Coupling aerosols to (cirrus) clouds in a global aerosol-climate model

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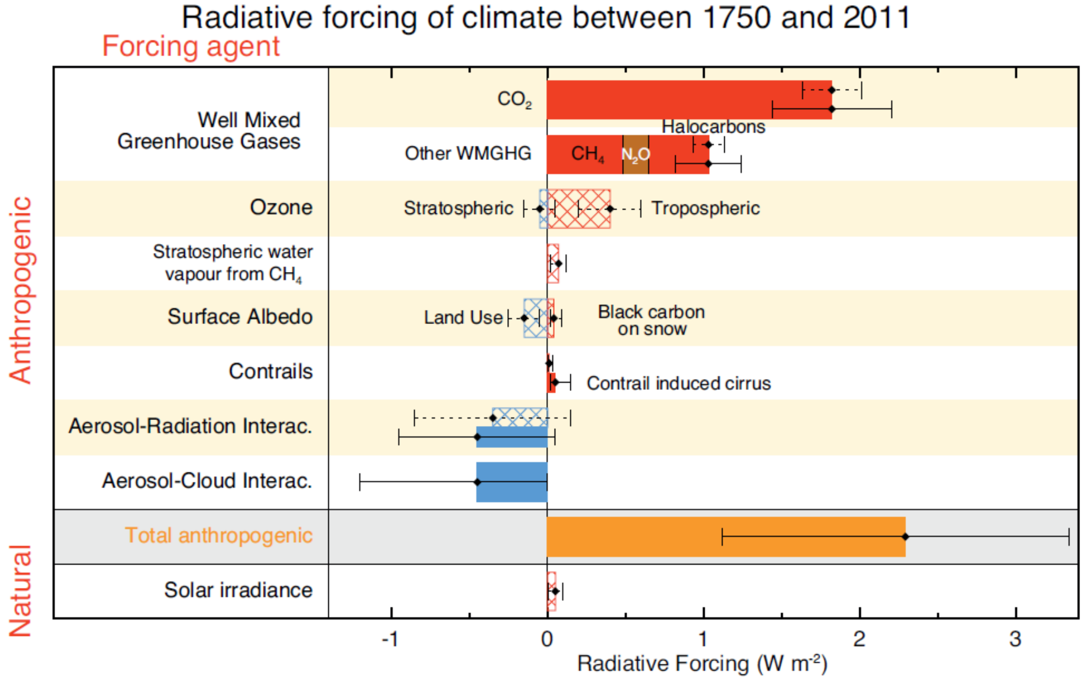
Knowledge for Tomorrow

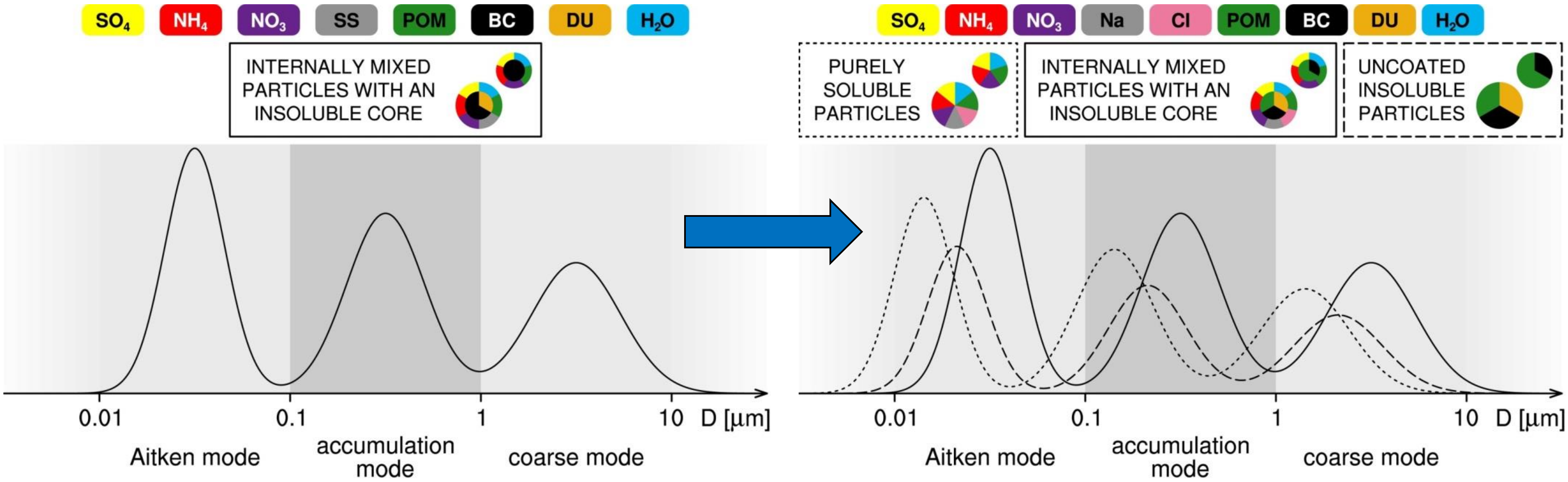
Motivation



- Ice crystals in the atmosphere affect the **radiative balance**, **precipitation** formation and the microphysical and optical properties of **clouds**
- The process of aerosol-induced **ice formation** in the upper troposphere is still **poorly understood**
- The resulting effects on **climate** are affected by very large **uncertainties**
- Aerosol effects on ice- and mixed-phase clouds were mostly not considered in the last **IPCC report**, but they are potentially important

