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Detailed coupled approach to ice particles nucleation induced by gravity waves in a global NWP model

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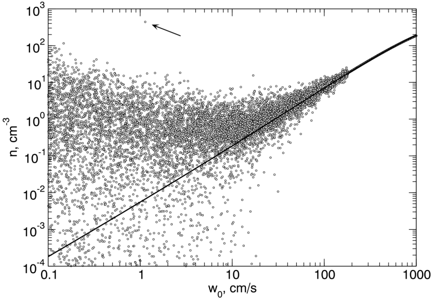
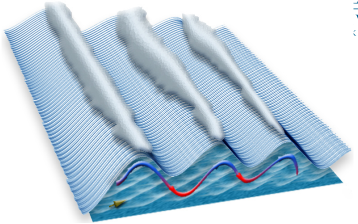
Motivation

▶ Cirrus play a key role in atmospheric thermodynamics via phase transitions, radiative effects.
▶ GWs modify local temperature and humidity, impacting cloud microphysics.
▶ Interaction of local dynamics with the ice physics is usually omitted in GCM & NWP.



Credits: Kärcher, Jensen, Lohmann; GFL 2019



Credits: https://www.brockmann-consult.de

Model's deficiencies:

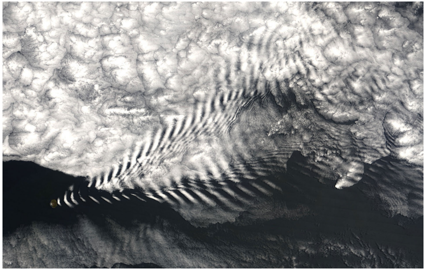
- Discrepancy in observed vs. modeled ice cloud properties;
- Cloud occurrence frequency biases;
- Prediction of supersaturation;
- Regional differences in cirrus cloud formation;
- Radiative impact sensitivity.

Key goal and Outline

Development & Implementation of a coupled approach for the description of GW-ice interaction in NWP models.

Current work:

- Theory and prototype parameterization
- Extension of the parameterization for variable mean mass
- Idealized parcel model simulations
- Modeling of the GW-ice interaction in wave-resolving model || S.Dolaptchiev visit PICO **EGU25-8712** ⟹
- Applications in the global ICON model



Credits: https://en.wikipedia.org/wiki/Wave_cloud

Assumptions used for the derivation:

- leading order terms
- no sedimentation
- no mass dependence in the deposition term

Homogeneous nucleation due to Gravity Waves

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Time resolved ice physics:

$$\left.\frac{Dn_i}{Dt}\right|_{homogeneous\ nucl.} = J\exp(B(S - S_c)), \tag{1}$$

$$\frac{DS}{Dt} = -D_0(S-1)Tn_i - S(\bar{w} + F(t)). \tag{2}$$

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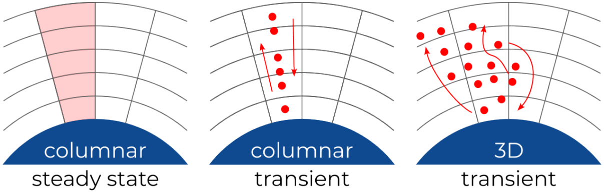
Asymptotic solution based on matched asymptotic technique and depending on n_{pre} and $\bar{w}, F(t_0)$:

$$n_{post} = \begin{cases} 2\frac{S_c(\bar{w}+F(t_0))}{D^*(S_c-1)} - n_{pre}, & \text{if } n_{pre} < \frac{S_c(\bar{w}+F(t_0))}{D^*(S_c-1)}, \\ n_{pre}. & \text{otherwise} \end{cases} \tag{3}$$

The Multi Scale Gravity Wave Model (MS-GWaM)

A 3D transient parameterization for IGWs in atmospheric models

G. S. Voelker, Y.-H. Kim, G. Bölöni, G. Zängl, and U. Achatz



Credits: G.S. Voelker

- non-orographic IGW model
- based on WKB theory
- global 3D ray tracing (online)
- implemented in ICON 2.6.2-nwp4

Added diagnostics:
GW perturbed fields of the vertical velocity $\hat{w}$, temperature $\hat{T}$ and pressure $\hat{p}$, and GW frequency ϕ_k

