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Impact of mesoscale dynamics and aerosols on the life cycle of cirrus clouds

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Introduction

Why should we care about cirrus clouds?

- Cirrus clouds cover ca. 20–30% of the Earth
- Cirrus clouds are important modulators for radiation
- Cirrus clouds are important for dehydration in the tropopause region and for stratospheric water vapour entry

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Introduction

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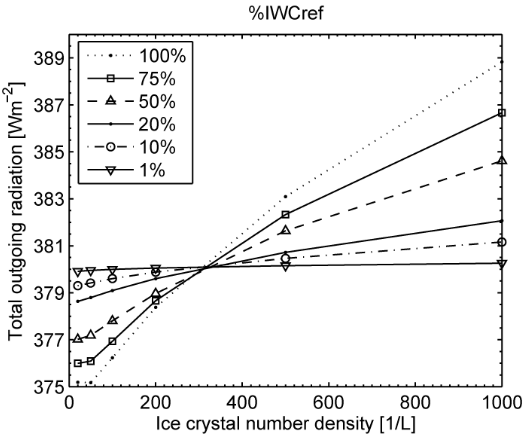
Do we understand cirrus clouds? Not really:

- Ice crystal formation is only partly understood, impact of aerosols?
- Life cycle of cirrus clouds? Impact of dynamics?
- Radiative impact of cirrus clouds (warming? cooling? see e.g. Fusina et al., 2007)?

Introduction: radiative impact of Ci

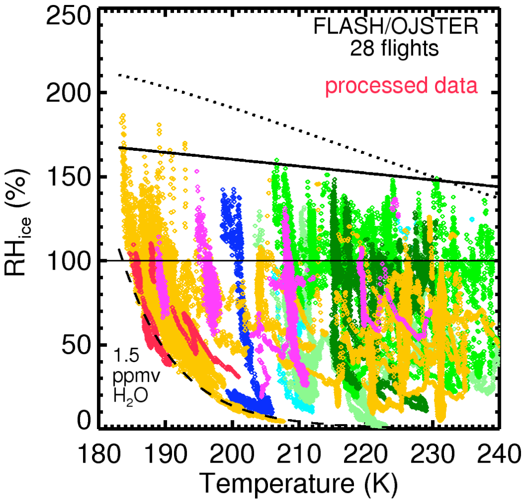


Fusina et al., 2007

total outgoing radiation = outgoing longwave radiation + reflected shortwave radiation (strong dependence on ice crystal number density)

Introduction - High ice supersaturation

Outside clouds:



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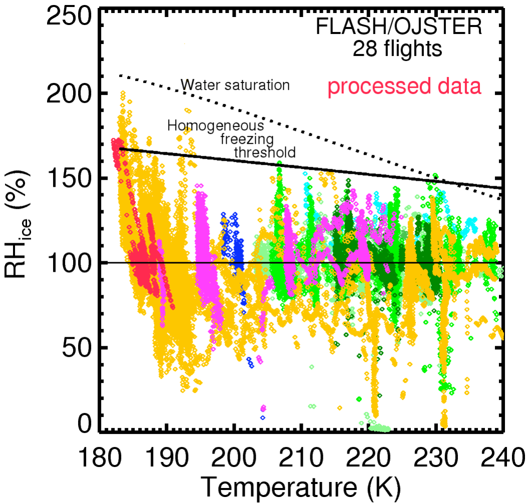
Introduction - High ice supersaturation

Inside clouds:



Introduction

Issues/problems discussed in cirrus community:

- High and persistent ice supersaturation inside cirrus clouds:
  - errors in measurements (see AquaVit comparison in 2007)?
  - exotic microphysics (cubic ice, organic substances, glassy particles)?
  - competition of different nucleation processes?
  - impact of dynamics?
- High ice crystal number densities:
  - shattering of large ice crystals?
  - other explanations (e.g. dynamics)?

⇒ Motivation for development of "new ice microphysics scheme" for cloud-resolving modelling (in EULAG)

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Introduction

New ice microphysics for the cold temperature regime ($T < 235$ K):

- To be able to differenciate between different formation mechanisms
- Explicit impact of aerosols
- Suitable for cloud–resolving scale (resolution in order of $10 - 100$ m)

Bulk microphysics, double moment scheme (prognostic equations for ice crystal number density and ice crystal mass concentration), including the following processes:

- Nucleation
- Diffusional growth/evaporation
- Sedimentation

Spichtinger and Gierens, ACPD, 2008a

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General basis

Arbitrary many classes of ice ($j = 1, \ldots, n$), discriminated by their formation mechanism. Each class consists of:

- Ice crystal number concentration $N_{c,j}$
- Cloud ice mass mixing ratio $q_{c,j}$
- Background aerosol number concentration $N_{a,j}$
- Background aerosol mass mixing ratio $q_{a,j}$

General mass ice distribution $f(m)$ (lognormal type with variable modal mass and fixed geometrical standard deviation).

