Final report for project **1368**
Project title: **nextGEMS aerosols**
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Report period: **2025-07-01 to 2026-06-30**

1 Purpose and scientific objectives

Project 1368 *nextgems aerosols* built on the nextGEMS framework to advance the representation of aerosols in global kilometer-scale Earth system simulations. As an early outcome of the project, the computationally efficient HAM-lite aerosol module was coupled with the ICON-MPIM model, resulting in ICON-HAM-lite v1.0 (Weiss et al., 2025). This model provided the foundation for the subsequent work, which focused on improving the representation of mineral dust and aerosol–cloud interactions in global simulations at approximately 5 km horizontal resolution. These developments were intended to strengthen the physical basis for investigating aerosol effects on weather, climate, and the Earth's radiation budget in kilometer-scale simulations.

A central objective of this project was to improve the simulation of mineral dust emissions by implementing and evaluating two physics-based dust emission schemes based on Shao (2004) and Kok et al. (2014). Compared with the semi-empirical scheme of Tegen et al. (2019) used in ICON-HAM-lite v1.0, these schemes allow dust emissions to respond dynamically to surface winds, soil properties, and soil moisture. The project therefore sought to quantify how different dust parameterizations affect global dust emission and deposition, with particular emphasis on dust generated by moist convective systems and wind gusts that can be explicitly represented in kilometer-scale simulations.

A second major objective was to advance the representation and understanding of aerosol–cloud interactions. This included supporting the introduction and evaluation of two-moment cloud microphysics in ICON-HAM-lite and using targeted simulations to examine how aerosol perturbations, microphysical assumptions, and model configuration affect cloud properties and cloud radiative effects. This work aimed to improve the physical basis for representing aerosol–cloud interactions in regional and global kilometer-scale simulations.

2 Results

2.1 Development and evaluation of ICON-HAM-lite

During the early stage of the project, we developed the computationally efficient one-moment aerosol module HAM-lite and coupled it to the ICON Earth system model (Weiss et al., 2025). HAM-lite was derived from the two-moment module HAM. It represents aerosols as an ensemble of lognormal modes with prescribed sizes and compositions, which makes kilometer-scale simulations with interactive aerosols feasible. To test the coupled model, ICON-HAM-lite v1.0, we performed a first global simulation with four aerosol modes (dust, sea salt, carbonaceous, and sulfuric aerosol) at a resolution of 5 km over one year. The simulation captured key aerosol processes across scales, from the emission of dust by cold pool outflows over the Sahara to the interaction of sea salt aerosol with shallow convective storms around the doldrums. The aerosol burdens and lifetimes were comparable to those of established coarse-resolution models, but the aerosol optical depths were lower than those observed by MODIS.

Building on the global configuration, we developed a limited-area mode (LAM) of ICON coupled to HAM-lite (Heinold et al., 2026). In this mode, regional domains are initialized and driven at their lateral boundaries by global meteorological and aerosol data sets, such as the CAMS reanalysis. The framework remains fully consistent with the global model, which enables targeted kilometer-scale studies of regional aerosol processes whose insights can feed back into the development of the global model. We demonstrated its flexibility in three case studies at a resolution of 2.5 km: PM2.5 pollution episodes over Central Europe (1–11 March 2019), the emission and transport of sea salt aerosol in the Atlantic Arctic (1–12 April 2020), and the smoke and desert dust plumes of the 2019–2020 Australian bushfire season (26–31 December 2019). The simulations captured the regional patterns and diurnal variability of the predominant aerosol types, in good agreement with in-situ measurements and space-borne lidar profiles. They also revealed systematic biases related to the simplified representation of aerosol emissions, microphysics, and chemistry, which will guide the future development of HAM-lite.

Together, the global and limited-area configurations established the modelling framework for the subsequent developments and scientific analyses carried out within the project. Figure 1 summarizes the global and regional applications of ICON-HAM-lite.

2.2 Advancing the representation of mineral dust

Building on ICON–HAM-lite v1.0, we successfully implemented two physics-based dust emission schemes following Shao (2004) and Kok et al. (2014). We conducted a series of sensitivity experiments at 160 km resolution to identify suitable model configurations and evaluate the performance of the new schemes. Both physics-based configurations showed better overall agreement with dust observations than the original Tegen et al. (2019) configuration (Klose et al., 2026, in prep.).

