chem rather than p-TOMCAT, and the other two works focused on aerosols rather than climate impacts.*

We thank the reviewer for this correction. We have revised the sentence to accurately reflect which model each study used. The revised text now reads: "Gong et al. (2023) and Ranjithkumar et al. (2025) implemented blowing snow SSA production in the GEOS-Chem and p-TOMCAT chemical transport models respectively."

✓ Addressed in revised manuscript

Lines 79, 83 — TOMCAT → p-TOMCAT

> *Change TOMCAT to p-TOMCAT.*

Corrected in the revised manuscript.

✓ Addressed in revised manuscript

Lines 124–125 — Definition of wintertime

> *'Most of the sea salt emissions due to blowing snow occur during Boreal wintertime', but March and April are spring. What is your definition of 'wintertime'?*

We thank the reviewer for this clarification. The original use of "wintertime" was imprecise. We have revised the sentence to explicitly state the seasons: "In the Arctic, most of the sea salt emissions due to blowing snow occur during Boreal wintertime (DJF) and spring time (MAM), whereas in the Antarctic the peak emissions occur during the Austral winter (JJA) and spring (SON) seasons."

✓ Addressed in revised manuscript

Line 212 — Rephrase size distribution sentence

> *Rephrase 'The particle size distribution of snow particles' — cannot follow what is meant.*

Rephrased in the revised manuscript; the sentence now begins "The blowing-snow particle size distribution, …".

✓ Addressed in revised manuscript

Line 222 — Unnecessary dot

> *Delete the unnecessary dot.*

Corrected in the revised manuscript.

✓ Addressed in revised manuscript

Page 15 — GOES → GEOS-Chem

> *Is 'GOES' the right name of GEOS-Chem?*

Corrected in the revised manuscript.

✓ Addressed in revised manuscript

Figure 4 — Sub-ticks on x-axis

> *Add sub-ticks to the x-axis.*

Sub-ticks have been added to the x-axis of Fig. 4 in the revised manuscript.

✓ Addressed in revised manuscript

Figures 6 & 7 — Model 'lev' on y-axis

It is unusual to use the model 'lev' when presenting latitude-height cross-section results. Use either the actual height in metres or kilometres, or the pressure on your y-axis.

We thank the reviewer for this suggestion. We have replaced the model level ('lev') coordinate on the y-axis of Figs. 6 and 7 with pressure (hPa) in the revised manuscript.

✓ Addressed in revised manuscript

Response to Reviewer 3

Major Comment 1 — Abstract

The abstract is method-focused; 'improved agreement with observations' is overstated given the marginal and statistically insignificant improvement; the description of radiative forcing is oversimplified; the word 'essential' is too strong.

We thank the reviewer for these points and have rewritten the abstract to be less method-focused, to hedge the agreement claim, to describe the radiative response more precisely, and to soften the word "essential". Specifically, we now state that including blowing snow allows TM5 to capture more of the observed peaks during the blowing-snow season while noting that the overall correlation improves only modestly and the full-year change is not statistically significant; we replace the single "globally negative" sentence with the hemispheric split (a wintertime longwave cloud warming of about +0.03 W m^{-2} poleward of 60°N and a negative shortwave cloud effect of about −0.15 W m^{-2} poleward of 60°S, the latter dominating); and we replace "essential" with "an important and currently underrepresented contributor", adding that the net climatic effect is modest and both seasonally and regionally dependent. The revised abstract reads:

"The Arctic and Antarctic regions experience significant climate impacts from aerosol–cloud–radiation interactions, yet the role of sea salt aerosols (SSA) emitted through blowing snow remains poorly quantified. We implement a parameterization of blowing-snow SSA production in the TM5 global chemical transport model and the EC-Earth3 global climate model, using atmosphere-only and fully coupled transient (SSP3-7.0, 2015–2051) experiments to assess the contribution of blowing snow to aerosol mass, number, cloud condensation nuclei (CCN), and radiative fluxes in both polar regions. TM5 results are evaluated against MOSAiC campaign data and observations from the coastal stations Villum, Zeppelin, and Alert. Blowing snow substantially increases SSA mass, particle number, and CCN during polar winter and spring, with the largest enhancements over Antarctic sea ice. Including blowing snow allows TM5 to capture more of the observed SSA and CCN peaks during the blowing-snow season, although the overall correlation with MOSAiC observations improves only modestly and the full-year change is not statistically significant. The associated surface radiative response is small and differs between hemispheres. Over the Arctic, blowing-snow SSA enhances the wintertime longwave cloud radiative effect (+0.45 W m^{-2}), partially offsetting a negative clear-sky radiative response, while the area-weighted annual-mean all-sky net surface radiative flux response remains slightly negative (−0.06 W m^{-2} poleward of 60°N). Over the Antarctic, the positive longwave cloud radiative effect is outweighed by a stronger negative shortwave cloud radiative effect, resulting in an

