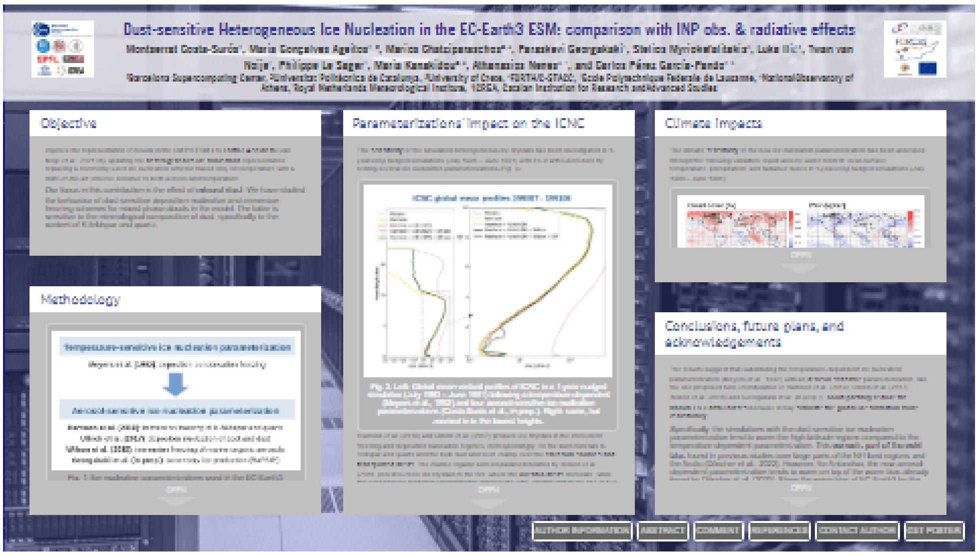
Dust-sensitive Heterogeneous Ice Nucleation in the EC-Earth3 ESM: comparison with INP obs. & radiative effects



Dust-sensitive Heterogeneous Ice Nucleation in the EC-Earth3 ESM: comparison with INP obs. & radiative effects

Objective

Methodology

Parameterizations' Impact on the ICNC

Climate Impacts

Conclusions, future plans, and acknowledgements

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PRESENTED AT:

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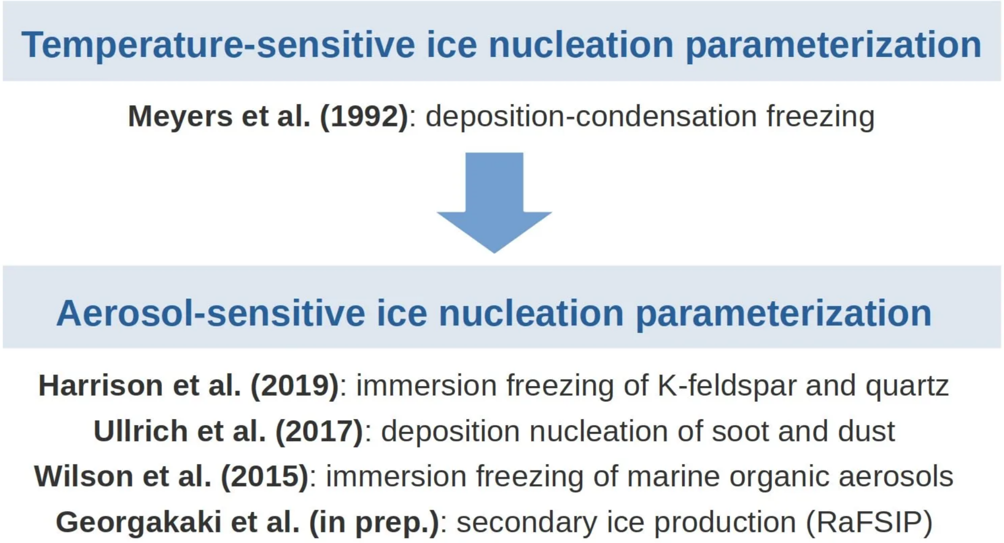
OBJECTIVE

Improve the representation of clouds in the CMIP6 ESM **EC-Earth3-AerChem** (van Noije et al., 2021) by updating the **heterogeneous ice nucleation** representation replacing a commonly used ice nucleation scheme based only on temperature with a state-of-the-art scheme sensitive to both aerosol and temperature.

