

Response to Reviewers

Manuscript: Hoshyaripour et al. (2025), GMD

We sincerely thank both reviewers for their detailed and constructive comments, which helped us improve the manuscript.

Reviewer comments are presented in blue, our replies follow in black, followed by the corresponding changes in the revised manuscript in italic format.

Reviewer 1:

1. The large number of the acronyms has been used in the whole manuscript and it is suggested to add a separate Appendix describing this manuscript.
 - We added an Appendix for clarity of Acronyms.

Appendix A: Acronyms

ICON	<i>ICOsahedral Non-hydrostatic</i>
ART	<i>Aerosols and Reactive Trace gases</i>
OEM	<i>Online Emission Module</i>
VPRM	<i>Vegetation Photosynthesis and Respiration Model</i>
ARI	<i>Aerosol-Radiation Interaction</i>
ACI	<i>Aerosol-Cloud Interaction</i>
CAMx	<i>Comprehensive Air Quality Model with Extensions</i>
CAABA	<i>Chemistry As A Boxmodel Application</i>
MECCA	<i>Module Efficiently Calculating the Chemistry of the Atmosphere</i>
KPP	<i>Kinetic Pre-Processor</i>
FKB	<i>Fortran-Keras Bridge</i>
LAM	<i>Limited-Area Mode</i>
MOZART	<i>Model for Ozone and Related chemical Tracers</i>
LINOZ	<i>LINearized OZone</i>
NMVOC	<i>Non-Methane Volatile Organic Compounds</i>
NO_x	<i>Nitrogen Oxides</i>
NO_y	<i>Reactive Nitrogen Compounds</i>
PSCs	<i>Polar Stratospheric Clouds</i>
NAT	<i>Nitric Acid Trihydrate</i>
STS	<i>Supercooled Ternary Solution</i>
INAS	<i>Ice Nucleation Active Site</i>
SPPs	<i>Subpollen Particles</i>
DRE	<i>Direct Radiative Effect</i>
EDGAR	<i>Emission Database for Global Atmospheric Research</i>
CAMS-REG	<i>Copernicus Atmosphere Monitoring Service Regional inventory</i>
GNFR	<i>Gridded Nomenclature For Reporting</i>
GFAS	<i>Global Fire Assimilation System</i>
FRP	<i>Fire Radiative Power</i>

2. The caption of the Table and Figure could be modified to be self-explanatory. e.g., Table 1-2 give the brief overview of the Basis v Implementation. It can re-written what basis is about etc.
- Both tables 1 and 2 are revised by providing additional info in the caption.

Table 1: Emissions in the ICON-ART model system including the main technical/scientific basis and references of the parameterization and the first published implementation in the ART framework.

Table 2: Types of chemistry in ART including reference to their main technical/scientific descriptions and the first published implementation in the ICON-ART framework.

3. As noted in lines 43–45, previous work with ICON-ART has been acknowledged, while this manuscript aims to present an updated overview. However, it would be helpful to clarify which components are entirely new in the version 25.04 and which represent updates to existing implementations. For instance, while the Online Emission Model (OEM) is mentioned as part of version 25.04, the manuscript does not clearly indicate how this anthropogenic emission component was handled in earlier versions. In contrast, Section 2.3, which covers volcanic eruptions, provides an excellent and detailed account of the updates made—offering a useful model for how other sections might be strengthened with similar clarity.
- Our intention in Table 1 and the accompanying text was to highlight only the new or substantially revised features introduced in this paper, while referring readers to the existing model description papers for all previously implemented components. To make this clearer, we have now highlighted in Table 1 the implementations that are new and represent updates of previously published implementations.

Table 1: Emissions in the ICON-ART model system including the main technical/scientific basis and references of the parameterization and the first published implementation in the ART framework. The new features presented in this work are shown in bold.

