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The role of aerosol-sensitive primary ice nucleation and secondary ice production in modulating mixed-phase clouds in EC-Earth4

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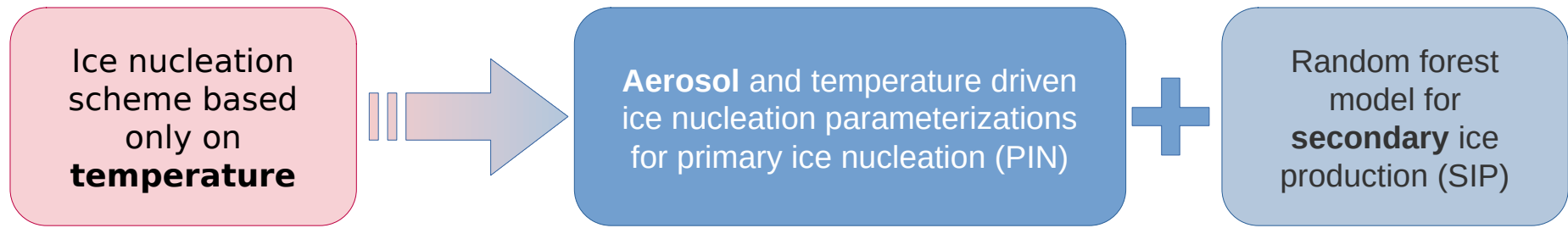


This project has received funding from Horizon Europe programme under Grant Agreement No 101137680 via project CERTAINTY (Cloud-aERosol inTeractions & their impActs IN The earth sYstem).

10/06/2026

Objective

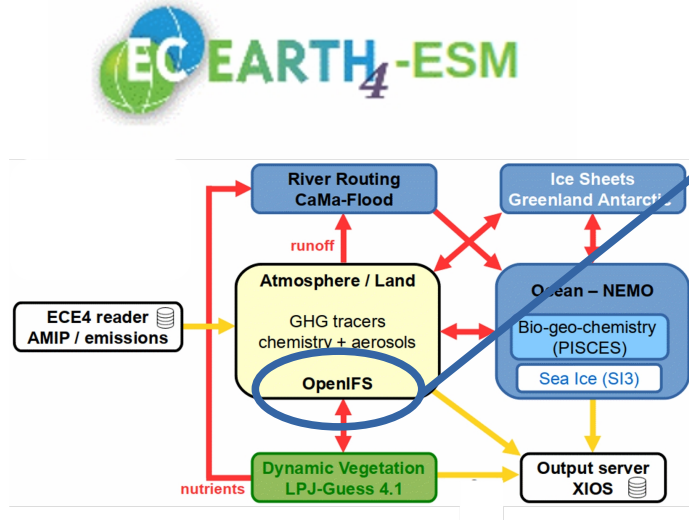
Improve cloud representation in the CMIP7 ESM EC-Earth4 by **updating the heterogeneous ice nucleation scheme**, enabling a more realistic sensitivity to present and future aerosol emissions and allowing assessment of their climate impact.



Outside the scope of the current CMIP7-Fast Track EC-Earth configuration

Methodology

1-year-long simulations (2018) with different ice nucleation parameterizations were run with the **OIFS48r1** model:



- Includes M7 module with:

- dust traced in 4 modes (acc./coa. & sol./insol.)
- black carbon traced in 2 modes (acc./coa. soluble)

- Vertical levels: 91

- Horizontal resolution: 255 lat x 512 lon. ($\sim 0.7^\circ$)