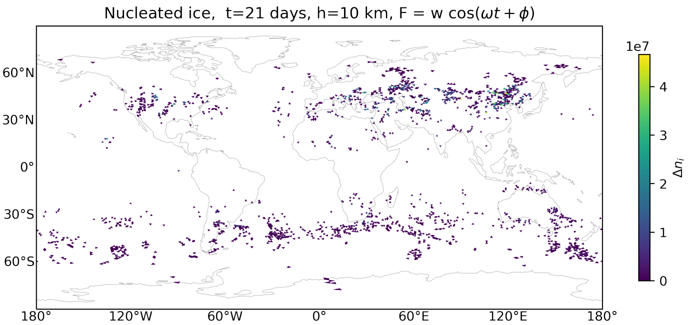
ICON results. Initial conditions and configurations

ICON 2.6.5-nwp1

120 vertical levels

horizontal grid:
R2B5 (∼80km),
also tested on R2B6

Initial conditions:
IFS for 05/2010



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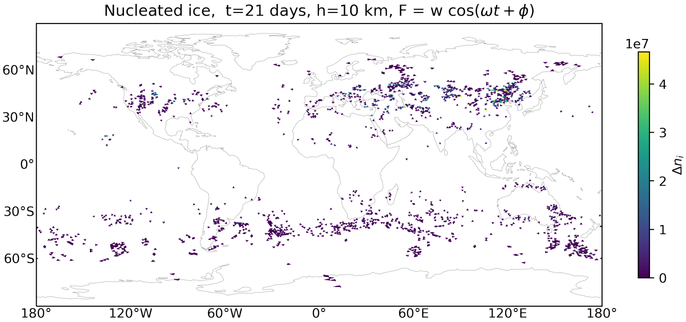

Considered configurations:

- original scheme K&S (homogeneous nucleation Kärcher&Lohman, 2002);

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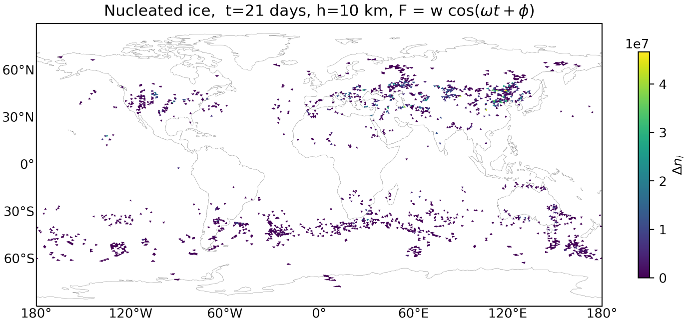

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- modified scheme (coupled ice-GW version (1)-(3), resolved);

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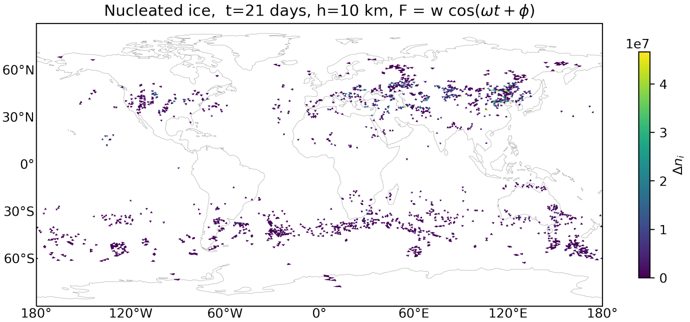


Considered configurations:

- original scheme K&S (homogeneous nucleation Kärcher&Lohman, 2002);
- modified scheme (coupled ice-GW version (1)-(3), resolved);
- modified asymptotic (coupled ice-GW version (3) + (4), parametrised).

Coupled results, new modified scheme

Resolved ice physics, Eqs. (1)-(3). Instantaneous outputs on 26/05/2010

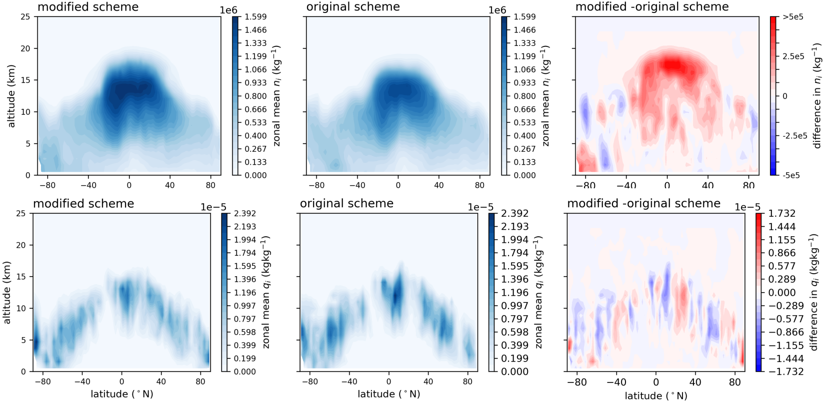


Figure: Zonal mean n_i (upper row), q_i (lower row)

Pronounced effects of the GWs in the UTLS region.