One-to-one relation between ice and aerosols:

$$\text{aerosol} \left\{ \begin{array}{c} \text{number} \\ \text{mass} \end{array} \right\} \text{concentration} \; \underset{\text{evaporation}}{\overset{\text{nucleation}}{\longleftrightarrow}} \; \text{ice} \left\{ \begin{array}{c} \text{number} \\ \text{mass} \end{array} \quad \text{concentration} \right\}$$

Prognostic equations

$$\frac{D\theta}{Dt} = \frac{L\,\theta_e}{c_p\,T_e}(\mathrm{NUC}+\mathrm{DEP}) \quad (1)$$

$$\frac{Dq_v}{Dt} = -(\mathrm{NUC}+\mathrm{DEP}) \quad (2)$$

$$\frac{Dq_{c,j}}{Dt} = \frac{1}{\overline{\rho}}\frac{\partial(\overline{\rho}q_{c,j}v_{m,j})}{\partial z} + \mathrm{NUC_j} + \mathrm{DEP_j} \quad (3)$$

$$\frac{DN_{c,j}}{Dt} = \frac{1}{\overline{\rho}}\frac{\partial(\overline{\rho}N_{c,j}v_{n,j})}{\partial z} + \mathrm{NNUC_j} + \mathrm{NDEP_j} \quad (4)$$

$$\frac{Dq_{a,j}}{Dt} = \mathrm{NUCA_j} + \mathrm{DEPA_j} \quad (5)$$

$$\frac{DN_{a,j}}{Dt} = -\mathrm{NNUC_j} + \mathrm{NDEP_j} \quad (6)$$

where j is the respective class index and

$$\mathrm{NUC} = \sum_{j=1}^{n}\mathrm{NUC_j},\;\; \mathrm{DEP} = \sum_{j=1}^{n}\mathrm{DEP_j}. \quad (7)$$

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
  → mass/size distribution of aqueous solution droplets which freeze homogeneously acc. to Koop et al. (2000), depending on water activity (i.e. relative humidity) 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 (more sophisticated schemes are under development, Spichtinger and Cziczo, in revision)

Both processes require high supersaturation with respect to ice.

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 ($\alpha = 0.5$):

$$\frac{dm}{dt} \approx a \cdot m^b \cdot \left(1 - \exp\left(-(m/m_0)^\gamma\right)\right) \tag{8}$$

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 mass concentration ($q_c = \mu_1[m]$) we obtain:

$$\frac{dq_c}{dt} \approx a \cdot \mu_b[m] \cdot \left(1 - \exp\left(-(\overline{m}/(m_0 \cdot \chi))^\gamma\right)\right) \tag{9}$$

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

Model description – Sedimentation

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

$$q_c \cdot v_{t,m} = \int_0^\infty f(m)\ m\ v_t(m)\ dm \qquad (10)$$

$$N_c \cdot v_{t,n} = \int_0^\infty f(m)\ v_t(m)\ dm \qquad (11)$$

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

$$\frac{v_t}{v_0} = \alpha \cdot \left(\frac{m}{m_0}\right)^\beta, \quad v_0, m_0 \text{ unit velocity/mass} \qquad (12)$$

and derive the following formulas for the terminal velocities:

$$v_{t,n} = v_0 \cdot \frac{\alpha}{m_0^\beta} \cdot \frac{\mu_\beta[m]}{\mu_0[m]} \qquad (13)$$

$$v_{t,m} = v_0 \cdot \frac{\alpha}{m_0^\beta} \cdot \frac{\mu_{\beta+1}[m]}{\mu_1[m]} \qquad (14)$$

