Project: **1005**

Project title: **Model-based quantification of aerosol and cloud processes and their effects in the Arctic**

Project lead: **Bernd Heinold**

Report period: **2025-07-01 to 2026-06-30**

Progress Report

The impact of aerosol on Arctic climate and ongoing rapid climate change is investigated through global and Arctic-focused simulations within the DFG Transregio TR 172 'Arctic Amplification (AC)³'. This HPC project focuses on performing and evaluating simulations to quantify aerosol sources, transport pathways, and their climatic effects. The previous project phase focused on modelling primary marine organic aerosol (PMOA), while in the current (AC)³ phase III, the scope has been broadened for a more comprehensive assessment of natural aerosols. The study employs the full HAMMOZ model family: the global aerosol-climate model ECHAM6.3-HAM2.3, its successor ICON-HAM2.3, and the convection-permitting ICON-HAM-lite configuration.

A major part of the resources granted was used to investigate the spatial distribution and long-term evolution of PMOA in the Arctic from 1990 to 2019 under changing climatic and sea-ice conditions. This analysis was performed with an extended version of ECHAM6.3-HAM2.3, which considers three key PMOA groups: polysaccharides, amino acids, and polar lipids. Marine biogeochemistry is prescribed from the model FESOM2.1-REcoM3, while the ocean-atmosphere transfer is parameterized using the OCEANFILMS scheme (Leon-Macros et al., 2025). The results show that PMOA emissions are mainly controlled by biological activity and sea-salt production, with the latter driven by near-surface winds. PMOA in the Arctic peaks between May and September, coinciding with phytoplankton blooms and minimum sea-ice extent. Over the 30-year period, Arctic PMOA emissions increased by ~7% between the first and second halves of the modelled period (Fig. 1a), resulting in a 4%-increase in atmospheric burdens. Summer trends indicate substantial sea-ice loss accompanied by rising biomolecular concentrations in Arctic waters. Positive emission anomalies have become more frequent, reflecting a persistent increase in PMOA production of ~0.8% per year since 1990, with considerable variability across species and regions (Fig. 1b) (Leon-Macros et al., 2026).

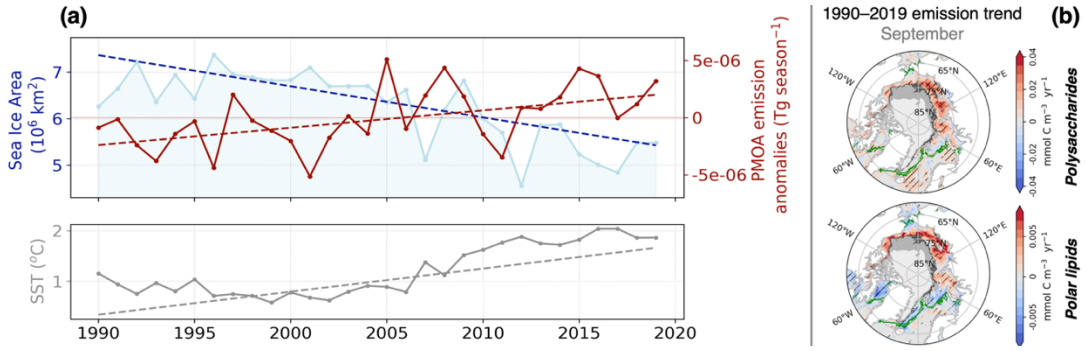

***Figure 1**: (a) Time series of sea-ice area (blue), PMOA emissions (red), and sea-surface temperature (SST; grey), averaged over the Arctic (>66°N) for July–September during 1990-2019, as simulated by ECHAM6.3-HAM2.3. (b) Spatial distribution of simulated emission trends for polysaccharides and polar lipids over 1990-2019.*

Substantial HPC resources were also used to develop and test the new limited-area (LAM) configuration of ICON-HAM-lite for regionally focused aerosol-climate simulations. As an example, a case study on the emission and transport of sea-salt aerosol in the Atlantic Arctic demonstrates its ability to capture regional patterns and diurnal variability (Fig. 2) (Heinold et

al., 2026). The simulations provide a basis for further development and application of the model framework.