Higher maximum n_i; Differences in n_i are up to 40%.

GW influence on the maximum n_i per column

Resolved ice physics, Eqs. (1)-(3). Instantaneous outputs on 26/05/2010.

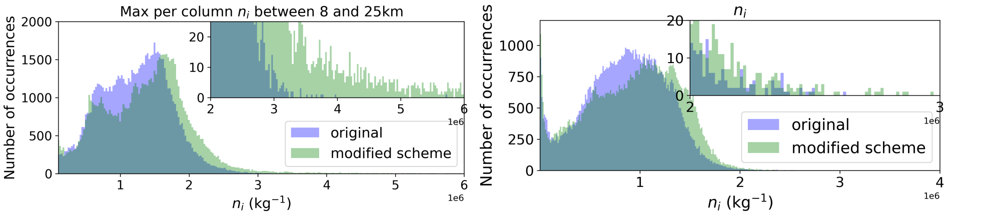


Figure: PDF of the maximum n_i per column (left), n_i distribution at 10km (right)

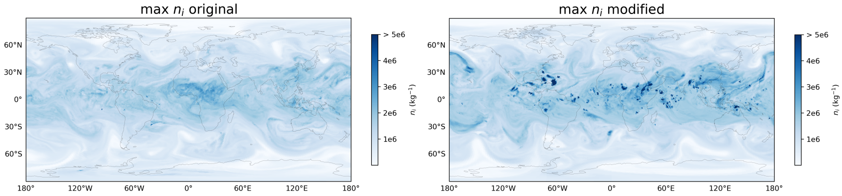


Figure: Maps for maximum n_i per column

Modified scheme. Asymptotics VS time resolved physics

Weekly mean outputs 15-22/06/2010.

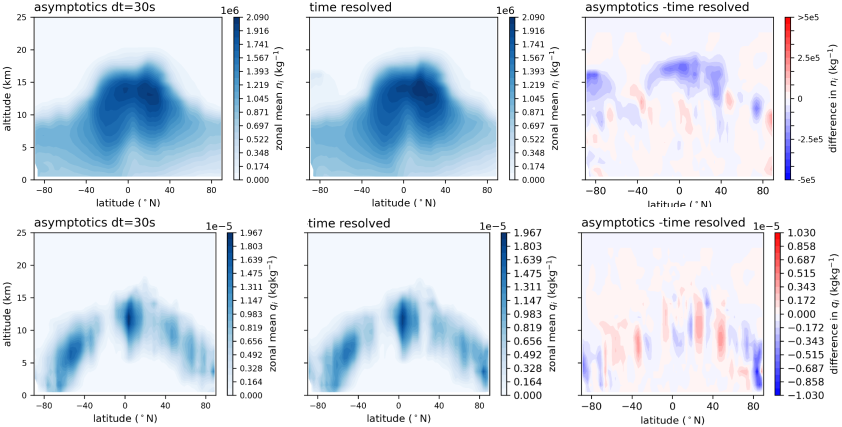


Figure: Zonal mean n_i (upper row), q_i (lower row)

Parametrization underestimates n_i, where maximum deviation from the resolved result is about 9%.

Asymptotics VS time resolved physics

Weekly mean outputs 15-22/06/2010.

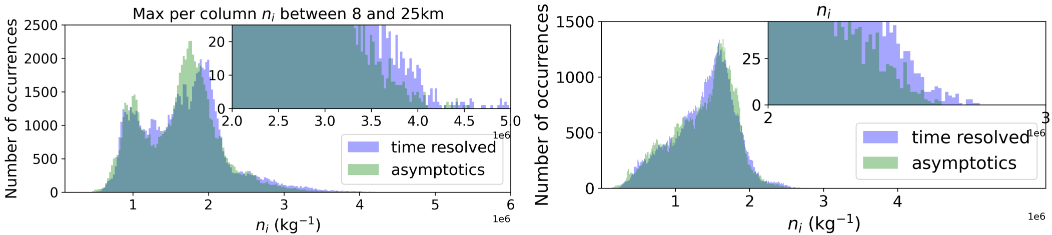
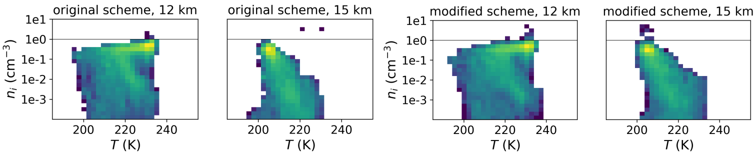


Figure: PDF of maximum per column n_i (left) and n_i at the 15km altitude (right)

- Parametrization underestimated the tail of the PDF for maximum number concentration
- Shows a good agreement with time resolved version for a particular altitude.