Our focus in this contribution is the effect of **mineral dust**. We have studied the behaviour of dust-sensitive deposition nucleation and immersion freezing schemes for mixed-phase clouds in the model. The latter is sensitive to the mineralogical composition of dust, specifically to the content of K-feldspar and quartz.

METHODOLOGY



Temperature-sensitive ice nucleation parameterization

Meyers et al. (1992): deposition-condensation freezing

Aerosol-sensitive ice nucleation parameterization

Harrison et al. (2019): immersion freezing of K-feldspar and quartz

Ullrich et al. (2017): deposition nucleation of soot and dust

Wilson et al. (2015): immersion freezing of marine organic aerosols

Georgakaki et al. (in prep.): secondary ice production (RaFSIP)

Fig. 1. Ice nucleation parameterizations used in the EC-Earth3-AerChem simulations. The combination under the "aerosol-dependent ice nucleation parameterization" provides a comprehensive **new parameterization** that can substitute the deposition-condensation-freezing temperature-dependent parameterization by Meyers et al. (1992).

The **EC-Earth3-AerChem** (van Noije et al., 2021) was configured as a nudged simulation towards ERA-5 running for one year (from July 1990 to June 1991) that produced monthly outputs. The resolution was 3 × 2º (longitude × latitude) with 91 vertical levels in the **Integrated Forecasting System** (IFS) and 31 in the Chemical Transport Model (CTM) TM5. The IFS time-step was 2700 seconds, and the coupling between TM5 was every 6 hours.

EC EARTH3

Five simulations with five different ice nucleation parameterizations were run (Fig. 1):

- Meyers et al. (1992) that consider deposition-condensation freezing processes.
- Harrison et al. (2019) for the immersion freezing of K-feldspar and quartz minerals.
- Harrison et al. (2019), in combination with Ullrich et al. (2017), for the bulk dust and soot particles in the deposition nucleation regime.
- Harrison et al. (2019), in combination with Ullrich et al. (2017) and Wilson et al. (2015), for the immersion freezing of marine organic particles.
- Harrison et al. (2019), in combination with Ullrich et al. (2017), Wilson et al. (2015) and Georgakaki et al. (in prep.) for the secondary ice production.

The model is able to incorporate the aerosol-dependent parameterizations because it includes separate **tracers** for K-feldspar, quartz, soot, dust and marine organic aerosols (Chatziparaschos et al., 2022). The ability to **nucleate ice** of the different immersion freezing and deposition nucleation parameterizations for the different species is shown in Fig. 2.

