New Aerosol-sensitive Heterogeneous Ice Nucleation Parameterization in the EC-Earth3 Earth System Model: evaluation and climate response

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Objective

Improve the representation of clouds in the CMIP6 ESM EC-Earth3-AerChem 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 and a secondary ice production parameterization based on random forest model.

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

The EC-Earth3-AerChem (van Noije et al., 2021) was configured as a nudged simulation towards ERA-5. The resolution was 3 × 2º (longitude × latitude) with 91 vertical levels in the Integrated Forecasting System (IFS) and 31 in the Chemical Transport Model TM5. The IFS time-step was 2700 seconds, and the coupling between TM5 was every 6 hours.

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

1) **Meyers** et al. (1992): consider deposition-condensation freezing processes.
2) **Aerosol-dependent** ice nucleation parameterization as a combination of the following primary ice production (PIP) processes: Harrison et al. (2019), Ullrich et al. (2017), and Wilson et al. (2015).
3) Aerosol-dependent ice nucleation parameterization (as in "2") in combination with a Random Forest regressor, **RaFSIPv1**, where the secondary ice production (SIP) processes are estimated from ice enhancement factors (Georgakaki et al., in prep.).
4) Same as in "3" but in combination with **RaFSIPv2**, where the SIP is directly estimated from the random forest parameterization.

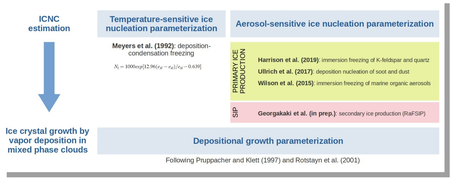
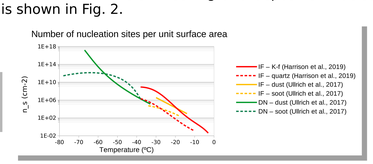


Fig. 1. Ice nucleation parameterizations used in the EC-Earth3-AerChem simulations. The combination under the "aerosol-dependent ice nucleation parameterization" provides a comprehensive new parameterization that can substitute the deposition-condensation-freezing temperature-dependent parameterization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

The 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 **RaFSIP** regressor is used to predict the ice crystal number concentration (ICNC) via SIP processes (Hallett-Mossop, collisional break-up, and/or droplet shattering) during freezing (temperatures 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).

Results

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. 1). The novel aerosol-sensitive parameterizations produce ICNC mainly over the **emission sources and transported areas** (Fig 3d). The global profiles show a reduction in ICNC with the new aerosol-dependent ice nucleation parameterization in comparison to Meyers et al. (Fig. 3a,c); 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. 3d,e).

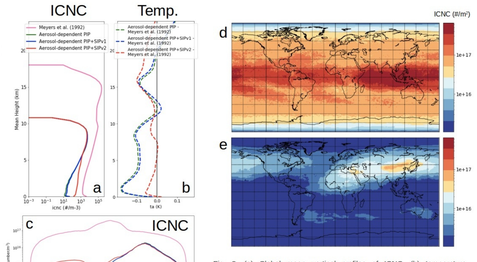


Fig. 3. (a) Global mean vertical profiles of ICNC, (b) temperature differences, and (c) latitudinal ICNC mean of the total column burden in a 1-year nudged simulation (July 1990 – June 1991) following a temperature-dependent (Meyers et al., 1992) and three aerosol-sensitive ice nucleation parameterizations (Costa-Surós et al., in prep.).

Average ICNC column burden following (d) Meyers et al. (1992) and (e) aerosol-dependent ice nucleation parameterization (PIP + SIPv2).

Climate impacts

The aerosol-dependent parameterization with the RaFSIPv2 version provides closer ICNC, LWC and IWC results to the Meyers' than the "only primary" or the version RaFSIPv1 (Figs. 3 and 4); therefore, it has been chosen for the climate sensitivity analysis in 1-year-long nudged simulations. Globally, there is, on average, an increase of 0.9 % in **cloud cover** (Fig. 5a), with the new ice nucleation parameterization (**PIP+SIPv2**) due to the increase of liquid clouds, **liquid water path** (LWP) increases 31 % while **ice water path** (IWP) decreases globally on average 0.002 % (Fig. 5c,d). Interestingly, the new aerosol- dependent parameterizations tend to increase the IWC over ~8 km (Fig. 4d) even though there are fewer (or non) ICNC > 8 km (Fig. 3b). This could be explained because homogeneous freezing dominates in these altitudes, and since the mean temperatures are lower (up to -0.1 K on average, Fig. 3b), more ice could be produced. Regarding the global near-surface **temperature**, there is, on average, an increase of 0.05 K, while regionally, the temperature change ranges from -2.4 to 3.6 K (Fig. 5b).

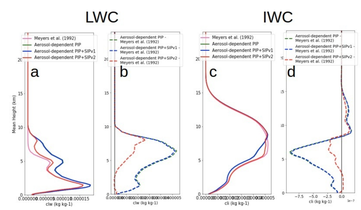


Fig. 4. Global mean vertical profiles of (a) liquid and (c) ice water content (LWC and IWC) in a 1-year nudged simulation (July 1990 – June 1991) following a temperature-dependent (Meyers et al., 1992) and three aerosol-sensitive ice nucleation parameterizations. (b) and (d) show the difference between the aerosol-dependent parameterizations subtracting Meyers parameterization results (Costa-Surós et al., in prep.).

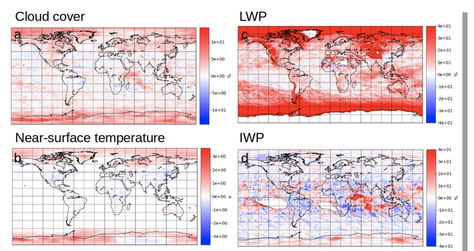


Fig. 5. Cloud cover (a), near-surface temperature (b), liquid water path (c) and ice water path (d) difference between the aerosol-dependent ice nucleation parameterization (PIP + SIPv2) and Meyers et al. (1992).

Radiative fluxes at the top of the atmosphere are consistent with the cloud cover differences. There is a clear increase in the short-wavelength (SW) radiation flux at the top of the atmosphere returning to space (global average of 3.9 W/m^2, Fig. 6a), and a global decrease of the long-wavelength (LW) counterpart (global average of -1.59 W/m^2, Fig. 6b).

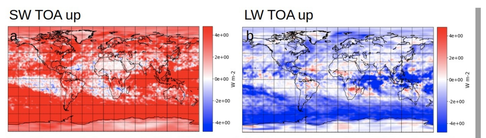


Fig. 6. Difference in (a) short-wavelength (SW) and (b) long-wavelength (LW) net upward radiative fluxes at the top of the atmosphere (TOA) between the aerosol-dependent and Meyers et al. parameterizations.

Key findings

- Although the ICNC with the new aerosol-dependent ice nucleation parameterization is globally smaller than 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**.
- The **RaFSIPv2** parameterization has been chosen for the sensitivity. The ICNC, LWC and IWC results are closer to those in Meyers et al. (1992), particularly over the SH, where the differences are larger with the "only primary" and the RaFSIPv1 simulations.
- Large **model sensitivity to ICNC** is found: globally increased cloud cover (+0.9%), LWP (+31%), SW upwards radiation flux at TOA (+3.9 W/m2) and near-surface temperature (+0.05 K, regionally ranges from -2.4 to 3.6 K). While there is a global decrease in IWP (-0.002 kg/m2) and LW upwards radiation flux at TOA (-1.59 W/m2).

Conclusions

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.

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

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