Authors' Response to Reviewers' Comments

Manuscript No.: egusphere-2026-328, submitted to GMD
Title: ICON coupled to HAM-lite 1.0 in limited-area mode: an efficient framework for targeted kilometer-scale simulations with interactive aerosols

Authors: Bernd Heinold, Philipp Weiss, Sadhitro De, Anne Kubin, Jason Müller, Fabian Senf, Philip Stier, and Ina Tegen

Anonymous Referee #1

Received and published: 7 Apr 2026

We would like to thank the anonymous reviewer for her/his time and constructive comments, and hope that we have responded satisfactorily to all the points raised.

The manuscript describes the first application of the HAM-lite aerosol microphysics model coupled to ICON in a limited area mode for computationally efficient high-resolution simulations on a regional scale. The model results are evaluated against various observations for three different regional case studies.

The paper is a relevant contribution to the field of scientific modelling and is well suited for GMD. It presents novel development and model applications of aerosol modelling on the regional scale that can serve as a basis for future studies with this model system. The methods and model description are well documented and the conclusions are well supported by the presented results. The manuscript is very well written and organized and there are, in my opinion, only a few issues that should be addressed or clarified.

General comments:

Please provide some representative quantitative metrics to describe the model's ability and performance when comparing against observations. The authors often mention a "good agreement" between model results and observations. While this is surely the case from looking at the respective comparisons, it should be underlined by providing some quantitative metrics (e.g. standard deviation, correlation coefficient, etc., see specific comments below). Maybe some representative numbers on the model performance could also be added to the abstract.

Many thanks for this valuable suggestion. We have added quantitative evaluation metrics to the corresponding figure panels, including the correlation coefficient (R), root mean square error (RMS), normalized RMS error (nRMS), bias, normalized bias, and the ratio between simulated and observed standard deviation (sigma_mod/sigma_obs). These metrics are now also briefly discussed in the revised manuscript to support the interpretation of the model performance. However, because the manuscript evaluates model performance across three distinct case studies and aerosol regimes with varying statistical behaviour, we consider a qualitative summary more appropriate for the abstract. Instead, we summarize the overall model performance and key systematic biases qualitatively, while the detailed quantitative *evaluation metrics are provided and described in the main text and figures (new Tab. 3, Figs. 3 and 5; please also see the responses below).*

Specific comments:

- Line 37: "… HAM-lite needs only one prognostic variable for each mode …". It could be stated already here that this is the number concentration.

  Thank you for this helpful suggestion. We have clarified the text by explicitly stating at this point already that the prognostic variable in HAM-lite is the aerosol number concentration of the respective mode.

- Table 1 provides not much information by itself and could potentially be combined with Table 2.

  Agreed. In the revised version of the manuscript, we have removed the original Table 1 and instead incorporated the information on aerosol size ranges into Table 2 (now Table 1), which now provides a comprehensive overview of the selected aerosol modes, including their size ranges, compositions and physical properties.

- Section 2.5.1 "Model configuration":

  - Line 191: Please also provide the resolution of the global ICON grid.

    We thank the reviewer for the comment. To avoid possible confusion with ICON configurations employing global grids plus regional refinement, we clarified in the revised manuscript that all simulations are performed exclusively in limited-area mode using the R2B10 grid.

  - Lines 205f: Please provide the information on how the different emissions are attributed to the respective aerosol modes (or refer again to the previous publication of Weiss et al., 2025)

    Many thanks for spotting this gap in the information. We added a brief clarification describing how anthropogenic emissions are assigned to aerosol modes in HAM-lite. Similar to Weiss et al. (2025), anthropogenic emissions are attributed to the internally mixed carbonaceous and sulfuric modes according to the prescribed modal composition. In contrast to Weiss et al. (2025), the anthropogenic and wildfire emission were taken from CEDS and GFAS instead of ACCMIP. The different mass fluxes lead to slightly different volume fractions (cf. Eqs. 5-7 in Weiss et al., 2025).

- Section 2.6 "Computational performance": Could you compare the computational cost of an ICON-HAM-lite LAM simulation with that of an ICON-HAM LAM? This would highlight the necessity for the simplified scheme regarding the aspect of computational efficiency also for the case of regional model simulations.

  We strongly agree that a direct comparison between a limited-area configuration of ICON–HAM-lite and the full ICON–HAM (M7 version) would be highly valuable for *quantifying the computational benefit of the simplified aerosol scheme. However, a LAM configuration of the ICON model coupled to the full HAM is currently still under development and therefore not yet available for a consistent benchmark comparison. For this reason, we are presently unable to provide a reliable estimate of the computational differences. Nevertheless, the reduction in computational cost is expected to be substantial, as HAM-lite requires only five aerosol tracers compared to 25 aerosol tracers in the full HAM-M7 configuration. Since tracer transport and associated aerosol processes represent a major contribution to the computational costs of aerosol-climate simulations, this reduction in prognostic variables is one of the key design features of HAM-lite.*

- Section 4.1 "PM2.5 pollution over Germany":

  – The observed PM2.5 values may also contain a contribution from e.g. NH4 and NO3 aerosol species, which are, however, not represented in the HAM-lite aerosol mode structure used here. The authors should discuss this bias in more detail. Is it possible to estimate the contribution of these missing aerosol components for the station comparisons, e.g. from a simulation with the full aerosol scheme HAM or from the observations itself?

