We appreciate the referee's insightful comments. Below, we present the reviewer's remarks in red italics, followed by our responses in regular text.

Reviewer 1

General comment

Persistent contrails might have an impact when placed into pre-existing ice clouds, changing the environment and the characteristics of the clouds and thus the life cycle of ice clouds. However, the qualitative and quantitative effect of such interactions is unclear. This study aims to investigate and to quantify the interactions of contrails and cirrus in the ICON-LEM model, thus providing important insights for anthropogenic and natural ice clouds.
However, in the current state this study is not appropriate for considering publication in ACP. Actually,I recommend rejection of the manuscript, and maybe reconsideration after a real major revision. In the following I will only explain my major concerns, but I will not go into details of the representation.

We thank the reviewer for their evaluation of the manuscript and for highlighting several important issues. We have addressed all reviewer comments in detail, and we believe the corresponding revisions have substantially improved the overall quality of the manuscript.

Major issues

1. The used model configuration is not appropriate for the investigation

There are several issues with the chosen model configuration, which essentially makes it very difficult (or even impossible) to determine the properties of contrails embedded into ice clouds, and their interactions. Generally, I have to say that the model description lacks of many details. For instance, it is not stated how ice crystals in contrails are treated, also in contrast to crystals in natural clouds; the choice of crystals' shape would change processes as evaporation/growth and also sedimentation. Thus, many important settings or choices for the parameterisations are just not stated.

• *Classes of ice*

For a meaningful investigation of contrails and embedded in ice clouds, one has to use separate classes of ice, i.e., one for natural ice clouds (formed by homogeneous/heterogeneous nucleation and other processes) and one for the placed contrail. From the very brief description of the cloud physics scheme I can only assume that the authors use just one class of ice. This is a major drawback, since key features cannot be diagnosed anymore (e.g. sizes of contrail ice vs. natural ice) or even worse, processes and process rates are artificially changed. For instance, once the contrail (with a number concentration of $N \sim 150 cm^{-3}$) is placed into the ice cloud, the mean quantities are completely changed, since two very different modes are mixed. Assuming a natural cloud with small ice number concentration and large crystals (thus sedimenting ice particles), the embedded contrail would immediately lead to very small ice particles in the respective grid cell (by adding concentrations), which cannot *sediment. Thus, sedimentation is artificially switched off just by placing the contrail. The same issue occurs for growth/evaporation of crystals, which is completely changed, but for all ice crystals, not only for the contrail part. Therefore, a model which does not distinguish between different ice classes with very different modes (small/many crystals vs. few/large crystals) is not suitable for such investigations.*

I suggest to implement a two-class ice scheme, based on the existing ice particle class in ICON. Otherwise, all investigations are biased by this artificial mixing of two very different ice classes, and thus not really meaningful.

We thank the reviewer for highlighting this well-known issue in aviation–climate modelling. We would like to emphasize that the goal of our study is not to develop a contrail parameterization for ICON-NWP or to focus on the detailed mixing between contrail and natural clouds. Rather, we investigate contrail growth in cloudy ice-supersaturated regions using ICON-LEM. This is also why, instead of simply comparing the contrail with adjacent regions, we compare each contrail simulation with its corresponding control run.

After the vortex phase, contrails can be approximated as narrow line-shaped populations of numerous small ice crystals. At this stage, they are subject to the same environmental conditions as the surrounding cirrus. Their subsequent evolution is governed by the same atmospheric processes as natural ice crystals. It depends on diffusional growth, evaporation, sedimentation, and turbulent mixing—not on nucleation or aircraft-induced dynamics. Under these conditions, applying the same microphysical parameterizations to all ice crystals is physically consistent.

The reviewer is correct that the high number concentration of contrail crystals results in smaller mean sizes and weaker sedimentation. However, this is not a numerical artefact but an expected physical response in a grid cell containing contrail ice: the injection of many small crystals into cirrus delays fallout and increases persistence, consistent with observations (e.g., Voigt et al., 2017).

We agree that multi-class schemes may be advantageous at coarser resolutions or when studying the contrail–cloud interactions during the vortex phase. However, for the post-vortex regime at fine LES scales, our single-class two-moment approach provides a practical and physically justified balance between fidelity and computational cost.

