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# Aerosol-sensitive Ice Nucleation Parameterizations in the EC-Earth3: evaluation and climate impacts


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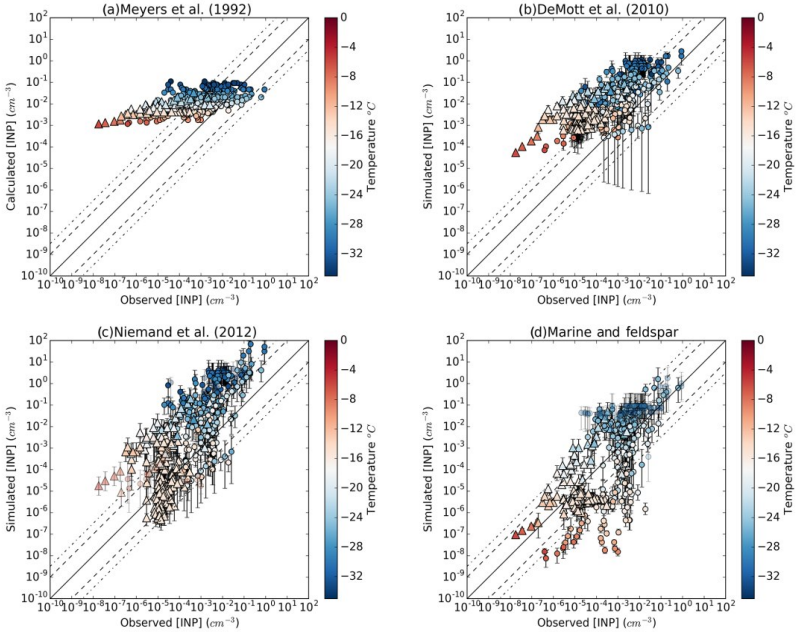
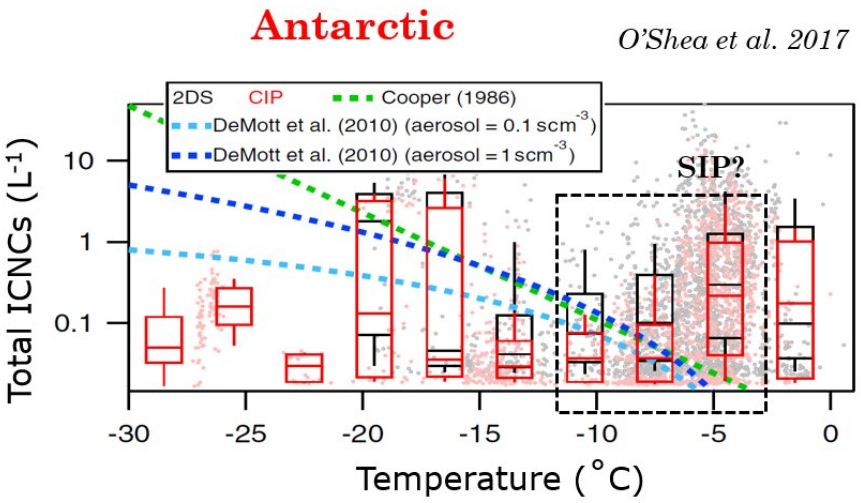
# Motivation

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.




*Vergara-Temprado et al., 2017*



# ECE3 with interactive aerosol mineralogy

## EC-Earth3-AerChem (van Noije et al., 2021) configuration

### IFS

Circulation nudged towards wind vorticity and divergence fields from the **ERA5** reanalysis in the uppermost model levels

Vertical levels: 91
Time step: 2700 s

Coupling every 6h

### TM5

Relevant tracers included:
K-feldspar, quartz, soot, dust and marine organic aerosols (coming from online calculated dust and sea salt)

Vertical levels: 34

Antropogenic sp. emissions from CMIP6-AMIP

Inidata: observed SST and sea ice area fraction (CMIP6-AMIP)

Model simulations setup: 1-year exp. (07/1990-06/1991) + spin-up (6 months) + nudging

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# New heterogeneous ice nucleation parameterization

**ICNC estimation**

**Temperature-sensitive ice nucleation parameterization**

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

$$N_i = 1000exp[12.96(e_{sl} - e_{si})/e_{si} - 0.639]$$

$N_i$: ice crystal number concentration
$e_{sl}$: saturation vapor pressure with respect to liquid water
$e_{si}$: saturation vapor pressure with respect to ice

**Aerosol-sensitive ice nucleation parameterization**

PRIMARY ICE PRODUCTION

**Immersion freezing**

**Atkinson et al. (2013)**: K-fedlspar
or
**Ullrich et al. (2017)**: soot and dust
or
**Harrison et al. (2019)**: K-feldspar and quartz

+

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

SECONDARY ICE PROCESSES

**Georgakaki et al. (in prep.)**: RaFSIP, which considers:
- Hallet-Mossop process
- Droplet shattering during freezing
- Fragmentation due to collisional break-up

**Ice crystal growth by vapor deposition**

**Depositional growth parameterization**

Following Pruppacher and Klett (1997) and Rotstayn et al. (2000)