    We agree that the absence of secondary inorganic aerosol species such as ammonium and nitrate likely contributes to the underestimation of PM2.5 concentrations, particularly at rural background stations and during pollution episodes influenced by long-range transport. However, a quantitative estimate of this missing contribution is difficult within the scope of the present study. The limited-area configuration of the full ICON–HAM model, including interactive aerosol microphysics and chemistry, is currently still under development and therefore not yet available for direct comparison simulations (see previous reply). In addition, the contribution of nitrate and ammonium aerosols is highly variable in space and time due to their strong dependence on temperature, humidity, and gas–particle partitioning processes. We have therefore chosen not to apply a simple offset correction to the model results. Instead, we expanded the discussion in the revised manuscript to clarify that missing secondary inorganic aerosol formation likely contributes to the systematic PM2.5 biases identified in the station comparisons.

  – The authors should add some quantitative metrics to Fig. 3 and to the text, e.g. standard deviation, correlation coefficient, etc. An overall metric considering all German stations (Fig. 2) would also help to address the model performance in this case study.

    As mentioned above, we have added quantitative evaluation metrics to the corresponding panels in Fig. 3. This includes the correlation coefficient (R), root mean square error (RMS), normalized RMS error (nRMS), bias, normalized bias, and the ratio between simulated and observed standard deviation (sigma_mod/ sigma_obs). The metrics are used to support the evaluation of the model performance in the respective sections of the text. In addition, those metrics were also calculated for the German stations shown in Fig. 2. However, rather than *providing a single aggregated metric over all stations, which would combine substantially different aerosol regimes and station environments, we evaluated the model performance separately for background and industrial stations. Mean statistical metrics for both station classes, have been included in an additional table in the revised manuscript. This separation provides a more meaningful assessment of the model performance across different observational environments.*

- Section 4.2 "Sea salt aerosol in the Atlantic Arctic":

  - Why is this evaluation performed on a daily-mean basis (i.e. with a lower temporal resolution than in the previous section)?

    Whilst measurements taken aboard the RV Polarstern are available at a higher temporal resolution of 90 seconds, only daily values are available for the EMEP stations shown. We have therefore decided to use the daily mean consistently for the comparison.

  - Again, the evaluation would benefit from additional quantitative metrics in Fig. 5 and in the text.

    Quantitative evaluation metrics have also been added to Fig. 5 and the corresponding text description. During this revision, we also noticed that the original submission inadvertently included an outdated version of Fig. 5. The figure and the corresponding discussion in the text have therefore been updated using the final model dataset. The overall interpretation and conclusions remain unchanged.

Technical corrections:

- Line 79: Add "geometric" in front of "standard deviation"

  Done.

- Line 158: Typo "… properties properties …"

  Corrected.

- Line 216: Typo "… kW,m-2"

  Corrected.

Anonymous Referee #2

Received and published: 26 Apr 2026

We would like to thank the anonymous reviewer for her/his time and constructive comments, and hope that we have responded satisfactorily to all the points raised.

This study develops and introduces a new limited-area version of the ICON-HAM-Lite model, enabling higher-resolution regional simulations with interactive aerosol representation while maintaining minimal computational cost. The authors further evaluate their simulations against observations and demonstrate generally good performance.

Overall, I consider this a valuable contribution to the community. In particular, using insights from LAM simulations to improve the global ICON-HAM-Lite model appears to be a very promising direction, given their seamless coupling framework. The manuscript is well written and well structured. I only have minor comments below and recommend the manuscript for publication in GMD once these have been addressed.

L74–76: Please also clarify the volume fractions used in the four-mode setup. Although they appear in Table 2, a brief mention or cross-reference here would improve readability.

We thank the reviewer for this helpful suggestion. To improve readability and clarify the 4-mode aerosol setup, we added a brief cross-reference in the general model description pointing the reader to Table 1, where the aerosol composition, including the applied volume fractions, is summarised.

Table 1: Are the nucleation and Aitken modes not considered in the model? If so, it would be clearer to remove them from Table 1 to avoid confusion.

That is correct; the nucleation and Aitken modes are not taken into account in the current model configuration, although they are in principle possible. In the revised manuscript, we have removed the original Table 1 to avoid redundancy and potential confusion regarding aerosol mode representation. Instead, the information on aerosol size ranges has been integrated into Table 2 (now Table 1), which now provides a unified overview of aerosol modes, including their size regimes, compositions, and physical properties. This modification clarifies that accumulation and coarse modes represent the actively simulated aerosol populations.