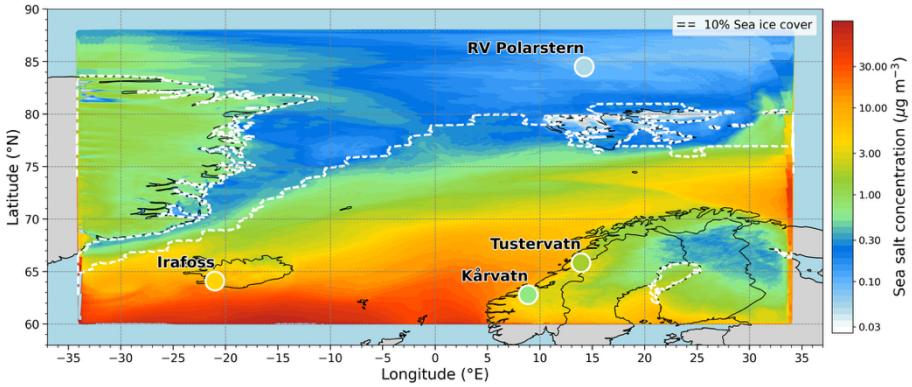

***Figure 2**: Surface sea salt over the North Atlantic (4-12 April 2020) simulated by ICON-HAM-lite, with observations from EMEP sites and RV Polarstern (MOSAiC) overlaid as circles. The dashed white line marks the sea-ice edge (10% concentration).*

Wildfire-favouring conditions are expected to become more frequent in a warming climate, potentially increasing fire activity, especially in boreal forests. Severe events can inject large amounts of smoke into the upper troposphere and lower stratosphere, leading to prolonged atmospheric perturbations, although their role in Arctic warming remains uncertain. Using tagged tracer simulations with ECHAM6.3-HAM2.3 (2016-2021), the contribution of boreal wildfire smoke to the Arctic aerosol burden was quantified. Despite representing a relatively small fraction of global emissions, boreal wildfires dominate the Arctic aerosol composition in summer: organic carbon (OC) contributes ~17% of global emissions but ~60% of the Arctic burden (Fig. 3), while black carbon (BC) contributes ~9% globally but ~52% in the Arctic. In winter, anthropogenic sources dominate Arctic OC and BC.

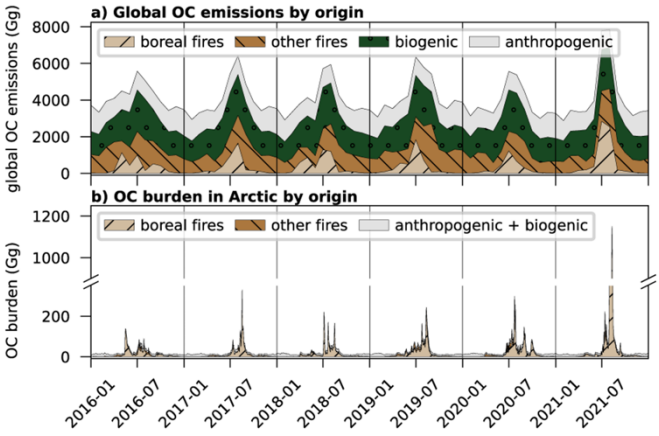

***Figure 3**: Time series of (a) global emissions and (b) Arctic burden of OC by source contribution, derived from tagged tracers in ECHAM6.3-HAM2.3.*

Perspectives

In the next allocation period, we will continue investigating past and future trends in natural aerosols in the Arctic. A particular focus will be on the impact of increasing PMOA on the budgets of cloud condensation nuclei and ice-nucleating particles, as well as on effective radiative forcing. These effects will be assessed in the context of other Arctic aerosols, especially smoke from boreal fires, which has increased dramatically in recent years.

References

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

Leon-Marcos, A., Zeising, M., van Pinxteren, M., Zeppenfeld, S., Bracher, A., Barbaro, E., Engel, A., Feltracco, M., Tegen, I., and Heinold, B.: Modelling emission and transport of key components of primary marine organic aerosol using the global aerosol-climate model ECHAM6.3–HAM2.3, Geosci. Model Dev., https://doi.org/10.5194/egusphere-2024-2917, accepted, 2025.

Leon-Marcos, A., van Pinxteren, M., Zeppenfeld, S., Zeising, M., Bracher, A., Oziel, L., Tegen, I., and Heinold, B.: Thirty years of arctic primary marine organic aerosols: patterns, seasonal dynamics, and trends (1990–2019), Atmos. Chem. Phys., 26, 1109–1144, https://doi.org/10.5194/acp-26-1109-2026, 2026.