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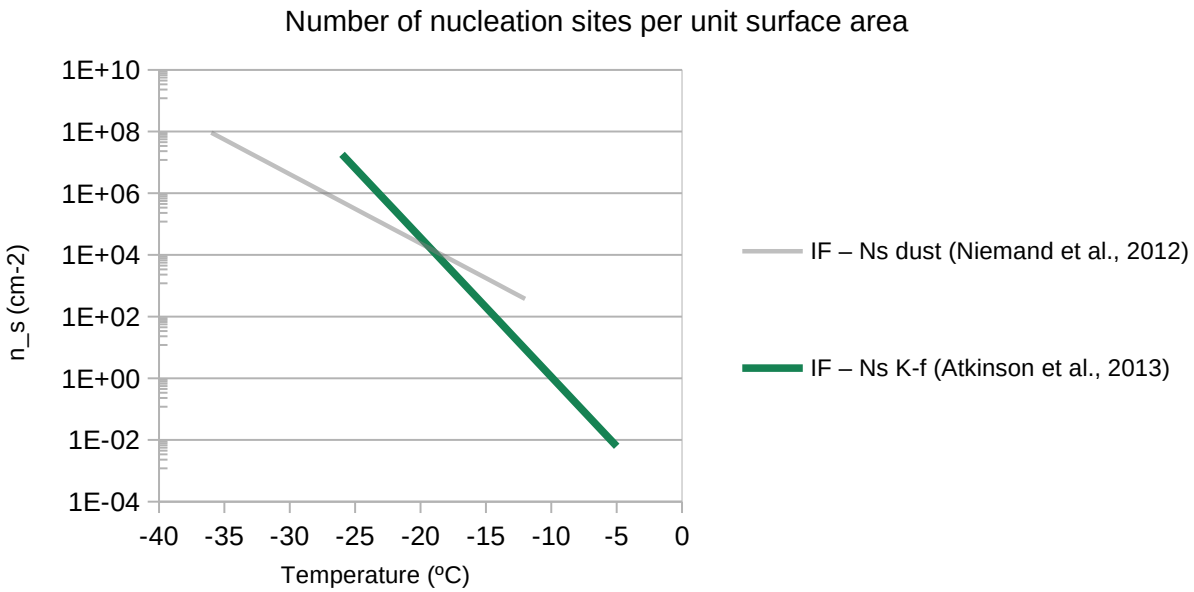
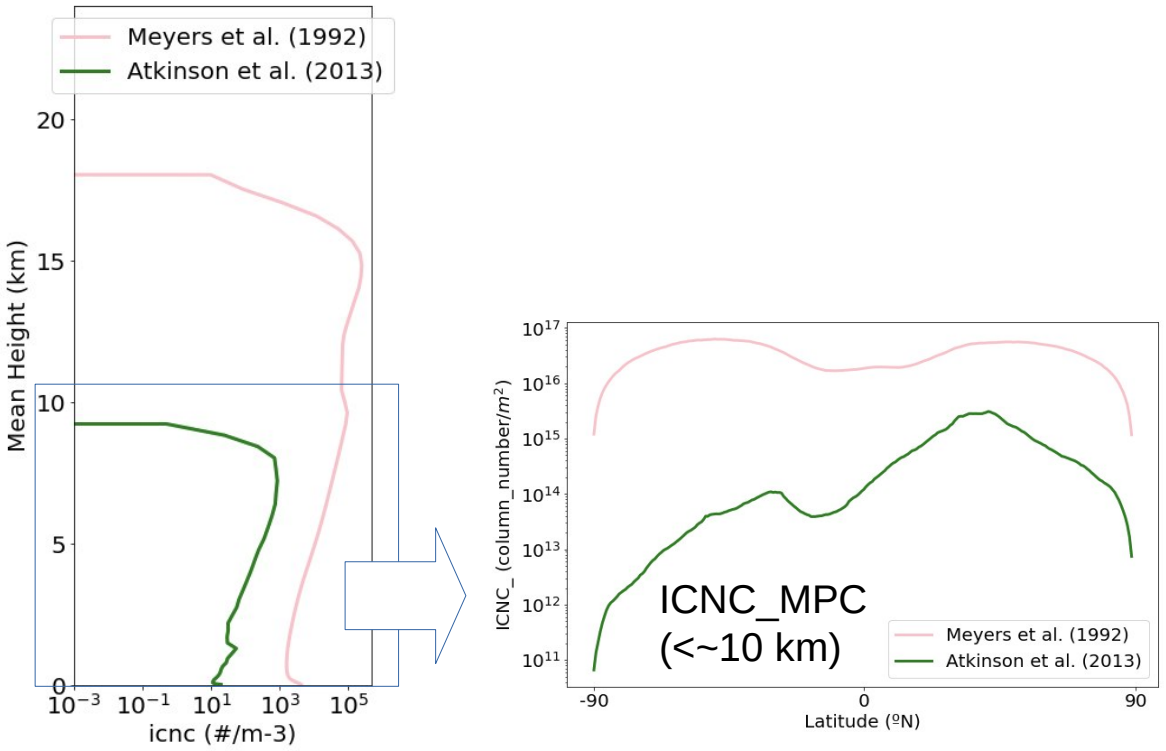
# Heterogeneous ice nucleation immersion freezing parameterizations

## Atkinson et al. (2013):

- K-feldspar mass (acc. and coarse insoluble modes)
- [-25.15, -5.15] ºC
- External mixing assumption