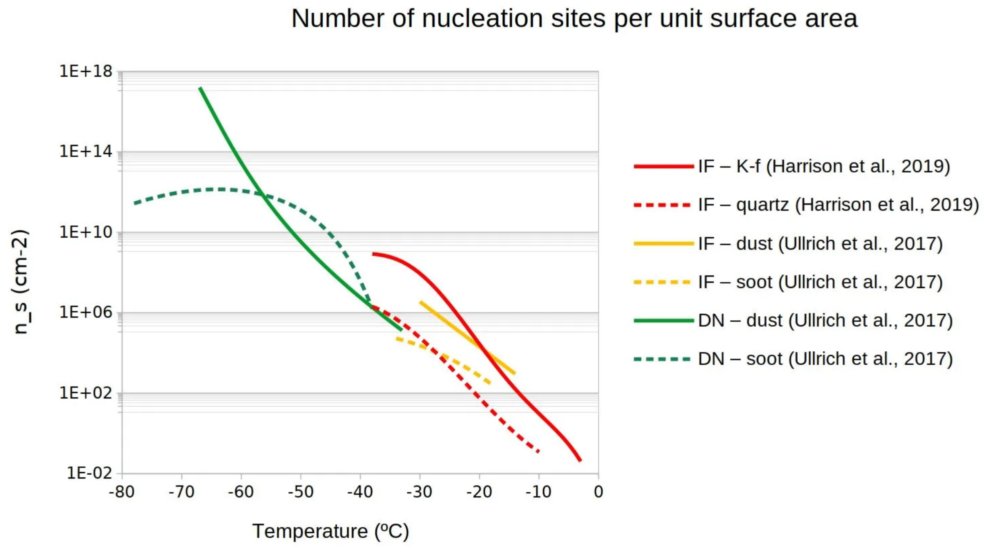


Fig. 2. Number of nucleation sites per unit surface area for two minerals in the immersion freezing (IF) mode (K-feldspar and quartz) and for bulk dust and soot in IF and deposition nucleation (DN) regimes.

The IFS cycle from the ECMWF used in EC-Earth3 as the atmospheric component does not explicitly represent the required species and interactions needed for an explicit parameterization of **secondary ice production** (SIP). Therefore, SIP is described by applying enhancement factors to the ice crystal number concentration (ICNC). These are parameterized using a Random Forest (**RaFSIP**) regressor developed by Georgakaki et al. (in prep.). The RaFSIP regressor takes into account the four water species in IFS (cloud droplets, cloud ice, snow, and rain), the temperature, and relative humidity with respect to ice to produce ice via the SIP process, namely the rime splintering (or the Hallett-Mossop process), collisional break-up, and/or droplet shattering during freezing. The RaFSIP also takes into account the **riming rates**, which are not explicitly described in IFS but diagnosed based on the mixing ratios of the 4 water species and the temperature. The RaFSIP is applied in the temperature range between -20 and -3 C.

The modeled ice nucleating particles (INPs) were **evaluated** in the previous version of the transport model (TM4), which uses the same principles as TM5, against **observations** from "Impact of Biogenic versus Anthropogenic emissions on Clouds and Climate: towards a Holistic UnderStanding" (BACCHUS) (http://www.bacchus-env.eu/in/index.php) and Wex et al. (2019) in Chatziparaschos et al. (2022).

PARAMETERIZATIONS' IMPACT ON THE ICNC

The **sensitivity** of the simulated heterogeneous ice crystals has been investigated in 1-year-long nudged simulations (July 1990 – June 1991) with EC-Earth3-AerChem by testing several ice nucleation parameterizations (Fig. 3).