- Time step: 1800 s

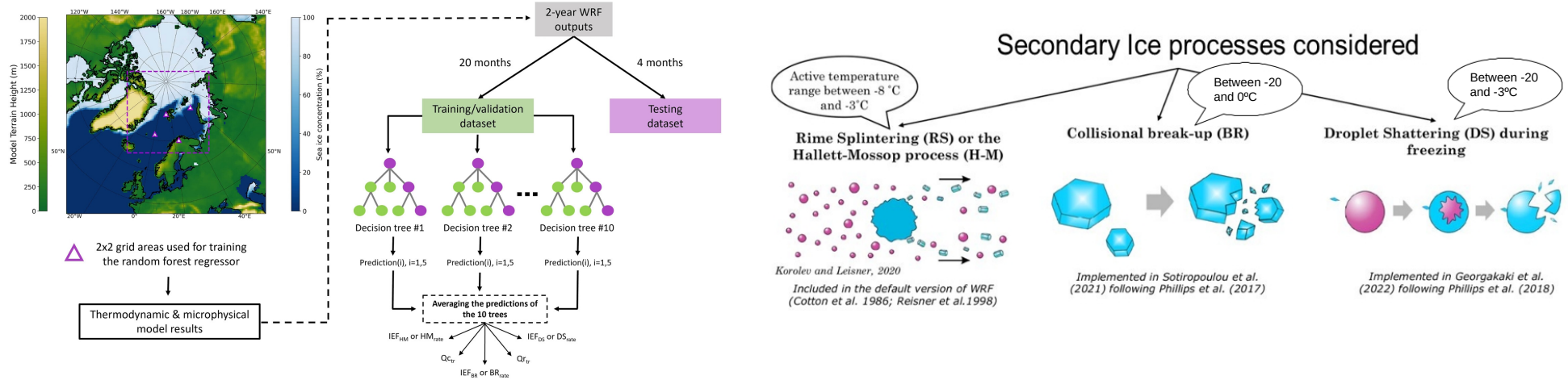
- Model output: 3h

Ice-nucleation parameterizations analyzed:

- 1) Meyers et al. (1992): temperature dependent
- 2) Ullrich et al. (2017): aerosol-sensitive to dust and soot
- 3) Ullrich et al. (2017) + RaFSIP (Georgakaki and Nenes, 2024)

Random Forest for Secondary Ice Processes (RaFSIP)

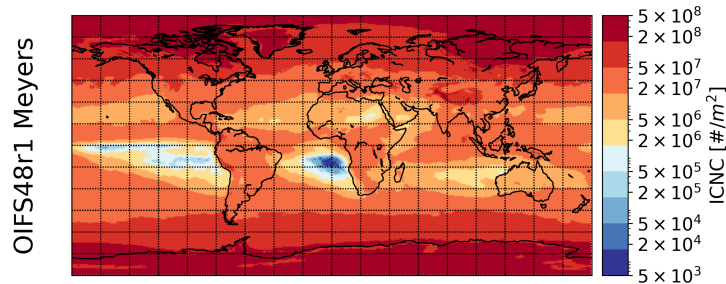
The RaFSIP (Georgakaki and Nenes, 2024) model was developed from 2-years of simulation data with WRF.