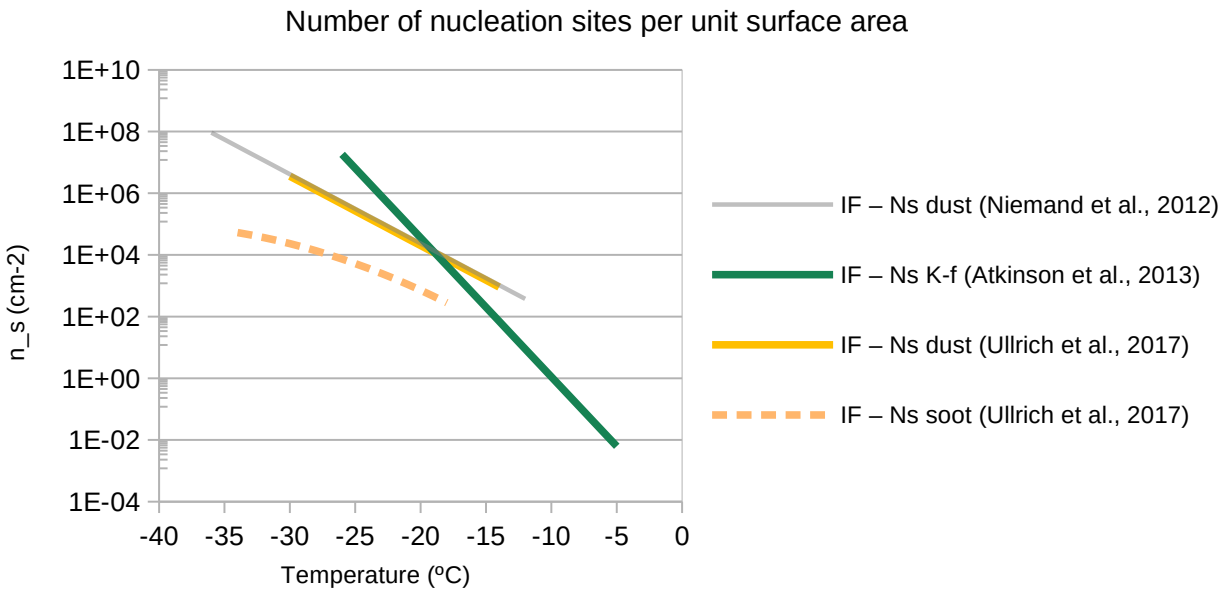

## 1-year nudged simulations ICNC_MPC results



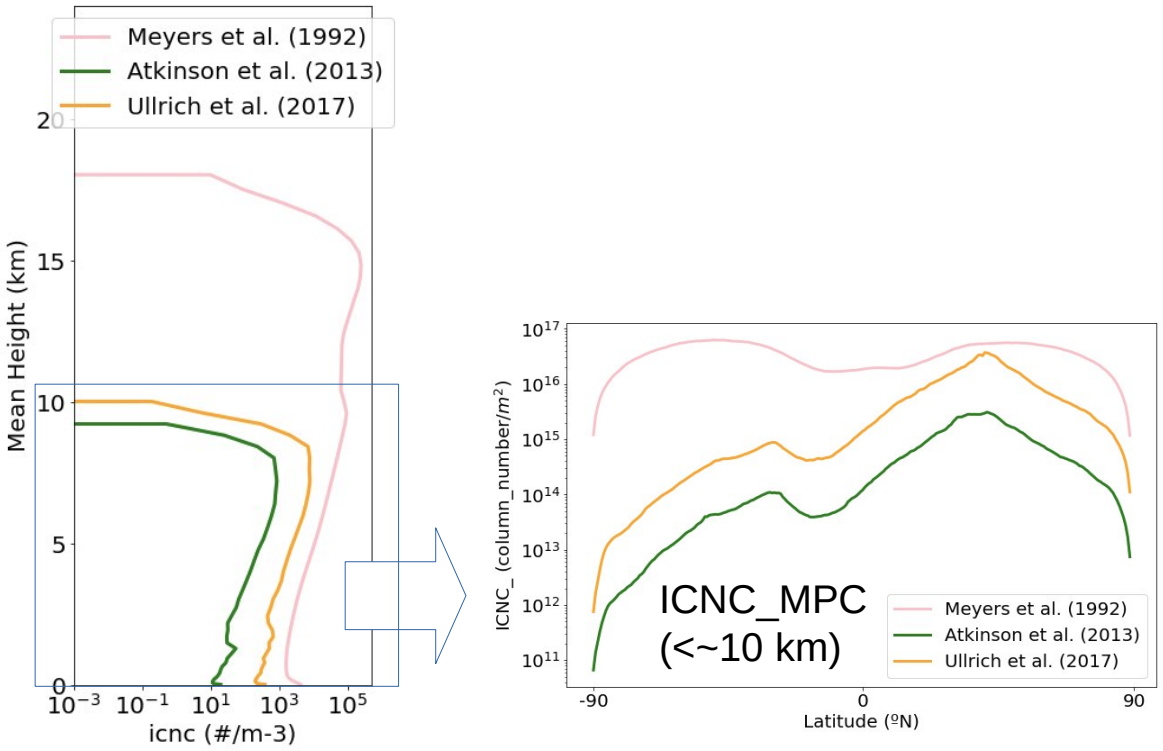
# Heterogeneous ice nucleation immersion freezing parameterizations

## Ullrich et al. (2017):

- Dust (accum. and coarse soluble and insoluble), and soot mass (accum. and coarse soluble modes)
- Dust: [-30, -14] ºC, and soot: [-34.15, -18.15] ºC
- External mixing (for insoluble) and internal mixing (for soluble).