Figure from Myhre et al., 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

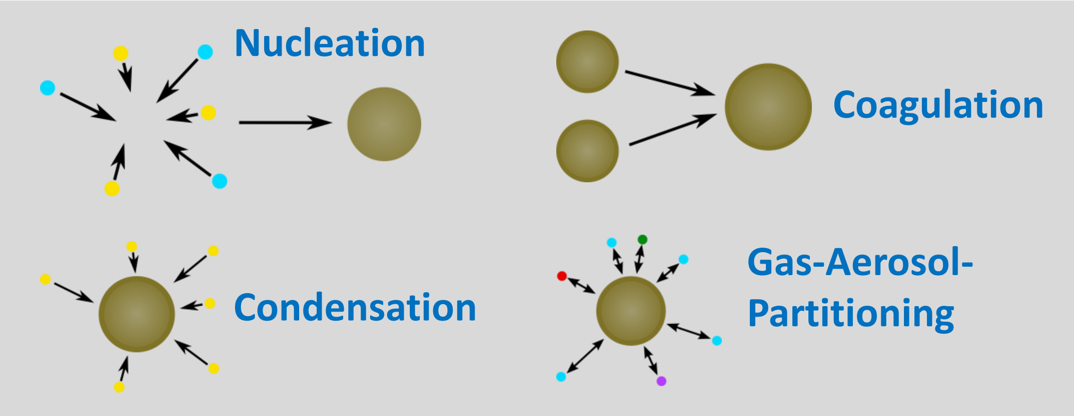
From MADE to MADE3



New features

- ✓ 2 additional aerosol **mixing states**
- ✓ Representation of gas-aerosol interactions in the **coarse mode**
- ✓ Representation of the **interactions** between **fine** and **coarse** modes
- ✓ New components **Na** and **Cl**
- ✓ Available since **EMAC** v2.54

