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High ice crystal number concentrations in mid latitude cirrus clouds driven by dynamics

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MARIE CURIE ACTIONS

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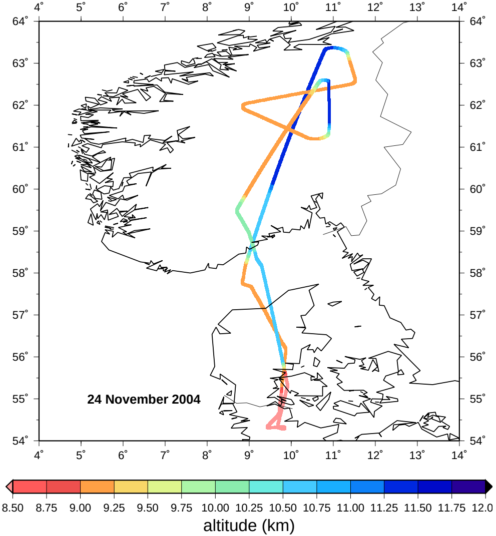
Introduction/Motivation

- Cirrus clouds cover 20–30% of Earth's surface
- In mid latitude cirrus mostly correlated with large-scale dynamics
- Problem: High ice crystal number concentrations measured by aircraft probes

Main question:
Could high ice crystal number concentrations be real in some cases or are they always a measuring artefact (shattering, e.g. Field et al.,)?

CIRRUS II campaign

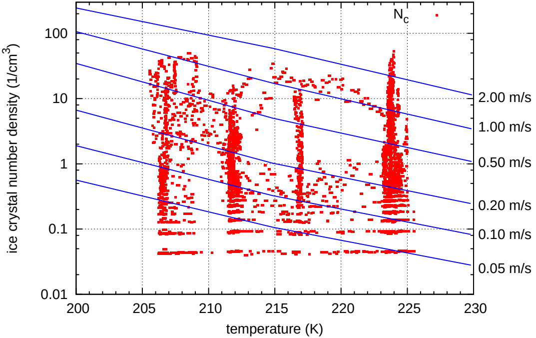
Flight pattern (24 November 2004, ca. 13:30 – 17:30 UTC):



CIRRUS II campaign

Measurements in warm front cirrus over Norway:

Very high ice crystal number densities were found in regions dominated by synoptic updrafts ($w \leq 5 \mathrm{cm\,s^{-1}}$)



High vertical velocity component is missing ...

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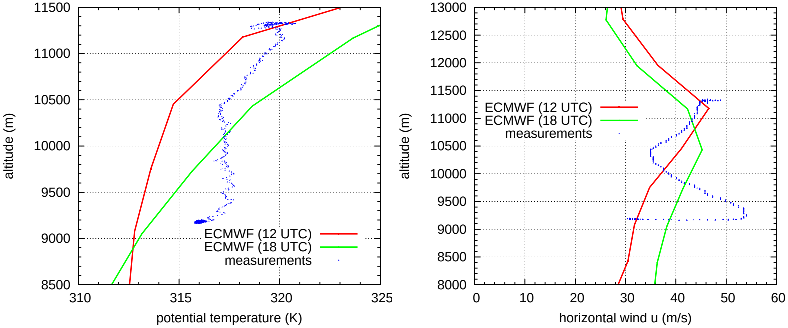
CIRRUS II: Vertical profile in ascent



⇒ Idealized model study using almost exclusively ECMWF fields

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Model description - ice microphysics

Recently developed bulk ice microphysics scheme for the low temperature range ($T < -38°$C) including:

- Nucleation (homogeneous/heterogeneous)
- Deposition growth/evaporation
- Sedimentation

Arbitrary many classes of ice, discriminated by their formation mechanism.

Consistent double moment scheme (ice crystal number and mass concentration N_c, q_c) with additional background aerosol (explicit impact on nucleation).

Spichtinger and Gierens, 2009a, ACP

First series of simulations

- horizontal extension $L_x = 51.1$ km, $dx = 100$ m, cyclic
- vertical extention $4 \leq z \leq 13$ km, $dz = 50$ m
- supersaturation layer (RHi=120%) in the vertical range $8500 \leq z \leq 11500$ m
- Gaussian temperature fluctuations $\sigma_T = 0.1$ K at initialisation
- Only homogeneous nucleation
- optionally: constant large scale lifting of the whole model domain $w = 3\ \mathrm{cm\,s^{-1}}$ (mean value from ECMWF/LAGRANTO trajectory calculations)

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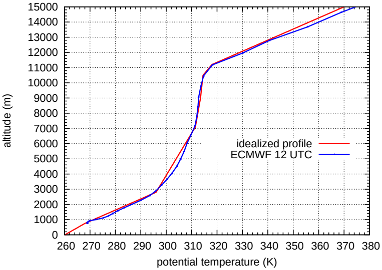
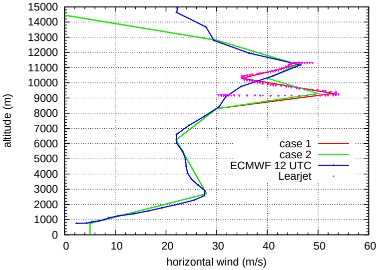
General setup (2D)

Profiles of potential temperature and horizontal wind:

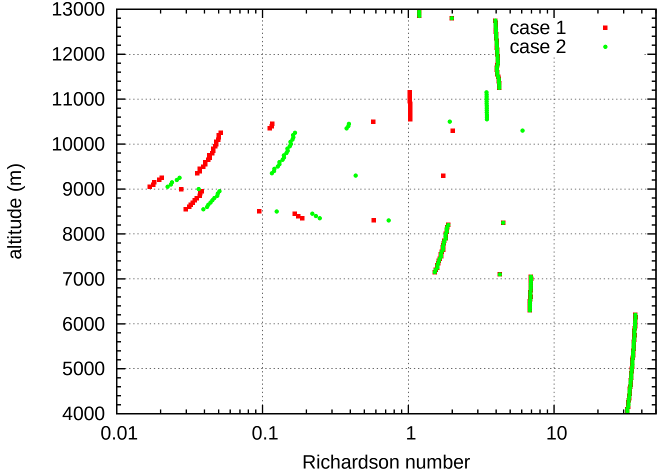




In general two cases with different wind profiles.

Kelvin-Helmholtz instability ?

