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. The commonly used ice nucleation scheme based only on temperature is replaced with a state-of-the-art scheme sensitive to both aerosol and temperature and a secondary ice production parameterization based on a random forest model.

Methodology

Four 1-year-long simulations (July 1990 – June 1991) with different ice nucleation parameterizations were run with the EC-Earth3-AerChem ESM with the configuration as in Fig. 1 and the ice nucleation and growth scheme as in Fig.2:

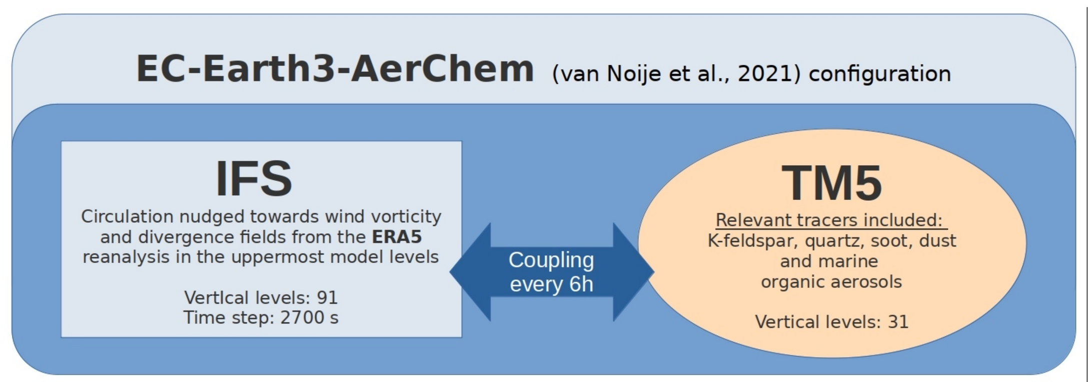

Fig. 1. EC-Earth-AerChem configuration

1) The **Meyers et al. (1992)** parameterization used in the original ECMWF IFS model.
2) **Aerosol-sensitive** (A-s) 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-sensitive 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.

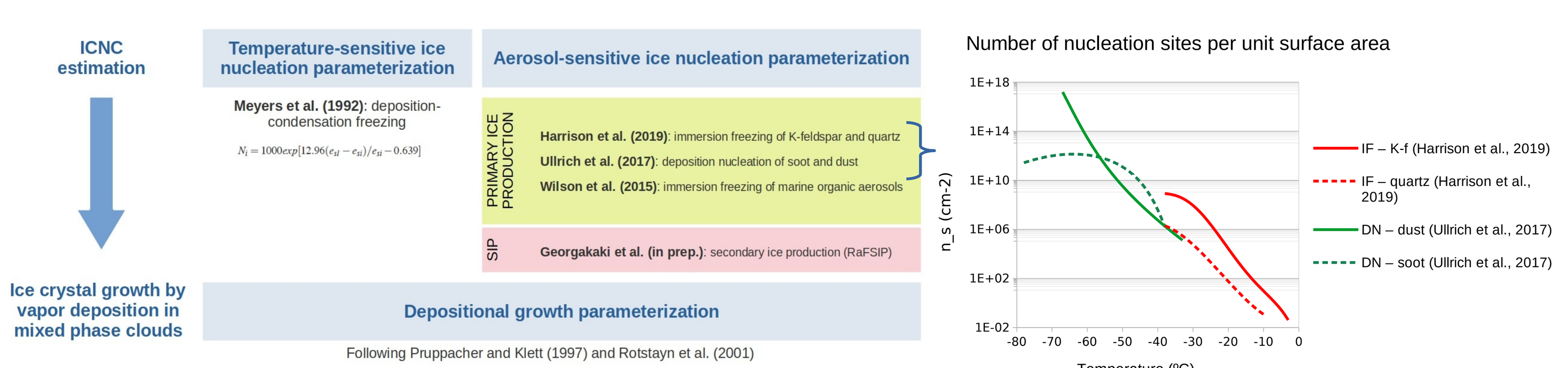

Fig. 2. Ice nucleation parameterizations used in the EC-Earth3-AerChem simulations. The ability to nucleate ice of the different immersion freezing and deposition nucleation parameterizations of two minerals in the immersion freezing (IF) mode (K-feldspar and quartz) and for bulk dust and soot in deposition nucleation (DN) regime (right).

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. (2023).