area-weighted annual-mean all-sky net surface radiative flux response of −0.25 W m⁻² poleward of 60°S. Overall, our results indicate that blowing-snow SSA emissions are an important and currently underrepresented contributor to polar aerosol burdens, seasonal cycles, and high-latitude aerosol–cloud feedbacks, although their influence on the annual-mean surface energy budget is modest, with pronounced seasonal and regional variability"

✓ Addressed in revised manuscript

Major Comment 2 — Introduction

> *While the introduction mentions SSA impacts on CCN, it could be more explicit about why blowing snow is physically different from standard sea spray (e.g., its dominance during winter/spring when open water is scarce). The transition from Arctic to Antarctic is abrupt.*

We thank the reviewer for these suggestions. To clarify why blowing-snow SSA is physically distinct from standard open-ocean sea spray, we have added the following to the introduction: "Unlike open-ocean sea spray, which is generated by bubble bursting and wave breaking and therefore requires open water, blowing-snow SSA originates from saline snow that is lofted from the sea-ice surface by wind. This mechanism is active precisely when open-water sources are suppressed, during winter and spring, when sea-ice cover is extensive and open water is scarce. Blowing snow can therefore dominate the SSA budget over consolidated sea ice in the wintertime."

✓ Addressed in revised manuscript

Major Comment 3 — Methods

> *More detail on how well-represented RH is in ERA5 and EC-Earth3 over sea ice is required. The authors should clarify critical wind speed thresholds verified against MOSAiC data. The authors should explain why the Yang et al. (2019) parameterization was chosen over more recent alternatives. The fixed snow salinity assumption needs justification. The resolution mismatch between the atmospheric model and TM5 should be addressed.*

We thank the reviewer for these comments. The Yang et al. (2019) parameterization was chosen because the newer alternative only became available after our simulations had been completed. We have added the following to the methods section: "Figure S1 shows a comparison of ERA5 10 m wind speed against in situ MOSAiC observations along the drift track, with the critical threshold wind speed overlaid. ERA5 reproduces the observed wind speed and captures the timing of threshold exceedance, confirming that the forcing adequately resolves the wind-driven onset of blowing snow. The relative humidity that controls sublimation is likewise well constrained over the Arctic: Graham et al. (2019) found that ERA5 reproduces observed temperature, wind, and humidity profiles with correlation coefficients exceeding 0.88."

✓ Addressed in revised manuscript

Major Comment 4 — Results

> *The correlation increase is marginal and statistically insignificant. The conflict between TM5 and GEOS-Chem Aitken mode responses needs discussion of which is more consistent with MOSAiC observations. The Arctic cooling should not be interpreted as a robust forced signal. The dehydration effect (drier lower troposphere) needs to be quantified. Antarctic vs Arctic differences should be discussed in context of fixed salinity assumption.*

We thank the reviewer for these comments and address each in turn.

Marginal and statistically insignificant correlation: we agree. The revised Results section now reports the full-year correlation explicitly (R = 0.37 baseline, R = 0.39 with blowing snow, N = 285) and states that this difference is not statistically significant according to Williams' test. We have added the blowing-snow-season correlation (November–April, N = 143), which improves more substantially from R = 0.59 to R = 0.63, and we explain that the modest full-year change reflects the dilution of the signal by summer months when no blowing-snow events occur and the two simulations are identical.