In coarse-resolution global or regional models, separate ice classes are indeed important to prevent artificial mixing of distinct ice modes and to enable clean diagnostics (e.g., Burkhardt & Kärcher, 2009; Gruber et al., 2018). In our high-resolution ICON-LEM setup (~150 m horizontally), however, turbulent motions and microphysical evolution are much more explicitly resolved, substantially reducing this bias. We therefore use a single ice class within the two-moment scheme of Seifert & Beheng (2006) for both natural ice and post-vortex contrails. At this resolution, it is reasonable to assume that a given grid cell predominantly contains either natural cirrus or contrail ice—an assumption central to our choice of 150 m rather than 600 m or 300 m resolution. We acknowledge that this remains an approximation.

In atmospheric models such as ICON-NWP, all parameterizations rely on assumptions and simplifications, as no model can fully capture real-world complexity. A clear example is cloud cover treatment in ICON. The default diagnostic PDF scheme (`inwp_cldcover = 1`) accounts for subgrid-scale variability in water vapor and cloud condensate by integrating inputs from turbulence, convection, and microphysics. At finer resolutions below ~1 km—where subgrid variability diminishes—the model switches to an all-or-nothing scheme (`inwp_cldcover = 5`), assuming each grid cell is either fully cloudy or completely clear. While still an approximation, this approach is widely adopted at high resolutions for computational efficiency.

All contrail models involve simplifications to balance realism and feasibility. Global fleet-scale tools such as CoCiP, for example, rely on 0D Lagrangian approximations driven by offline weather data without two-way coupling. Our ICON-LEM framework resolves turbulence and microphysics at high resolution within smaller domains. No single model can capture all relevant processes (e.g., CoCiP, APCEMM, ECHAM), and model choice and configuration necessarily depend on the scientific purpose of the study.

In response to the reviewer's comments, we have added two paragraphs to subsection 2.4 ("Contrail Formation and Initialization in ICON") of the revised manuscript (lines 230-239) and a paragraph to the conclusion section of the revised manuscript (lines 566-573) to clarify these points.

Lines 230-239 of the revised manuscript:

> In the present study, a single ice category is used within the two-moment bulk microphysics scheme (Seifert & Beheng, 2006). At ~150m horizontal resolution, we approximate that each cloudy grid cell is predominantly occupied by either natural cloud ice or contrail ice. This assumption is consistent with the characterization of a post-vortex contrail as a narrow line-shaped population of numerous small ice crystals. Since our analysis focuses on the post-vortex stage—when contrail and natural ice evolve through similar growth, evaporation, sedimentation, and mixing processes—this simplification is considered acceptable for our purposes.
>
> Using a single ice category may introduce biases, particularly once contrail and natural ice begin to mix within the same grid cell. This effect is resolution-dependent: coarser grids enhance numerical blending, whereas finer grids reduce it. Future sensitivity studies using both finer and coarser resolutions would help quantify the influence of grid spacing on these mixing-related effects.

Lines 566–573 of the revised manuscript:

> In our ICON-LEM configuration (~150 m horizontal resolution), we used the standard two-moment microphysics scheme with a single ice category. At this resolution, we assume that a cloudy grid cell is predominantly occupied by either natural cirrus ice or contrail ice. We acknowledge that this simplification may introduce some biases in the results; however, the fine LES resolution substantially reduces artificial mixing of distinct ice modes and is adequate for studying the dispersion phase of contrails. Given that LES studies of dispersion-phase contrail evolution remain limited, our approach provides a useful step toward improving our understanding of these processes. In future work, applying the same framework at both finer and coarser resolutions would help assess the sensitivity of the results to grid spacing and further clarify the role of resolution in simulating dispersion-phase contrails.

- ***Parameterisation of ice physics***

The description of the ice physics parameterisation is very short, the authors only refer to the standard two moment scheme by Seifert & Beheng (SB06), extended by the Kärcher et al.

(2006) scheme (and the Phillips 2008 scheme). While the SB06 scheme is standard and was used for the ICON-LEM before, it seems that the ice physics scheme was extended using the Kärcher scheme.

