

Response to Referees

Glaciogenic seeding-induced hole-punch clouds and their sensitivity to the clouds' background state

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Dear editor and referees,

We would like to thank the editor for handling our manuscript and the referees for their careful evaluation of the revised manuscript. Below we address our detailed responses to all the comments. In this response-to-review document we try to clarify and address each of the suggestions, comments, and questions made during the review process. Therefore we have copied the comments in lavender boxes and have addressed them one by one. In the response we use italic fonts to quote text from the revised manuscript. Additional to the revised manuscript, we have uploaded a version of the manuscript with highlighted tracked changes.

Best regards, Nadja Omanovic et al.

Response to referee #1

Comments to the Author

The manuscript by Omanovic et al. explores hole-punch clouds measured during the CLOUDLAB field campaign. Simulations are performed with the NWP model ICON in a large-eddy simulation setup with varying liquid water path and Smagorinsky constants (c_s) to explore the sensitivity of the clouds to these variables. While large impacts are found from a varied LWP, the impact of a varied c_s is negligible.

This manuscript is nicely written and follows a logical structure. Some parts could benefit from some more clarifications to make the manuscript more approachable for non-experts, please see Specific Comments below. The study is a short but interesting one, providing thus far, unexplored topics, and deserves publication after some revisions. I have no major concerns. Some discussion points are provided below

We thank the referee for the constructive comments and we will address the concerns below.

General comments

GC1 There is no mention of cloud droplet size distribution. Has this been explored if it has any impact on the rate of glaciation?

Thank you for this input. This is indeed interesting and we have not yet explored it. We chose to achieve a similar cloud droplet number concentration as observed ($\approx 500 \text{ cm}^{-3}$). Quantifying the effect of cloud droplet size distribution could be challenging given the inherent limitations of a two-moment microphysics scheme as well as the saturation adjustment governing the growth and evaporation of cloud droplets, which treats all cloud droplets equally. We nonetheless believe that this investigation could indeed be insightful and will pursue this in the follow-up project of CLOUDLAB.

GC2 In regard to L99-L101, have the authors tried to vary the Smagorinsky constant by, say a factor of 10? The values chosen span a small range and it is surprising to see no impacts from varying this constant.

The chosen values for C_s are based on theoretical derivations of C_s and commonly applied to the sugrid-scale closures. C_s cannot be larger than one. Therefore, we did not perform tests with factor 10. We did test the effect of setting it to zero. However, then our simulation turned unstable because no damping was applied to the numerical

diffusion. Please see for more details the response to referee #2, their second comment "Physical interpretation of the sub-grid mixing length scale".

GC3 In L119 the authors state "We hypothesize that the explicitly resolved turbulence (grid-scale) is of higher importance." To this effect, have the authors explored other horizontal grid spacings? It would be interesting to see how large impact this has on the rate of glaciation.

In previous studies we have increased the horizontal resolution from 130 m (Omanovic, Ferrachat, Fuchs, Henneberger, et al., 2024) to 65 m (Omanovic, Ferrachat, Fuchs, F. Ramelli, et al., 2025). However, we did not conduct a systematic analysis of the changes. We are currently working on a study with a focus on this. We added the following to the results (line 154): "*Hence, the subgrid-scale mixing seems not to be a crucial parameter in changing cloud microphysical processes for this particular cloud type. This is in contrast to other studies (Bryan et al., 2003; Takemi and Rotunno, 2003; Matheou et al., 2011), which found a dependence of C_s , but also employed coarser horizontal grid resolutions. We hypothesize that in our case the explicitly resolved turbulence (grid-scale at 65 m) is dominant enough, such that the sub-grid scale effect plays a minor role. A more thorough analysis of horizontal grid spacing is the subject of a future study building on the work in CLOUDLAB.*"

Specific Comments

L22 "It takes place because of different saturation water vapor pressures over water and ice" While not wrong I would like a longer explanation to make it more accessible to non-experts. Also include the standard statements on the constraint on vapour pressure ($e_{liq} > e > e_{ice}$).