L107: It would be helpful for general readers to specify which intermediate transformation steps are missing here.

We have clarified the description by explicitly indicating the types of intermediate processes that are not resolved in the prescribed emission approach. In particular, these include secondary aerosol formation and aging processes such as gas-to-particle conversion (e.g. secondary inorganic and organic aerosol formation), coagulation, and condensation-driven particle growth. In the revised manuscript, we now specify that these processes are not explicitly simulated but are partly represented in a bulk sense through the prescribed modal composition and size distribution.

The model offers good flexibility to adjust modal radii, volume fractions, and densities. However, this also raises a question: should the same setup be adopted in both the global and LAM versions of ICON-HAM-lite, especially if the LAM is intended to inform development of the global version?

In principle, using consistent aerosol settings in both the global and LAM configurations is desirable, especially since one aim of the regionalized ICON–HAM-lite framework is to support developments that can later be transferred to the global model version. At the same time, the prescribed aerosol properties in the present simplified modal setup represent effective aerosol characteristics at the respective model scale. Because explicit aerosol microphysics and aging processes are not included, the prescribed properties in the global configuration must implicitly reflect aerosol evolution during long-range transport and large-scale mixing, while regional LAM applications may focus more strongly on local or source-specific aerosol conditions. The extent to which identical parameter settings are appropriate may also depend on the aerosol species itself, as different aerosol types exhibit distinct source characteristics, atmospheric lifetimes, transport pathways, and aging behaviour. Therefore, identical parameter settings are not necessarily optimal for both configurations. Nevertheless, preserving a physically consistent framework between regional and global applications remains an important objective for future model development.

To address this particular point in the manuscript, the following sentence was added at the end of Section 2.1: 'The optimal choice of prescribed aerosol properties may differ between global and regional configurations, depending on aerosol-specific transport, mixing, and aging characteristics across scales.'

L191: The LAM model is run at 2.5 km resolution. It would be very interesting to clarify which key processes are still parameterized and which are explicitly resolved at this scale.

Although the 2.5 km configuration explicitly resolves deep convection and associated mesoscale dynamics, several sub-grid-scale processes still require parameterization. We therefore added a brief clarification in the manuscript noting that cloud microphysics, radiation, turbulence, and aerosol-related processes such as activation, deposition, sedimentation, and optical properties remain parameterized in the ICON–HAM-lite LAM configuration.

Table 3: The time periods listed in the table do not appear to be consistent with those in the main text. Please check and correct if necessary.

Thank you very much for pointing out this inconsistency, which originates from an earlier version of the manuscript. The data in the table were correct and have been incorporated into the main text.

L207: Are the biogenic emissions also taken from CEDS? If not, does it also provide data for the simulation year?

The biogenic emissions are not taken from CEDS but follow the inventory of Guenther et al. (1995), consistent with the original HAM configuration, as stated in the manuscript. The applied dataset is representative of climatological conditions around the year 2000 rather than the specific simulation years. To clarify this point, we extended the following sentence:

“The biogenic emissions are taken from the inventory of Guenther et al. (1995), which represents climatological biogenic emissions.”

L229-232: Have you tested how the results change if CAMS lateral boundary conditions are also applied to the Arctic and Australian cases?

Contrary to the original wording in the manuscript, CAMS aerosol lateral boundary conditions were also applied in the Atlantic Arctic case (April 2020) to account for long-range transport of sea-spray aerosols. Only the Australian bushfire smoke and desert dust case (December 2019) was performed without aerosol lateral boundary conditions, since the dominant aerosol sources are located within the model domain. We added a corresponding clarification to the manuscript.

L261-263: The ICON-HAM-lite model uses accumulation and coarse modes; I wonder how PM2.5 is calculated here. Typo: μor◊ μm

For comparison with measured PM2.5, aerosol mass concentrations are calculated offline from simulated number concentrations using the volume-mean (mass-equivalent) radius and prescribed particle density of each log-normally distributed aerosol mode. Total aerosol mass is obtained by summing contributions from the four model aerosol modes, and a PM2.5 size cut-off is applied. A corresponding sentence was added to this paragraph; the typo was corrected.

L304: I’m not sure if nitrates and ammonium are good examples here as HAM-lite doesn’t consider these species. This also partially contributes the underestimation of PM2.5 by model.

We thank the reviewer for this helpful comment. We agree that nitrates and ammonium are not particularly good examples, as they are not explicitly represented in the current HAM-lite configuration, and therefore should not be highlighted in the introductory discussion of PM2.5. We revised the text accordingly and now refer more generally to long-range transport contributions and secondary aerosol formation. The missing representation of secondary inorganic aerosol is further discussed later in the manuscript as a likely contributor to the model underestimation of PM2.5.