Microphysical processes

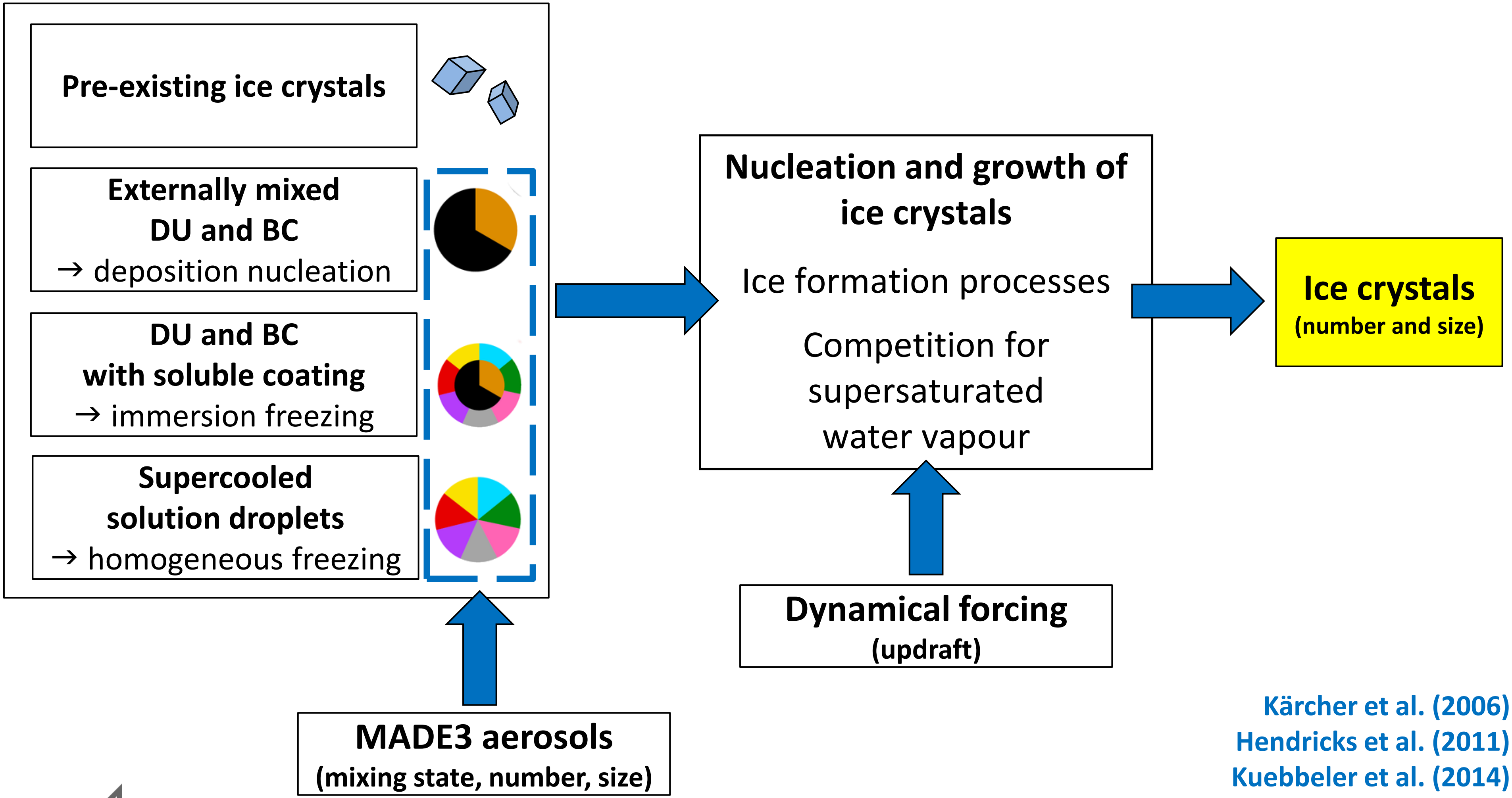


Kaiser et al. (GMD, 2014, 2019)

Parametrization of ice formation in cirrus (T < -38°C)

Key processes: ***immersion freezing***, ***deposition nucleation*** and ***homogeneous freezing***

Ice nucleating particles: **Dust** (DU), **Soot** (BC)



Pre-existing ice crystals

Externally mixed DU and BC
→ deposition nucleation

DU and BC with soluble coating
→ immersion freezing

Supercooled solution droplets
→ homogeneous freezing

MADE3 aerosols
(mixing state, number, size)

Nucleation and growth of ice crystals

Ice formation processes

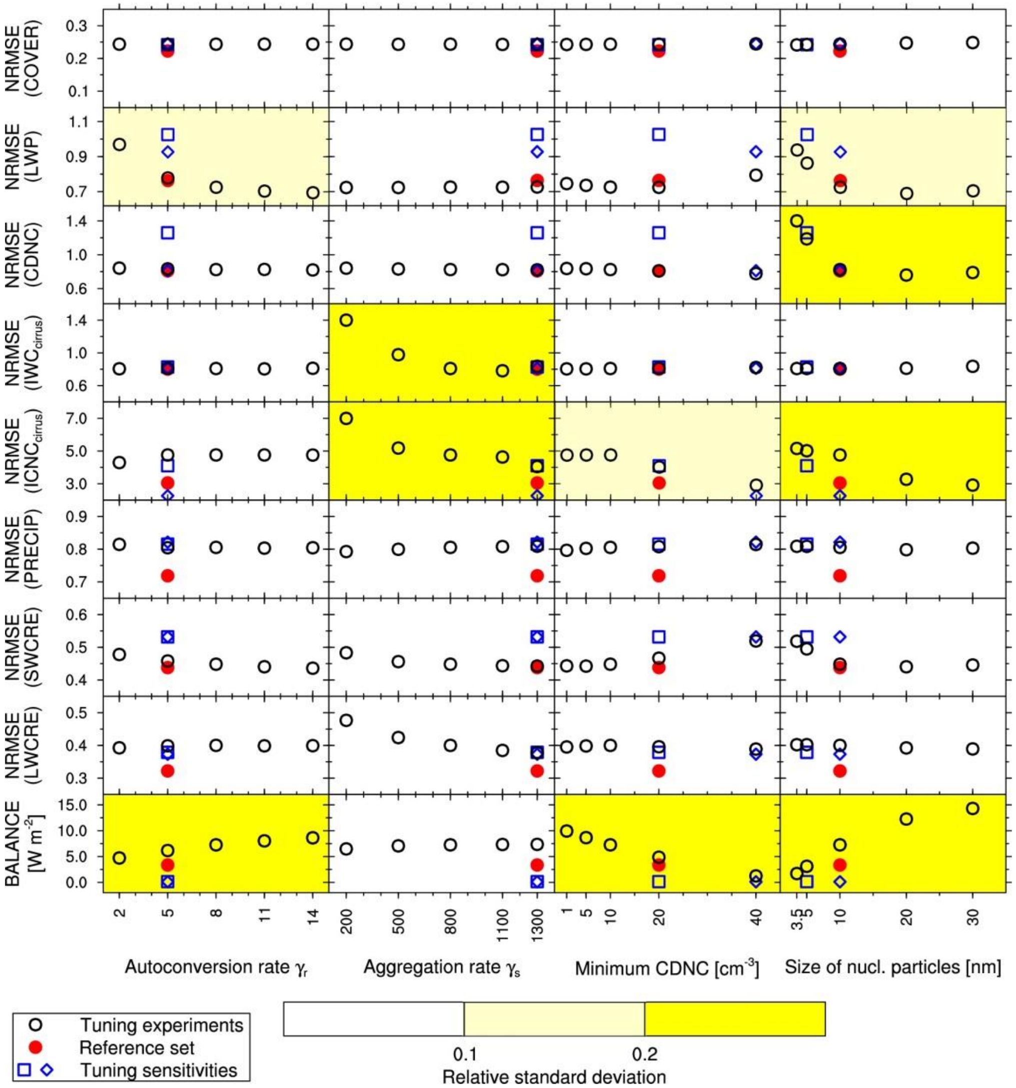
Competition for supersaturated water vapour