Thank you, we extended now the description by the following (line 22): "*It takes place because of different saturation water vapor pressures over water ($e_{s,w}$) and ice ($e_{s,i}$). At water-subsaturated conditions cloud droplets will evaporate, while ice crystals continue to grow as long as they experience ice supersaturated conditions ($e_{s,i} < e < e_{s,w}$, where e is the ambient water vapor pressure). Moreover, the evaporating cloud droplets serve as a reservoir of water vapor, which can be taken up by the ice crystals. In the case of $e > e_{s,w}$, both hydrometeors grow while in case of $e < e_{s,i}$, cloud droplet evaporate and ice crystals sublimate. During the WBF process, ice crystals grow large enough to start to sediment and form fallstreaks below the cloud.*"

L53 How is the 'void of ice crystals' requirement upstream from the field site ascertained in the experiments?

We added the following explanation in line 55: "*They are often void of any ice crystals because of low INP concentrations as well as cloud top temperatures being $< -10^\circ\text{C}$. Hence, they are the ideal candidate for cloud seeding.*" as well as in line 79: "*It is clearly notable that the reductions in LWC are co-located with the presence of ice crystals. Furthermore, ice crystals were measured only during the seeding signal, further highlighting the absence of any naturally formed ice crystals in the cloud. After the passage of the seeding plume, the cloud reverts to its background state ...*"

L61-62 This sentence is a bit unclear to me. Is the size threshold of 25 μm the limit of detection?

Thank you, we adapted the following (line 64): "*All particles with diameters smaller than 25 μm are classified as cloud droplets. For particles larger than 25 μm we distinguish between cloud droplets and ice crystals.*". The reason is that we need a certain size to distinguish fully round (cloud droplets) from non-round (ice crystals) particles.

L63 Please add the reasoning behind the change in analyzing frequency for seeding and non-seeding experiments

We added following clarification (line 66): "*The difference in analysis frequency is due to the rather low ICNC ($< 0.5 \text{ cm}^{-3}$) as well as the measurement time of the seeding signal ($\approx 6 \text{ min}$) compared to the one of the background. The goal was to achieve a robust data population during the passage of the seeding plume, while during non-seeding conditions, we can average over a longer time period, since the cloud is expected to remain stable and no significant changes are anticipated on that timescale.*"

Fig. 1 (d) Does the y-label indicate that the ceilometer is placed just below 20m? If so, this could perhaps be mentioned in the field site setup to make it clearer.

We added in the caption of Figure 1 the following to make it clearer: “*The vertical axis indicates the height above the ceilometer, which can be interpreted as the height above ground.*”

L73 Perhaps I’m not aware of the correct terminology but “the attenuated backscatter signal moves higher up” sounds a bit awkward?

We reformulated that part to make it clearer (line 82): “*Moreover, a ceilometer, located at the main field site, also captured the change in cloud base. Before and after the seeding the maximum of attenuated backscatter is close to the ceilometer (see Fig. 1d). During seeding, the attenuated backscatter is decreasing in the levels close to the ceilometer, while we see an increase in the backscatter at heights between 50 m to 70 m above the ceilometer.*”

L78 The “we already demonstrated” sounds like it has been done in this manuscript. Perhaps “In previous studies” or similar would be more appropriate.

Thank you, we adapted it as follows (line 89): “*In previous studies we demonstrated ...*”.

L89-95 From a modelling perspective the method makes a lot of sense, but do the authors have an indication whether a hole-punch cloud did occur in the observations during the seeding during this day? And if not, is there an explanation to why that does not occur?

The observations of hole-punch clouds only occurred on 12 January 2024, because the cloud layer was shallow and the perturbation from the cloud seeding was enough to dissipate the cloud. For other experiment days, we did not observe complete dissipation of the cloud across its vertical extent. We added this as follows (line 108): “*To evaluate the impact of the cloud’s LWP on the emergence, size, and lifetime of the hole-punch cloud, we chose a model simulation day, 24 January 2023, that was one of the field experiment days within CLOUDLAB. During this day, we conducted 9 seeding experiments in the field, none of which showed any signs of hole-punch clouds. This is mostly because the cloud was much thicker (extent of up to 500 m, see Figure 2a in Fabiola Ramelli et al. (2024)) preventing its complete dissipation after the given observation time. In the model simulations for this day, we have varying LWPs while temperatures agree with the one from the field experiments of a hole-punch cloud (-5.5 ± 0.2 °C).*”.