Emission Type	Technical Basis & Reference(s)	Implementation in ART
Anthropogenic	Prescribed (Weimer et al., 2017), OEM (Jähn et al., 2020)	Weimer et al. (2017); Jähn et al. (2020), see Sect. 2.1
Wildfires	GFAS (Kaiser et al., 2012) and Plume-rise model (Freitas et al., 2007)	Walter et al. (2016), see Sect. 2.2
Volcanic	1D model FPlume (Folch et al., 2016)	Bruckert et al. (2022), see Sect. 2.3
Desert Dust	Saltation-based (Vogel et al., 2006)	Rieger et al. (2017)
Sea Salt	Wave breaking and whitecap formation (Monahan et al., 1986; Smith and Harrison, 1998; Mårtensson et al., 2003), SST-dependant (Grythe et al., 2014)	Lundgren et al. (2013); Rieger et al. (2015); see Sect. 2.4
DMS	DMS conc. in ocean (Lana et al., 2011)	see Sect. 2.5
Biogenic VOCs	MEGAN (Guenther et al., 2012)	Weimer et al. (2017)
Pollen	EMPOL (Zink et al., 2013)	Zink et al. (2013), see Sect. 2.6
Point source	Rieger et al. (2015)	Rieger et al. (2015)

4. Section 5.2 provides a comprehensive description of the CCN activation and its coupling with ICON microphysics for liquid-phase clouds. While the methodological explanation is clear, given that ACI is emphasized in the abstract as a key development, this section could be further strengthened by including a brief quantitative validation or sensitivity analysis demonstrating the realized impact of ACI. The INAS-based treatment for ice-phase ACI is still under development and may be incorporated in future work.
 - We have added the following text and figures to the CCN activation. As mentioned in the paper, INAS-based activation is already implemented and available in ART but not yet coupled to the 2-mom scheme of ICON.

Figures 11 and 22 show preliminary results from idealized simulations of a warm bubble. The model setup follows the Weisman-Klemp test case (Weisman and Klemp, 1982). A predefined sea salt concentration of 2×10^7 #/kg is uniformly distributed throughout the domain and equally distributed between the accumulation and coarse modes. Figure 11 displays the number of activated cloud condensation nuclei (n_{ccn}) in #/kg, accumulated over 640 seconds from the start of the simulation. Sea salt aerosols are activated within the updraft region generated by the warm bubble. Figure 12 illustrates the ratio of activated particles to available sea salt aerosols as a function of vertical velocity, for (a) accumulation and (b) coarse mode. The results indicate that, as expected, a substantial fraction of sea salt in the coarse mode gets activated, whereas only a small portion of sea salt in the accumulation mode undergoes activation. This outcome aligns with Köhler theory, which predicts that larger particles are more likely to be activated due to their lower critical supersaturation.

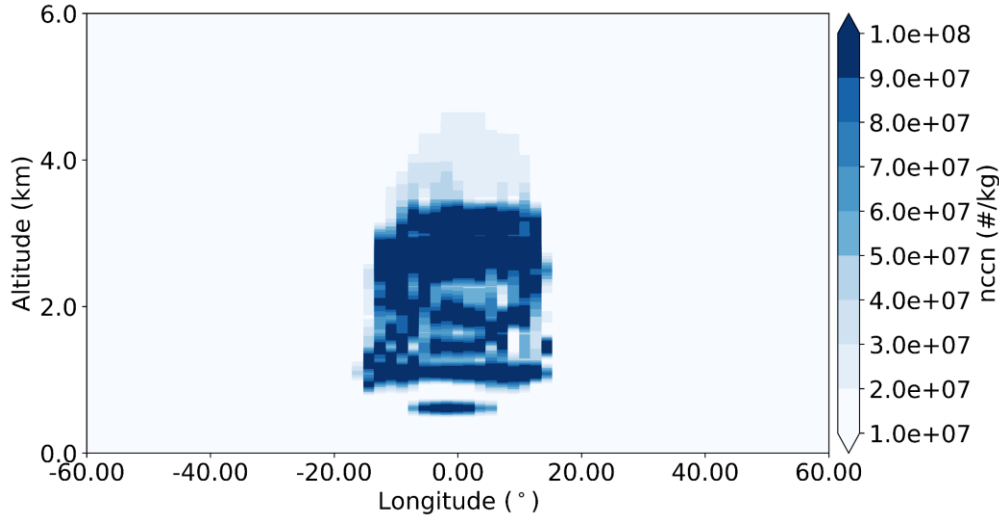


Figure 11: Number of activated sea salt aerosols from an idealized warm bubble simulation based on the Weisman-Klemp test case (Weisman and Klemp, 1982).