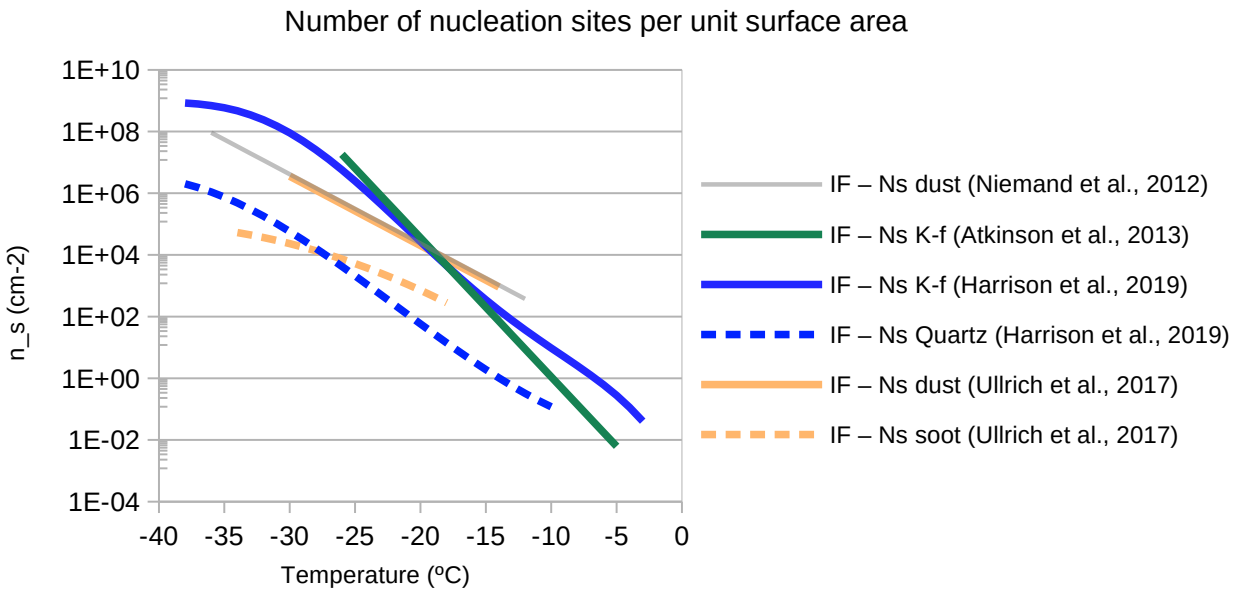

## 1-year nudged simulations ICNC_MPC results



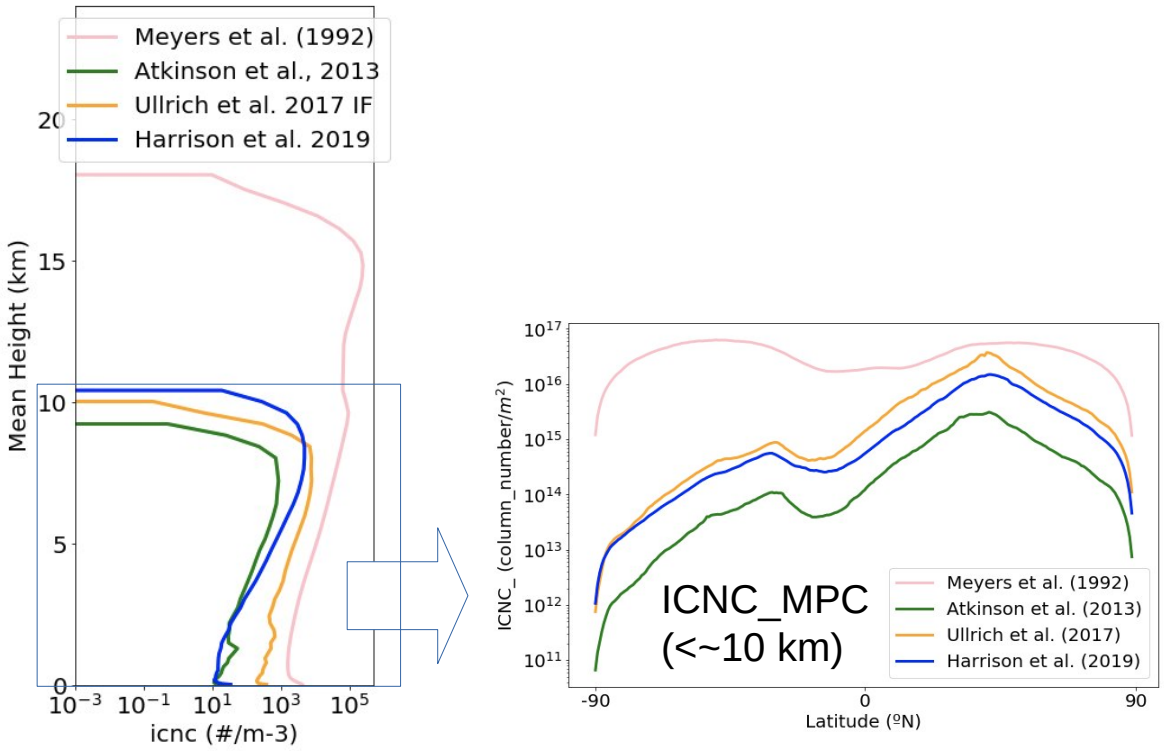
# Heterogeneous ice nucleation immersion freezing parameterizations

## Harrison et al. (2019):

- K-feldspar and quartz mass (acc. and coarse insoluble modes).
- K-f: [-37.51, -3.5] ºC, quartz: [-37.51, -10.5ºC]
- External mixing assumption