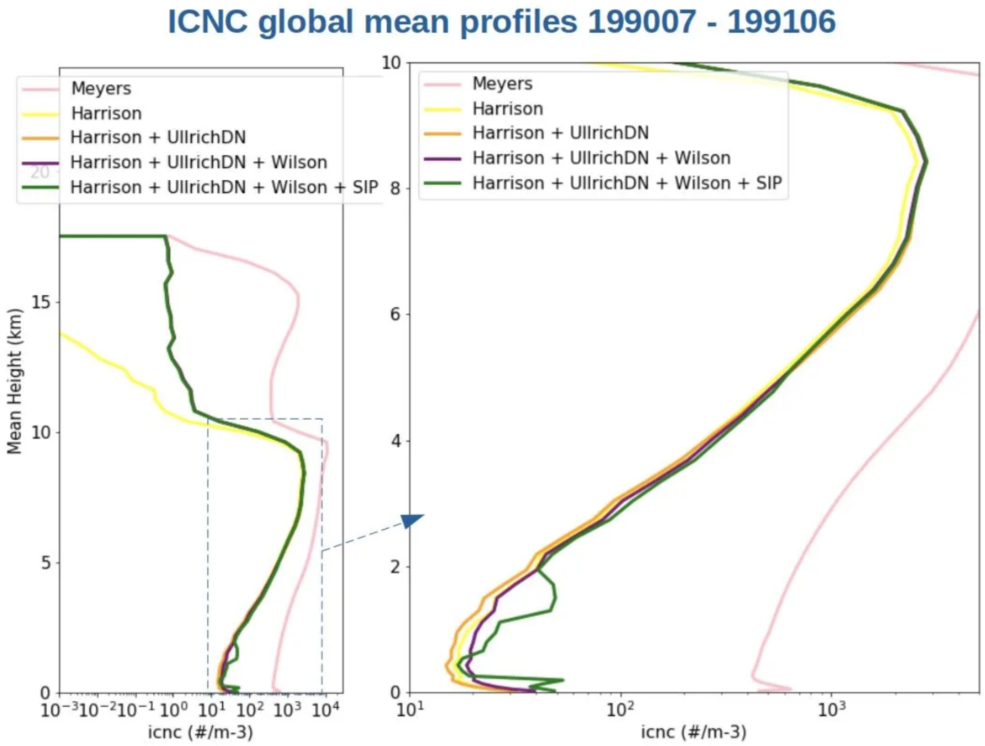
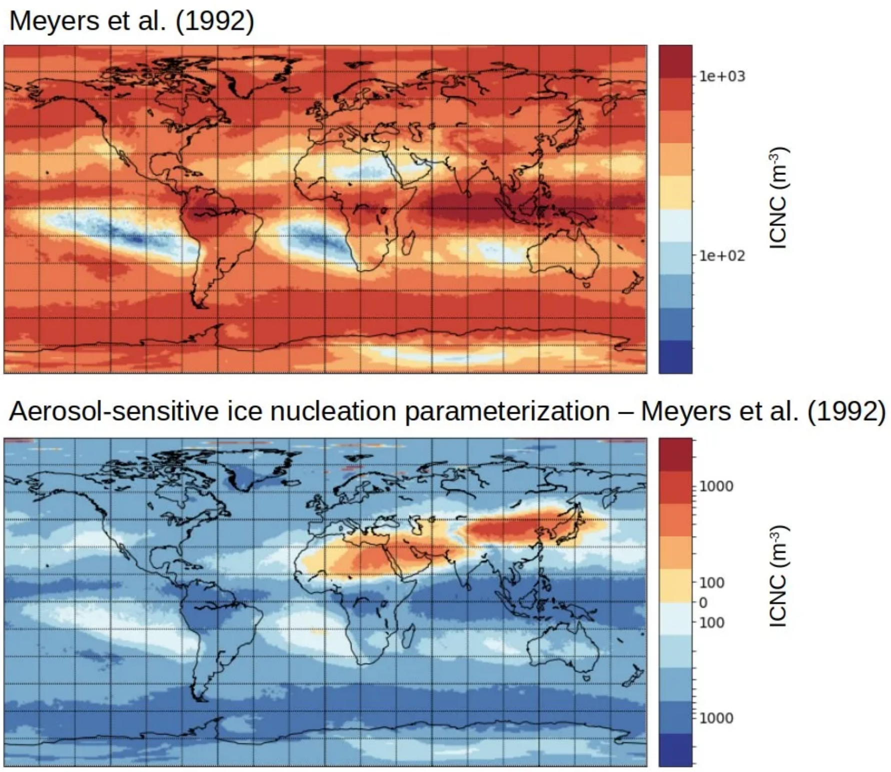


Fig. 3. Left: Global mean vertical profiles of ICNC in a 1-year nudged simulation (July 1990 – June 1991) following a temperature-dependent (Meyers et al., 1992) and four aerosol-sensitive ice nucleation parameterizations (Costa-Surós et al., in prep.). Right: same, but zoomed in to the lowest heights.

Harrison et al. (2019) and Ullrich et al. (2017) produce ice crystals in the immersion freezing and deposition nucleation regimes, correspondingly, for the dust minerals K-feldspar and quartz and the bulk dust and soot, mainly over the **emission sources and transported areas**. The marine organic aerosol parameterization by Wilson et al. (2015, provides more ice crystals to the SH, where the **oceanic areas** dominate, while the secondary ice production parameterization increases the ICNC uniformly globally by one or two orders of magnitude, mainly below 10 km.

The global profiles show a reduction in ICNC with the new aerosol-dependent ice nucleation parameterization in comparison to Meyers et al. (Fig. 3); however, the distribution seems **more realistic** since it depicts a clear association of the simulated ICNC with the **mineral-dust emission sources and transported areas** (Fig. 4).