Richardson Number ($Ri = N^2/(du/dz)^2$) for case 1 & 2



Dynamically unstable ($Ri < 0.25$) in range $8.5 \leq z \leq 10.5$ km

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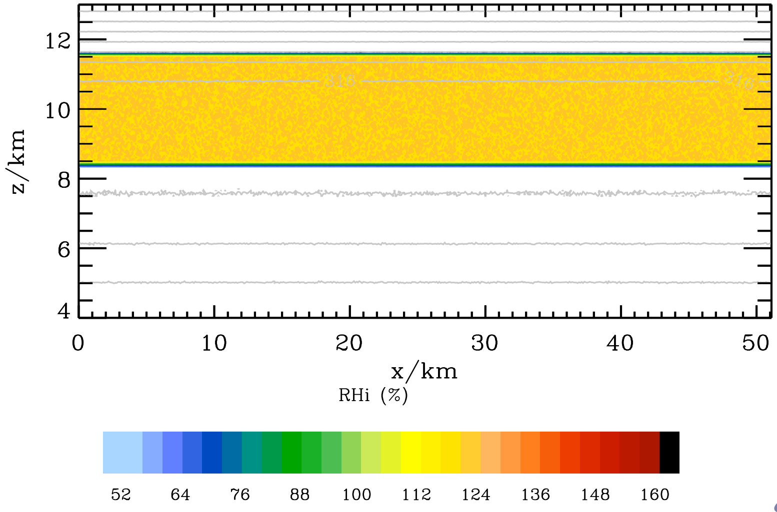
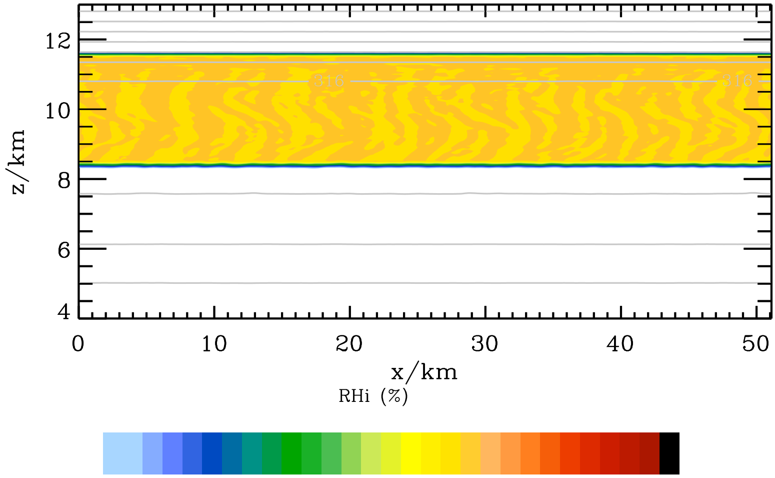
Case 1, without lifting

t= 000 min



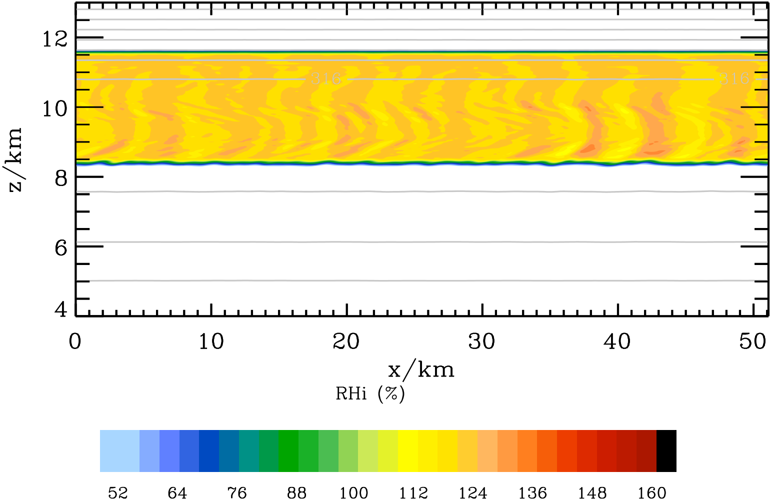
Case 1, without lifting

t= 010 min



Case 1, without lifting

t= 020 min



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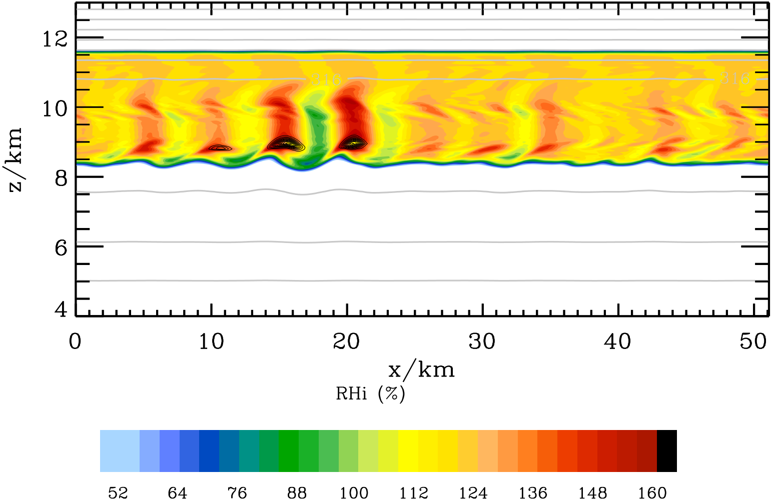
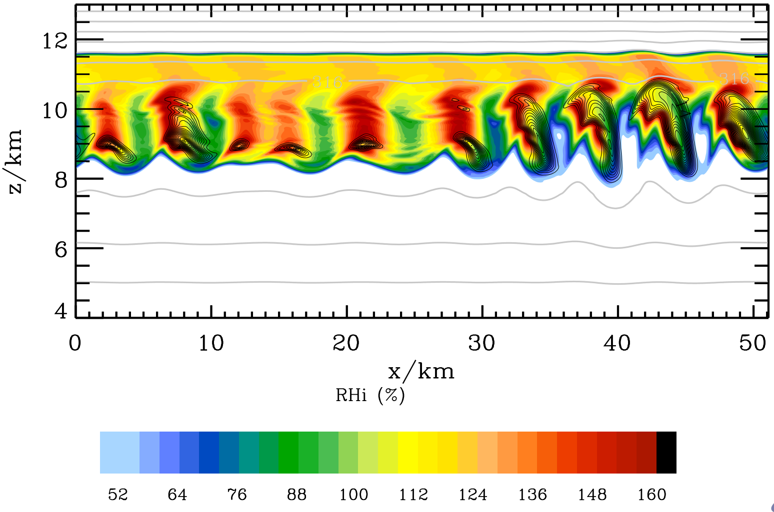
Case 1, without lifting