Based on these sensitivity experiments, we performed two one-year global simulations at approximately 5 km horizontal resolution using the Shao (2004) and Kok et al. (2014) schemes, respectively. Both simulations reproduced the major dust source regions, long-range transport pathways, and broad seasonal characteristics of the global dust cycle, and showed good agreement with available observations. These experiments demonstrated that both physics-based schemes are suitable for global kilometer-scale aerosol simulations.

We then used the kilometer-scale simulations to investigate moist-convection-driven dust emissions. We developed an automated algorithm to identify and track haboobs and attribute the associated dust emissions to individual events. The method combines information on convective cooling, vertical motion, dust concentration changes, and near-surface winds to detect haboob leading edges and delineate the associated cold-pool regions. Figure 2 presents examples from North Africa and Australia, showing that the algorithm can identify haboobs under different regional conditions. We subsequently applied the algorithm to the full annual global simulation and conducted a systematic assessment of the contribution of haboobs to the global dust cycle (Li et al., 2026, in prep.).

2.3 Advancing aerosol–cloud interactions

To advance the representation of aerosol–cloud interactions in ICON-HAM-lite, we combined model development and testing with targeted studies using ICON-HAM and high-resolution ICON configurations. These studies examined the sensitivity of clouds and cloud radiative effects to aerosol perturbations, cloud microphysics, and model configuration across Arctic, Amazonian, and continental deep-convective environments.

2.3.1 Arctic aerosol–cloud interactions

We used the global aerosol–climate model ICON-HAM to examine the aerosol–cloud interactions that may result from increased Arctic ship traffic under pre- and post-IMO2020 fuel standards. We also evaluated the two-moment scheme in ICON-HAM to inform the introduction of two-moment cloud microphysics into ICON-HAM-lite. We ran a control experiment, a high-sulphur experiment, and a low-sulphur experiment at 160 km resolution in ICON-HAM for the years 2025–2100. We found that high-sulphur emissions produced a significant cooling over the 75–year mean as shown by the net atmospheric column cloud radiative effect, but that a change to low-sulphur emissions reduced the cloud radiative response in direct proportion to the sulphur reduction, leaving a signal indistinguishable from interannual variability (Fig. 3). We found that the aerosol–cloud interactions from projected ship emissions are unlikely to result in local cooling in a scenario that accounts for the IMO2020 reformulation of shipping fuels. Additionally, we found that the ICON-HAM default of a fixed minimum cloud droplet number concentrations (CDNC) of 40 cm^{-3} was too high for the purposes of simulating aerosol–cloud interactions in pristine regions. This finding directly informed the incorporation of two-moment cloud microphysics into ICON-HAM-lite v1.0.

2.3.2 Cloud-microphysical sensitivity in kilometer-scale simulations

We investigated the sensitivity of deep-convective cloud structure to cloud microphysics and model-domain configuration using regional and global kilometer-scale simulations over the Amazon. The comparison included regional simulations with single- and double-moment microphysics and a global