This scheme was developed for coarse resolution models (e.g. climate models) with a typical time step of about 30 min (as they stated in their article). It is not clear to me if this scheme is really appropriate for the high resolution model with a time step of 2 seconds. Actually, I would assume that for such a small time step one can resolve nucleation events directly (maybe with some time sub stepping). The authors should check and explain if and why the Kärcher scheme really works for their high resolution approach, and might consider to implement a nucleation parameterisation resolving the nucleation events.

We thank the reviewer for raising concerns about the suitability of the Kärcher et al. (2006) scheme for our high-resolution LES configuration with a 2s time step. The parameterization is indeed the default two-moment scheme of Seifert and Beheng (2006; SB06), extended by Kärcher et al. (2006) for homogeneous ice nucleation and Phillips et al. (2008) for heterogeneous processes, as implemented in ICON-LEM without modifications (see also Heinze et al., 2017). This setup is standard for ICON in LES mode and has been widely used in previous cloud studies; we clarified this more explicitly in the revised manuscript.

Unlike convection parameterizations—which deactivate at resolutions finer than ~3 km (deep and mid-level convection resolved explicitly, with shallow convection retained)—or cloud-cover schemes (switching from PDF-based to grid-scale diagnostics at fine resolution), ICON has no equivalent "switch-off" mechanism for ice nucleation. In LES mode, nucleation events are effectively resolved via frequent supersaturation updates on short time steps, without requiring substepping or alternative microphysical formulations. Although originally developed for coarser models, the Kärcher et al. (2006) extension has been shown to perform well in high-resolution ICON-LEM setups, as demonstrated in several studies:

• **Heinze et al. (2017)**: LES simulations over Germany at 625, 312 and 156 m resolution, explicitly using ice nucleation following Kärcher et al. (2006); high-resolution runs better captured small- to mesoscale variability

• **Bley et al. (2017)**: evaluation of warm convective cloud fields in ICON-LEM.

• **Kiszler et al. (2022)**: benchmark of cloud and humidity performance in Arctic cloud-resolving ICON-LEM simulations

• **Schemann and Ebell (2020)**: Arctic mixed-phase clouds using SB06 (3 s step, 75–600 m resolution), demonstrating effectively handling ice processes

• **Verma and Burkhardt (2022)**: contrail-cirrus simulations using SB06 + Kärcher et al. (2006) (3 s step, 625 m resolution), confirming reliable ice formation in LES

Since our study applies ICON-LEM in its standard LES configuration without any source-code modifications, we rely on this well-documented and validated microphysical setup rather than implementing a new nucleation parameterization. A full reproduction of the parameterization details is beyond the scope of this manuscript, and we instead refer readers to the cited literature.

To clarify these points, we have added a paragraph to Section 2.1 (ICON Model Configuration, lines 160-164) in the revised manuscript.

• Resolution of the model

The authors claim that they will use a high resolution for resolving contrails and their interaction with natural cirrus. First, they never state clearly which resolution they use. For the horizontal grid spacing two different numbers are stated here and there (154m vs. 156 m), but for the vertical the resolution is not clearly stated, a number of approximately 150m is reported for the utls region. This raises the question why they use the same resolution for the horizontal and the vertical extension. Since the atmosphere is anisotropic, one would expect a finer resolution in the vertical. Or putting the other way round: For resolving a contrail with a vertical extension of about 500m at the initial state of placement in the model, one would have expected a finer resolution, while for the horizontal extension the resolution seems to be OK.

The authors should explain their choice of resolution and maybe change it to a more appropriate setting.

We thank the reviewer for raising this important point regarding the horizontal and vertical resolution used in our ICON-LEM simulations.

Horizontal resolution

Our simulations use the triangular ICON grid at **R2B14**. According to Eq. 2.1 in the ICON documentation (Prill et al., 2023), the effective mesh size is **~154 m**. Many ICON publications and user guides (e.g. the ICON quick-start wiki, see here), however, use the idealized halving sequence (2.5 km → 1.25 km → 625 m → 312 m → **156 m**) instead of the exact value calculated from Eq. 2.1 in Prill et al, (2023), whereas the internal grid files list slightly different numbers (e.g., 2462 m, 1231 m, 616 m, 308 m, 154 m). Both conventions are commonly used within the ICON community.

