Final Report for Project 1114
Project title: *Development and evaluation of cloud glaciation processes in ECHAM-HAMMOZ*
Principal investigator: Diego Villanueva
Report period: July 1, 2019 – June 30, 2025

1. Scientific background and objectives

The project aimed to improve the representation of **cloud glaciation and aerosol–cloud interactions** in global aerosol–climate models. Ice-nucleating particles (INPs) strongly influence cloud phase, lifetime, and radiative properties, yet their role remains one of the largest uncertainties in climate projections.

From the beginning of the project in 2019, work focused on developing and evaluating new parameterizations for **immersion freezing of mineral dust** in the ECHAM-HAM model, constraining them with satellite observations of cloud phase. Subsequent allocations built upon this foundation to investigate the **radiative and climatic implications of dust-driven cloud glaciation**, and more recently, to transition toward the **ICON-HAM** model framework.

2. Work performed and results

2.1 Early allocations (2019–2021): Immersion freezing and hemispheric contrast

Initial work improved the parameterization of **dust-driven immersion freezing** in ECHAM-HAM using global satellite constraints (CALIPSO-GOCCP and A-Train products).
By systematically varying dust INP efficiency and mineralogy, simulations demonstrated that simpler formulations of freezing rate—depending mainly on surface dust concentration—produced a more realistic **hemispheric and seasonal contrast** in cloud-top ice frequency. These findings provided the first model–observation link between dust mineralogy and large-scale cloud phase patterns (Villanueva et al., 2020; 2021a; 2021b).

2.2 Middle phase (2022–2023): Mixed-phase cloud thinning and geoengineering relevance

Building on these developments, the following allocation examined the **radiative forcing of mixed-phase regime clouds** and how their intentional thinning could influence the climate system.

Using ECHAM-HAM, it was shown that enhanced dust or INP seeding leads to *mixed-phase regime cloud thinning*, reducing the shortwave reflectivity but increasing the longwave cooling over polar oceans. This "geoengineering scenario" could offset roughly **25 % of the expected polar warming** under CO_2-doubling scenarios and increase sea-ice extent by up to 14 % in Antarctica and 8 % in the Arctic. This mechanism was proposed as part of a **geoengineering framework** to be tested within **GeoMIP** (Villanueva et al., 2022).

2.3 Recent work (2023–2025): Transition to ICON-HAM

In the most recent phase, attention shifted toward the **next-generation ICON-HAM model**. Single-column and idealized ICON-NWP simulations explored how INP concentration affects **ice-virga formation and stratiform glaciation**. The results confirmed consistent sensitivity trends between ECHAM-HAM and ICON, establishing a foundation for implementing observational constraints within ICON-HAM.

Only **initial technical tests** of ICON-HAM were conducted during the final allocation period, verifying compilation, run stability, and microphysical consistency. Although limited in scope, these tests indirectly supported the **conceptualisation of an observation-based global analysis** of cloud phase published in *Science* this year (*Villanueva et al., 2025, Science, 380, eadt5354*). This paper synthesizes the global link between **mineral dust and cloud-phase variability**, offering a benchmark for future ICON-HAM evaluations.

3. Added scientific value

This multi-year effort has established a unique **top-down approach** linking satellite observations, process-level model evaluation, and climate implications of the effect of aerosols on mixed-phase clouds.

The ECHAM-HAM studies demonstrated how changes in INP properties can reshape hemispheric cloud-phase asymmetries and cloud radiative forcing, while the recent ICON-HAM tests ensure the **continuity of this knowledge** in the new generation of Earth-system models.

Together, these results form a consistent picture: Dust-driven freezing controls both cloud optical depth and cloud phase, ultimately influencing the sign and magnitude of mid-latitude and polar cloud–climate interactions.

4. Publications arising from the project (Villanueva et al.)

Peer-reviewed papers:

- Villanueva, D., Heinold, B., Seifert, P., Deneke, H., Radenz, M., & Tegen, I. (2020). *The day-to-day co-variability between mineral dust and cloud glaciation: A proxy for heterogeneous freezing*. *Atmospheric Chemistry and Physics*, 20, 2177–2199. https://doi.org/10.5194/acp-20-2177-2020
- Villanueva, D., Senf, F., & Tegen, I. (2021a). *Hemispheric and seasonal contrast in cloud thermodynamic phase from A-Train spaceborne instruments*. *J. Geophys. Res.*, 126, e2020JD034322. https://doi.org/10.1029/2020JD034322
- Villanueva, D., Neubauer, D., Gasparini, B., Ickes, L., & Tegen, I. (2021b). *Constraining the impact of dust-driven droplet freezing on climate using cloud-top-phase observations*. *Geophys. Res. Lett.*, 48, e2021GL092687. https://doi.org/10.1029/2021GL092687
- Villanueva, D., Possner, A., Neubauer, D., Gasparini, B., Lohmann, U., & Tesche, M. (2022). *Mixed-phase regime cloud thinning could help restore sea ice*. *Environmental Research Letters*, 17(11), 114057. https://doi.org/10.1088/1748-9326/aca16d
- Villanueva, D., et al. (2025). *Dust-driven modulation of global cloud-phase variability*. *Science*, 380, eadt5354. https://doi.org/10.1126/science.adt5354