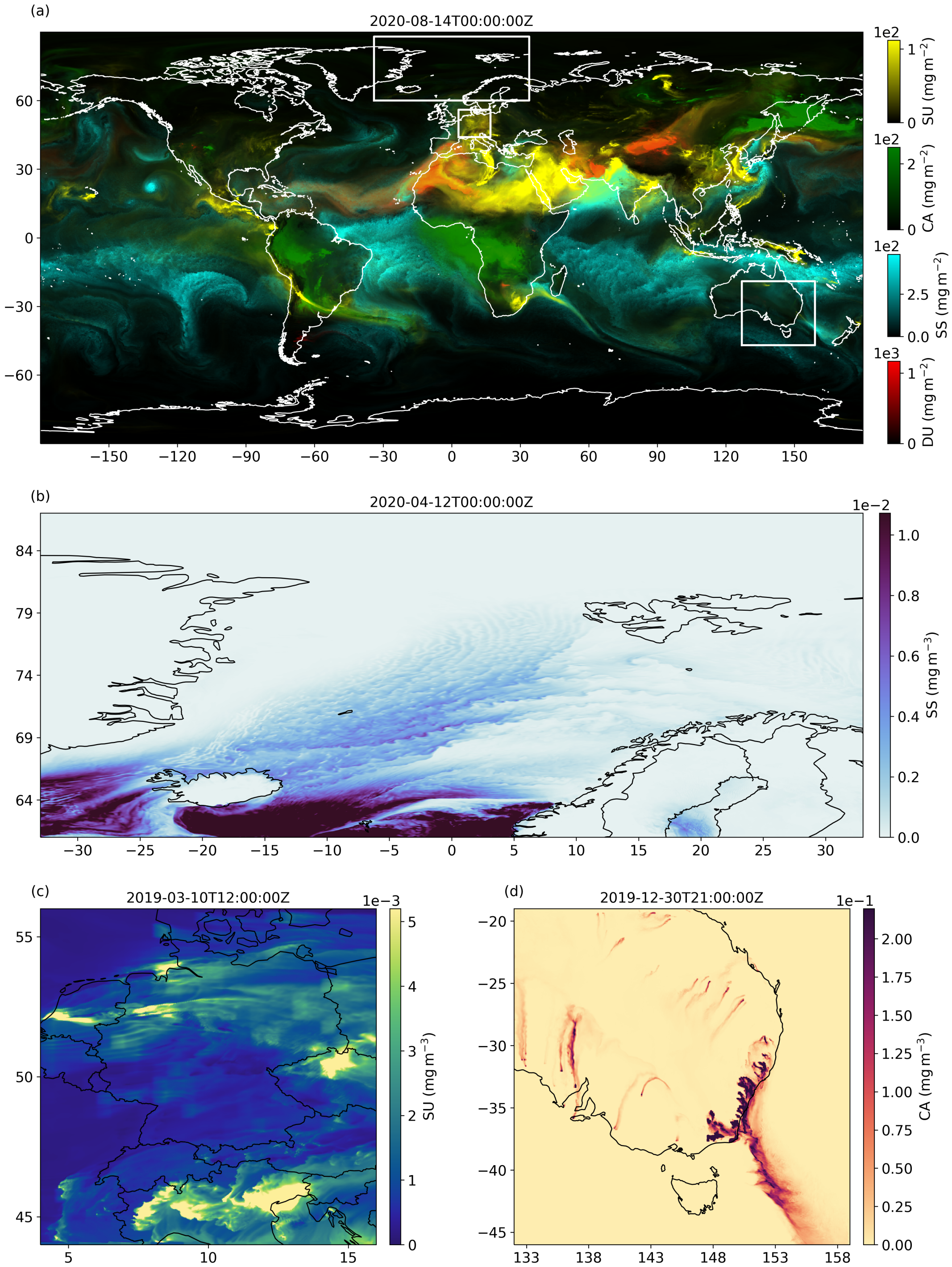

Figure 1: Scenes from the global simulation at a resolution of 5 km by Weiss et al. (2025) (a) and from the three regional simulations at a resolution of 2.5 km by Heinold et al. (2026) [(b), (c), and (d)]. Panel (a) shows column burdens of dust (DU), sea salt aerosol (SS), carbonaceous aerosol (CA), and sulfuric aerosol (SU) as well as the boundaries of the three regional simulations. The panels below show snapshot surface concentrations for individual examples of (b) sea salt (SS) over the Arctic, (c) sulfuric aerosol (SU) over Germany, and (d) carbonaceous aerosol (CA) over Australia.

simulation with single-moment microphysics. The simulations showed substantial differences in the vertical distribution of hydrometeors, particularly in near-surface cloud liquid water, fog, and ice-phase hydrometeors. The double-moment simulation produced much less near-surface cloud water than the regional single-moment simulation, whereas the global single-moment simulation produced the largest