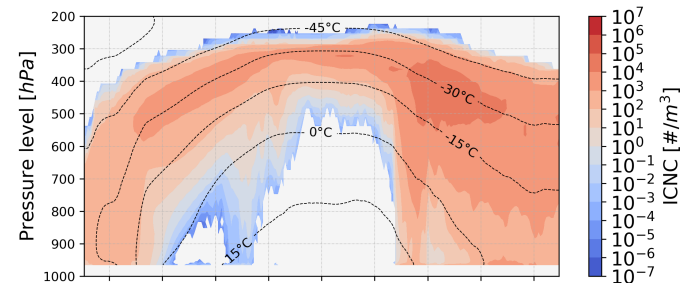
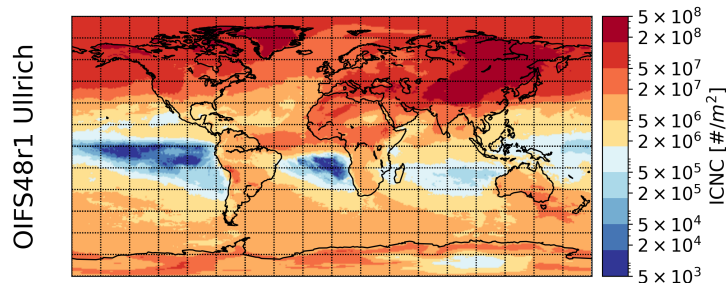
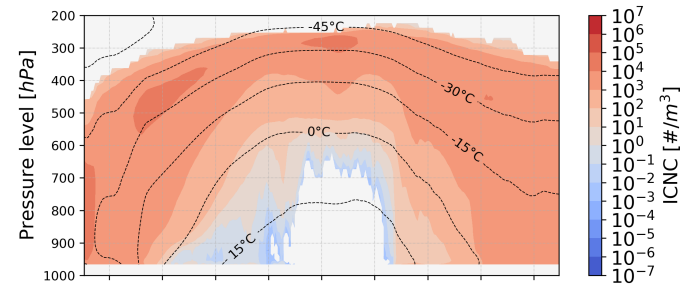
Impact of aerosol-sensitive PIN parameterization on ICNC

The aerosol-dependent ice nucleation parameterization generally reduces ICNC compared to Meyers et al. (1992), although some regions in the NH show localized increases. However, consistent with previous findings in EC-Earth3 (Costa-Surós et al., 2026), the resulting spatial distribution appears **more realistic**, showing a clear association between simulated ICNC and mineral **dust emission sources** and **transport pathways**.

In-MPC ICNC column burden



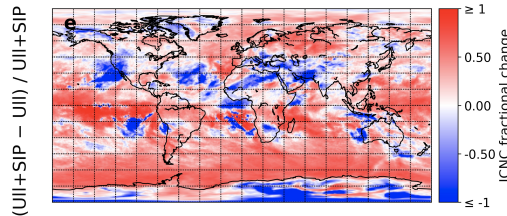
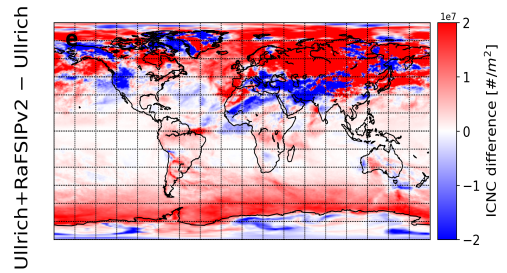
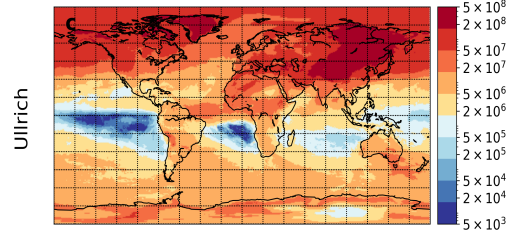
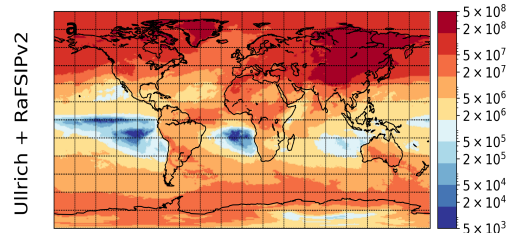
In-MPC ICNC zonal mean