Results

Parameterizations' impact on the ICNC

The global profiles and zonal means show a reduction in ice crystals number concentration (ICNC) with the new aerosol-dependent ice nucleation parameterization in comparison to Meyers et al. (Fig. 3a,b); 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. 3c,d).

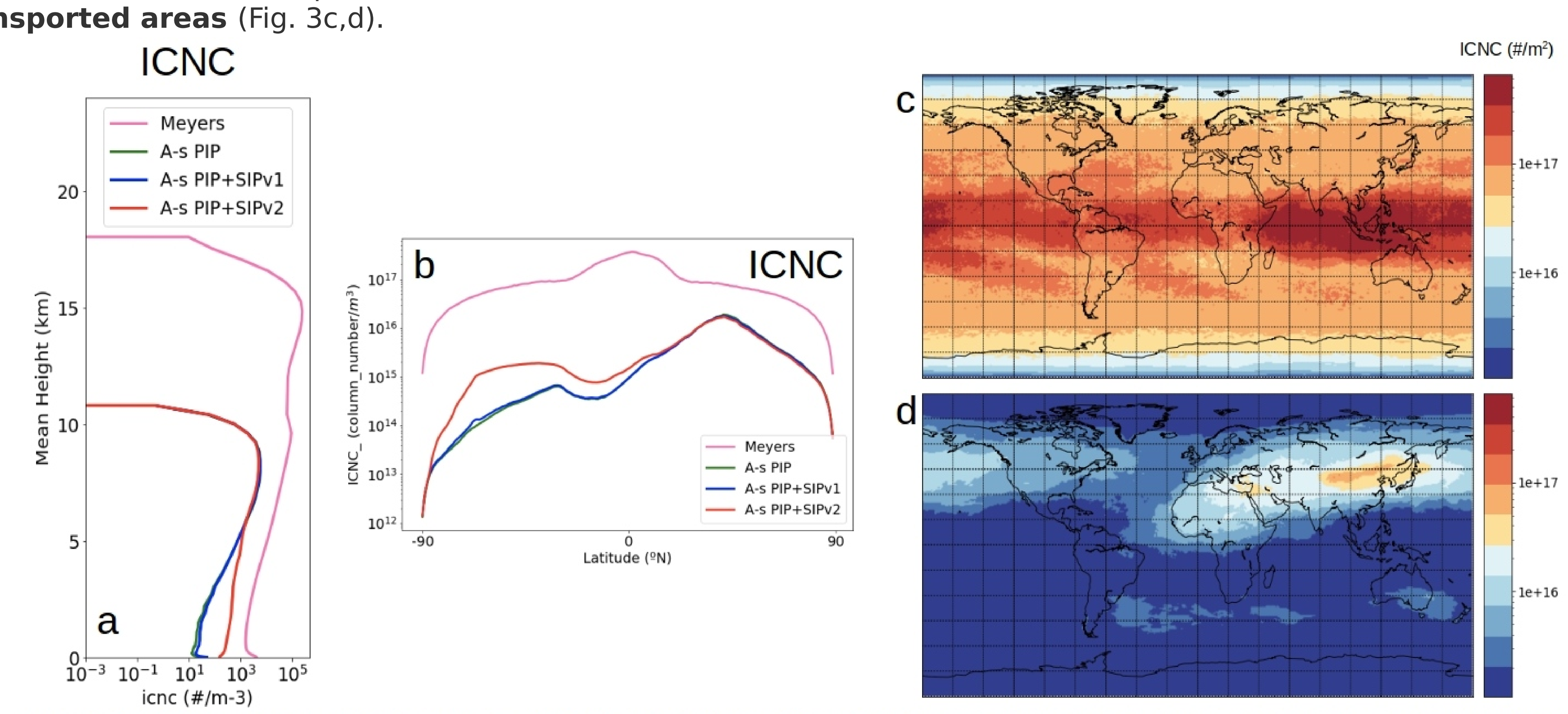

Fig. 3. (a) Global mean vertical profiles of ICNC and (b) latitudinal ICNC mean of the total column burden in a 1-year nudged simulation (July 1990 – June 1991) following a temperature-dependent (Meyers et al., 1992) and three aerosol-sensitive (A-s) ice nucleation parameterizations (Costa-Surós et al., in prep.). Average ICNC full-column burden following (c) Meyers et al. (1992) and (d) aerosol-sensitive ice nucleation parameterization (PIP + SIPv2). Horizontal grid size: 3 × 2º (longitude × latitude).