We thank the reviewer for pointing out the inconsistency in the manuscript; in the revised version we use a single value (154 m) throughout for clarity.

Vertical resolution

Our ICON-LEM configuration employs **160 vertical levels** with a model top at **22 km**. The vertical grid spacing is height-based and stretched (ICON-NWP documentation, Sect. 3.4 in Prill et al., 2023), with (see Figure 1 below):

- **20 m** spacing near the surface,
- gradually increasing layer thickness aloft,
- **~150 m** spacing between 8–12 km altitude corresponding to typical commercial flight levels
- a maximum of **~400 m** near the model top.

The average vertical spacing is **~138 m**. This configuration is consistent with earlier ICON-LEM studies using similar vertical grids, such as Heinze et al. (2017), who used R2B14 with 150 vertical levels and a 21 km model top.

Justification of the chosen resolution

We agree that a finer vertical grid can further improve the representation of sharp gradients in the upper troposphere. Our chosen configuration reflects a compromise between accuracy and computational feasibility:

- The horizontal grid spacing is fixed across all heights;
- Our 160-level setup already provides **substantially finer vertical resolution** than the ~75–90 levels commonly used in many cloud-resolving ICON studies;
- Substantially refining the vertical grid spacing in the upper troposphere would further reduce the CFL-limited time step. This would significantly increase computational cost and make running our simulations impractical.

The optimal LES vertical resolution depends on atmospheric region and research focus. In our study, we deliberately increased the number of vertical levels (**~150 m** spacing in 8–12 km altitude) to ensure a reasonably fine resolution while maintaining feasible compute cost.

To address the reviewer's concern, we have updated the Methods section to more clearly describe the vertical grid structure, the stretched nature of the coordinates, and the spacing in the upper troposphere. This information now appears in lines 144–149 of the revised manuscript.

References to comparable configurations

Our chosen resolution aligns well with previous high-resolution ICON-LEM studies:

- **Heinze et al. (2017)** – R2B14 (156 m), **150** vertical levels, 21 km top.
- **Dixit et al. (2021)** – 150 m grid, **150** vertical levels.
- **Kiszler et al. (2023)** – 600 m grid, **100** vertical levels.
- **Singh & Kalthoff (2022)** – 156 m grid, **90** vertical levels, 20 km top.

Regarding the vertical extent of the contrail initialization, the perturbation is always imposed within a single vertical grid cell, corresponding to a thickness of approximately 150 m (lines 219-220 in the revised manuscript).