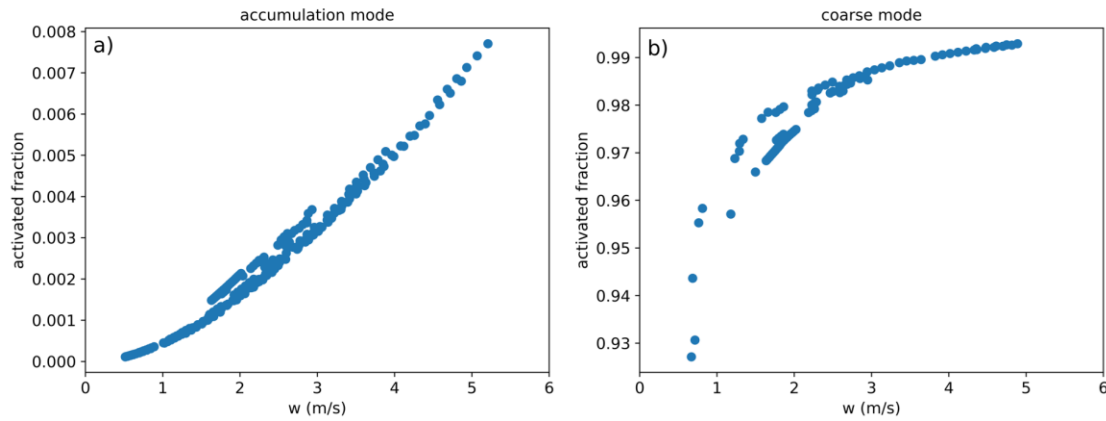


Figure 12: Ratio of activated particles to available sea salt aerosols as a function of vertical velocity, shown for (a) accumulation mode and (b) coarse mode.

5. Emission processes such as desert dust and biogenic VOCs (e.g., VPRM, mentioned later) are not discussed in the manuscript. It is suggested to include a brief discussion at the end of these in Section 2, or alternatively, add short descriptions to Table 1 (e.g., in Basis column) to make their inclusion and treatment clearer.
- To improve clarity, we have added short descriptive phrases for the desert dust and biogenic VOC emission processes in Table 1. These components are part of the established ICON-ART emission suite and are not newly implemented in version 25.04; therefore, they were originally described only briefly. We now additionally clarify this in

Section 2 by noting that these processes remain unchanged in the current model version and are summarized in Table 1 with full details available in the cited model description papers. For the modification of Table 1 please see the previous answer. The following text is added to the paper in section 2:

Processes that are already well established in ICON-ART, such as desert dust and biogenic VOC emissions, remain unchanged in version 25.04 and are therefore only briefly summarized in Table 1, with full details provided in the cited model description papers.

- In addition, we have added a short description of how VPRM is used for the simulation of CO₂ and added a reference to Ponomarev et al. (2025), where more details are provided. The text describing VPRM is:

VPRM was introduced to enable the simulation of atmospheric carbon dioxide, which is not only affected by anthropogenic emissions but also by exchange with the biosphere. A first application of VPRM in ICON-ART was demonstrated by Ponomarev et al. (2025).

6. Line 28-29 Page2: Repetition in the abbreviation defining, ICON, ART etc.

- Since this is a model description paper, the model names (ICON, ART, and ICON-ART) are essential identifiers and should appear clearly in the abstract. We therefore retained their definitions in the abstract for clarity and discoverability but removed the repeated definitions from the Introduction. The Introduction now refers to the models directly, assuming prior definition in the abstract.