Fig 2 d-f Should ‘minimum’ not rather be ‘maximum’ as it refers to the largest reduction in LWC? Furthermore, at heights above the seeding level the reductions are very abruptly cut off, why is this? Should it not return to 0 rather than no values? Is it constrained by plotting or physics? In 2 d-f minor xticks could be added to improve readability.

In accordance with referee # 2, we adapted the term “reduction” to “change” throughout the manuscript to avoid this kind of confusion. Only in places, where its meaning is unambiguous we kept “reduction”. The LWC is abruptly cut off because we identify the seeding plume by masking for grid points where $ICNC > 0.001 \text{ cm}^{-3}$. This can lead to this flat top because above the cloud top there is a strong inversion with low humidity, leading to the sublimation and melting of the ice crystals. We added a clarification in the figure caption: “*The abrupt cutoff at height 1300 m is caused by the masking of the seeding plume with $ICNC > 0.001 \text{ cm}^{-3}$ (see Sect. 2).*”

L118 Perhaps this insensitivity is due to the characteristics of the clouds? This statement seems a bit too generic for this reason, could the authors add “for these clouds” or similar?

Thank you, we added the following (line 155): “*...for this particular cloud type*”.

L129-130 1) and 2) could be added to better distinguish the processes.

Thank you, that was added (line 172 and 173).

L132 This would also require a quite homogeneous temperature at seeding height as this is done at quite warm temperatures if I understand the setup correctly. Have the authors looked into the activation rate of the seeding particles in terms of spatial heterogeneity? And how this may impact the obtained ICNC.

For finding the best matching seeding level in the model setup, we averaged the temperature along the drone flight legs with only slight variations across the grid points (<0.1 °C). The reported temperature by the field experiments

is calculated in a similar fashion, i.e., averaging the temperature along the drone seeding legs during the seeding. While there is definitely a strong dependence on temperature for the ice nucleation of the seeding particles, within the small range of temperature, the nucleation rates are rather similar. In the specific case discussed in this manuscript, we found a frozen fraction of 0.025 ± 0.002 . Moreover, the horizontal temperature distribution is rather homogeneous given that we have stable conditions with steady north-easterly winds. We extended our hypothesis regarding the larger area of seeding (line 175): "*To achieve faster and more wide-spread reductions, a stronger seeding perturbation across a larger area (i.e., longer seeding legs with higher seeding concentrations and/or during a longer seeding time period to achieve higher ICNC) would be required.*"

L137-138 As the authors have model output that spans the region of the seeding plume to the field site, could this not be confirmed by evaluating the upstream path?

Thank you, this is true and we changed the statement to be clearer on that. We rechecked the conditions and it is correct, that the cloud layer changes in space and time, thus the relative changes in LWC can be explained (line 180): "*It also notable that for seven out of nine seeding simulations a second local minimum is achieved (between 20 and 25 min), which is also associated with -100% LWC reductions. As the seeding plume is advected in space, it encounters background states with first lower and then again higher LWCs, such that a renewed reduction in LWC is possible at later times.*"

Conclusions I am missing some references and comparisons to other work. As this topic is quite unique I can see that it's hard to find good references, but some references and discussion to whether the reduction in LWP has been previously been seen to this effect should ideally be included here. One example could be: "Large-Eddy Simulations of the Impact of Ground-Based Glaciogenic Seeding on Shallow Orographic Convection: A Case Study" Chu et al. 2017. Also a discussion on the varied Smagorinsky constant in comparison to other LES papers would be appropriate, while other papers may not discuss glaciation, a discussion on whether changes in the clouds are seen could be done.

Thank you, we extended the discussion on the Smagorinsky constant. For more detail, please see the response to referee #2, their second comment "Physical interpretation of the sub-grid mixing length scale". Thank you for the reference to Chu et al., 2017. We extended our conclusion part by the following (line 200): "*This raises the question if the explicitly resolved turbulence is dominant enough, such that no additional subgrid-scale turbulence is required. Xue et al., [2016] and Chu, Xue, et al., [2014]; Chu, Geerts, et al., [2017] both found a strong dependence of simulating glaciogenic cloud seeding on horizontal resolution. With increasing resolution, the efficiency through the WBF process to form precipitation increased. Hence, if one wants to successfully simulate glaciogenic seeding at coarser horizontal resolutions, the subgrid-scale turbulence may be of higher importance.*"

Technical Corrections

L1 "is usually" instead of "usually is"

Thank you, it is adapted.