Qualitative comparison with cirrus climatology

Figure: $n_i(T)$ histograms for 12km and 15km altitudes



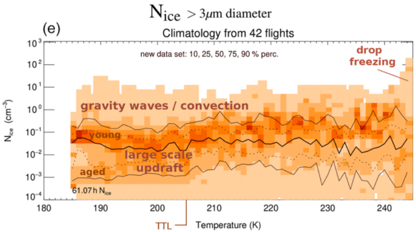


Figure: Krämer et al., ACP 2020. Cirrus climatology from flight observations.

Representation of the region for colder cirrus with high n_i is improved by new modified scheme.

Conclusions

- The new coupled approach to GW-cirrus interaction is implemented in ICON, parametrisation and resolved version of nucleation show similar results.
- The GW coupling leads to pronounced effects on n_i distribution, and shifts ice occurrence to higher altitudes.

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Outlook:

- Extension of the coupled approach to account for a mean mass variability.
- Sensitivity studies; analysis of the TOA radiation; comparison with observations.

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- The new coupled approach to GW-cirrus interaction is implemented in ICON, parametrisation and resolved version of nucleation show similar results.
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Outlook:

- Extension of the coupled approach to account for a mean mass variability.
- Sensitivity studies; analysis of the TOA radiation; comparison with observations.

Applications:

- Better prediction of ice distribution and size variability.
- Prediction of the supersaturated regions.

Thank you for attention!

References

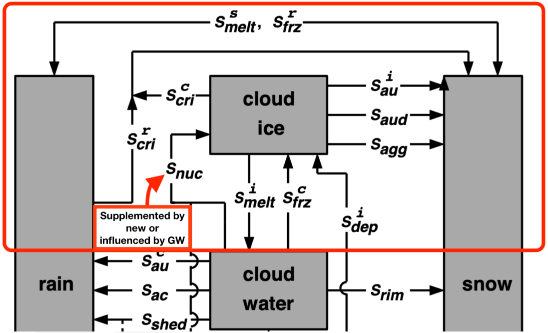
- S. Dolaptchiev, P. Spichtinger, M. Baumgartner, U. Achatz, JAS 2023
- A. Kosareva, S. Dolaptchiev, P. Spichtinger, U. Achatz, GMD (in review)
- A. Kosareva, S. I. Dolaptchiev, A. Seifert, P. Spichtinger, U. Achatz (in prep.)

Special thanks to Y-H. Kim and G.S. Voelker
for help with the MS-GWaM and ICON details

Coupled version and feedback

Single moment scheme + double-moment ice (gscp3)

$q_v, q_c, q_r, q_i, q_s, q_g, n_i$



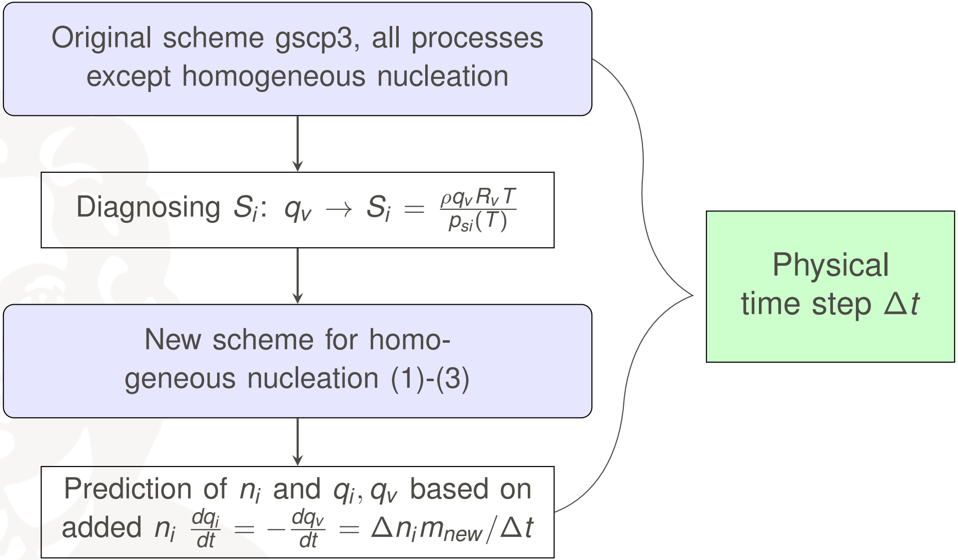
COSMO tutorial 2021

Options for GW coupling:

- directly to original gscp3 scheme: $\hat{w}$, $\hat{T}$, $\hat{S}_i$
- using new coupled formulation for homogeneous nucleation

Original scheme: Köhler, Seifert, 2015; Seifert and Beheng, 2005; COSMO documentation.