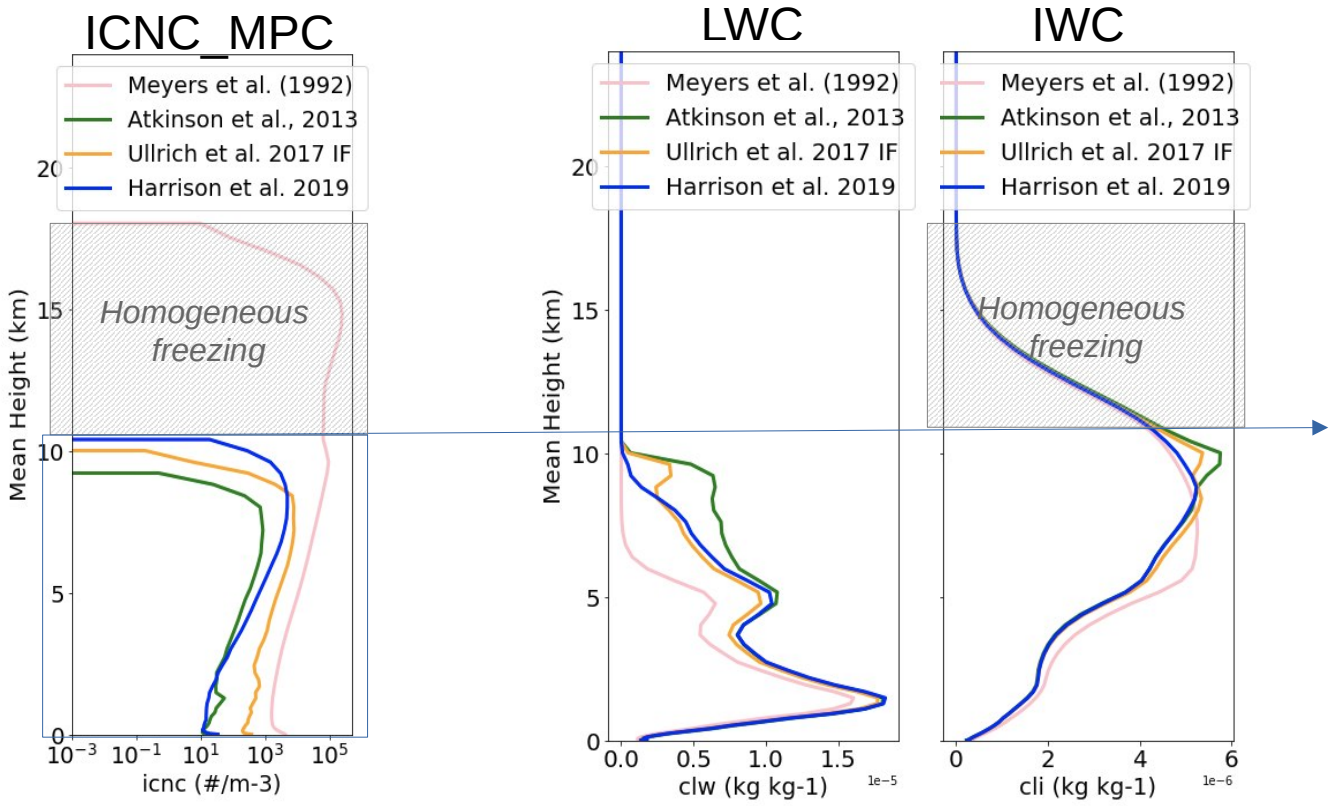



## 1-year nudged simulations ICNC_MPC results



# Impact of the aerosol-sensitive parameterizations in the clouds

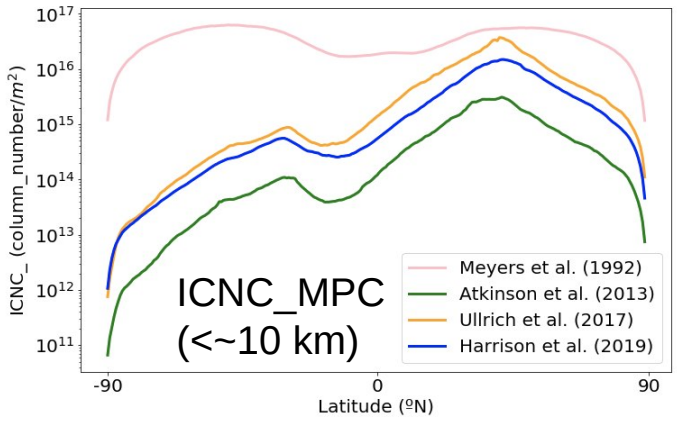
ICNC in the **mixed-phase cloud regime** used for the calculation of ice mass by depositional growth




Above ~ 10-11km **homogeneous freezing** dominates

(Meyers ICNC > 10-11km are not effective for heterogeneous ice production)

# ICNC in MPC regime: results of 1-year nudged simulations




Less ICNC_MPC from aerosol-sensitive ice nucelation parameterizations than from Meyers, especially at the SH.

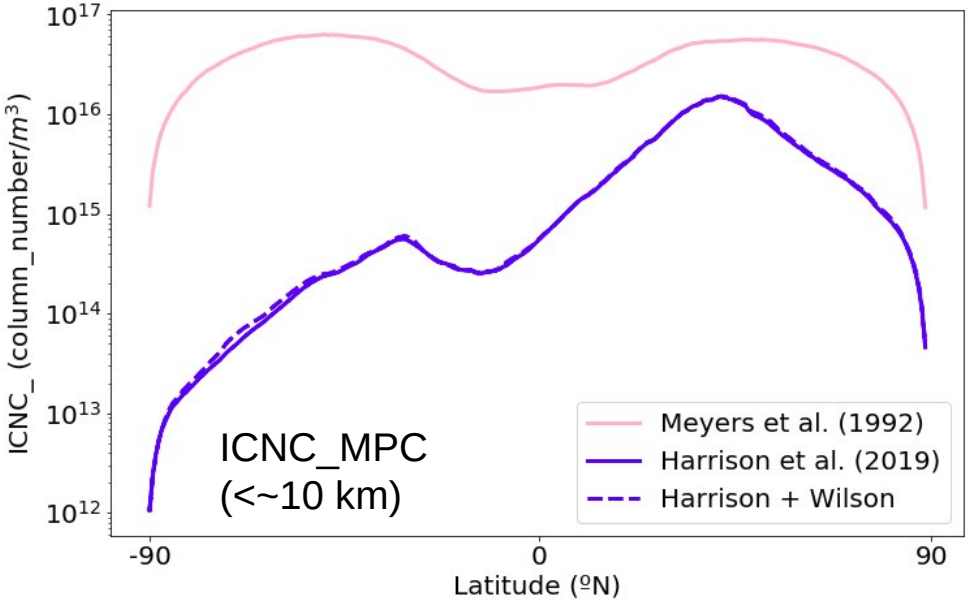
Need to take into account other processes and aerosols:

- Include parameterization depending on immersion freezing of **marine organic aerosols**
- **Secondary ice production**

# Heterogeneous ice nucleation immersion freezing parameterizations

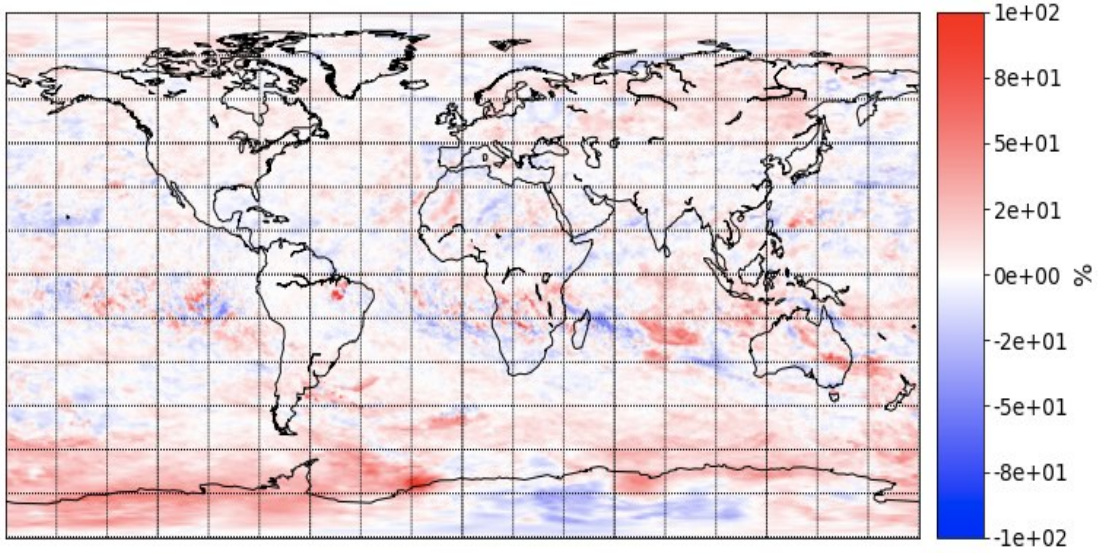
## Wilson et al. (2015):

- Marine organic aerosol particles (acc. soluble)
- [-28, -6.5] ºC




ICNC_MPC increase (%):

(Harrison + Wilson) - Harrison (+3.6%)