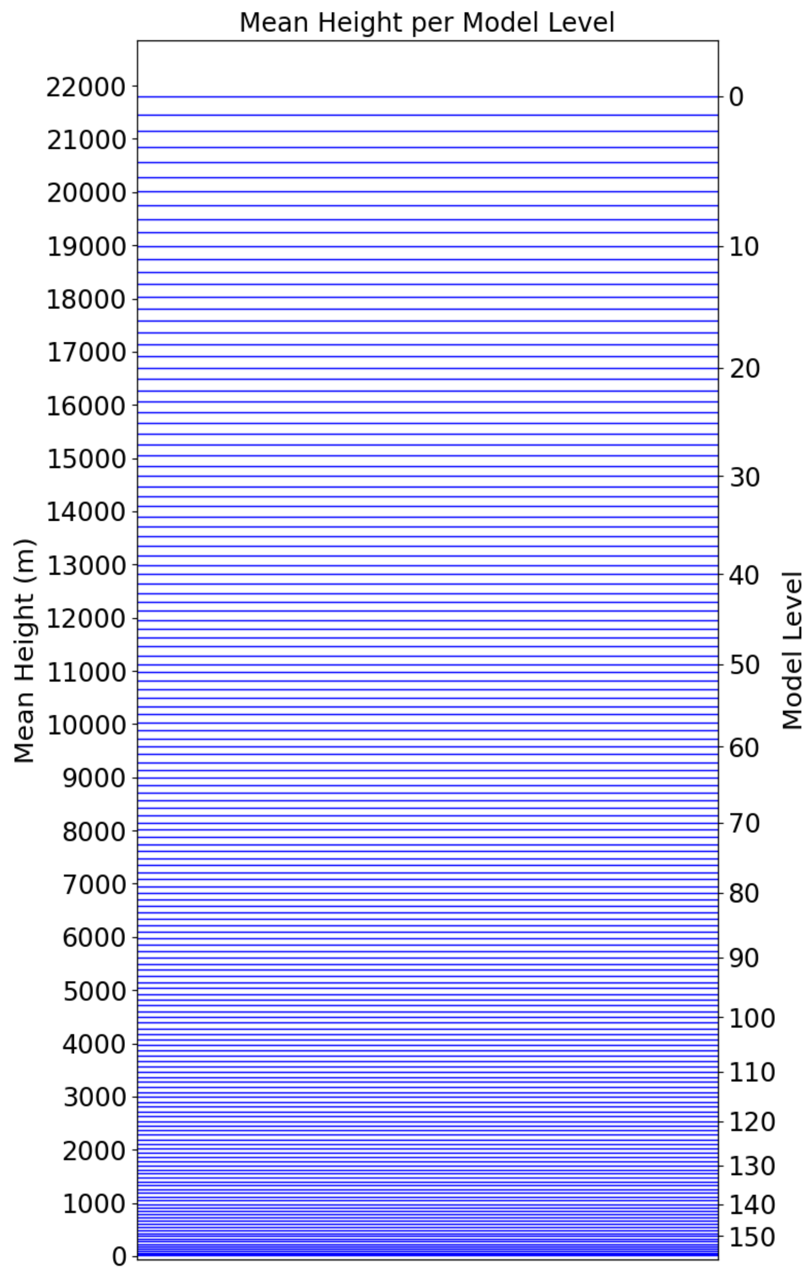

Figure 1: Mean geometric height (m) corresponding to each model vertical level. The left vertical axis shows height in meter, while the right vertical axis indicates the model level index (0–160).

2. Basic physics processes

The investigation and evaluation of the model results are on a very descriptive level, but lacks of using basic physics for the quantitative investigation. Actually, there are only few physical processes for driving the system ice clouds, and for all of them there are characteristic features. The processes are

• nucleation (i.e. formation of natural ice particles)

• growth and evaporation

• sedimentation

and as a forcing the vertical upward motion leading to adiabatic cooling and thus to a source (or even a sink) of supersaturation. After nucleation/placing the contrail only the processes growth and sedimentation play a role. For growth/evaporation one can easily determine time scales, as e.g. derived from the mass growth equation $dm/dt = c(Si - 1)m^3$*. Assuming a constant supersaturation one can solve the equation analytically, or estimate the growth time scale directly. For sedimentation, the (mean) size/mass of the ice particles determines the terminal velocity (here, one would need to know the shape of the particle) and thus one can estimate typical fall distances in the model (as compared to the vertical thickness of the layers). Finally, the vertical upward motion directly determine the sources/sinks for supersaturation, thus one can diagnose directly if the crystals should shrink or grow.*

I completely miss a quantitative analysis using such basis physics consideration. Actually, all features explained in a very descriptive manner in the different simulation can be explained just by the basis processes, e.g., if there is a vertical updraft from below, there is a source of supersaturation, leading to growth of ice particles (no evaporation at the level) and thus enhanced sedimentation – large particles can fall to lower levels, since they can survive longer in subsaturated air . . . and so on.

All the evaluations should be based on quantitative investigations using time scales and other key features of the physical processes.

We thank the reviewer for highlighting the importance of quantitative, process-based diagnostics such as growth and evaporation time scales, sedimentation time scales, and supersaturation tendencies. We fully agree that these basic physical considerations provide valuable tools for interpreting ice-cloud evolution.

In this study, however, our primary objective was not to derive absolute microphysical time scales, but to examine **how an identical initial perturbation of ice crystals perturbation evolves under eight different cloudy, ice-supersaturated background states**. For this reason, the analyses remain intentionally more descriptive than fully quantitative. Our approach aims to identify the dominant environmental controls—such as temporal moisture supply, the vertical structure of ice supersaturation below flight level, and atmospheric stability—that lead to contrasting contrail growth and decay across the cases.