Coupling strategy



Coupling of the MS-GWaM to the ice physics

Recalculation of vertical velocity per ray volume

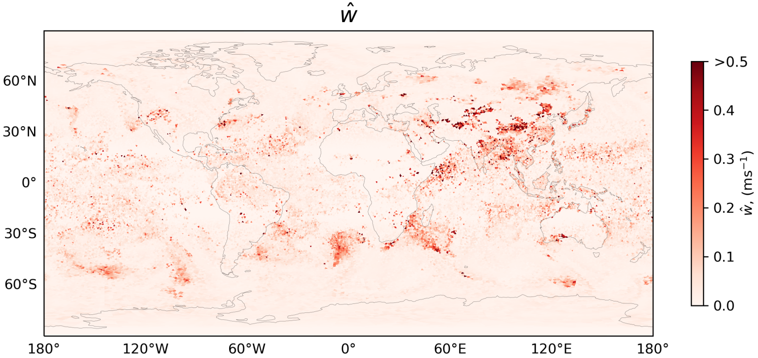
↓

Selection of maximum $\hat{w}$ per cell

↓

Picking up the corresponding frequency

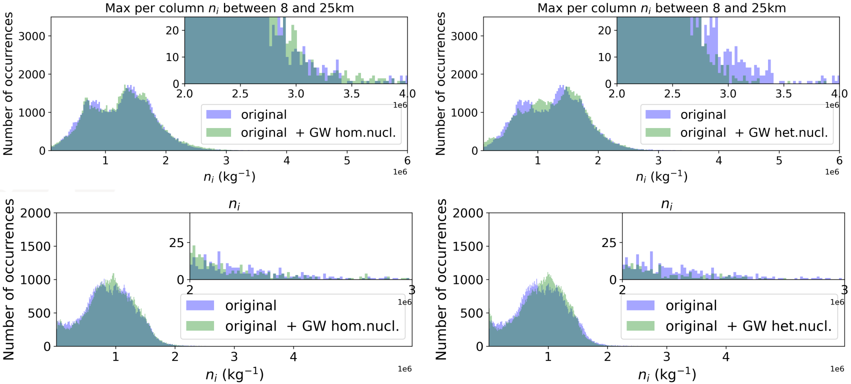
↓



Choosing the phase: 0) Using $\phi = 0$,
1) Random phase ,
2) Tracking the evolution of phase by adding new prognostic equation for ray volume.

GW influence on double moment scheme by Köhler&Seifert

Modification of the original scheme (homogeneous and heterogeneous nucleation by K&L) with $\hat{w}$ and $\hat{T}$ from the MS-GWaM. Instantaneous outputs 28/05/2010.



PDF of the maximum n_i per column (upper panel); n_i at 10km (lower pannel). The straightforward addition of the GW induced perturbations shows a slight shift of the distribution in case where heterogeneous nucleation is supplemented.

Instantaneous output 10/05/2010

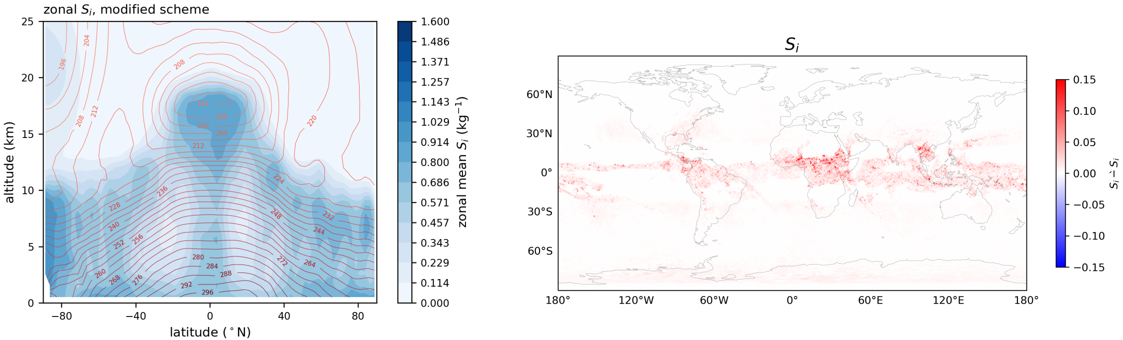


Figure: Zonal mean saturation ratio over ice and S' fluctuation from the GW based on the MS-GWaM GW fileds at 15km altitude