Meyers et al. (1992)

Aerosol-sensitive ice nucleation parameterization – Meyers et al. (1992)

Fig. 4. Average column ICNC following (top) Meyers et al. (1992) ice nucleation parameterization and (bottom) absolute difference between the proposed aerosol-dependent ice nucleation parameterization (Harrison et al. (2019) + Ullrich et al. (2017) deposition nucleation regime + Wilson et al. (2015) + RaFSIP) and Meyers et al. (1992) parameterization.

CLIMATE IMPACTS

The climate **sensitivity** of the new ice nucleation parameterization has been assessed through the following variables: liquid and ice water content, near-surface temperature, precipitation, and radiative fluxes in 1-year-long nudged simulations (July 1990 – June 1991).

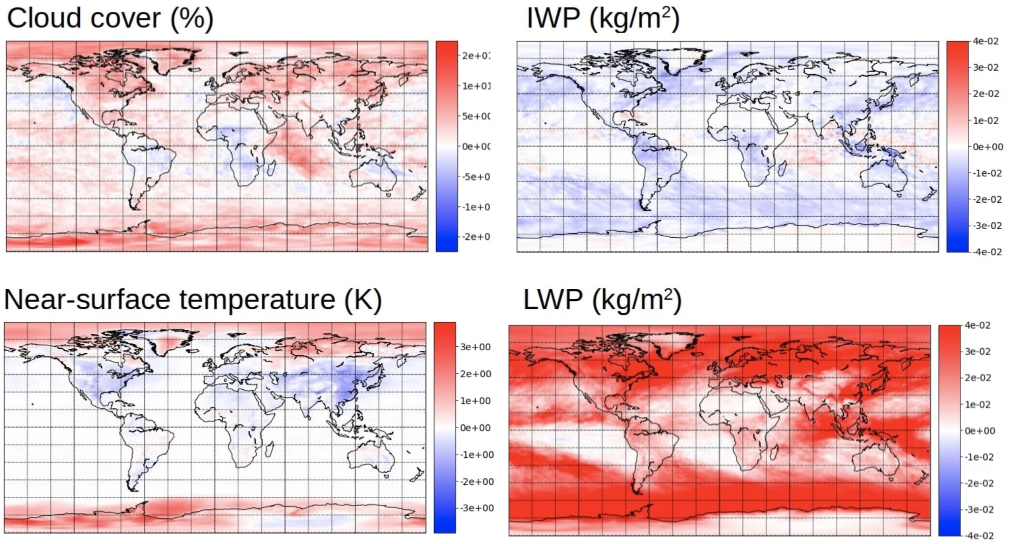


Fig. 5. Cloud cover (top left), near-surface temperature (bottom left), ice water path (IWP, top right) and liquid water path (LWP, bottom right) difference between the aerosol-dependent ice nucleation parameterization and Meyers et al. (1992).Caption

Globally, there is, on average, an increase of 1.6 % in **cloud cover** with the new ice nucleation parameterization due to the increase of liquid clouds (**ice water path** (IWP) decreases globally on average -0.002 kg/m^2, and the liquid water path (LWP) increases 0.02 kg/m^2 (Fig. 5)). Regarding the global near-surface **temperature**, there is, on average, an increase of 0.01 K, while regionally, the temperature change ranges from -1.98 to 3.92 K.

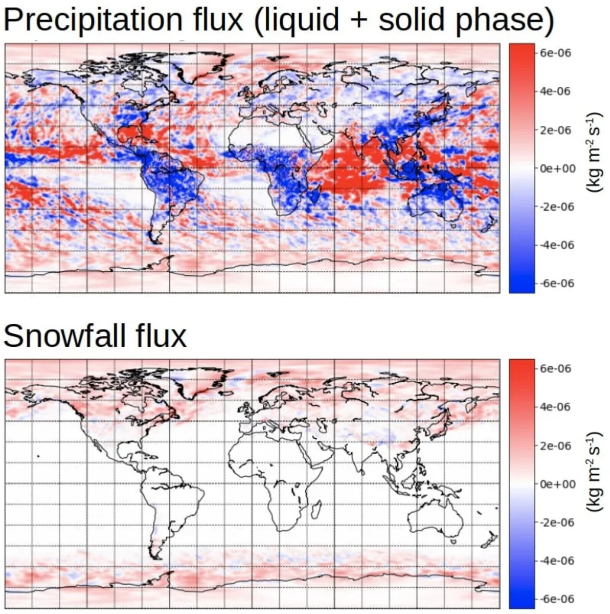


Fig. 6. Precipitation fluxes difference between the aerosol-dependent parameterization and Meyers et al.