L74 add "the" for "the cloud top"

Thank you, it is adapted.

References

- Bryan, George H., John C. Wyngaard, and J. Michael Fritsch (2003). “Resolution Requirements for the Simulation of Deep Moist Convection”. In: *Monthly Weather Review* 131.10, pp. 2394–2416. ISSN: 1520-0493, 0027-0644. DOI: [10.1175/1520-0493\(2003\)131<2394:RRFTSO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<2394:RRFTSO>2.0.CO;2).
- Chu, Xia, Bart Geerts, Lulin Xue, and Binod Pokharel (2017). “A Case Study of Cloud Radar Observations and Large-Eddy Simulations of a Shallow Stratiform Orographic Cloud, and the Impact of Glaciogenic Seeding”. In: *Journal of Applied Meteorology and Climatology* 56.5, pp. 1285–1304. ISSN: 1558-8424, 1558-8432. DOI: [10.1175/JAMC-D-16-0364.1](https://doi.org/10.1175/JAMC-D-16-0364.1).
- Chu, Xia, Lulin Xue, Bart Geerts, Roy Rasmussen, and Daniel Breed (2014). “A Case Study of Radar Observations and WRF LES Simulations of the Impact of Ground-Based Glaciogenic Seeding on Orographic Clouds and Precipitation. Part I: Observations and Model Validations”. In: *Journal of Applied Meteorology and Climatology* 53.10, pp. 2264–2286. ISSN: 1558-8424, 1558-8432. DOI: [10.1175/JAMC-D-14-0017.1](https://doi.org/10.1175/JAMC-D-14-0017.1).
- Deardorff, James W. (1970). “A Numerical Study of Three-Dimensional Turbulent Channel Flow at Large Reynolds Numbers”. In: *Journal of Fluid Mechanics* 41.2, pp. 453–480. ISSN: 1469-7645, 0022-1120. DOI: [10.1017/S0022112070000691](https://doi.org/10.1017/S0022112070000691).
- Dipankar, Anurag, Bjorn Stevens, Rieke Heinze, Christopher Moseley, Günther Zängl, Marco Giorgetta, and Slavko Brdar (2015). “Large Eddy Simulation Using the General Circulation Model ICON”. In: *Journal of Advances in Modeling Earth Systems* 7.3, pp. 963–986. ISSN: 1942-2466. DOI: [10.1002/2015MS000431](https://doi.org/10.1002/2015MS000431).
- Lilly, D. K. (1962). “On the Numerical Simulation of Buoyant Convection”. In: *Tellus* 14.2, pp. 148–172. ISSN: 2153-3490. DOI: [10.1111/j.2153-3490.1962.tb00128.x](https://doi.org/10.1111/j.2153-3490.1962.tb00128.x).
- (1967). “The representation of small-scale turbulence in numerical simulation experiments”. In: *Proc. 10th Scientific Computing Symp. on Environmental Sciences*, pp. 195–210.
- Marculli, Claudia, Baban Nagare, André Welti, and Ulrike Lohmann (2016). “Ice Nucleation Efficiency of AgI: Review and New Insights”. In: *Atmospheric Chemistry and Physics* 16.14, pp. 8915–8937. ISSN: 1680-7324. DOI: [10.5194/acp-16-8915-2016](https://doi.org/10.5194/acp-16-8915-2016).
- Mason, P. J. and A. R. Brown (1999). “On Subgrid Models and Filter Operations in Large Eddy Simulations”. In: *Journal of the Atmospheric Sciences* 56.13, pp. 2101–2114. ISSN: 0022-4928, 1520-0469. DOI: [10.1175/1520-0469\(1999\)056<2101:OSMAFO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1999)056<2101:OSMAFO>2.0.CO;2).
- Matheou, Georgios, Daniel Chung, Louise Nuijens, Bjorn Stevens, and Joao Teixeira (2011). “On the Fidelity of Large-Eddy Simulation of Shallow Precipitating Cumulus Convection”. In: *Monthly Weather Review* 139.9, pp. 2918–2939. ISSN: 1520-0493, 0027-0644. DOI: [10.1175/2011MWR3599.1](https://doi.org/10.1175/2011MWR3599.1).
