Project: **1215**

Project title: **A big unknown in the climate impact of atmospheric aerosol: Mineral soil dust**

Principal investigator: **Martina Klose**

Report period: **2025-11-01 to 2026-10-31**

Work in the reporting period has focused on three main aspects: (1) Size-resolved dust transport, (2) dust impacts on renewable energy systems, and (3) dust mineralogical composition in ICON-ART. Results obtained are summarized in the following:

Size-resolved dust transport:

Dust particles as large as a few hundred micrometers can be transported over thousands of kilometers in the atmosphere. The physical mechanisms leading to the continued suspension of such large (and heavy particles) are still debated and models are hence still unable to reproduce the long-term transport of giant (> 63 µm in diameter) and partly of super-coarse (10 – 63 µm) dust particles.

During the reporting period, we worked on coupling the ICON single-column model (SCM) with the ART (Aerosols and Reactive Trace gases) module to investigate the impact of various processes and configurations on vertical dust transport. SCM represents the conditions and evolution of one single grid cell. It runs on a torus grid made up of a number of grid cells that are identical with no horizontal transport between cells. The initial coupling for dust was successful and requires the additional initialization of dust number and mass concentrations. ***Figure 1*** shows an example of the evolution of the vertical profiles of dust mass concentration during an ICON-ART-SCM experiment.

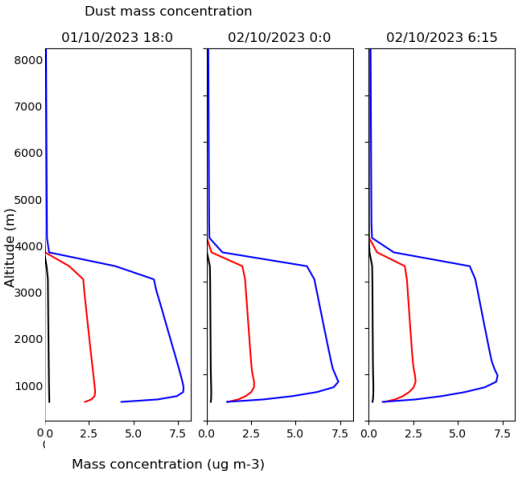


Fig. 1*: Evolution of the vertical profile of dust mass concentration during an example SCM simulation.*

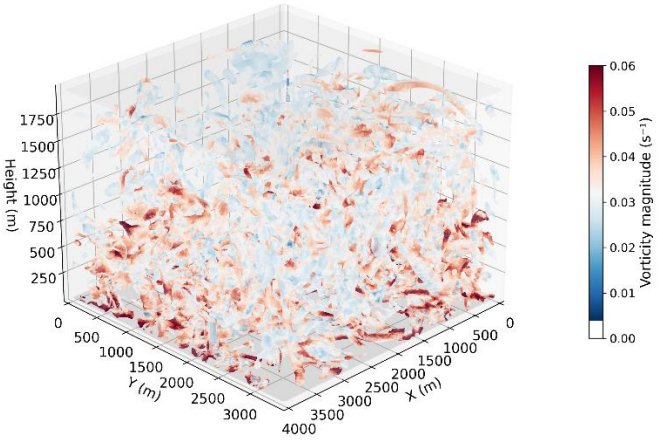


Fig. 2*: Visualization of coherent structures using the Q-criterion with a threshold of Q_{thr} = 0.00015 s^{-2}. The large-eddy simulations were performed with 40 m grid resolution, initial friction velocity u^* = 0.3 m s^{-1} and surface heat flux h = 600 W m^{-2}*

To investigate the role of boundary layer turbulence on the vertical transport of dust particles by size, we performed idealized large-eddy simulations, and utilized quadrant analysis to study turbulent motions and their influence on dust transport. Ejection was found to be the dominant mechanism for vertical transport, but its contribution decreased as particle size increased. To investigate the temporal evolution of coherent turbulent structures, we employed integrated quadrant analysis (IQA) and the Q-criterion (***Fig. 2***). We found that vortical regions have a weaker effect than the background flow (strain-dominated regions) on downward dust transport in the surface layer, although the contribution of coherent structures became comparable with an increase in particle size. We also found that thermal plumes are able to enhance vertical dust transport in a size-dependent manner, i.e., a stronger enhancement for PM10 than for PM2.5.

Dust impacts on renewable energy systems:

The large-scale expansion of solar photovoltaic and wind power across Europe introduces feedback that is seldom considered in integrated energy-system analyses: the same climate change motivating the renewable transition also alters the meteorological resource base on which that transition relies. In the framework of a Master thesis (T. Reimus, 2026, doi:10.5445/IR/ 1000197048), we analyzed how renewable-energy-relevant meteorological variables changed from 2020 to 2049 and evaluated their implications for future energy markets and systems. A modelling workflow was built that links global climate projections with electricity market simulation and power flow analysis across Europe under two CMIP6

scenarios (SSP2-4.5 and SSP5-8.5) plus a Present-day reference. We conducted climate simulations using ICON-SmART (https://www.hans-ertel-zentrum.de/Projekte/ICON-SmART.html), which couples the ICON XPP configuration with the ART module, allowing an explicit representation of how dust and land-surface changes interact with the atmosphere.