TM5 versus GEOS-Chem Aitken-mode response: we now discuss which response is more consistent with the MOSAiC observations. The observations of Gong et al. (2023) identify abundant fine-mode (Aitken) sea salt as the primary driver of CCN enhancement during blowing-snow events, so the Aitken-mode increase simulated by GEOS-Chem-TOMAS is more consistent with the observations than the slight Aitken-mode decrease produced by TM5. We attribute the TM5 behaviour to its M7 modal scheme, which transfers mass from smaller to larger modes through coagulation so that newly emitted accumulation-mode SSA acts as a sink for Aitken particles, and we now flag this explicitly as a model limitation that means our CCN enhancements and associated longwave forcing likely represent a lower bound.

Arctic cooling: we agree it should not be interpreted as a robust forced signal. The revised text states that the transient Arctic cooling (up to 4°C in individual years) is consistent with the range of unforced internal variability in EC-Earth3, that a large ensemble would be required to detect the weak forced signal above this noise, and that we therefore do not interpret it as a robust forced response. Isolating the forced signal with a multi-member ensemble is identified as a priority for future work.

Quantification of the dehydration effect: We investigated the effect directly and, on the basis of that analysis, have chosen to remove the claim rather than quantify it . The Arctic clear-sky longwave surface flux (poleward of 60°N) decreases by -0.54 W m^{-2} in winter (range -0.82 to $+0.15$ W m^{-2} across the latitude band) and by -0.20 W m^{-2} in the annual mean (range -0.31 to -0.10 W m^{-2}). However these do not confirm the reduction in lower-tropospheric humidity in the blowing-snow experiment. The simulations do not show a statistically detectable lower-tropospheric humidity change. These values have been added to Sect. 4.1.

Antarctic versus Arctic differences in the context of the fixed salinity assumption: the same snow-salinity distribution, based on Weddell Sea measurements (Frey et al., 2020), is prescribed at both poles, so the simulated Antarctic–Arctic difference in blowing-snow SSA production reflects differences in sea-ice extent, wind speed, and sublimation flux rather than salinity. This distribution is observationally grounded for the Antarctic, but its frequency-weighted mean of approximately 0.92 psu exceeds the MOSAiC-observed Arctic snow salinities of 0.09–0.48 psu (Ranjithkumar et al., 2025), so the prescribed salinity most likely overestimates Arctic SSA mass. The better-constrained Antarctic together with the likely Arctic overestimate imply that the simulated dominance of Antarctic over Arctic blowing-snow SSA production is robust. We have added this discussion to Sect. 5.

✓ Addressed in revised manuscript

Major Comment 5 — Conclusions

> *The Arctic cooling should be mentioned with a caveat about internal climate variability. The authors should explain how blowing snow changes understanding of Arctic Amplification. A stronger conclusion should suggest which model representation (TM5 or GEOS) likely reflects reality better based on MOSAiC observations.*

We thank the reviewer for these suggestions and have revised the conclusions accordingly. First, the Arctic cooling is now presented explicitly as an internal-variability caveat rather than a forced response: the magnitude of the cooling (up to 4°C in individual years) is consistent with the range of unforced internal variability in EC-Earth3, the weak forced signal would require a large ensemble to be detectable above this noise, and we therefore do not interpret it as a robust forced response. Second, regarding Arctic amplification, we have added a sentence noting that blowing-snow SSA acts as an additional wintertime longwave cloud warming mechanism over sea ice, operating precisely in the season and region where Arctic amplification is strongest; however, because this source requires sea-ice-covered surfaces, it is expected to weaken as sea ice retreats, so it is unlikely to constitute a sustained amplifying feedback under continued warming. Third, on which model better reflects reality: the MOSAiC observations and Gong et al. (2023) identify fine-mode (sub-300 nm) sea salt as the primary driver of CCN enhancement during blowing-snow events. TM5's M7 modal scheme suppresses rather than produces Aitken-mode SSA, whereas the sectional GEOS-Chem-TOMAS scheme reproduces the observed fine-mode increase. We have therefore added a statement that, for the fine-mode response most relevant to CCN, the GEOS-Chem representation is more consistent with MOSAiC observations, and that the TM5 results presented here should be regarded as a lower bound on the CCN and associated longwave climate impact of blowing-snow SSA.