t= 030 min



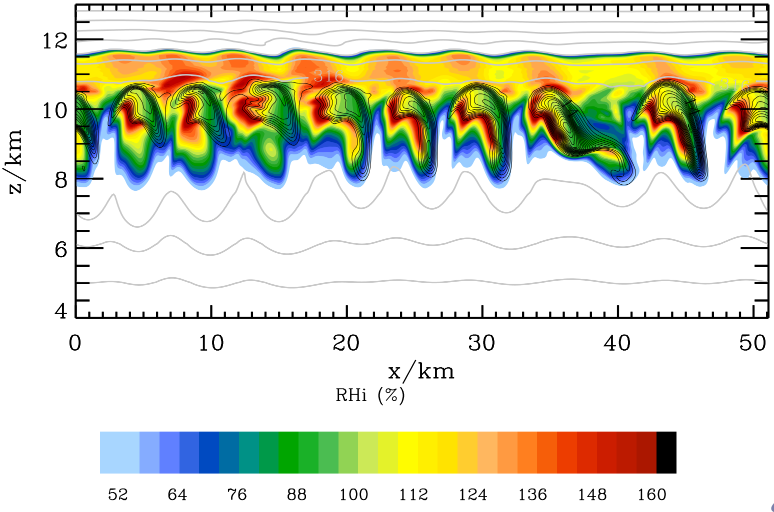
Case 1, without lifting

t= 040 min



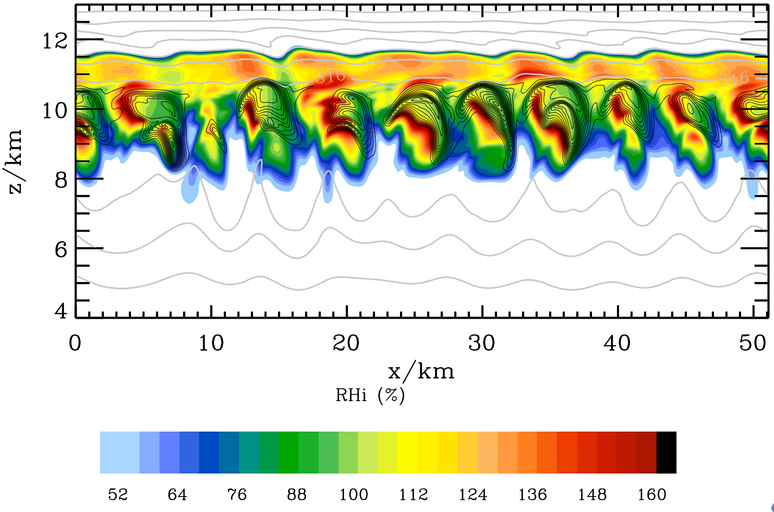
Case 1, without lifting

t= 050 min



Case 1, without lifting

t= 060 min



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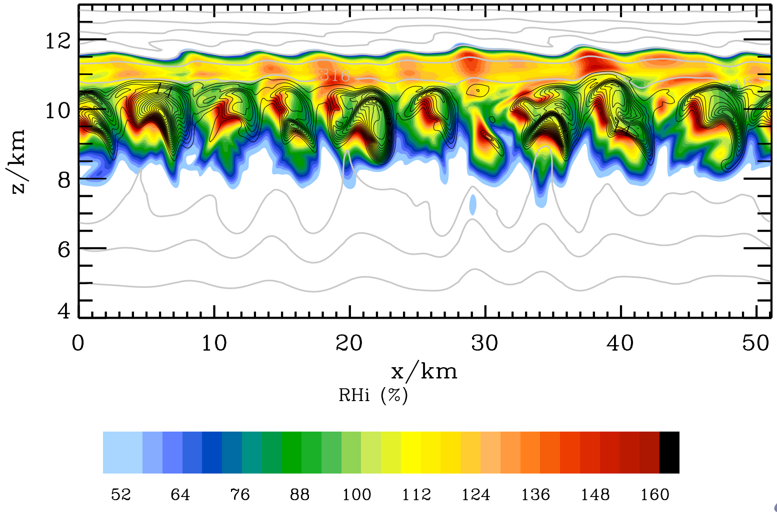
Case 1, without lifting

t= 070 min



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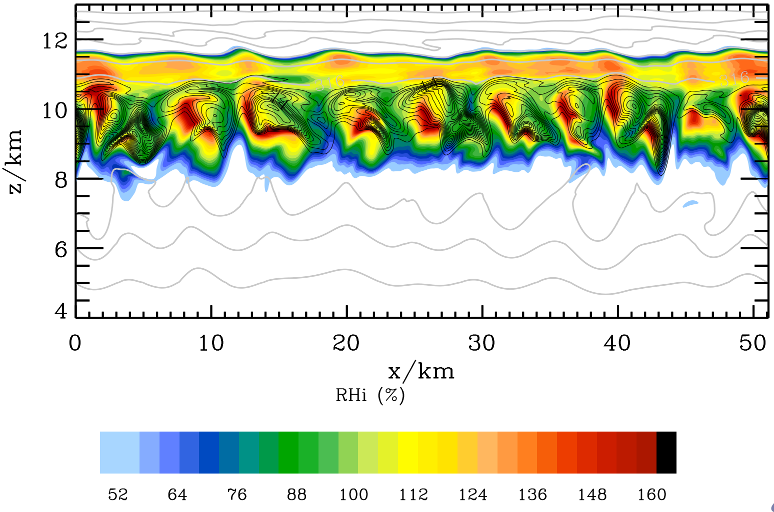
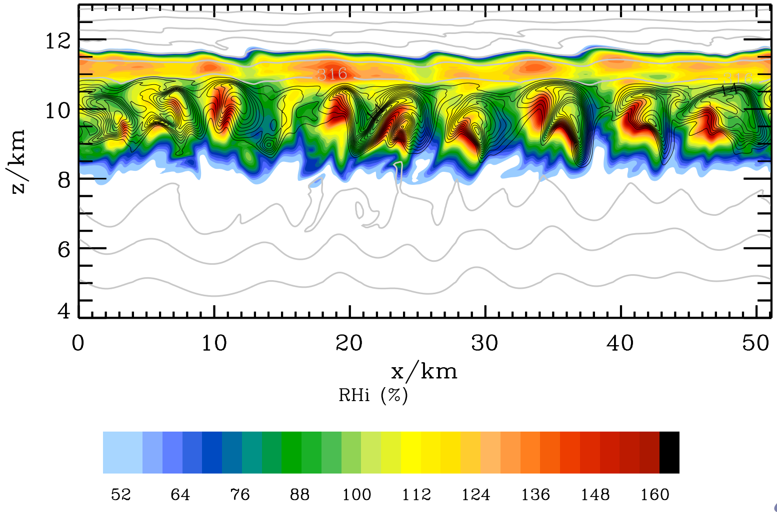
Case 1, without lifting