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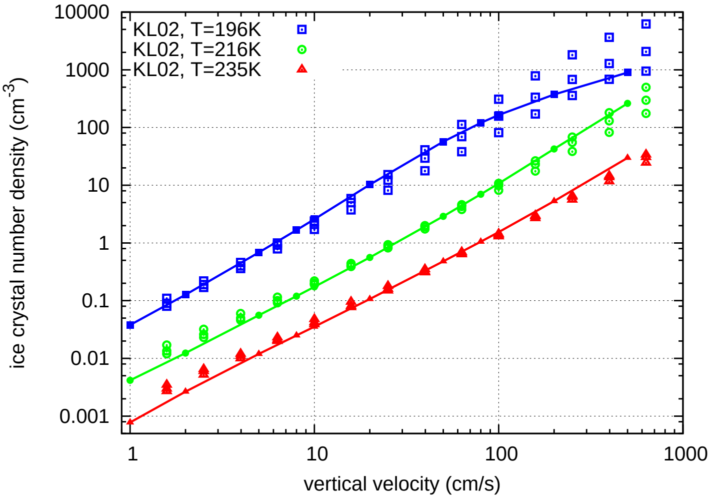
Validation

From boxmodel calculations compared to detailed microphysics:

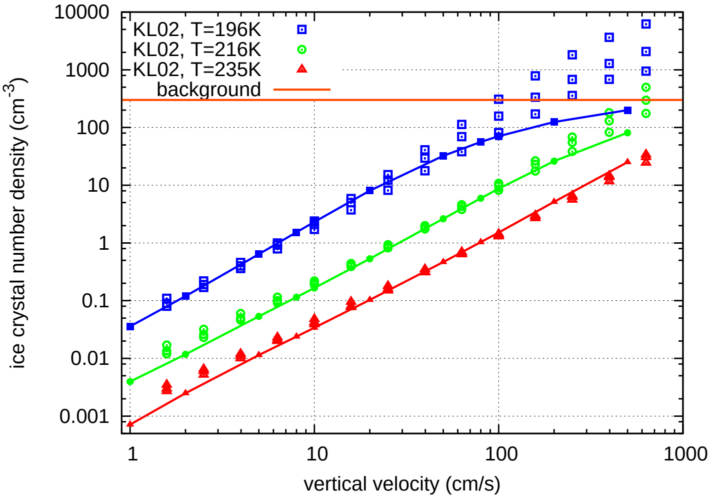
Ideal simulations: no limitation due background ($N_a = 10000\mathrm{cm}^{-3}$)



Validation

From boxmodel calculations compared to detailed microphysics:

Real simulations: limitation due background ($N_a = 300\mathrm{cm}^{-3}$)



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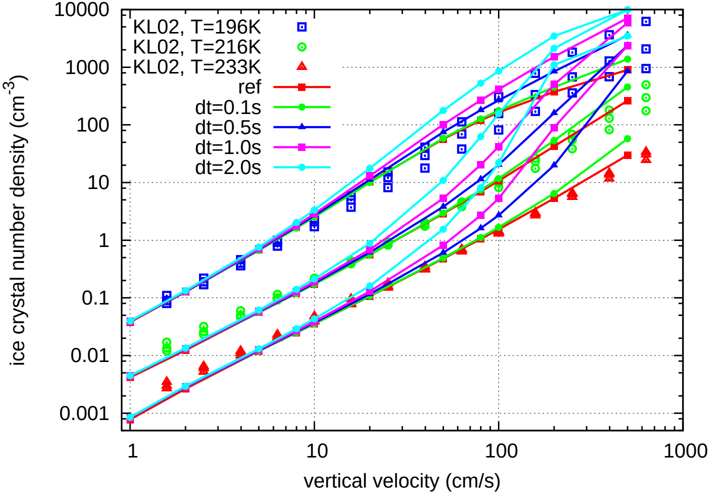
Validation

From boxmodel calculations compared to detailed microphysics:

Highly sensitive to time step (i.e. microphysical time step)

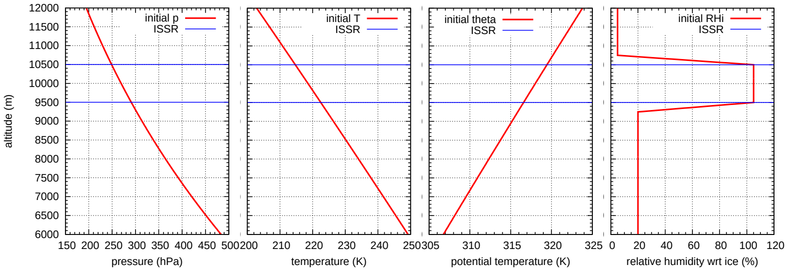


Setup (2D)