✓ Addressed in revised manuscript

Comment 6 — Figures

Figure 1

> *The caption should state the averaging period, the model experiment, the flux units, and whether panels c–d show percentage changes in total particle number or only sea-salt aerosol particles. Please also improve the unit formatting for panels a–b.*

We thank the reviewer for these suggestions and have revised the Figure 1 caption to specify the averaging period, the experiment, and the units, to clarify that panels (c) and (d) show the percentage change in total particle number, and to improve the unit formatting. The revised caption reads: "Time-mean sea salt aerosol particle number flux from blowing snow simulated by TM5 in the Blowing snow experiment (2019–2020, driven by ERA5 meteorology). (a) Arctic and (b) Antarctic mean flux (particles m^{-2} s^{-1}), shown by the white-to-black shading. In panel (a), red dots mark the MOSAiC track and the green dot the closest corresponding TM5 grid point, and the three Arctic land-based stations (Villum, Zeppelin, and Alert) are marked together with their closest corresponding TM5 grid points. Panels (c) and (d) show the increase in total particle number due to blowing snow, expressed as a percentage relative to the Baseline simulation (without blowing snow), for the Arctic and Antarctic respectively."

✓ Addressed in revised manuscript

Figure 2

> *The caption and legend should be made consistent. Please clarify whether the black curve represents an absolute concentration difference or a relative increase. Correct the misspelling 'consentration' to 'concentration'.*

We thank the reviewer. We have corrected the misspelling "consentration" to "concentration" and made the caption and panel (b) legend consistent. Panel (b) shows a relative increase: the percentage change in particle number concentration relative to the Baseline simulation, and the legend and axis label have been updated to state this explicitly. The revised caption reads: "Time series of sea salt aerosol number concentration along the MOSAiC track. Grey shaded areas indicate periods identified as blowing snow events. (a) Observed particle number concentration (blue, MOSAiC campaign) compared to TM5 results without blowing snow emissions (orange) and with blowing snow emissions (green). (b) Relative increase in particle number concentration due to blowing snow in the TM5 simulation, expressed as the percentage change relative to the Baseline simulation."

✓ Addressed in revised manuscript

Figure 3

> *The caption should specify that CCN are shown at 0.3% supersaturation. Please also state the temporal resolution of the observations and model output, define how blowing-snow events were identified, and specify the spatial range.*

We thank the reviewer and have revised Fig. 3 accordingly. The caption now specifies that CCN are shown at 0.3% supersaturation, states the temporal resolution (the native observations are at 1-min resolution and the figure shows daily-averaged values, with the TM5 output shown at the same daily resolution), notes that the blowing-snow events (grey shading) are identified from exceedance of the critical wind-speed threshold for blowing snow shown in Fig. S1, and refers to Fig. 1 for the spatial range of the MOSAiC track. The revised caption reads: "Time series of sea salt CCN concentration at 0.3\% supersaturation from the MOSAiC campaign. Grey shaded areas indicate periods identified as blowing snow events. (a) Observed CCN concentration (blue dots, MOSAiC campaign) compared to TM5 model results without blowing snow emissions (orange dashed line) and with blowing snow emissions (red dotted line). (b) Difference in CCN concentration between the TM5 simulation with blowing snow emissions and the base simulation, showing the contribution of blowing snow to CCN concentrations"

✓ Addressed in revised manuscript

Figure 4

> *The text refers to monthly median size distributions, whereas the caption states monthly mean distributions — make consistent. Define the green shaded observational range and explain the use of different y-axes for TM5 versus observations/GEOS-Chem. Use consistent terminology for GEOS/GEOS-Chem throughout.*

We thank the reviewer and have revised Fig. 4 accordingly. The text and caption have been made consistent: both now refer to monthly median size distributions. The green shaded observational range is now defined in the caption as the 25th–75th percentile range, shown as error bars on the observed distribution. We have also clarified the use of different y-axes: the TM5 results are daily-mean values whereas the GEOS-Chem results are at sub-daily resolution, so separate y-axes are used to allow the distribution shapes to be compared despite the difference in sampling and magnitude. The observational and GEOS-Chem data are taken from Gong et al. (2023), and the terminology has been standardised to "GEOS-Chem" throughout. The revised caption reads: "Monthly median aerosol size distributions along the MOSAiC track. Observations are shown in green. TM5 model results without blowing snow (baseline) are shown as a dashed black line, while TM5 results including blowing snow are shown as a solid black line. GEOS-Chem model results without blowing snow are shown as a dashed blue line, and GEOS-Chem results with blowing snow are shown as a solid blue line"