The ICON model has been developed and widely used for weather and climate prediction across scales. It solves the 3D non-hydrostatic and compressible Navier–Stokes equations on an icosahedral-triangular grid (Gassmann and Herzog, 2008), facilitating precise predictions across scales (Zängl et al., 2015; Heinze et al., 2017; Giorgetta et al., 2018). The ART module, integrated into the ICON framework, enables comprehensive modeling of atmospheric composition.

7. Line 52-53: The reference needed which describe OEM in COSMO-ART.

- This is further provided in Table 1 and section 2.1.

8. Line 68: Hermes or HERMES (High-Elective Resolution Modelling Emission System)?

- Corrected to HERMES

9. Line 67 Is there anything missing in the line '[e.g.,]]]' ?

- Corrected to (e.g., Menut et al., 2024; Woo et al., 2012)

10. Line 175-180: The new Grythe et al. (2014) sea-salt emission parametrization is introduced in Section 2.4. A brief quantitative or visual comparison with the Monahan scheme could further illustrate the improvement in sea-salt emission estimates.

- To address this, we have expanded Section 2.4 with a short qualitative description of the key conceptual differences between the two parameterizations, focusing on their

treatment of whitecap coverage, particle-size distribution, and the explicit SST dependence introduced in Grythe et al. (2014). A detailed quantitative or visual comparison of emission fluxes would require a comprehensive analysis of the full emission–transport–deposition chain to ensure meaningful interpretation. Such an investigation goes beyond the scope of the present manuscript, which aims primarily to document the model developments and technical implementation. We therefore consider the new qualitative comparison sufficient for the purpose of this paper, while a full evaluation is planned for a dedicated follow-up study currently in preparation.

MMS and G14 sea-salt emission schemes differ not only in their whitecap formulations but also in their treatment of particle-size distributions and SST-dependent scaling (Grythe et al., 2014; Barthel et al., 2019; Li et al., 2024). Barthel et al. (2019) demonstrated that SST corrections can substantially reduce coarse-mode concentrations and may even have a larger impact than switching between source functions. They also found the strongest divergences for particles larger than PM_{2.5}, with SST effects further amplifying these differences. These insights highlight that the structural contrasts between MMS and G14 schemes, particularly the inclusion of SST dependence and the size-resolved flux formulation, can significantly influence emitted mass. While a quantitative evaluation is beyond the scope of this study, this context helps to clarify the expected behavior of the new G14 implementation.

11. Line 211: Meccatracer?

- We changed the sentence to:

The most complex tracers in ICON are those participating in chemical reactions described by a coupled system of Ordinary Differential Equations (ODE). These tracers are called meccatracer, because they are solved by the atmospheric chemistry module MECCA as described in Section 3.2.

12. Line 424-426: The sedimentation terms in Equations (12)–(13) use inconsistent symbols ($\Phi \rightarrow \Psi$). Please ensure consistent notation for the prognostic variable, either using the hat over Ψ throughout or omitting it consistently.

- This was a typo and is corrected accordingly. We use Ψ consistently through the paper.

$$\frac{\partial (\bar{\rho}_a \hat{\Psi}_{0,l})}{\partial t} = -\nabla \cdot (\hat{v} \bar{\rho}_a \hat{\Psi}_{0,l}) - \nabla \cdot (\overline{\rho_a v'' \Psi''_{0,l}}) - \frac{\partial}{\partial z} (v_{\text{sed},0,l} \bar{\rho}_a \hat{\Psi}_{0,l}) - W a_{0,l} - C a_{0,l} - N u_{0,l} - E m_{0,l} \quad (12)$$

$$\frac{\partial (\bar{\rho}_a \hat{\Psi}_{3,l})}{\partial t} = -\nabla \cdot (\hat{v} \bar{\rho}_a \hat{\Psi}_{3,l}) - \nabla \cdot (\overline{\rho_a v'' \Psi''_{3,l}}) - \frac{\partial}{\partial z} (v_{\text{sed},3,l} \bar{\rho}_a \hat{\Psi}_{3,l}) - W a_{3,l} - C a_{3,l} - N u_{3,l} - E m_{3,l} - C o_{3,l} - C h_{3,l} - E q_{3,l} \quad (13)$$

13. Line 515: ARI is already defined earlier in text.

- Definition is removed

14. The sub-labels in Figure 9 are difficult to read due to the white font color. Consider enclosing the letters in a contrasting box or background to improve visibility.