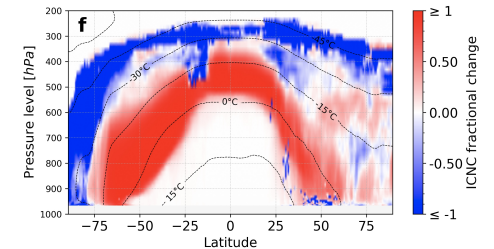
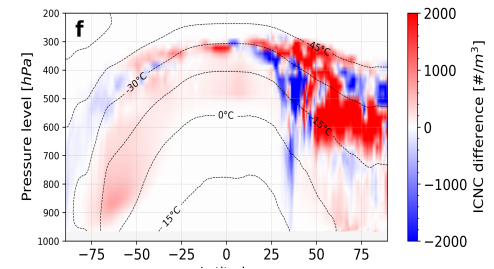
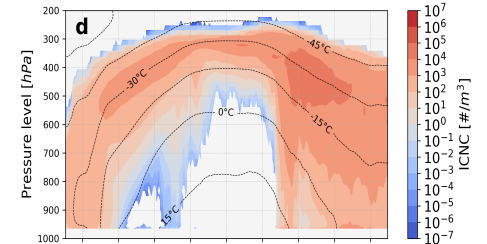
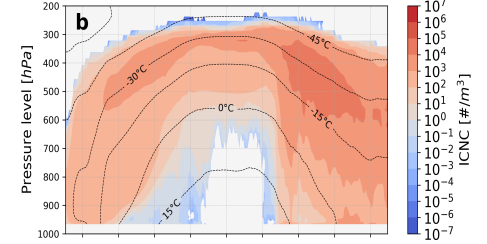
Impact of SIP on ICNC

Global increase in in-MPC ICNC, with largest absolute changes at mid-high NH latitudes and strongest relative increases at low to mid-level altitudes where ICNC is lowest.