Horizontal extension: 6.3 km, cyclic, $dx = 100$ m, $dz = 10$ m

Two classes of ice (homogeneous freezing acc. to Koop et al., 2000, heterogeneous nucleation with threshold $RHi = 130\%$)

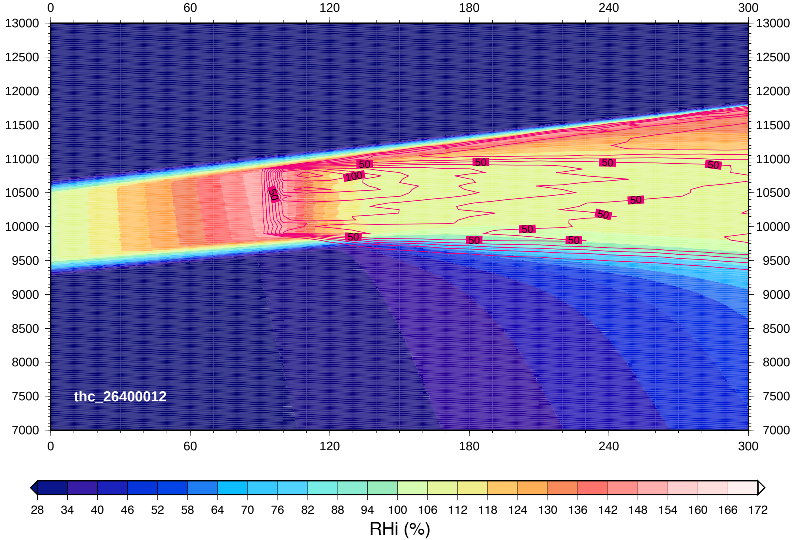
Constant uplift with $w = 0.06\mathrm{m\,s^{-1}}$, initial profiles:



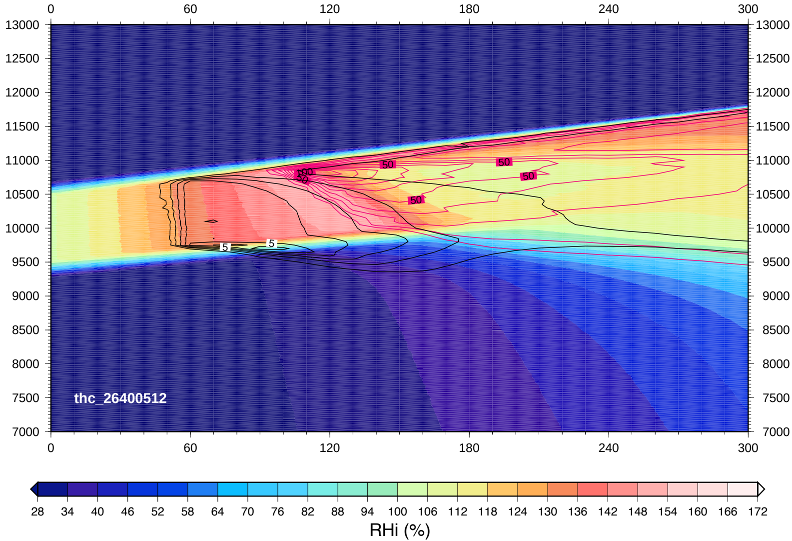
Following pictures: lines indicate ice crystal number density.