✓ Addressed in revised manuscript

Figure 5

> *State the observational period, whether model values are sampled at the nearest grid point, and whether the reported mass is total sea salt or sodium-equivalent sea salt. Provide the latitude and longitude of each station and adjust the x-axis tick labels as months 11 and 12 overlap.*

We thank the reviewer and have revised Fig. 5 accordingly. The caption now states the observational period (2020, sampled from daily data), clarifies that the model values are sampled at the nearest TM5 grid point to each station, and specifies that the reported quantity is total sea salt aerosol mass. The station locations and their closest corresponding TM5 grid points have been added to Fig. 1, so the latitude and longitude of each station are now shown explicitly. The x-axis tick labels have been adjusted so that months 11 and 12 no longer overlap. The revised caption reads: "Monthly mean total sea salt aerosol mass concentrations at three Arctic land-based stations: Villum (a), Zeppelin (b), and Alert (c).

Blue lines represent observations, orange bars show TM5 model results without blowing snow emissions, and green bars show TM5 results including blowing snow emissions. The monthly mean value is indicated by the black line, and the height of the bar indicates the standard deviation within the month of modelled sea salt mass. Observations cover 2020 and are sampled from daily data."

✓ Addressed in revised manuscript

Figure 6

> *The vertical coordinate 'lev' is not sufficiently informative. Use pressure or altitude. State that differences are calculated as 'with blowing snow minus baseline' and indicate whether FDR correction was applied. Improve colorbar unit formatting.*

We thank the reviewer and have revised Fig. 6 accordingly. The vertical coordinate has been converted from model level to pressure (hPa). The caption now states explicitly that the differences are calculated as "blowing snow − baseline", that an FDR correction has been applied, and the colorbar unit formatting has been corrected to use proper superscripts. The revised caption reads: "Annual zonal mean difference (blowing snow − baseline) in particle number concentration due to blowing snow for the Aitken mode (a) and accumulation mode (b) in the TM5 simulations. Shading shows the change in number concentration (particles cm^{-3}), calculated as the difference between simulations with and without blowing snow emissions. Positive values indicate an increase in concentration attributed to blowing snow events. All coloured regions are statistically significant at the $p < 0.05$ level after the FDR correction is applied."

✓ Addressed in revised manuscript

Figure 7

> *State that the figure shows annual zonal-mean differences in CCN at 0.3% supersaturation, in cm^{-3}, calculated as 'with blowing snow minus baseline'. Convert the vertical coordinate to pressure or altitude. Improve colorbar unit formatting and make x-axis tick labels more publication-ready with latitude units.*

We thank the reviewer and have revised Fig. 7 accordingly. The caption now states that the figure shows annual zonal-mean differences in CCN at 0.3% supersaturation, in cm^{-3}, calculated as "with blowing snow minus baseline". The vertical coordinate has been converted from model level to pressure (hPa), the colorbar unit formatting has been corrected to use proper superscripts (cm^{-3}), and the x-axis tick labels have been made publication-ready with explicit latitude units (e.g. 60°S, 30°S, 0°, 30°N, 60°N).

✓ Addressed in revised manuscript

Figure 8

> *State the sign convention explicitly. Clarify whether positive values indicate increased downward surface flux. Label x-axes with units and y-axes with both the variable name and units. Correct 'new downward solar' to 'net downward solar'.*

We thank the reviewer and have revised Fig. 8 accordingly. The sign convention is now stated explicitly in the caption: positive values indicate an increase in radiation reaching the surface due to blowing snow. The typo “new downward solar” has been corrected to “net downward solar”, and the y-axes are now labelled with units. The revised caption reads: “Zonal mean annual-mean changes (blowing snow – baseline) in surface radiative fluxes (W m^{-2}) simulated with EC-Earth3, comparing AMIP-type experiments with and without the blowing snow sea-salt aerosol parameterization. (a) all-sky surface radiative fluxes, (b) clear-sky contributions, (c) The curve shows changes in cloud radiative effects. Shows changes in net downward solar (blue), thermal (orange), and net (green) components. Positive values show an increase in radiation reaching the surface due to blowing snow.”