30-year experiments, starting in Jan 2020, were conducted organized in six consecutive five-year chunks. Three experiment members were simulated in parallel, corresponding to the climate scenarios SSP2-4.5 and SSP5-8.5 (O'Neill et al., 2016) as well as a present-day control member, allowing for a comparison of climate responses across different radiative forcing pathways. Experiments were run using the auto-icon simulation workflow manager (*Baer et al.,* 2025). Details on the experiment configuration is given in *Reimus* (2026). Model outputs were processed with atlite (*Hofmann et al.,* 2021) to derive wind and solar capacity factors, which fed the agent-based market model PowerACE (e.g. *Sensfuß*, 2007; *Zimmermann*, 2024).

Results show wind speed and solar irradiance trends vary considerably by region and scenario, with wind speeds generally declining and solar irradiance generally increasing under the SSP scenarios. The direct radiative effect of mineral dust on incoming radiation intensified under both future scenarios. Dark doldrum conditions became more frequent in certain regions, strongest under SSP5-8.5 over Iberia, southwestern France, and northern Germany, while light breeze frequencies shifted regionally without a clear trend.

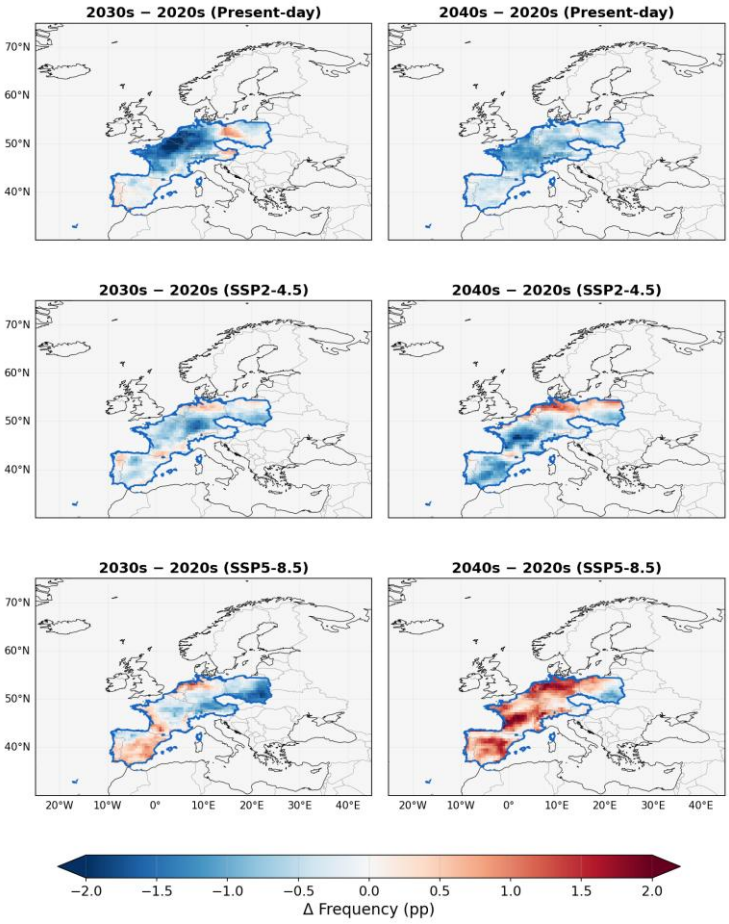


***Fig. 3**: Decadal change in dark doldrum frequency relative to the 2020s baseline for each climate scenario. Blue outlines highlight the analysis region. From Reimus (2026).*

Dust mineralogical composition in ICON-ART:

The composition of mineral dust aerosol has strong implications on its interactions with clouds and radiation. Toward better quantifying these interactions, we have conducted simulations to investigate the impact of dust composition on dust-cloud interactions. For this purpose, a mineralogy-sensitive ice-nucleating active site (INAS) density parameterization was developed based on laboratory experiments (Vergara Palacio et al., 2026) and implemented in ICON-ART to test the role of Icelandic dust as ice nucleating particle (INP) (Vergara Palacio, 2026). Initial results suggested that the contribution of Icelandic dust to total INP was small, but led to significant differences in cloud radiative effects, closer to observations. The research will be expanded in the next reporting period, together with the implementation of meteorology-aware dust emissions in ICON-ART.

References:

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