t= 080 min



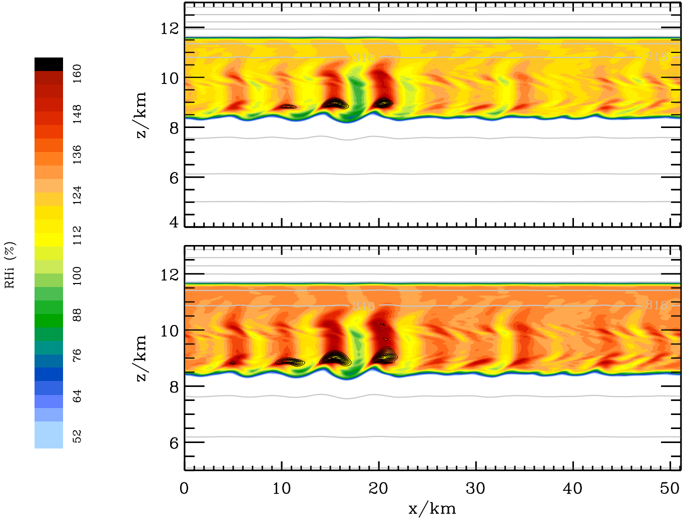
Case 1, without lifting

t= 090 min



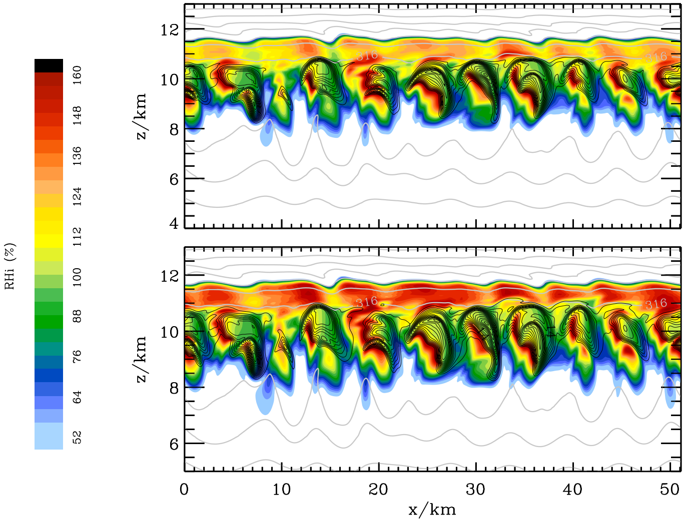
comparison without/with lifting

t= 030 min, top: $w = 0 \text{ cm s}^{-1}$, bottom: $w = 3 \text{ cm s}^{-1}$



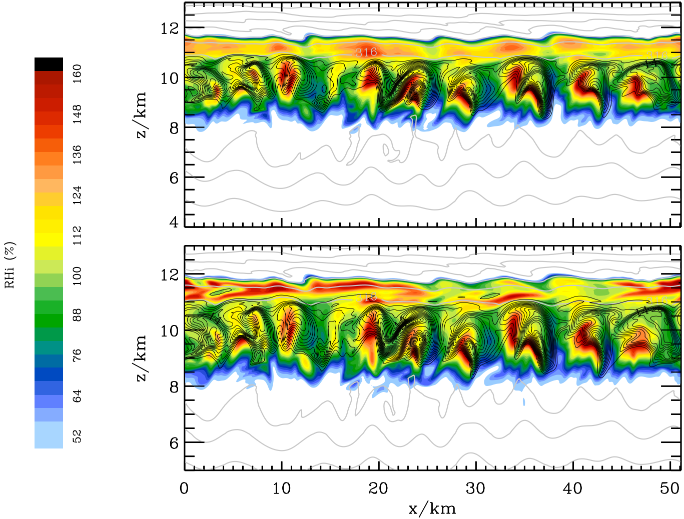
comparison without/with lifting

t= 060 min, top: $w = 0\ \mathrm{cm\,s^{-1}}$, bottom: $w = 3\ \mathrm{cm\,s^{-1}}$

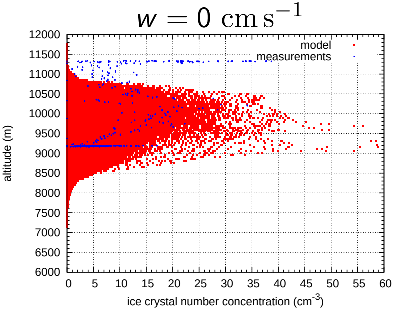


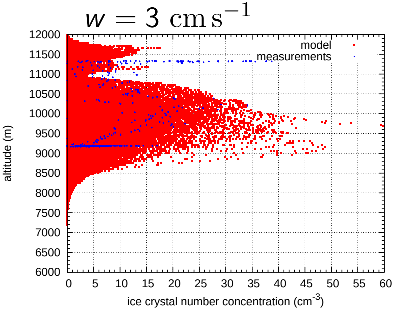
comparison without/with lifting

t= 090 min, top: $w = 0\ \mathrm{cm\,s^{-1}}$, bottom: $w = 3\ \mathrm{cm\,s^{-1}}$



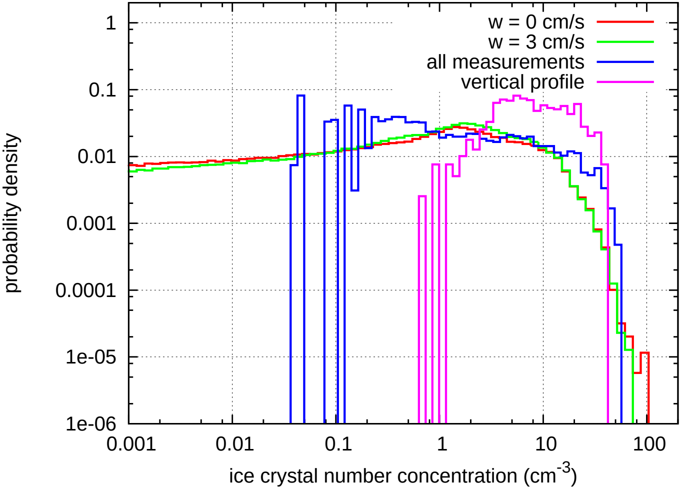
Ice crystal number concentrations





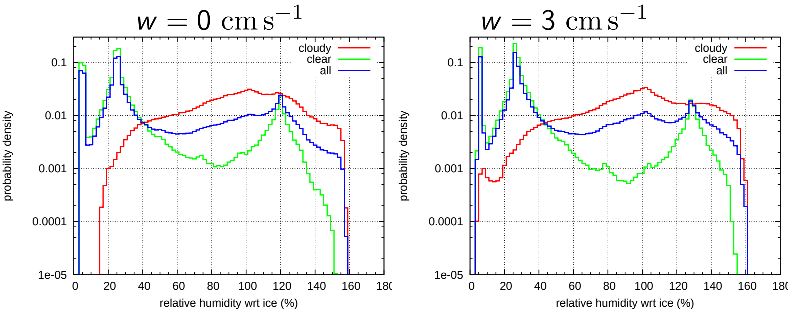
Statistics

Ice crystal number concentration distributions:



Statistics

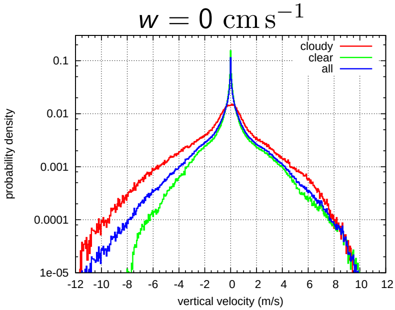
Relative humidity distributions:

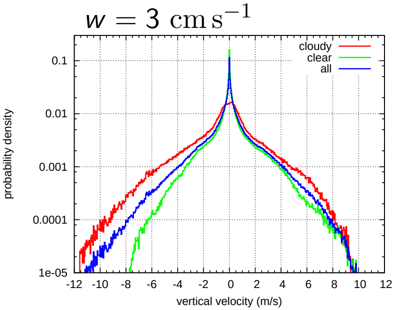


High ice supersaturation inside cirrus cloud possible.

Statistics

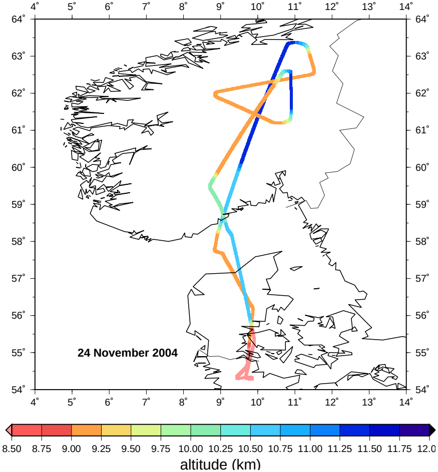
Vertical velocity distributions:





orographic waves???

Remember flight pattern over Norway:



What about flow over mountains? Orographic waves?

Second series of simulations

- horizontal extension $L_x = 255.5$ km, $dx = 500$ m, open
- vertical extention $0 \leq z \leq 15$ km, $dz = 50$ m
- Bell–shaped mountain (amplitude $h = 750$ m, width $a = 15$ km)
- supersaturation layer (RHi=120%) in the vertical range $8500 \leq z \leq 11500$ m
- Gaussian temperature fluctuations $\sigma_T = 0.1$ K at initialisation
- Only homogeneous nucleation

Remark: Due to a coarser resolution we expect lower vertical velocities inside the Kelvin-Helmholtz instability.

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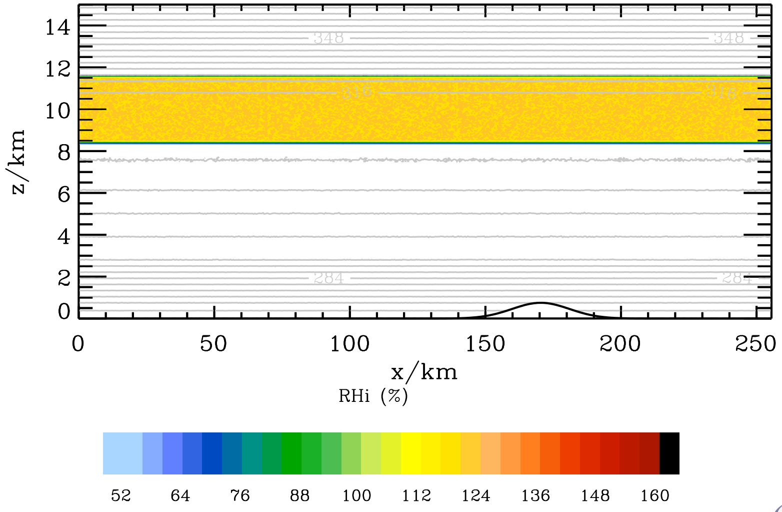
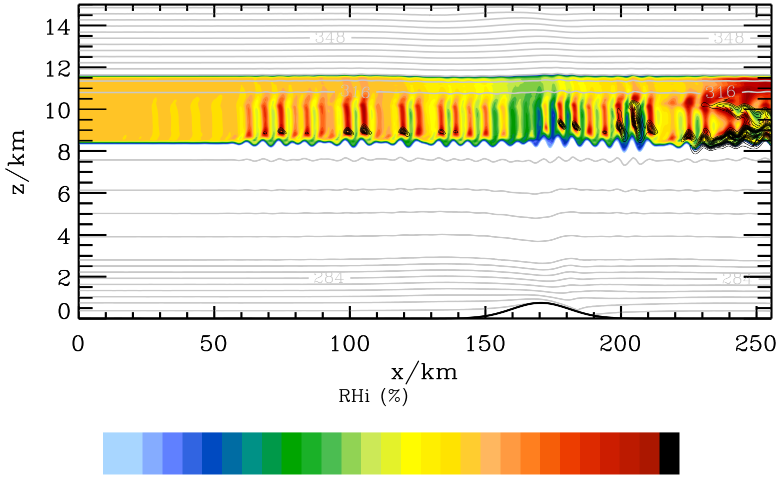
Case 1