- Corrected

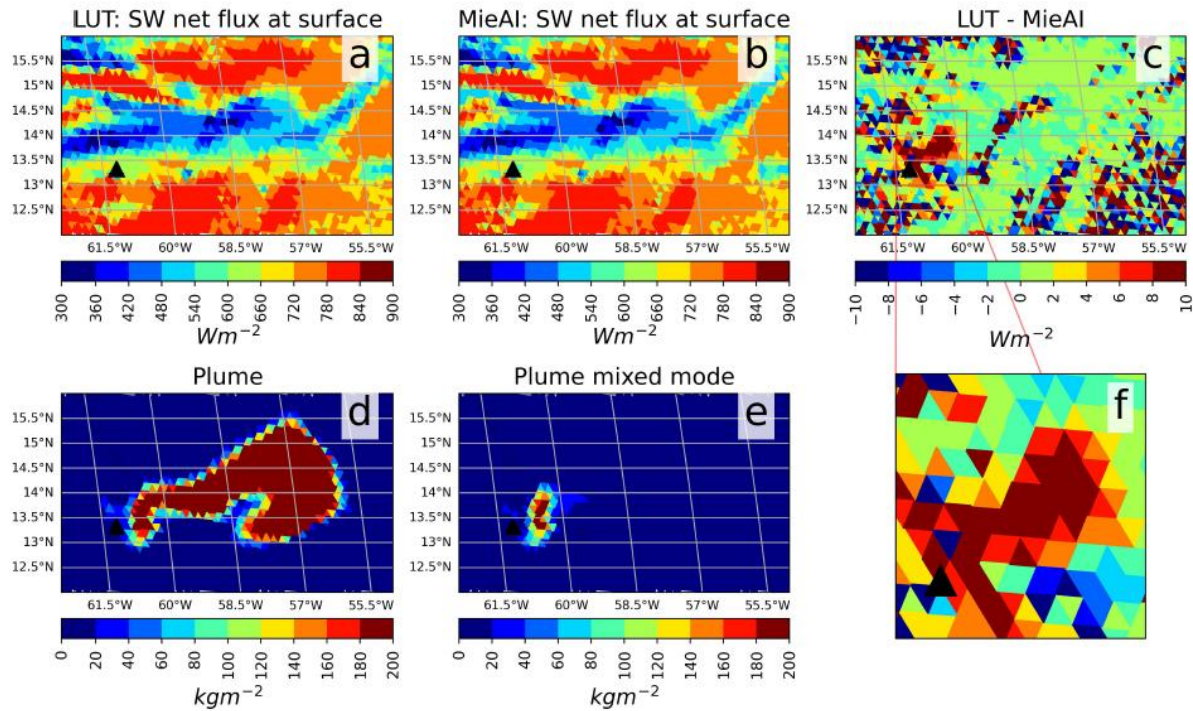


Figure 9. Comparison of net shortwave radiative flux estimated using MieAI against those estimated using Look-up table (LUT) approach for a case study involving the La Soufrière volcanic eruption (denoted by the black triangle) event simulated using ICON-ART. Here, panel a) shows the net SW flux estimated using LUT, b) shows the same estimated using MieAI and c) shows the absolute difference between them. The volcanic plume is depicted in panel d) whereas panel e) shows the mixed mode aerosols within the plume. Panel f) zooms panel c) over the plume region.

15. Line 697: Online Emission Module→ OEM

- Corrected

16. Line 712-713: vegetation photosynthesis and respiration model (VPRM)?

- As mentioned earlier, we have added a short description of how VPRM is used for the simulation of CO_2 including references to the original VPRM publication and to the first publication using VPRM within ICON-ART.

17. Appendix D and E do not seem cited or discussed in the text.

- Appendix D is indeed cited in section 3.2. A citation to appendix E is added to section 2.1:

XML tags and namelist settings for OEM are described in Appendix E.