Dynamical forcing
(updraft)

Ice crystals
(number and size)

Kärcher et al. (2006)
Hendricks et al. (2011)
Kuebbeler et al. (2014)

Tuning of the new model configuration



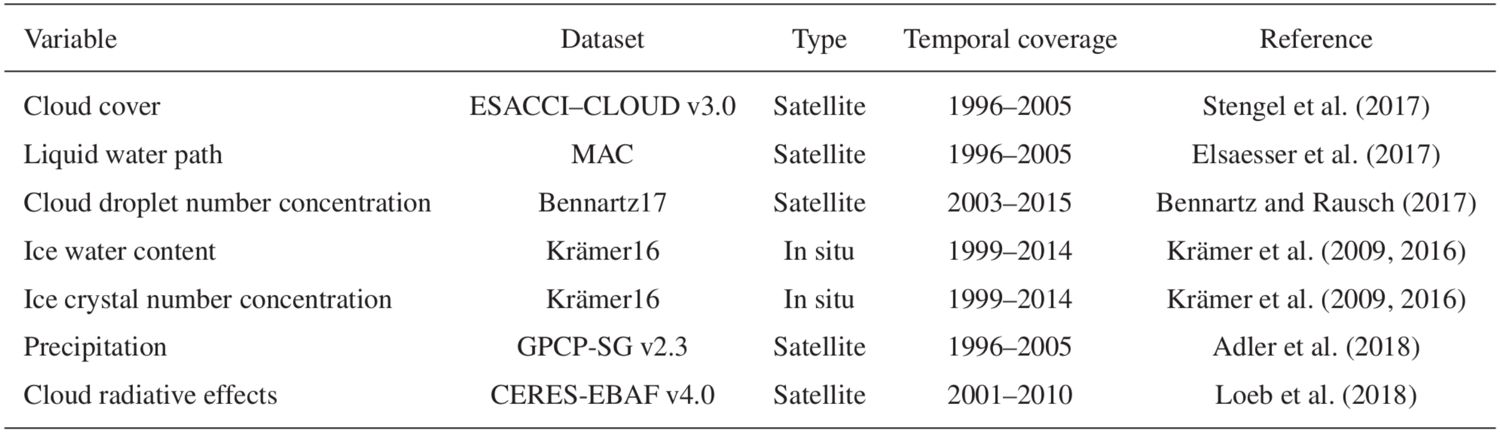
Righi et al. (2019)

- Focus on **4 tuning parameters**:
    - Autoconversion rate
    - Aggregation rate
    - Minimum CDNC
    - Size of newly nucleated aerosol particles
- For each tuning parameter **5 different values** are tested
- This results in **17+3 tuning simulations**
- The impact of a specific tuning parameter on the model (cloud and radiation) variables is quantified by means of a **normalized RMSE**:

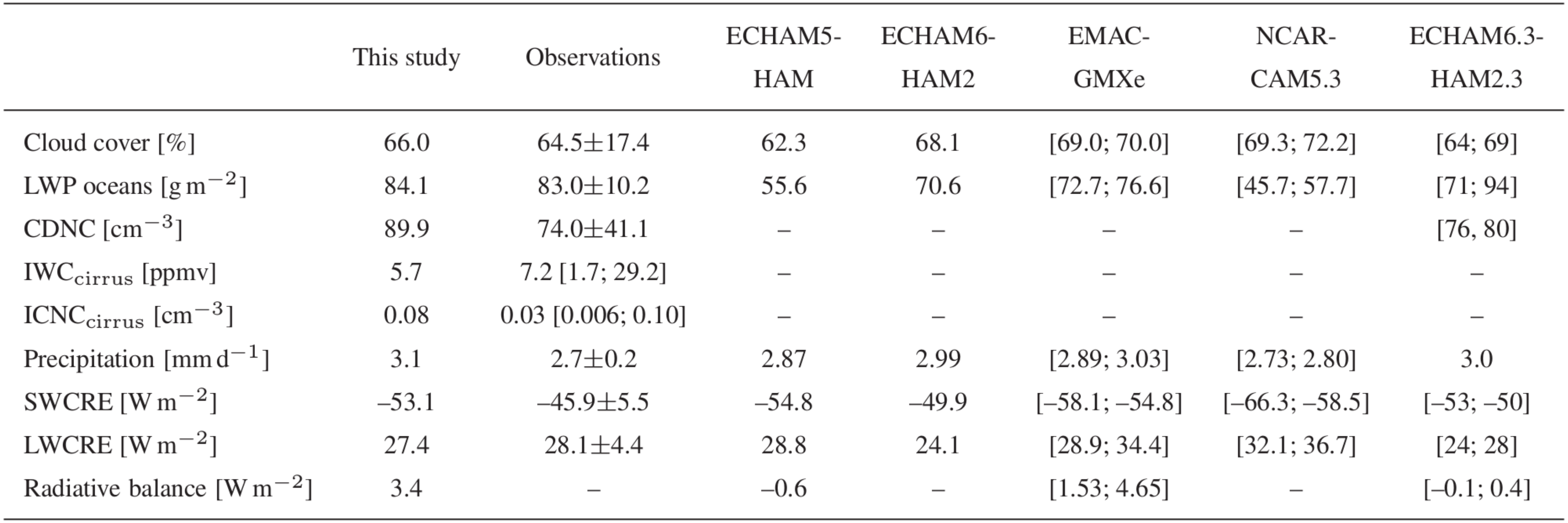
$$NRMSE = \sqrt{\frac{\sum_i (M_i - O_i)^2}{n}} \Bigg/ \frac{\sum_i O_i}{n}$$