We acknowledge that a rigorous, quantitative time-scale analysis (e.g., analytical solutions to the growth law, estimates of sedimentation distances from terminal velocities, or explicit diagnosis of supersaturation tendencies from vertical motion) would further strengthen the physical interpretation. However, such an analysis would require additional sensitivity simulations (e.g., varying vertical and horizontal resolution, and initial ice-crystal concentrations) to ensure that the derived time scales are robust and not resolution-dependent. Conducting these additional experiments lies beyond the scope of the present study but represents a valuable direction for future work.

In the revised manuscript, we have nevertheless added more quantitative context where appropriate to complement the descriptive–comparative analysis. We believe this approach remains appropriate for the goals of the study and provides a clear foundation on which more detailed time-scale-based analyses may build in subsequent work.

To address the reviewer's comment, we have added a paragraph in subsection 3.2 ("Contrail-Induced Changes in Relative Humidity within Ice-Supersaturated Regions") of the revised manuscript (lines 305–310).

3. Simulation scenarios

The authors use 8 different scenarios, which are completely simulated using the nested approach and all the investigations. However, it is never stated anywhere, why they choose these cases. For me it is completely unclear what the authors want to show or investigate with these different cases. In consequence it remains completely unclear what differences in the meteorological conditions have an influence on the life cycle of the contrail- ice cloud system. This kind of arbitrary choice is reflected in the description of the results. There is not really an attempt to make a kind of generalization of the features one has found in the different cases.

The authors should rethink their choice of simulation scenarios, also in terms of evaluations of the results using the physics based investigations as mentioned above. Maybe it would be better to use more idealized scenarios in order to determine the impact of contrails under certain, clearly prescribed, conditions, before using realistic scenarios.

We thank the reviewer for noting that the rationale behind our eight simulation scenarios was insufficiently explained. The cases were chosen to represent a range of **realistic, cloudy, and ice-supersaturated environments**.

In the preprint manuscript version, Figure A1 attempted to visually compare the different control cases. However, we agree with the reviewer that the manuscript did not clearly explain the selection criteria or quantitatively describe the background conditions.

In the revised version, we have added a dedicated subsection —

Section 2.3: Simulation Case Selection and Background Conditions —

where we now clearly describe the motivation for selecting these eight cases. We provide a quantitative characterization of each background state using tables and relevant time series. Furthermore, we merged the former Sections 2.3 and 2.4 into a single, streamlined section (**now Section 2.4: Contrail Formation and Initialization in ICON**) for improved clarity.

We acknowledge the reviewer's concern that drawing general conclusions from non-idealized, realistic simulations is challenging. This is precisely why we were cautious about making strong quantitative generalizations in the manuscript. Our purpose in comparing the same perturbation across eight different cloudy backgrounds is to emphasize that **contrail evolution in cloudy ISSRs is influenced by more than relative humidity and the Schmidt–Appleman criterion alone**. Specifically, the simulations demonstrate the importance of:

- temporal moisture supply,
- the vertical structure of the ISS layer below flight level, and

- atmospheric stability.

These factors jointly determine contrail persistence and growth. The revised manuscript now lays out this rationale and the background conditions more clearly, enabling the reader to better understand why these eight scenarios were selected and what physical insights they provide. we have also clarified the purpose of the simulations in subsection 2.5 ("Designing Aircraft Flight Paths Considering Persistent Contrail Formation Zones") of the revised manuscript (lines 249–251).

4. Presentation of results

It is really difficult to understand what the key findings of the study really are. The different simulations are described with plain text and some numbers in the text, however, a clear picture is lacking. The figures are also not really convincing. For instance, it is not really appropriate to use model levels (or even difference in model levels) as vertical coordinate.

The whole section of results should be rewritten along the main physical features (guided by the physical processes and their interactions) in order to highlight the major results.

We agree with the reviewer that presenting vertical extent solely in terms of model-level differences is not ideal, and we appreciate the reviewer's comment. Although the "height level differences" used in the original figures conveniently indicated the relative distance from flight altitude—given the nearly uniform layer thickness in the upper troposphere. In the revised manuscript, all relevant vertical axes now include geometric altitude (m) in addition to the model-level differences to provide a clearer and more intuitive representation.