The precipitation fluxes (Fig. 6) show that there is more snow precipitating with the new parameterization at high latitudes and, on the other hand, that there is, in general, a decrease in total precipitation over the continents. In contrast, the precipitation is increased over the oceans, in particular over the Indian Ocean.

Radiative fluxes at the top of the atmosphere are consistent with the cloud cover differences (Fig. 7). There is a clear increase in the short-wavelength (SW) radiation flux at the top of the atmosphere returning to space (global average of 9.3 W/m^2) due to an increase of the cloud cover, and a global decrease of the long-wavelength (LW) counterpart (global average of -2.82 W/m^2).

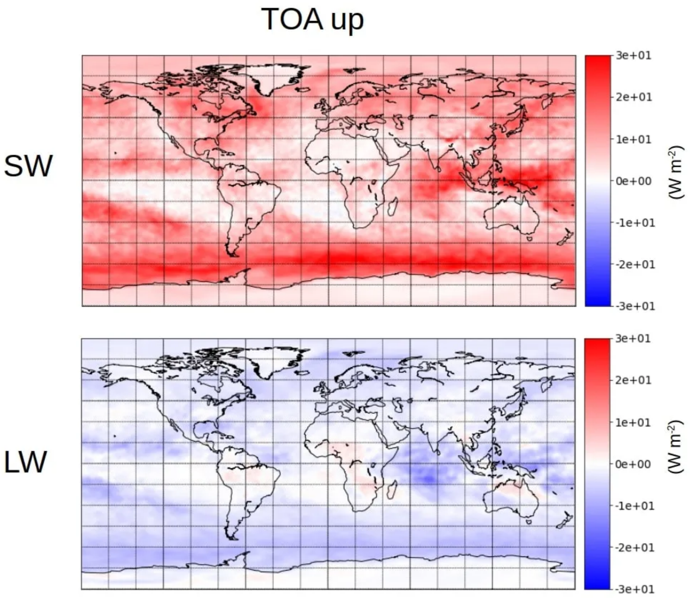


Fig. 7. Difference in short-wavelength (SW, top) and long-wavelength (LW, bottom) net upward radiative fluxes at the top of the atmosphere (TOA) between the aerosol-dependent and Meyers et al. parameterizations.

CONCLUSIONS, FUTURE PLANS, AND ACKNOWLEDGEMENTS

The results suggest that substituting the temperature-dependent ice nucleation parameterization (Meyers et al., 1992) with an **aerosol-sensitive** parameterization, like the one proposed here (combination of Harrison et al. (2019), Ullrich et al. (2017), Wilson et al. (2015) and Georgakaki et al. (in prep.)), **could partially reduce the known EC-Earth3 biases** because it may **simulate the global ice formation more realistically**.

Specifically, the simulations with the dust-sensitive ice nucleation parameterization tend to warm the high-latitude regions compared to the temperature-dependent parameterization. This **corrects part of the cold bias** found in previous studies over large parts of the NH land regions and the Arctic (Döscher et al., 2022). However, for Antarctica, the new aerosol-dependent parameterization tends to warm on top of the warm bias already found by Döscher et al. (2022). Since the warm bias of EC-Earth3 for the Southern Ocean and Antarctica has been attributed to biases in shortwave cloud radiative effects, it is probable that modifications in the cloud scheme will reduce them.

Summary of the **key findings**:

- In contrast to Meyers et al., the new aerosol-sensitive parameterization produces more ice crystals because of immersion freezing and deposition nucleation processes over the aerosol (dust and soot) emission sources and transported areas. The immersion freezing parameterization that considers marine organic aerosols provides ICNC over the oceanic regions, particularly the SH, and the RaFSIP parameterization enhances the ICNC uniformly globally.