- The sensitivity of a given model variable to the variation of a specific tuning parameter is estimated with the **relative standard deviation** (RSD).
- This method allows to identify the most important **parameter-variable combinations** and optimally tune them.

Evaluation of the new model configuration



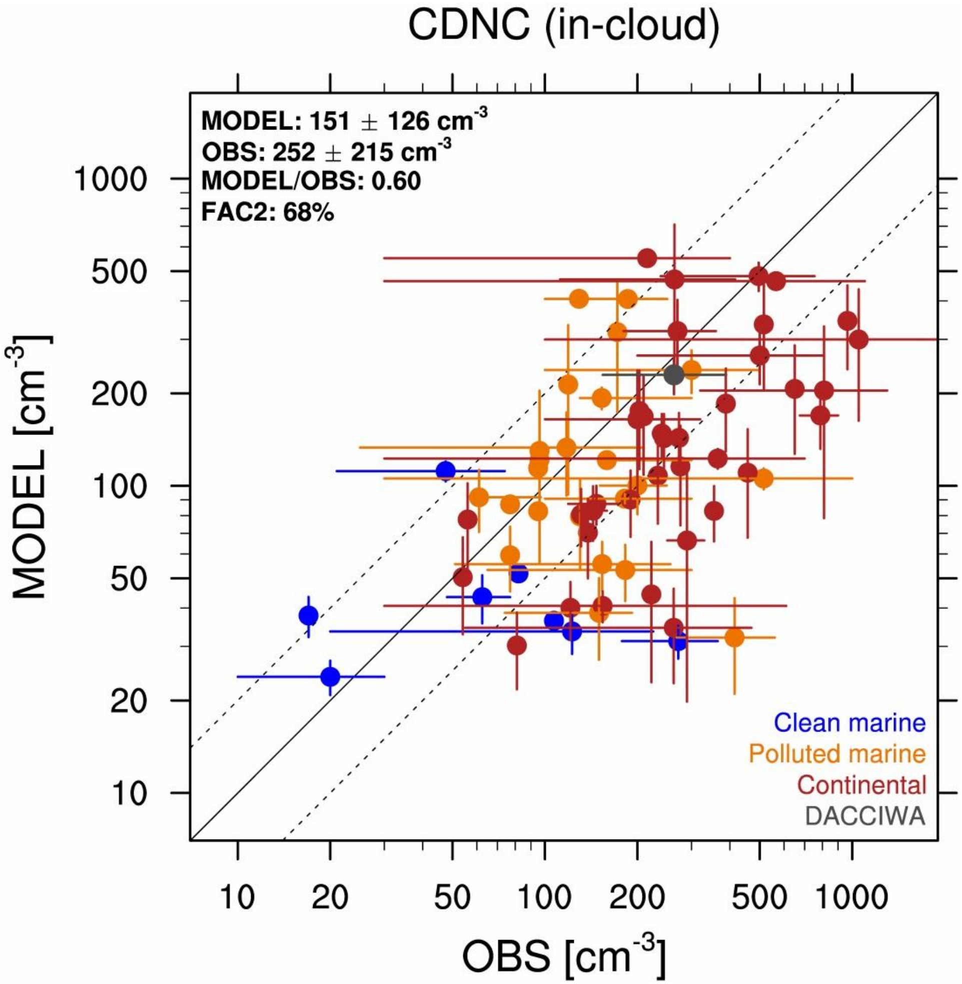
Variable	Dataset	Type	Temporal coverage	Reference
Cloud cover	ESACCI–CLOUD v3.0	Satellite	1996–2005	Stengel et al. (2017)
Liquid water path	MAC	Satellite	1996–2005	Elsaesser et al. (2017)
Cloud droplet number concentration	Bennartz17	Satellite	2003–2015	Bennartz and Rausch (2017)
Ice water content	Krämer16	In situ	1999–2014	Krämer et al. (2009, 2016)
Ice crystal number concentration	Krämer16	In situ	1999–2014	Krämer et al. (2009, 2016)
Precipitation	GPCP-SG v2.3	Satellite	1996–2005	Adler et al. (2018)
Cloud radiative effects	CERES-EBAF v4.0	Satellite	2001–2010	Loeb et al. (2018)