Regarding the presentation of the results, our intention was to compare how an identical initial ice-crystal-number perturbation (the contrail) evolves within different supersaturated cloudy backgrounds. The simulations show that contrail growth in cloudy ISSRs depends not only on relative humidity and the Schmidt–Appleman criterion, but also on the time-varying structure of the surrounding atmosphere, particularly:

- the temporal supply of moisture,
- the vertical structure and depth of the ISS layer below flight altitude, and
- the degree of atmospheric stability.

References

Bley, S., Deneke, H., Senf, F., and Scheck, L.: Metrics for the evaluation of warm convective cloud fields in a large-eddy simulation with
Meteosat images, Quarterly Journal of the Royal Meteorological Society, 143, 2050–2060, 2017.

Burkhardt, U. and Kärcher, B.: Process-based simulation of contrail cirrus in a global climate model, Journal of Geophysical Research: Atmospheres, 114, 2009.

Dixit, V., Nuijens, L., and Helfer, K. C.: Counter-gradient momentum transport through subtropical shallow convection in ICON-LEM
simulations, Journal of Advances in Modeling Earth Systems, 13, e2020MS002 352, 2021.

Gruber, S., Unterstrasser, S., Bechtold, J., Vogel, H., Jung, M., Pak, H., and Vogel, B.: Contrails and their impact on shortwave radiation and
photovoltaic power production–a regional model study, Atmospheric Chemistry and Physics, 18, 6393–6411, 2018.

Heinze, R., Dipankar, A., Henken, C. C., Moseley, C., Sourdeval, O., Trömel, S., Xie, X., Adamidis, P., Ament, F., Baars, H., et al.: Large-
eddy simulations over Germany using ICON: A comprehensive evaluation, Quarterly Journal of the Royal Meteorological Society, 143,
69–100, https://doi.org/10.1002/qj.2947, 2017.

Kärcher, B., Hendricks, J., and Lohmann, U.: Physically based parameterization of cirrus cloud formation for use in global atmospheric
models, Journal of Geophysical Research: Atmospheres, 111, https://doi.org/10.1029/2005JD006219, 2006.

Kiszler, T., Chellini, G., Ebell, K., Kneifel, S., and Schemann, V.: A performance baseline for the representation of clouds and humidity for
cloud-resolving ICON-LEM simulations, in: EGU General Assembly Conference Abstracts, pp. EGU22–8575, 2022.

Phillips, V. T., DeMott, P. J., and Andronache, C.: An empirical parameterization of heterogeneous ice nucleation for multiple chemical
species of aerosol, Journal of the atmospheric sciences, 65, 2757–2783, https://doi.org/10.1175/2007JAS2546.1, 2008.

Prill, F., Reinert, D., Rieger, D., and Zängl, G.: ICON tutorial 2023: Working with the ICON model, Deutscher Wetterdienst, 2023.

Schemann, V. and Ebell, K.: Simulation of mixed-phase clouds with the ICON large-eddy model in the complex Arctic environment around Ny-Ålesund, Atmospheric Chemistry and Physics, 20, 475–485, 2020.

Seifert, A. and Beheng, K. D.: A two-moment cloud microphysics parameterization for mixed-phase clouds. Part 1: Model description, Meteorology and atmospheric physics, 92, 45–66, https://doi.org/10.1007/s00703-005-0112-4, 2006

Singh, S. and Kalthoff, N.: Process studies of the impact of land-surface resolution on convective precipitation based on high-resolution
ICON simulations, Meteorology, 1, 254–273, 2022

Verma, P. and Burkhardt, U.: Contrail formation within cirrus: ICON-LEM simulations of the impact of cirrus cloud properties on contrail
formation, Atmospheric Chemistry and Physics, 22, 8819–8842, https://doi.org/10.5194/acp-22-8819-2022, 2022.

Voigt, C., Schumann, U., Minikin, A., Abdelmonem, A., Afchine, A., Borrmann, S., Boettcher, M., Buchholz, B., Bugliaro, L., Costa, A.,
et al.: The airborne experiment on natural cirrus and contrail cirrus with the high-Altitude long-range research aircraft halo, B. Am.
Meteorol. Soc., 98, 271–288, 2017.