- Although the ICNC with the new aerosol-dependent ice nucleation parameterization is globally smaller compared to Meyers et al., the distribution seems **more realistic** since it depicts a clear association of the simulated ICNC with the **mineral-dust emission sources and transported areas**.

- Large model sensitivity to ICNC is found: globally increased cloud cover (+1.6 %), LWP (+0.02 kg/m^2), total precipitation (+2.43 x 10^{-7} kg/m^{2}s), SW upwards radiation flux at TOA (+9.3 W/m^2), and near-surface temperature (+0.01 K, regionally ranges from -1.98 to 3.92 K). While there is a global decrease in IWP (-0.002 kg/m^2) and LW upwards radiation flux at TOA (-2.82 W/m^2).

The following further improvements and refinements of the aerosol-dependent parameterization are **planned**:

- Better representation of the ice formation processes by including other INPs as precursors of ice crystals (e.g. pollen).
- Consider other immersion freezing parameterizations (e.g. McCluskey et al., 2018).
- The SIP parameterization will be tested further with other primary IN parameterizations to see its behaviour (in collaboration with EPFL/CSTACC).
- The simulation period will be extended to climatological scales to assess the variability of the results over longer periods.

The aerosol-sensitive ice nucleation parameterization suggested here will soon be integrated with other developments from the EU **FORCeS** project to help improve the representation of aerosols and their interactions with warm and cold clouds.

Acknowledgements:

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AUTHOR INFORMATION

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Dr Montserrat Costa Surós graduated with an Extraordinary Award from a BSc Degree in Environmental Sciences (2005), and with a Master's Degree in Environment (2009) from the University of Girona (UdG, Spain). During her doctoral studies (FPI fellow, 2008-2012), she did a research stay at the Pacific Northwest National Laboratory (USA, 2011) where she worked within the ARM program team, and another research stay at the company Vaisala Oyj. (Finland, 2012). After obtaining her PhD in Experimental Sciences and Sustainability (UdG, Spain, 2014), she had her first postdoctoral position at the Institute of Geophysics of the University of Warsaw (Poland, 2014-2016), where she was mainly involved in observations of aerosols, clouds, and water vapor by the means of a multi-wavelength Raman depolarization Lidar. She was also involved in the "MULTIPLY Project for the development of a European HSRL airborne facility", funded by the European Space Agency (ESA). From 2006 until the end of 2019, she held a postdoctoral position at the Remote Sensing Group of the Institute for Geophysics and Meteorology of the University of Cologne (Germany). She was involved in the High Definition of Clouds and Precipitation for Climate Prediction (HD(CP)2) German Project analyzing the effects of aerosols on clouds and precipitation through model simulations and observations, investigating the sensitivity of aerosol perturbations to observables, and evaluating the ICON-LES model performance by comparing its output to several kinds of observations. In 2020, she joined the Barcelona Supercomputing Center (BSC, Spain) as a Research Scientist in Climate Data Quality Control at the Earth Sciences Department, performing a technical assessment of the climate datasets served by the Copernicus Climate Change Service (C3S). In 2021, she obtained a STARS fellowship (Marie-Sklodowska-Curie Action COFUND, within the H2020 Programme) for investigating the mineralogy in dust-cloud interactions and associated radiative forcing in the Atmospheric Composition group at the BSC. She is part of the FORCeS project (https://forces-project.eu/).

Interests: aerosol-cloud interactions, radiative effects upon climate, aerosol and cloud observations, model evaluation.

ABSTRACT

Clouds are amongst the largest contributors to uncertainty in climate projections. There is evidence that aerosol-sensitive ice nucleating parameterizations match better global compilations of ice nucleating particle (INP) observations than temperature-based ones, which should allow to better represent the cloud fields, and, ultimately, the Earth's changing energy budget.