	This study	Observations	ECHAM5-HAM	ECHAM6-HAM2	EMAC-GMXe	NCAR-CAM5.3	ECHAM6.3-HAM2.3
Cloud cover [%]	66.0	64.5±17.4	62.3	68.1	[69.0; 70.0]	[69.3; 72.2]	[64; 69]
LWP oceans [$\mathrm{g\,m^{-2}}$]	84.1	83.0±10.2	55.6	70.6	[72.7; 76.6]	[45.7; 57.7]	[71; 94]
CDNC [$\mathrm{cm^{-3}}$]	89.9	74.0±41.1	–	–	–	–	[76, 80]
$\mathrm{IWC_{cirrus}}$ [ppmv]	5.7	7.2 [1.7; 29.2]	–	–	–	–	–
$\mathrm{ICNC_{cirrus}}$ [$\mathrm{cm^{-3}}$]	0.08	0.03 [0.006; 0.10]	–	–	–	–	–
Precipitation [$\mathrm{mm\,d^{-1}}$]	3.1	2.7±0.2	2.87	2.99	[2.89; 3.03]	[2.73; 2.80]	3.0
SWCRE [$\mathrm{W\,m^{-2}}$]	–53.1	–45.9±5.5	–54.8	–49.9	[–58.1; –54.8]	[–66.3; –58.5]	[–53; –50]
LWCRE [$\mathrm{W\,m^{-2}}$]	27.4	28.1±4.4	28.8	24.1	[28.9; 34.4]	[32.1; 36.7]	[24; 28]
Radiative balance [$\mathrm{W\,m^{-2}}$]	3.4	–	–0.6	–	[1.53; 4.65]	–	[–0.1; 0.4]

Righi et al. (2020)

CDNC evaluation



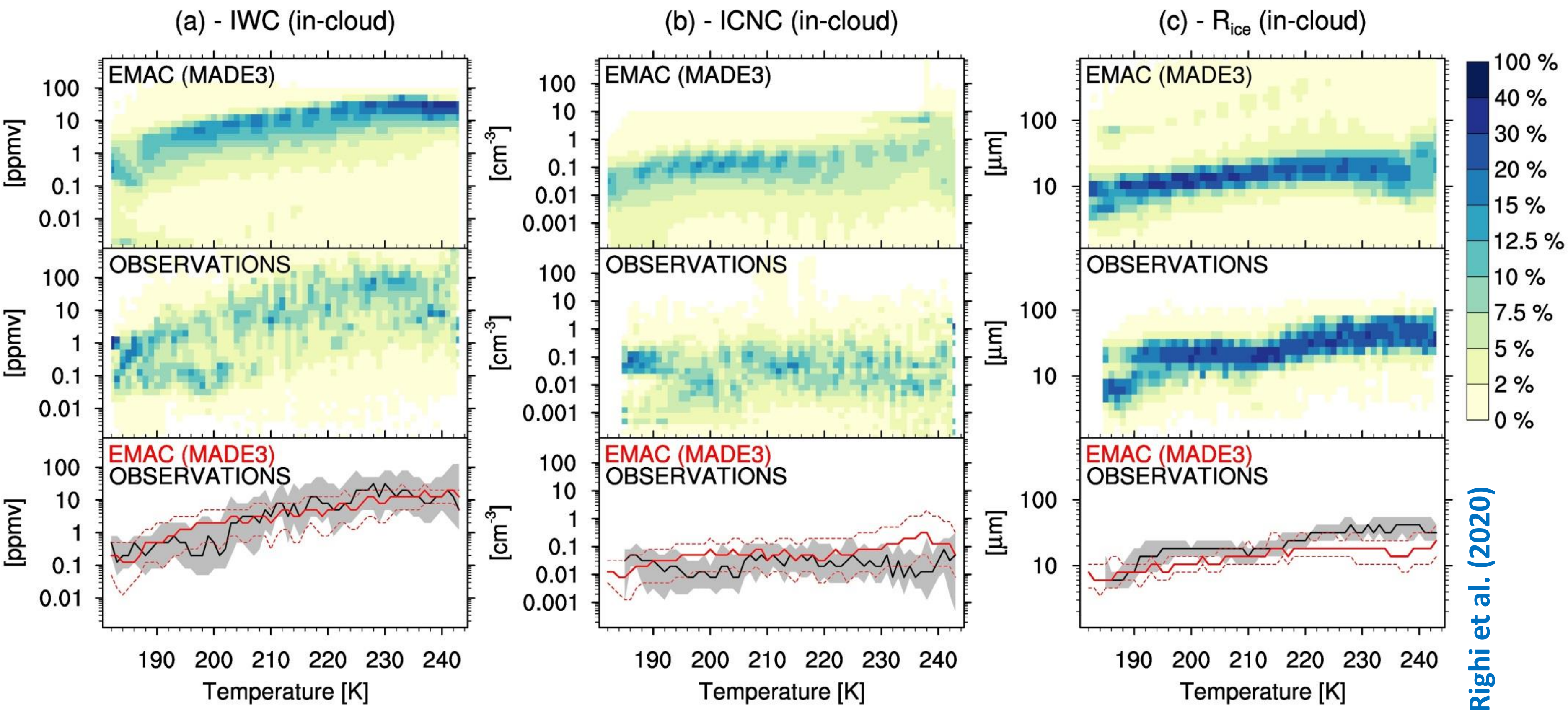
- General good agreement
- Overestimated concentration in some continental regions
- Role of anthropogenic emissions to be investigated
- Performance in line with other global aerosol models