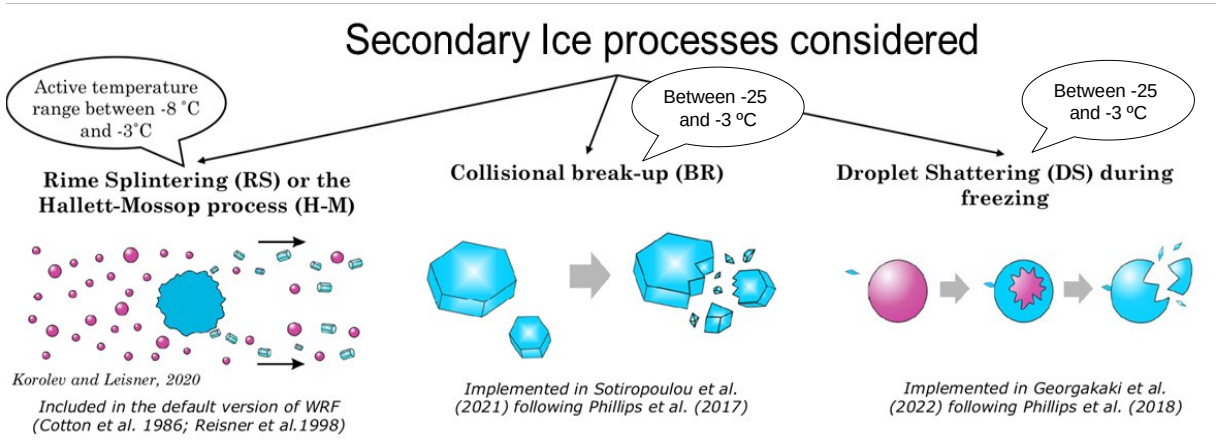



Including a parameterization depending on immersion freezing of **marine organic aerosols** increasess lower levels ice formation in the <u>oceanic regions</u>

# Secondary ice production parameterization

## Georgakaki et al. (in prep.):

Parameterization developed from 2 years of simulation data with WRF that includes secondary ice microphysics:





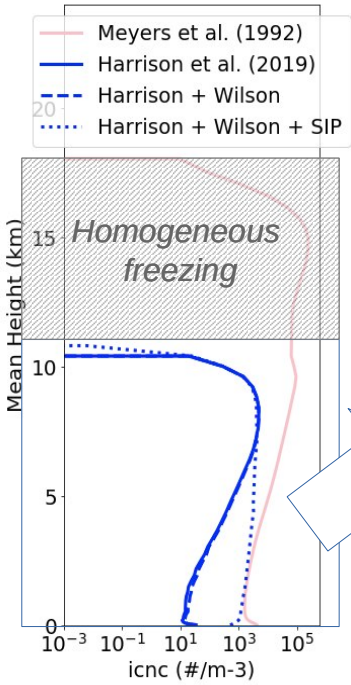
The methodology has been tested in the NorESM, ECE3-AerChem, ECHAM-HAM, and Polar-WRF models and now implemented in the ICON.

Two approaches available:

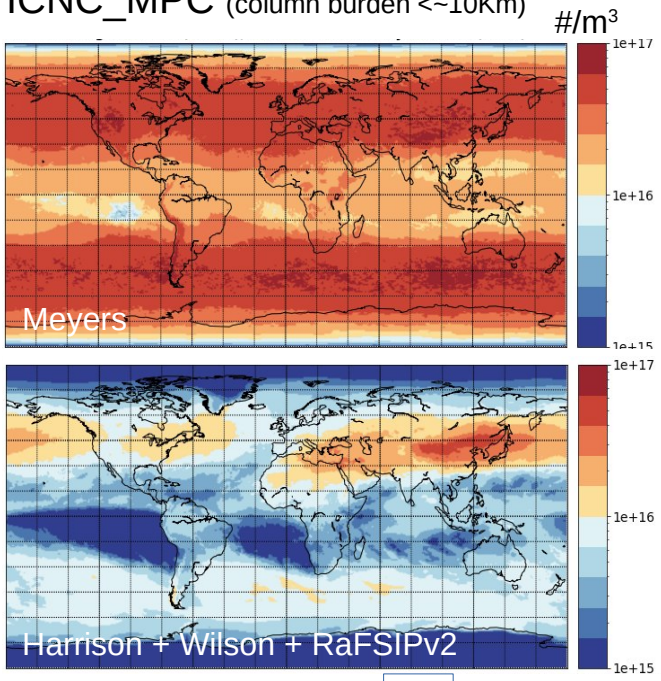
- RaFSIPv1: multiply the primary ice in each grid cell for each time step with an Ice Enhancement Factor (IEF) that accounts for SIP effects (not shown)
- **RaFSIPv2: the SIP is directly estimated from the random forest parameterization**

# Secondary ice production parameterization (RaFSIPv2)

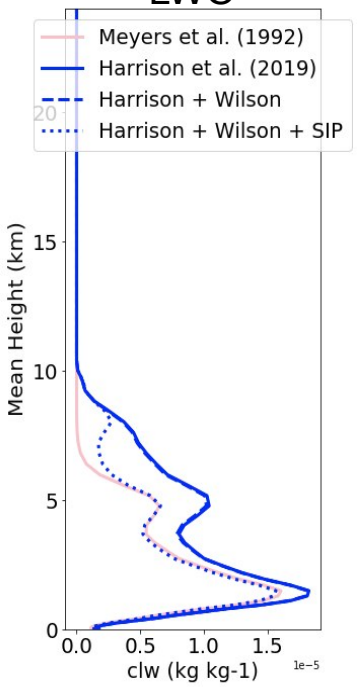
ICNC_MPC



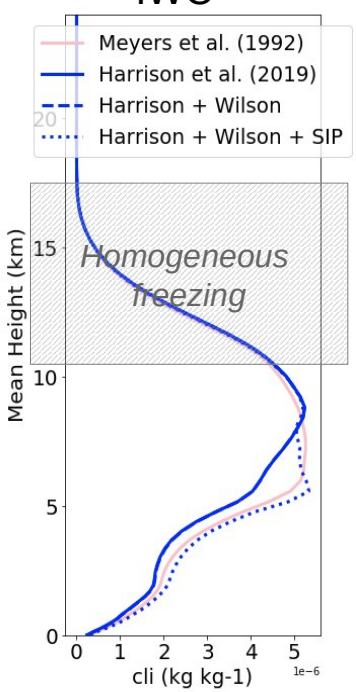

ICNC_MPC (column burden <~10Km)