t= 000 min



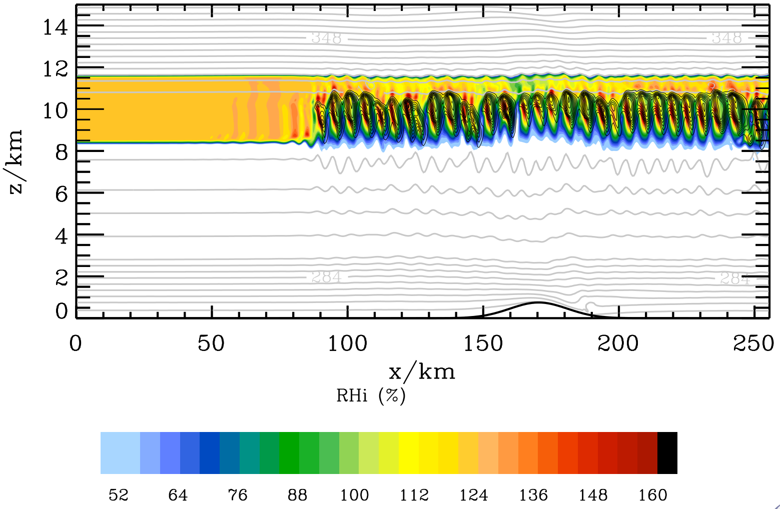
Case 1

t= 030 min



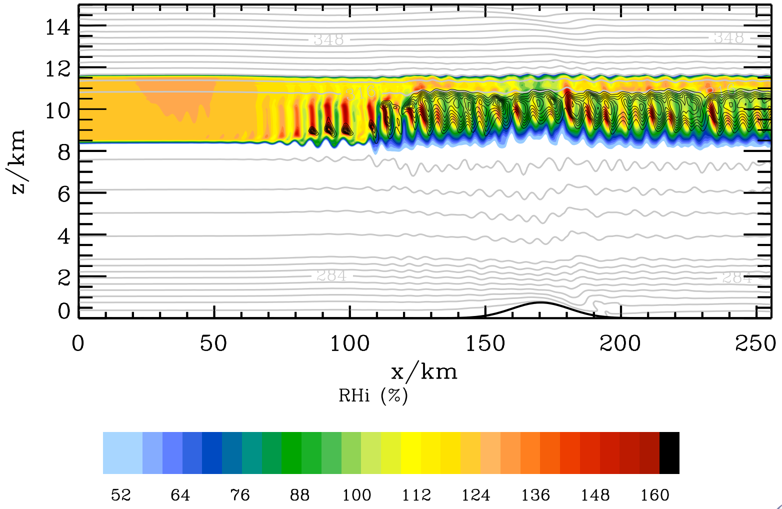
Case 1

t= 045 min



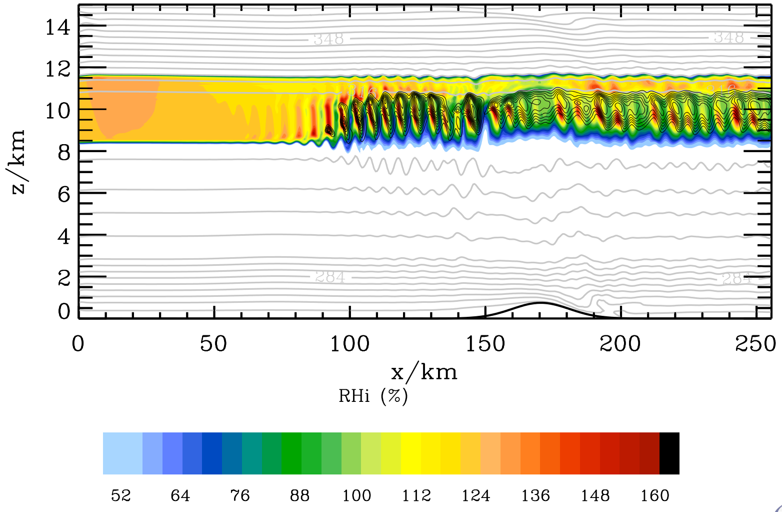
Case 1

t= 060 min



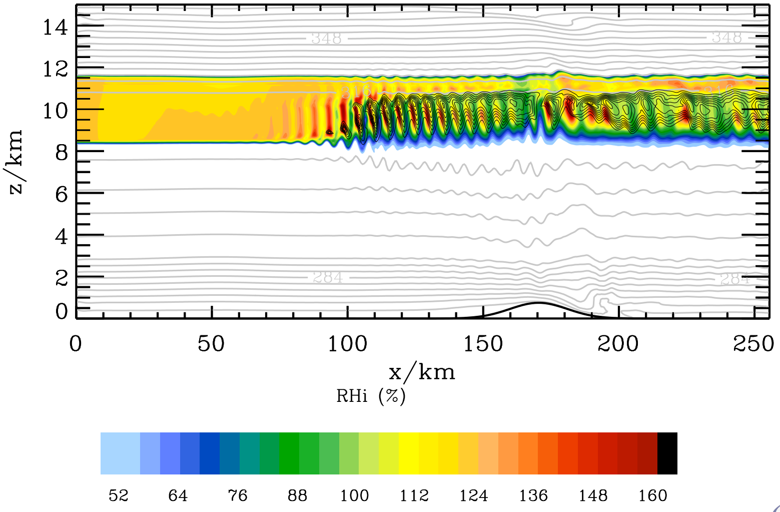
Case 1

t= 075 min



Case 1

t= 090 min



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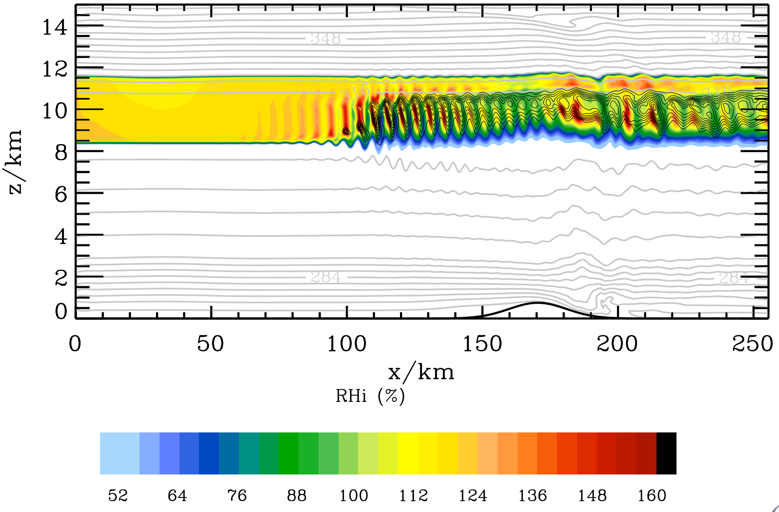
Case 1