In-MPC ICNC column burden

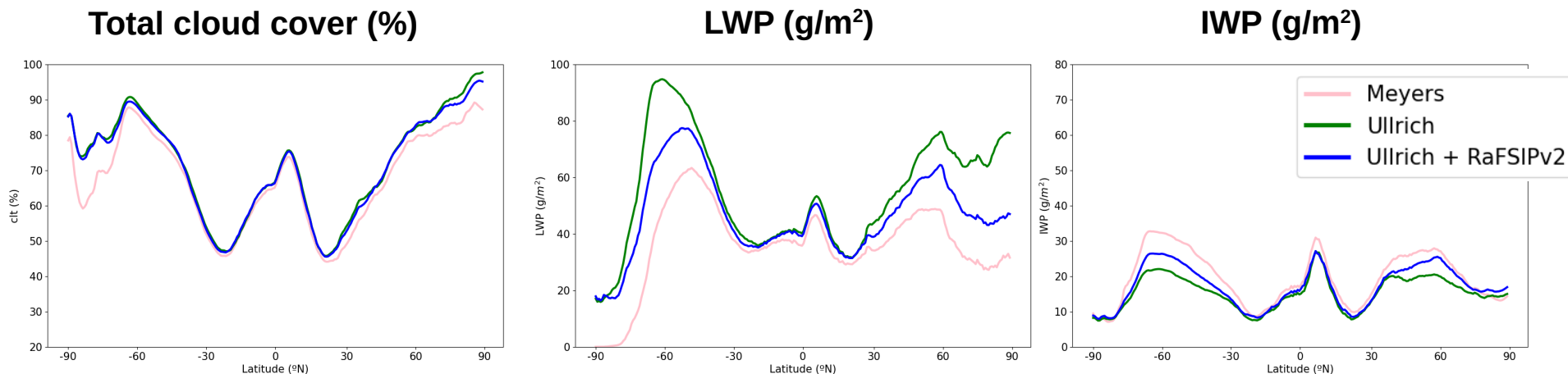


In-MPC ICNC zonal mean



Impact of the new aerosol-driven parameterization and SIP on cloud fields

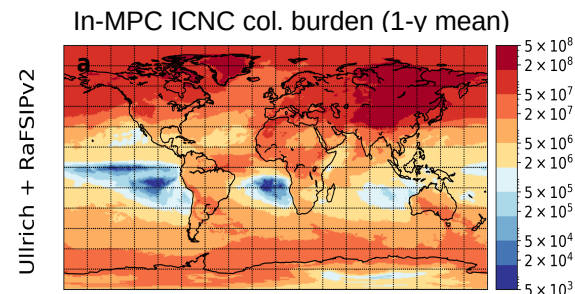
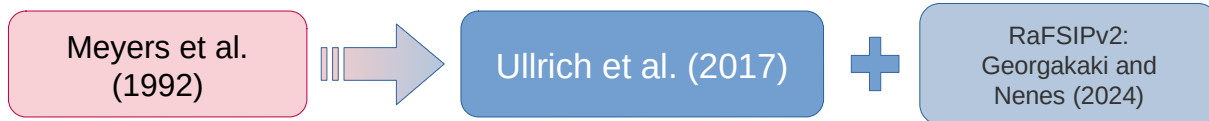
Globally, the new ice nucleation parameterization (PIP+SIP) leads, on average, to an **increase in cloud cover** compared to the Meyers et al. (1992) simulation. This increase is more pronounced at mid- to high latitudes and is primarily driven by an **increase in LWP**, which outweighs the comparatively smaller **reduction in IWP**.



With the addition of **RaFSIPv2**, LWP decreases and becomes closer to Meyers, although it remains higher. IWP increases and is now also closer to Meyers than before. This suggests that more sources of INPs still need to be added to the scheme in order to better represent ice nucleation in regions less influenced by mineral dust.

Summary:

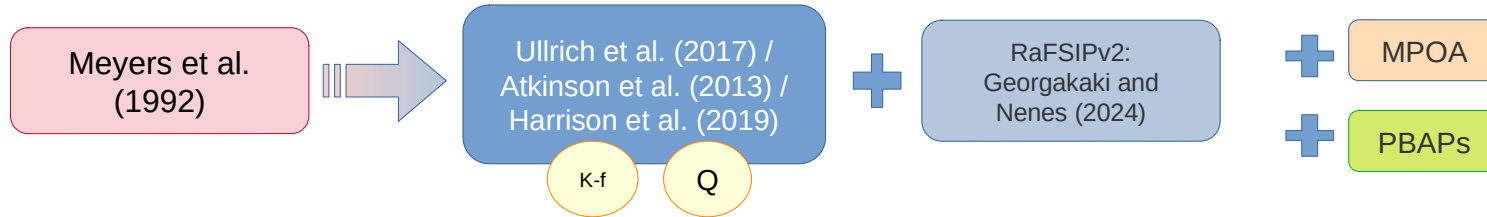
- The novel aerosol-sensitive ice nucleation parameterization provides a comprehensive new parameterization that can substitute the temperature-dependent parameterization in OIFS48r1, and seems more realistic.



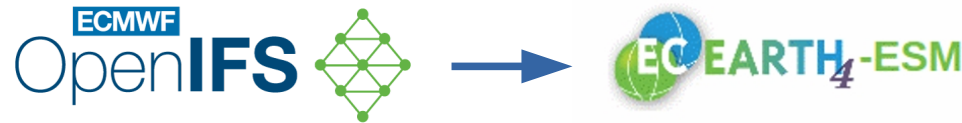
- Large model sensitivity to ICNC is found: globally increased cloud cover (+3.8%) linked to an increase in LWP (+19.6%) and decrease in IWP (-13.2%).
- The results suggest that more sources of INPs still need to be added to the scheme in order to better represent ice nucleation in regions less influenced by mineral dust.

Next steps:

- Implement quartz, feldspar, marine organic aerosols, and primary biological aerosol particles in the parameterization framework, and test additional aerosol-dependent ice nucleation schemes (Atkinson et al., 2013; Harrison et al., 2019; Wilson et al., 2015).



- Integration of the aerosol-sensitive primary and secondary ice production parameterizations into EC-Earth4.



- Implement the COSPv2 simulator for comparison with MODIS and CALIPSO satellite observations.
- Assess the long-term climate impacts of these developments.



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Special acknowledgement:
EC-Earth Atmospheric
Composition Working Group



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