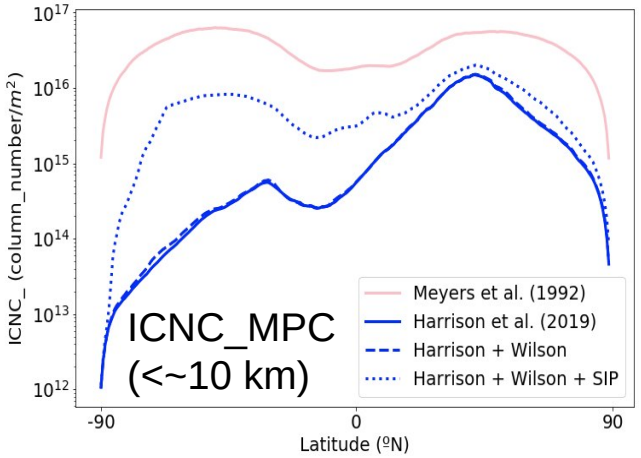



LWC

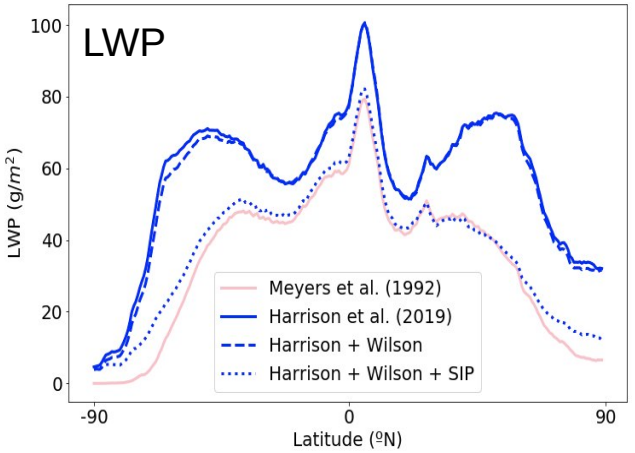


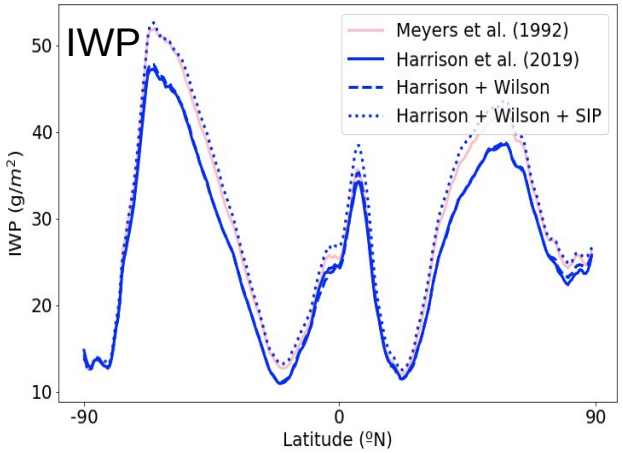

IWC




**More realistic** distribution since it depicts a clear association of the simulated ICNC with the **mineral-dust emission sources and transported areas.**

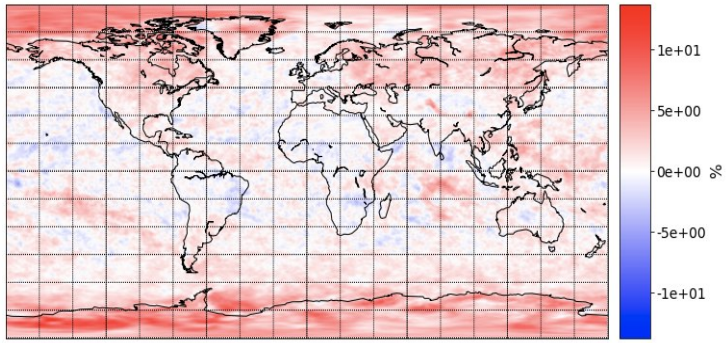


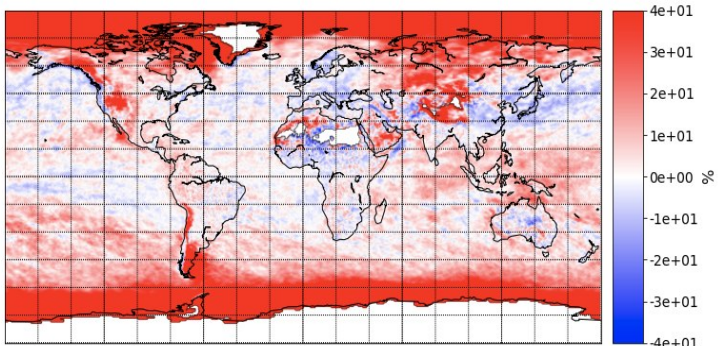
# Climate impacts

Difference between aerosol-sensitive param. (Harrison et al. (2019) + Wilson et al. (2015) + RaFSIPv2) and Meyers et al. (1992)
(1-year nudged simulations)

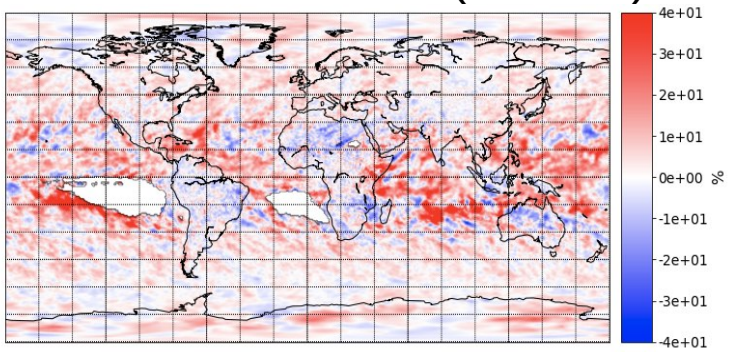
Cloud cover (+0.9%)