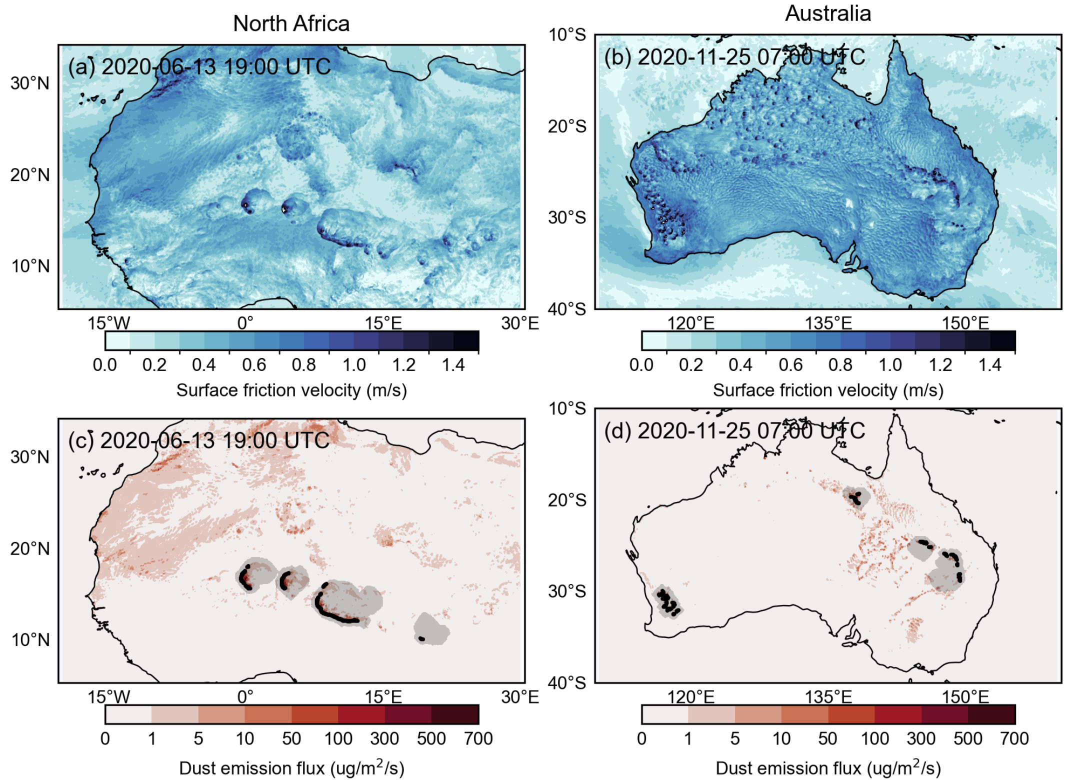

Figure 2: Examples of haboob identification over North Africa and Australia. Panels (a) and (b) show surface friction velocity, while panels (c) and (d) show the corresponding dust emission flux. Black dots in (c)–(d) indicate the identified haboob leading edges, and gray shading denotes the associated cold-pool regions.

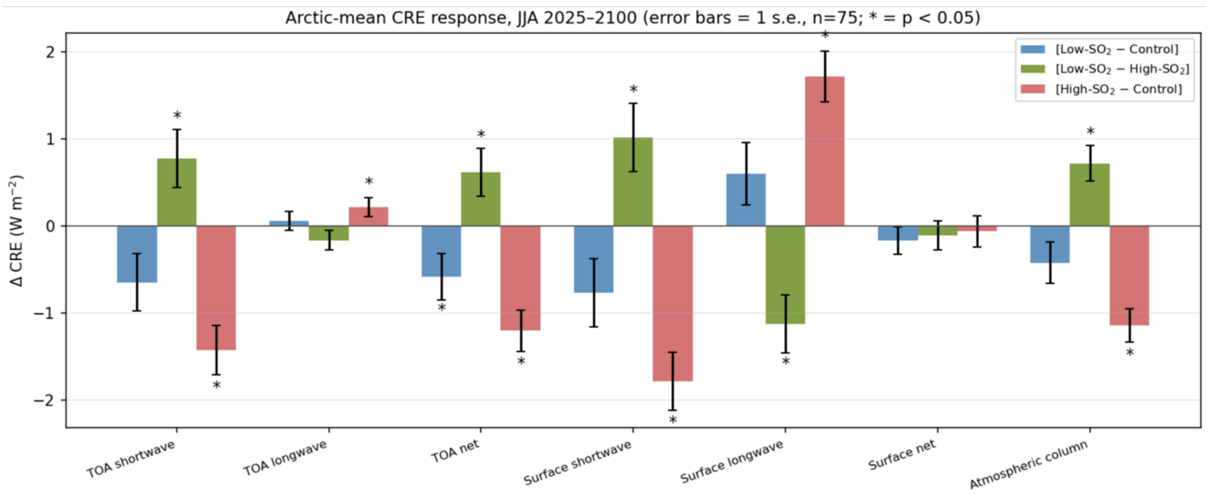

Figure 3: Arctic-mean changes in cloud radiative effect (CRE) for low-sulfur, high-sulfur, and control shipping-emission experiments over June–July–August 2025–2100. Bars show the mean responses in shortwave, longwave, and net cloud radiative effects at the top of the atmosphere, surface, and atmospheric column. Error bars indicate one standard error, and asterisks denote statistically significant differences at the 5 % level.