t= 105 min



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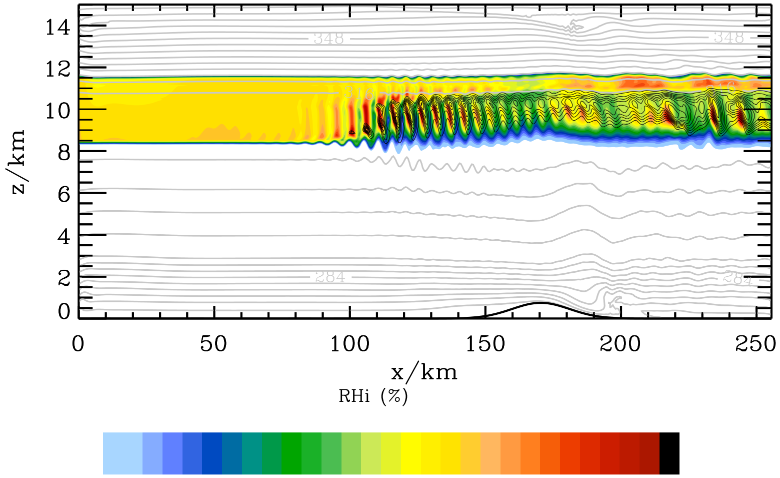
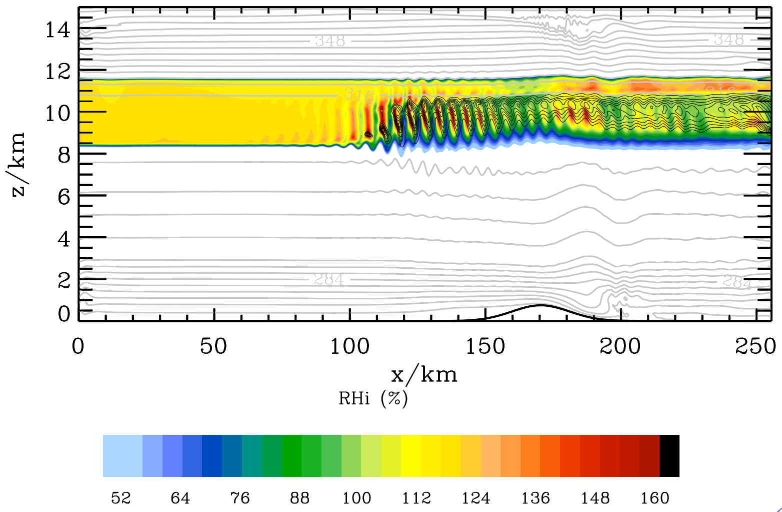
Case 1

t= 120 min



Case 1

t= 135 min



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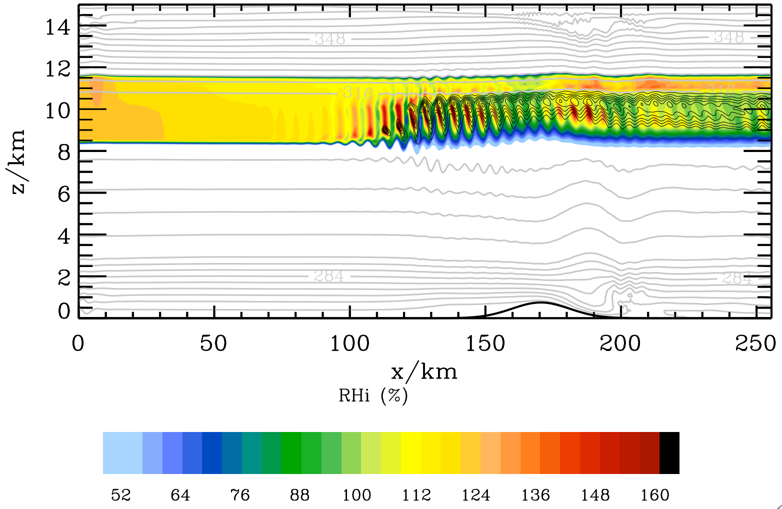
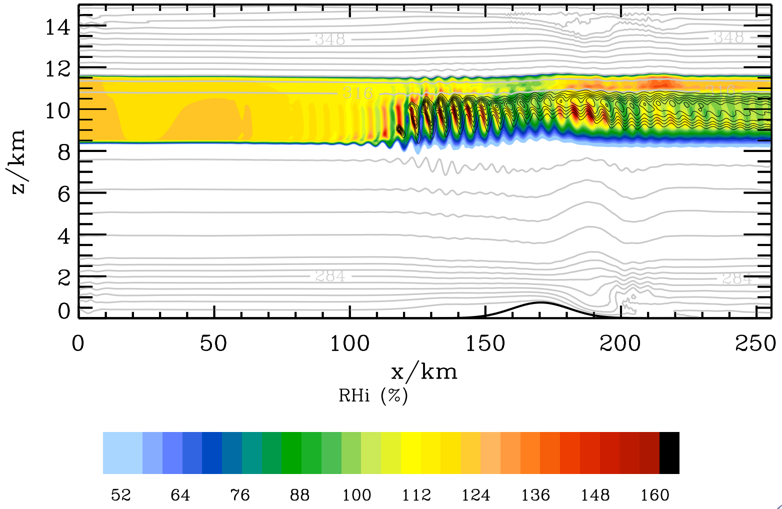
Case 1