Regarding the request to label the y-axes with both the variable name and units: each panel plots several different radiative flux components (net downward solar, thermal, and net) simultaneously, so a single y-axis variable name would not be meaningful. We have therefore retained the flux unit (W m^{-2}) on the y-axis and identified the individual variables through the legend and colour coding (blue, orange, green) described in the caption.

✓ Addressed in revised manuscript

Figure 9

> *Specify that the plotted fields are zonal-mean differences between the blowing-snow and baseline transient EC-Earth3 simulations. State the averaging interval, sign convention, and whether these are single-realization differences. Make y-axis labelling more publication-ready.*

We thank the reviewer and have revised Fig. 9 accordingly. The caption now specifies that the plotted fields are zonal-mean differences between the blowing-snow and baseline transient EC-Earth3 simulations, computed as “with blowing snow minus baseline”. The averaging interval is stated explicitly, and the caption now notes that these are differences from a single ensemble member, so the signal cannot be separated from internal climate variability (consistent with the caveat added in Sect. 5). The sign convention is given, and the y-axis labelling has been made publication-ready with the variable name and pressure (hPa) units.

✓ Addressed in revised manuscript

Minor Comments

Line 4 — Define AMIP

> *Please define the abbreviation AMIP at first use.*

Corrected in the revised manuscript; AMIP is now spelled out as “atmosphere-only (AMIP-type)” at first use in the abstract.

✓ Addressed in revised manuscript

Lines 26–29 — Rephrase SSA sentence

> *Suggested wording: 'Sea salt aerosols (SSA) are an important source of cloud condensation nuclei (CCN) in the polar regions. Model estimates suggest that SSA account for more than one quarter of Arctic aerosol number concentrations. As Arctic sea ice declines, increased open-ocean area and more frequent sea-ice leads are expected to enhance SSA emissions, thereby increasing Arctic CCN concentrations (Emme and Horowitz, 2025).'*

We thank the reviewer for the suggested wording and have revised Lines 26–29 accordingly. The revised text now reads: 'Model estimates show that SSA account for more than a quarter of the Arctic aerosol number concentration, and even up to 45% locally (Gong et al., 2023). As Arctic sea ice declines, increased open-ocean area and more frequent sea-ice leads are expected to enhance SSA emissions, thereby increasing Arctic CCN concentrations (Emme and Horowitz, 2025).' This incorporates the reviewer's suggested clarification on the future trajectory of Arctic SSA emissions while grounding the present-day estimate in the quantitative results of Gong et al. (2023). The sentence on SSA as a source of CCN already appears earlier in the paragraph, so the restructuring avoids repetition while retaining all the content the reviewer requested.

✓ Addressed in revised manuscript

Line 30 — Space before citation

> *Please add a space between 'ice' and the citation '(Lapere et al., 2024)'.*

Corrected in the revised manuscript; the missing space before the citation has been added.

✓ Addressed in revised manuscript

Lines 31–32 — Winter/spring importance

> *Please briefly explain why blowing-snow SSA emissions are especially important during winter and spring.*

This is now explained by the text we added to the introduction in response to Major Comment 2: unlike open-ocean sea spray, which requires open water, blowing-snow SSA is produced from saline snow lofted off the sea-ice surface, so it is most active during winter and spring, when sea-ice cover is extensive, open-water sources are suppressed, and strong winds are frequent. Blowing snow can therefore dominate the SSA budget over consolidated sea ice in these seasons.

✓ Addressed in revised manuscript

Lines 99–100 — M7 nucleation mode

> *The statement that each M7 mode is further divided into soluble and insoluble fractions may be misleading, since the nucleation mode does not have an insoluble counterpart. Please revise.*

We thank the reviewer for catching this. The reviewer is correct: in the M7 scheme the nucleation mode is soluble only and has no insoluble counterpart, so the seven modes comprise a soluble nucleation mode together with soluble and insoluble Aitken, accumulation, and coarse modes. We have revised the sentence in Sect. 2.4.1 to read: “These modes comprise a soluble nucleation mode and soluble and insoluble Aitken, accumulation, and coarse modes.”

✓ Addressed in revised manuscript

Line 227 — 'Most interesting finding'

> *The phrase 'most interesting finding' is subjective. Consider using 'A notable finding' or 'One key result'.*

Corrected in the revised manuscript; “Perhaps the most interesting finding” has been changed to “One key result”.

✓ Addressed in revised manuscript