fog amounts (Fig. 4). The corresponding spatial distributions show that fog occurrence was considerably more widespread in the global simulation, while the regional double-moment simulation produced the lowest fog frequency across most of the domain (Fig. 5). It further shows that domain configuration controls how these sensitivities manifest, through differences in circulation, moisture transport, and convective organisation between regional and global km-scale simulations (Sela et al., 2025).

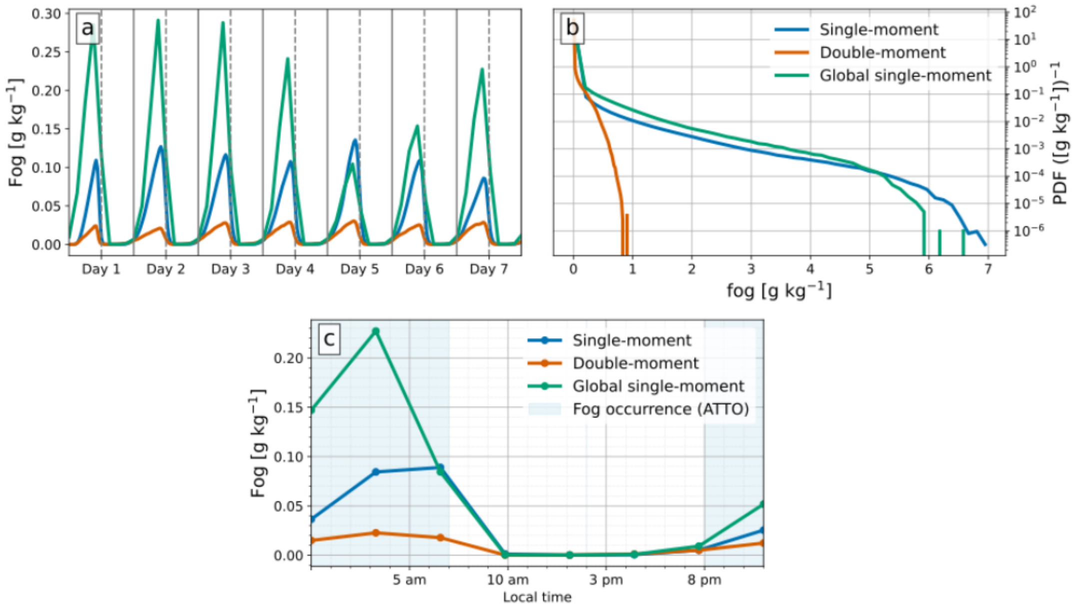

Figure 4: Sensitivity of simulated Amazon fog to cloud microphysics and domain configuration in ICON. The figure shows the (a) domain-mean time series, (b) probability density functions, and (c) mean diurnal cycle of cloud liquid water mixing ratio at the lowest model level for regional single-moment (blue), regional double-moment (red), and global single-moment (green) simulations. The comparison illustrates large differences in simulated fog between configurations, highlighting that both microphysical assumptions and domain setup can strongly affect near-surface cloud structure in kilometer-scale simulations.