t= 150 min



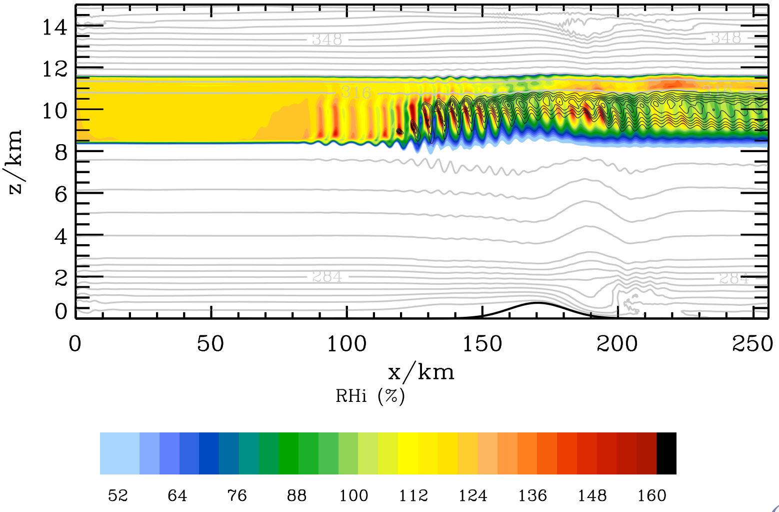
Case 1

t= 165 min



Case 1

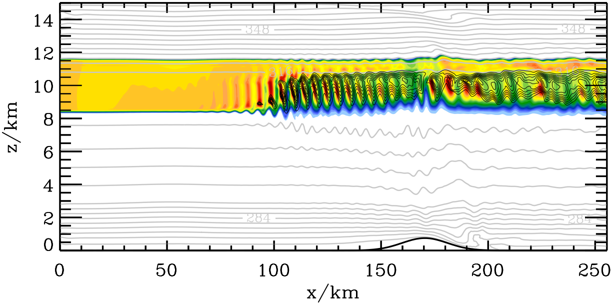
t= 180 min



Modification by orographic wave

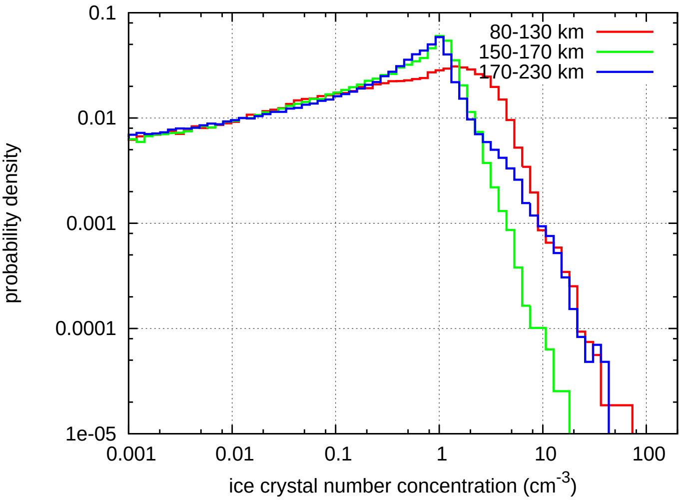
Three horizontal sections:

- $80 \leq x \leq 130$ km (Kelvin-Helmholtz instability)
- $150 \leq x \leq 170$ km (downdraught region of mountain wave)
- $170 \leq x \leq 230$ km (updraught region of mountain wave)



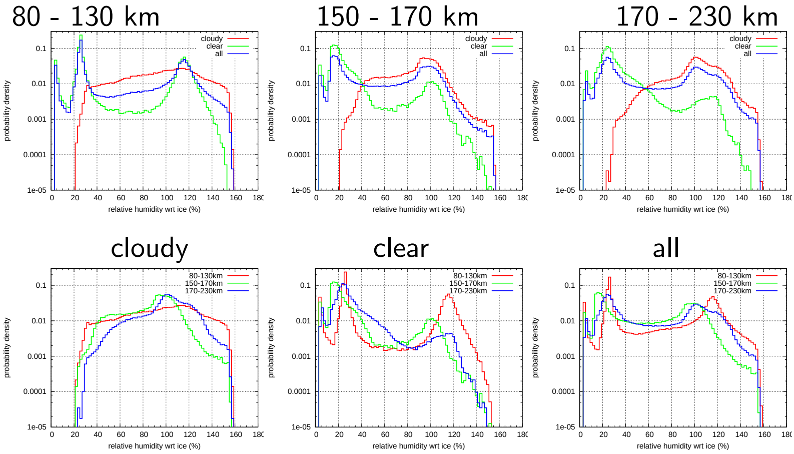
Statistics

Ice crystal number concentration distributions:



Statistics

Relative humidity distributions:



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Summary

- Idealized study of Kelvin-Helmholtz instability triggering high ice crystal number concentrations
- Superpostion of large-scale motion (warm front) and K-H instability
- Additional modification by orographic waves (classical multiscale situation for formation of cirrus clouds)

In this case, high ice crystal number concentrations can be explained very well by impact of dynamics

Representativity of such events remains unclear, further research on this topic will be carried out.

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Thank you for your attention

Acknowledgements:

- Marian deReus, Stephan Borrmann (MPI Mainz/University of Mainz)
- European Commission for funding (Marie Curie fellowship)
- ECMWF for computing time (Special Project: "Ice supersaturation and cirrus clouds")

Model description – Deposition

For diffusion growth/evaporation we generally use the ansatz by Koenig (1971), which is modified using a correction derived from the numerical solution of the growth equation ($\alpha = 0.5$):

$$\frac{dm}{dt} \approx a \cdot m^b \cdot \left(1 - \exp\left(-(m/m_0)^\gamma\right)\right) \quad (1)$$

Using general moments of the mass distribution $f(m)$ (kth moment: $\mu_k[m] := \int f(m) m^k \, dm$) and the definition of the ice water content ($\mathrm{IWC} = \mu_1[m]$) we obtain:

$$\frac{d\mathrm{IWC}}{dt} \approx a \cdot \mu_b[m] \cdot \left(1 - \exp\left(-(\overline{m}/(m_0 \cdot \chi))^\gamma\right)\right) \quad (2)$$

with the mean mass $\overline{m} = \mu_1/\mu_0$ of the mass distribution and a correction factor $\chi \approx 20$

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Model description – Sedimentation

Two different terminal velocities (mass weighted and number weighted, $v_{t,m}, v_{t,n}$):

$$\mathrm{IWC} \cdot v_{t,m} = \int_0^\infty f(m)\ m\ v_t(m)\ dm \qquad (3)$$

$$N_i \cdot v_{t,n} = \int_0^\infty f(m)\ v_t(m)\ dm \qquad (4)$$

We use mass–velocity relations by Heymsfield and Iaquinta (2000):

$$\frac{v_t}{v_0} = \alpha \cdot \left(\frac{m}{m_0}\right)^\beta, \quad v_0, m_0 \text{ unit velocity/mass} \qquad (5)$$

and derive the following formulas for the terminal velocities:

$$v_{t,n} = v_0 \cdot \frac{\alpha}{m_0^\beta} \cdot \frac{\mu_\beta[m]}{\mu_0[m]} \qquad (6)$$

$$v_{t,m} = v_0 \cdot \frac{\alpha}{m_0^\beta} \cdot \frac{\mu_{\beta+1}[m]}{\mu_1[m]} \qquad (7)$$

Model description – Nucleation

Two different processes, both determined by the background aerosols, respectively:

- homogeneous nucleation: the number concentration of sulfuric acid is prescribed as background aerosol
  $\rightarrow$ size distribution of aqueous solution droplets which freeze homogeneously acc. to Koop et al. (2000), depending on water activity and temperature.
- heterogeneous nucleation: Background aerosol determines the maximal number of ice nuclei. After passing a threshold RHi_{het} all available aerosol particles act as ice nuclei and form ice crystals

in both cases: washout possible

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