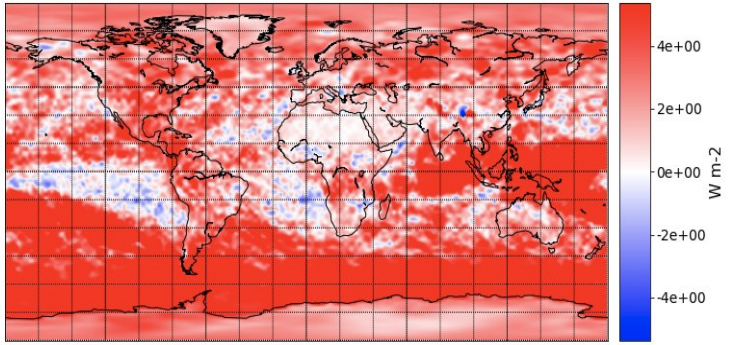

LWP (+32.5%)



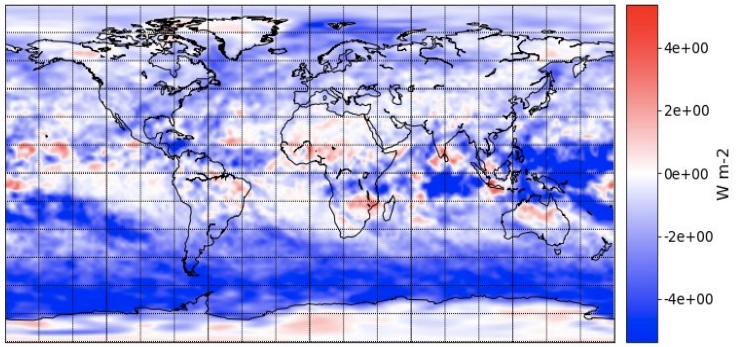

IWP (+0.05%)



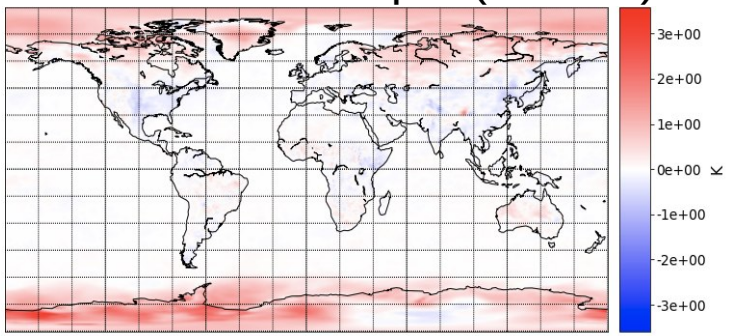

TOA out. SW rad. (+3.5W/m2)




TOA out. LW rad. (-1.7W/m2)




Near-Surf. air temp. (+0.06K)

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# Key findings

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

**2** 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**.

**3** Large **model sensitivity** to ICNC is found: globally increased cloud cover (+0.9%), LWP (+33%), SW (+3.5 W/m$^2$) and LW (-1.7 W/m$^2$) upwards radiation flux at TOA, and near-surface temperature (+0.06 K, regionally ranges from -0.2 to 3.6 K).

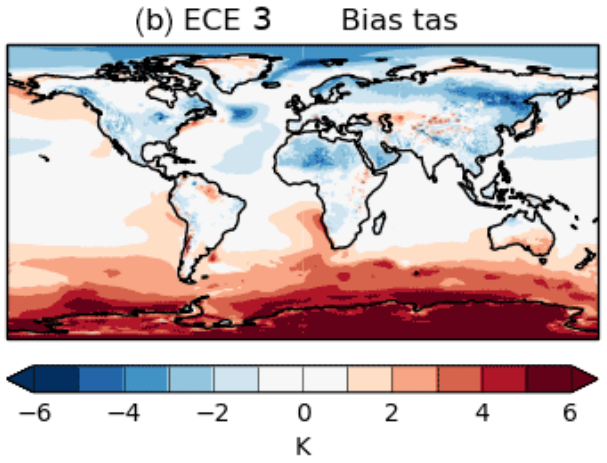
# Conclusions

The results suggest that substituting the temperature-dependent ice nucleation parameterization with an **aerosol-sensitive** parameterization, **could partially reduce the known EC-Earth3 biases** (Döscher et al., 2022) because it may **simulate the global ice formation more realistically**.

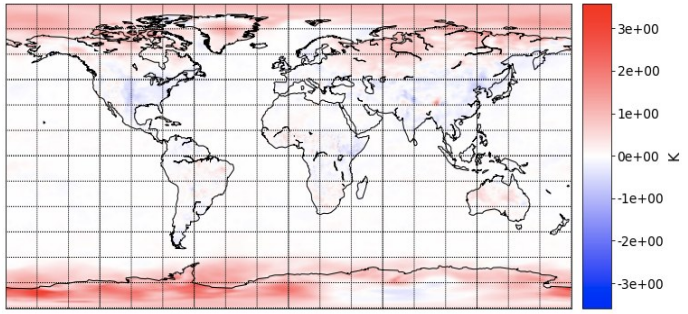
- The simulations with the dust-sensitive IN param. tend to warm the high-latitude regions compared to the temperature-dependent parameterization. This **corrects part of the cold bias** over large parts of the NH land regions and the Arctic.
- For Antarctica, the new aerosol-sensitive parameterization tends to warm on top of the warm bias. Since it 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.

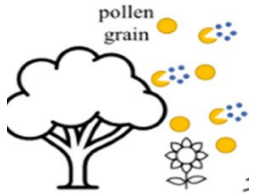
Döscher et al. (2022) EC-Earth3 ensemble mean TAS biases compared to ERA5 (1980 – 2010)



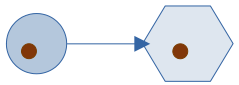

TAS Difference between aerosol-sensitive param. and temperature-dependent



# Future plans

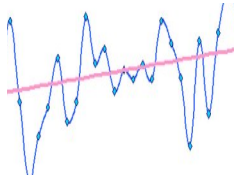



Better representation of the ice formation processes by including other **INPs** as precursors of ice crystals (e.g. pollen).



Consider other **immersion freezing** parameterizations (e.g. McCluskey et al., 2018).

The SIP parameterization will be further tested in the **FOR-ICE** intercomparison project.



The simulation period will be extended to **climatological** scales to assess the variability of the results over longer periods.

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MARIE CURIE ACTIONS
STARS POST-DOCTORAL PROGRAMME
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