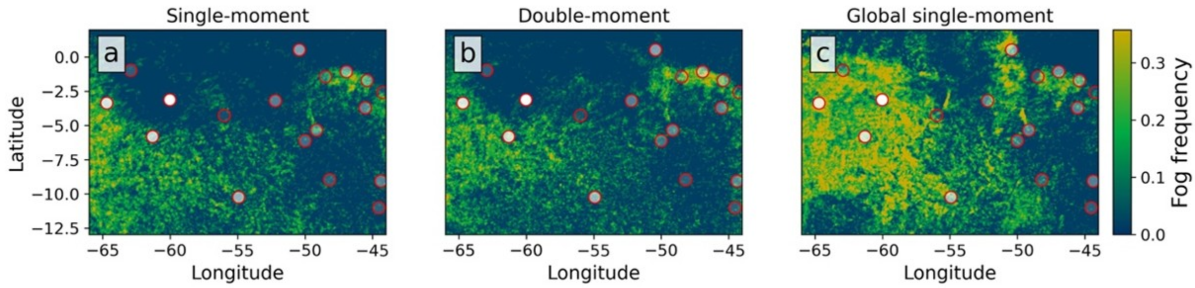

Figure 5: Spatial distribution of simulated fog occurrence frequency in ICON. The figure shows the fraction of analysed time steps in which the fog mass mixing ratio exceeds 0.01 g kg^{-1} for the (a) regional single-moment, (b) regional double-moment, and (c) global single-moment simulations. Red circles indicate SYNOP stations, with marker opacity representing the normalised observed frequency of fog events during the study period, defined using visibility below 1.5 km. Higher opacity corresponds to more frequent observed fog reports.

In a complementary study over the TRACER-MIP/Houston region, we examined how anthropogenic aerosol perturbations affect deep-convective-cloud lifecycles and associated cloud radiative effects from a cloud-microphysical perspective. Across two dynamically distinct case studies, aerosol perturbations affect convection, bulk deep-convective-cloud properties, vertical hydrometeor distributions, and cloud radiative effects, with polluted conditions producing approximately 3–4 W m^{-2} stronger cooling. The analysis further indicates a shift in dominant microphysical pathways, from stronger removal through riming under cleaner conditions toward enhanced suspension through nucleation and depositional growth under polluted conditions.

3 Summary

Overall, the project established ICON-HAM-lite as a framework for global and regional kilometer-scale aerosol simulations. Building on this framework, we improved the representation of mineral dust and advanced the treatment of aerosol–cloud interactions. The simulations and process studies carried out within the project provided new insights into aerosol emissions, transport, cloud processes, and radiative effects across a range of atmospheric environments. Together, these developments strengthen the basis for future applications of ICON-HAM-lite in kilometer-scale weather and climate research.

4 Resource usage

Table 1: Computational resources used by project 1368.

Resource	Amount
CPU time	456,794 node hours
Archived data	312.15 TiB

5 Publications from this project

Heinold, B., P. Weiss, S. De, A. Kubin, J. Müller, F. Senf, P. Stier, and I. Tegen (2026). "ICON coupled to HAM-lite 1.0 in limited-area mode: an efficient framework for targeted kilometer-scale simulations with interactive aerosols". *EGUsphere* 2026, pp. 1–31. https://doi.org/10.5194/egusphere-2026-328.

Klose, M., R. Li, P. Weiss, A. Baer, M. Gonçalves Ageitos, F. Marangio, P. Stier, and C. Pérez García-Pando (2026). "Advancing the mineral dust representation in ICON-HAM-lite 1.0: implementation and evaluation of two physics-based dust emission schemes". Manuscript in preparation.

Li, R., A. Baer, and M. Klose (2026). "The global footprint of haboobs revealed by kilometre-scale Earth system modelling". Manuscript in preparation.

Sela, M., P. Weiss, and P. Stier (2025). "Sensitivity of cloud structure and precipitation to cloud microphysics schemes in ICON and implications for global km-scale simulations". *EGUsphere* 2025, pp. 1–27. https://doi.org/10.5194/egusphere-2025-5803.

Weiss, P., R. Herbert, and P. Stier (2025). "ICON-HAM-lite 1.0: simulating the Earth system with interactive aerosols at kilometer scales". *Geoscientific Model Development* 18.12, pp. 3877–3894. https://doi.org/10.5194/gmd-18-3877-2025.

6 References

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Shao, Y. (2004). "Simplification of a dust emission scheme and comparison with data". *Journal of Geophysical Research: Atmospheres* 109.D10. https://doi.org/10.1029/2003JD004372.

Tegen, I., D. Neubauer, S. Ferrachat, C. Siegenthaler-Le Drian, I. Bey, N. Schutgens, P. Stier, D. Watson-Parris, T. Stanelle, H. Schmidt, S. Rast, H. Kokkola, M. Schultz, S. Schroeder, N. Daskalakis, S. Barthel, B. Heinold, and U. Lohmann (2019). "The global aerosol–climate model ECHAM6.3–HAM2.3 – Part 1: Aerosol evaluation". *Geoscientific Model Development* 12.4, pp. 1643–1677. https://doi.org/10.5194/gmd-12-1643-2019.