With the aim of improving the representation of clouds in EC-Earth3, which is one of the CMIP6 Earth System Models, we have updated the heterogeneous ice nucleation representation by replacing a commonly used ice nucleation scheme based only on temperature with a state-of-the-art scheme sensitive to both aerosol and temperature. Our focus in this contribution is the effect of mineral dust. In that sense, we have studied the behaviour of dust-sensitive deposition nucleation schemes for cirrus clouds and dust-sensitive immersion freezing schemes for mixed-phase clouds in the model. The latter is sensitive to the mineralogical composition of dust, specifically to the content of K-feldspar and of quartz.

Our model includes separate mineral tracers for quartz and feldspar and can use the two currently available soil mineralogy atlases that provide soil mass fraction estimates for these minerals. We also use brittle fragmentation theory to transform the soil mineral fractions into size-resolved emitted mineral fractions. We evaluate the model against an extended observational dataset of INP concentrations and analyse the effect of modeled dust mineralogy upon heterogeneous ice nucleation in mixed-phase clouds and cirrus clouds produced with the new parameterizations. We also investigate the sensitivity of the simulated liquid and ice water content and the atmospheric radiative fluxes to the two different soil mineralogy atlases. Preliminary results with the new ice nucleation parameterizations show a clear association of the simulated ice crystal number concentrations with the dust sources.

REFERENCES

References:

- Chatziparaschos, M., et al.: Role of K-feldspar and quartz in global ice nucleation by mineral dust in mixed-phase clouds, Atmos. Chem. Phys. Discuss. [preprint], https://doi.org/10.5194/acp-2022-551, in review, 2022.

- Claquin, T., et al..: Modeling the mineralogy of atmospheric dust sources, J. Geophys. Res., 104(D18), 22243, https://doi:10.1029/1999JD900416, 1999.

- Costa-Surós, M, et al.: Novel Dust-sensitive Ice Nucleation parameterization for the EC-Earth3 Earth System Model: implementation, evaluation and effects. In prep.

- Döscher, R., et al.: The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6, Geosci. Model Dev., 15, 2973–3020, https://doi.org/10.5194/gmd-15-2973-2022, 2022.

- Harrison, A. D., et al.: The ice-nucleating ability of quartz immersed in water and its atmospheric importance compared to K-feldspar. Atmos. Chem. Phys., 19, 11343-11361, https://doi.org/10.5194/acp-19-11343-2019, 2019.

- Journet, E., et al.: A new data set of soil mineralogy for dust-cycle modeling, Atmos. Chem. Phys., 14, 3801–3816, https://doi.org/10.5194/acp-14-3801-2014, 2014.

- Kok, J. F.: Does the size distribution of mineral dust aerosols depend on the wind speed at emission?, Atmos. Chem. Phys., 11, 10149–10156, https://doi.org/10.5194/acp-11-10149-2011, 2011.

- McCluskey, C. S., et al.: Marine and terrestrial organic ice-nucleating particles in pristine marine to continentally influenced Northeast Atlantic airmasses.J. Geophys. Res. Atmos.,123, 6196–6212. https://doi.org/10.1029/2017JD028033, 2018.

- Meyers, M. P., et al.: New Primary Ice-Nucleation Parameterizations in an Explicit Cloud Model, J. Appl. Meteorol. Climatol., 31(7), 708-721, 1992.

- van Noije, T., et al., EC-Earth3-AerChem: a global climate model with interactive aerosols and atmospheric chemistry participating in CMIP6, Geosci. Model Dev., 14, 5637–5668, https://doi.org/10.5194/gmd-14-5637-2021, 2021.

- Ullrich, R., et al.: A New Ice Nucleation Active Site Parameterization for Desert Dust and Soot, J. Atmos. Sci., 74(3), 699-717, https://doi.org/10.1175/JAS-D-16-0074.1, 2017.

- Wex, H. et al.: Annual concentrations of ice nucleating particles at different Arctic stations. PANGAEA, https://doi.org/10.1594/PANGAEA.899701, 2019.

- Wilson, T., et al.:A marine biogenic source of atmospheric ice-nucleating particles. Nature, 525, 234–238, https://doi.org/10.1038/nature14986, 2015.