- Miller, Anna J., Christopher Fuchs, Fabiola Ramelli, Huiying Zhang, Nadja Omanovic, Robert Spirig, Claudia Marculli, Zamin A. Kanji, Ulrike Lohmann, and Jan Henneberger (2025). “Quantified Ice-Nucleating Ability of AgI-containing Seeding Particles in Natural Clouds”. In: *Atmospheric Chemistry and Physics* 25.11, pp. 5387–5407. ISSN: 1680-7316. DOI: [10.5194/acp-25-5387-2025](https://doi.org/10.5194/acp-25-5387-2025).
- Omanovic, N., S. Ferrachat, C. Fuchs, J. Henneberger, A. J. Miller, K. Ohneiser, F. Ramelli, P. Seifert, R. Spirig, H. Zhang, and Ul Lohmann (2024). “Evaluating the Wegener–Bergeron–Findeisen Process in ICON in Large-Eddy Mode with in Situ Observations from the CLOUDLAB Project”. In: *Atmospheric Chemistry and Physics* 24.11, pp. 6825–6844. ISSN: 1680-7316. DOI: [10.5194/acp-24-6825-2024](https://doi.org/10.5194/acp-24-6825-2024).
- Omanovic, N., S. Ferrachat, C. Fuchs, F. Ramelli, J. Henneberger, A. J. Miller, R. Spirig, H. Zhang, and U. Lohmann (2025). “Chasing Ice Crystals: Interlinking Cloud Microphysics and Dynamics in Cloud Seeding Plumes With Lagrangian Trajectories”. In: *Journal of Advances in Modeling Earth Systems* 17.7, e2025MS005016. ISSN: 1942-2466. DOI: [10.1029/2025MS005016](https://doi.org/10.1029/2025MS005016).
- Ramelli, Fabiola, Jan Henneberger, Christopher Fuchs, Anna J Miller, Nadja Omanovic, Robert Spirig, Huiying Zhang, Robert O David, Kevin Ohneiser, Patric Seifert, and Ulrike Lohmann (2024). “Repurposing Weather Modification for Cloud Research Showcased by Ice Crystal Growth”. In: *PNAS Nexus* 3.9, pgae402. ISSN: 2752-6542. DOI: [10.1093/pnasnexus/pgae402](https://doi.org/10.1093/pnasnexus/pgae402).
- Samgorisnky, J. (1963). “General circulation experiments with the primitive equations. I. The basic experiment”. In: *Monthly Weather Review* 91, pp. 99–164.
- Takemi, Tetsuya and Richard Rotunno (2003). “The Effects of Subgrid Model Mixing and Numerical Filtering in Simulations of Mesoscale Cloud Systems”. In: *Monthly Weather Review* 131.9, pp. 2085–2101. ISSN: 1520-0493, 0027-0644. DOI: [10.1175/1520-0493\(2003\)131<2085:TEOSMM>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<2085:TEOSMM>2.0.CO;2).
- Ullrich, Romy, Corinna Hoose, Ottmar Möhler, Monika Niemand, Robert Wagner, Kristina Höhler, Naruki Hiranuma, Harald Saathoff, and Thomas Leisner (2017). “A New Ice Nucleation Active Site Parameterization for Desert Dust and Soot”. In: *Journal of the Atmospheric Sciences* 74.3, pp. 699–717. ISSN: 0022-4928, 1520-0469. DOI: [10.1175/JAS-D-16-0074.1](https://doi.org/10.1175/JAS-D-16-0074.1).

Xue, Lulin, Xia Chu, Roy Rasmussen, Daniel Breed, and Bart Geerts (2016). “A Case Study of Radar Observations and WRF LES Simulations of the Impact of Ground-Based Glaciogenic Seeding on Orographic Clouds and Precipitation. Part II: AgI Dispersion and Seeding Signals Simulated by WRF”. In: *Journal of Applied Meteorology and Climatology* 55.2, pp. 445–464. ISSN: 1558-8424, 1558-8432. DOI: [10.1175/JAMC-D-15-0115.1](https://doi.org/10.1175/JAMC-D-15-0115.1).