Observational data collection by Karydis et al. (2011, 2017)

Righi et al. (2020)

Cirrus evaluation - Climatology

Climatology 1999-2014 based on several aircraft campaign
71h of measurements in cirrus (75°N – 25°S) – Krämer et al. (2016, 2020)



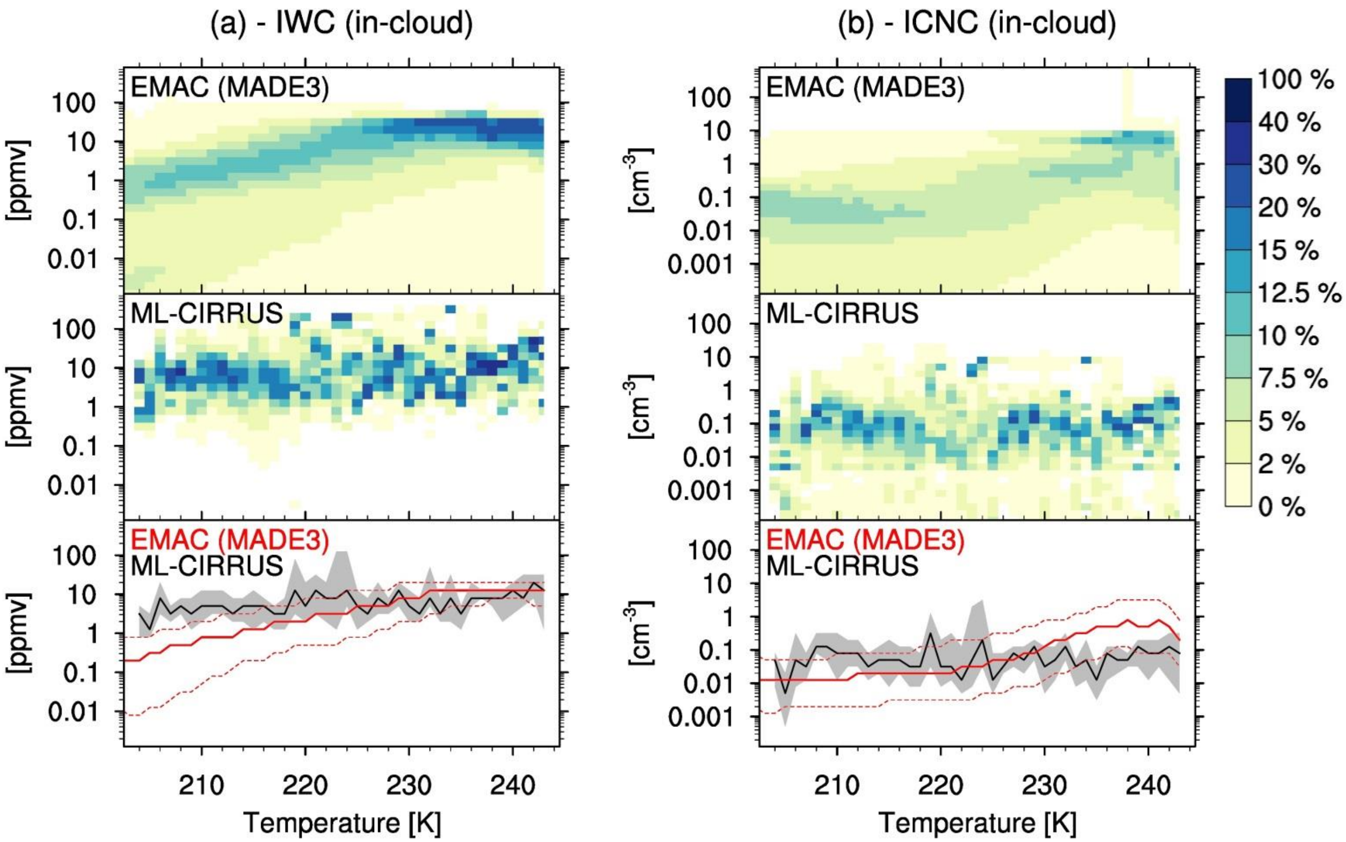
Righi et al. (2020)

- **Very good agreement for IWC**
- **Good agreement for ICNC, overestimated concentrations at higher temperatures**