Climate impacts

Globally, there is, on average, an increase in **cloud cover** with the new ice nucleation parameterization (**PIP+SIPv2**), in comparison to the Meyers et al. (1992) simulation, due to increase of **liquid water path** (Fig. 4). The global near-surface **temperature** increases on average by 0.05 K, while regionally, the temperature change ranges from -2.4 to 3.6 K (Fig. 4b). **Radiative fluxes** changes at the top of the atmosphere (TOA) are consistent with the cloud cover differences. There is a clear increase in the short-wavelength (SW) radiation flux at the TOA returning to space and a global decrease of the long-wavelength (LW) counterpart (Fig. 4d,f).

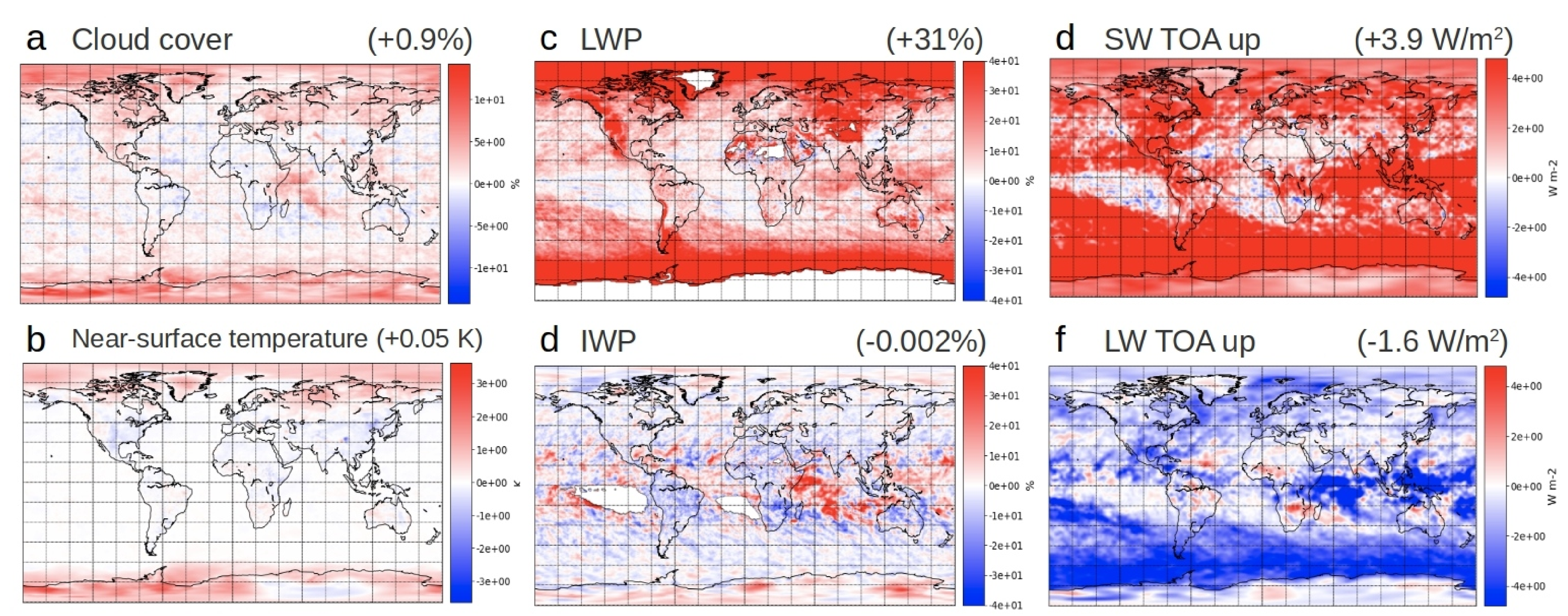

Fig. 4. Difference between the aerosol-sensitive ice nucleation parameterization (PIP + SIPv2) and Meyers et al. (1992) for (a) cloud cover, (b) near-surface temperature, (c) liquid water path, (d) ice water path, (e) short-wavelength and (f) long-wavelength upward radiative fluxes at the TOA.

Key findings

- The novel aerosol-sensitive ice nucleation parameterization, including primary ice nucleation and secondary ice processes, provides a **comprehensive new parameterization** that can substitute the deposition-condensation-freezing temperature-dependent parameterization by Meyers et al. (1992).
- The new ICNC 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 (+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).

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-sensitive 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 from later IFS cycles 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.

Acknowlgements

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