Cirrus evaluation – ML-CIRRUS campaign

ML-CIRRUS aircraft campaign

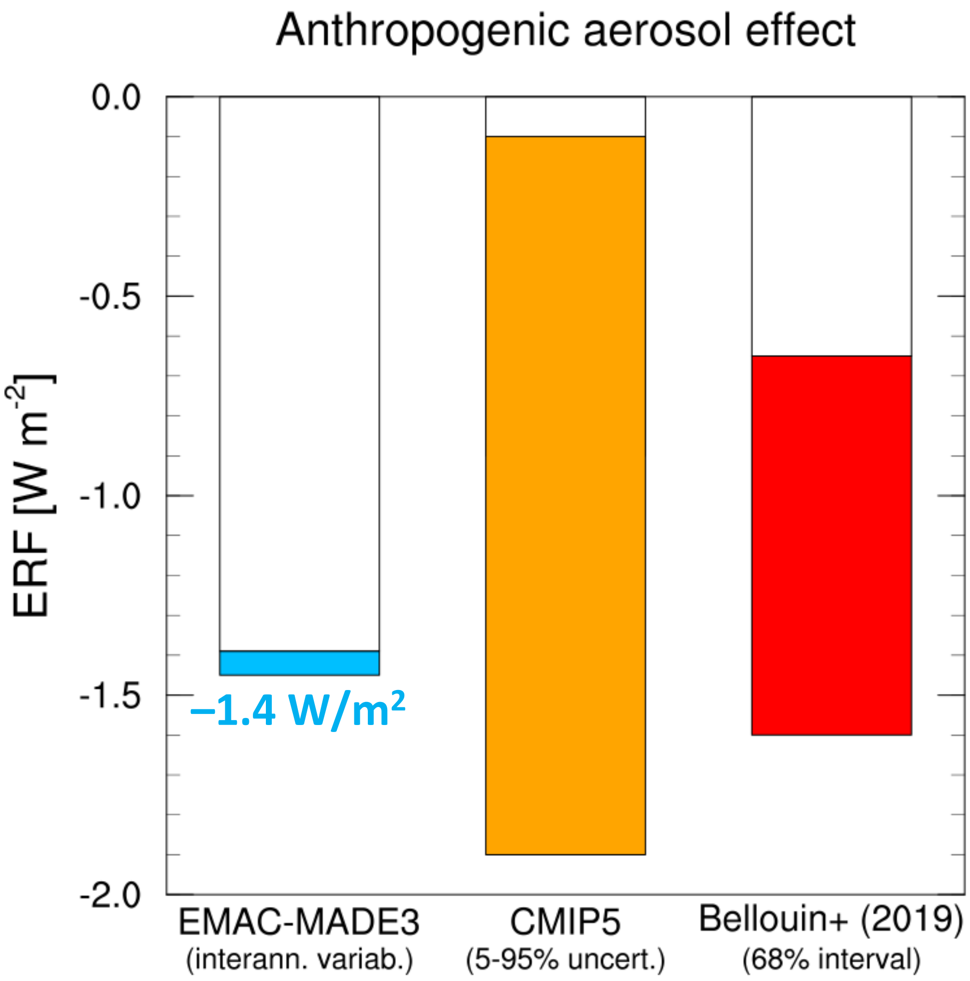
18 h of measurements above the North Atlantic – Voigt et al. (2017)



- **Basically confirms the results of the comparison with the Krämer climatology**
- **Interesting region for aviation impacts**

Righi et al. (2020)

Global anthropogenic aerosol effect



- The **anthropogenic aerosol effect** simulated with EMAC-MADE3 is within the range of the **CMIP5** estimated (model- and satellite-based)
- A large fraction of this effect (–0.96 W m^{-2}, 68%) is due to **aerosol cloud interactions** (estimated as all-sky minus clear-sky)
- The role of aerosol interactions with **cirrus clouds** will be further investigated in sensitivity studies.
- The role of **BC ice nucleating properties** is particularly uncertain but the resulting climate impact is potentially important

Conclusions and outlook

1. EMAC-MADE3 is able to reproduce the **global pattern** of the main **cloud** and **radiation** variables in comparison with satellite and in situ data.
2. Specific **deviations**, in particular in the representation of **liquid water path** which could point to **an overestimated cloud lifetime**, mostly confirm **known biases** of the ECHAM5 model and can therefore not be attributed to the new cloud scheme introduced in this work.
3. A more detailed evaluation of cloud variables in the cirrus regime against an **aircraft-based** climatology of in situ measurements demonstrates the ability of EMAC-MADE3 to adequately represent **ice water content** and **ice crystal number concentration** in cirrus clouds over a wide range of temperatures, albeit with a positive bias for the ice crystal number at higher temperatures.
4. The overall performance of EMAC-MADE3 in simulating global cloud and radiation variables is **in line with the results of the CMIP5 models**.
5. Model **biases** in the representation of cirrus clouds are **common to other models**, such as ECHAM5-HAM, EMAC-GMXe, and NCAR-CAM3.5, using various parameterizations for aerosol-induced ice formation in cirrus clouds.
6. Further work is ongoing to characterize the role of aerosol-induced ice formation on climate.

Righi et al., *Geosci. Model Dev.*, 13, 1635–1661, doi:10.5194/gmd-13-1635-2020, 2020