Purple: homogeneous freezing, black: heterogeneous nucleation

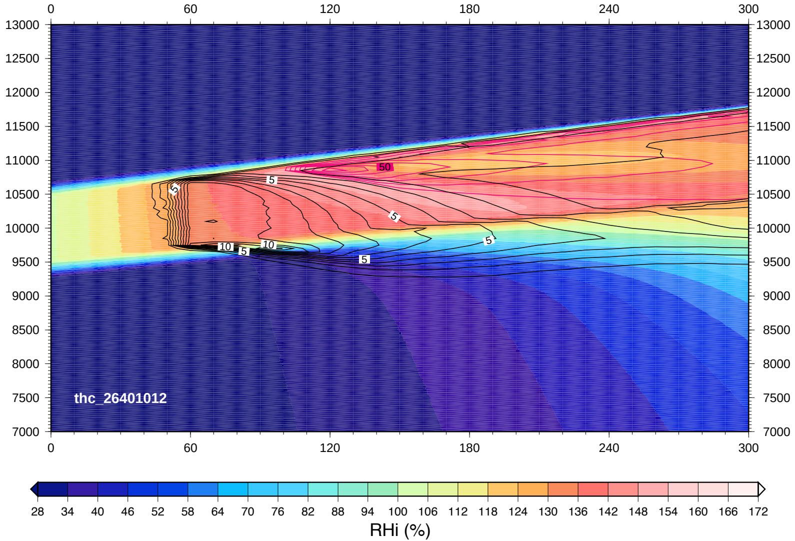
Reference simulation



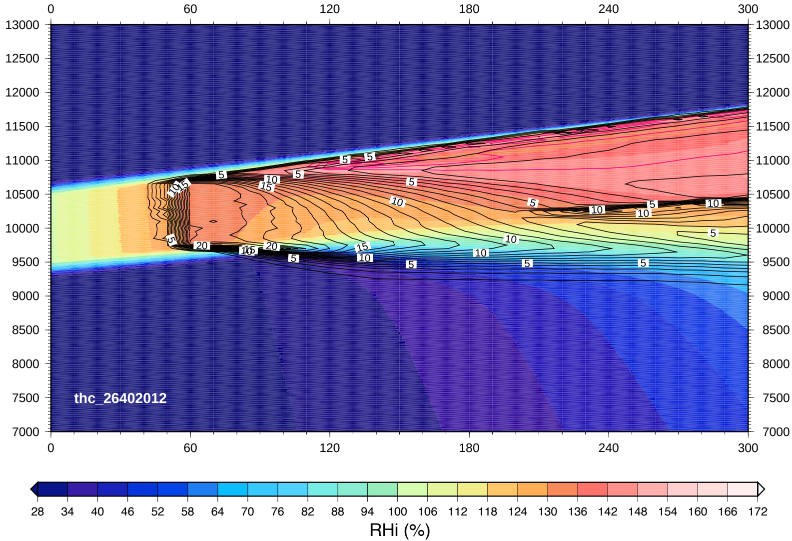
Changing IN concentrations: $N = 5\mathrm{L}^{-1}$



Changing IN concentrations: $N = 10\mathrm{L}^{-1}$



Changing IN concentrations: $N = 20\mathrm{L}^{-1}$



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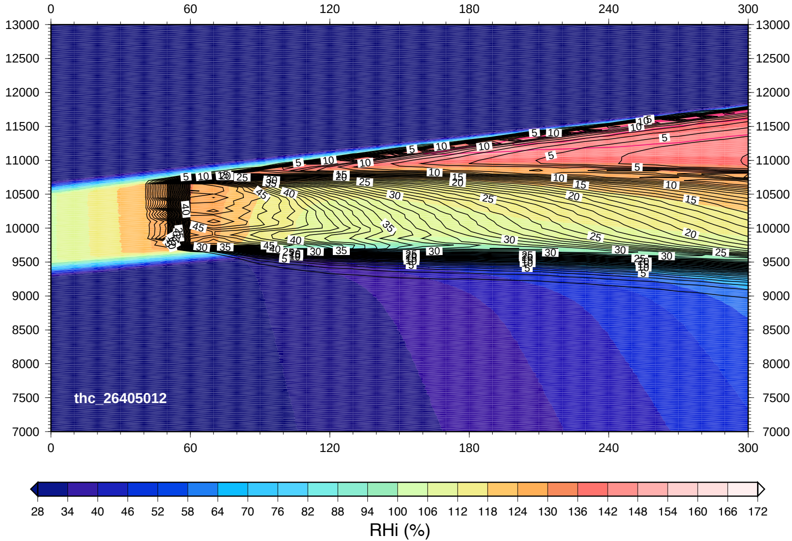
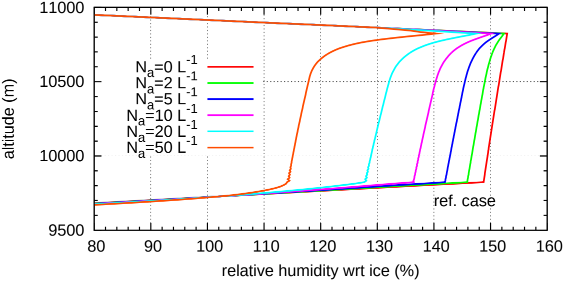
Changing IN concentrations: $N = 50\mathrm{L}^{-1}$



Interpretation



heterogeneously formed ice crystals reduce ice supersaturation, thus impacting the following homogeneous nucleation event

Interpretation

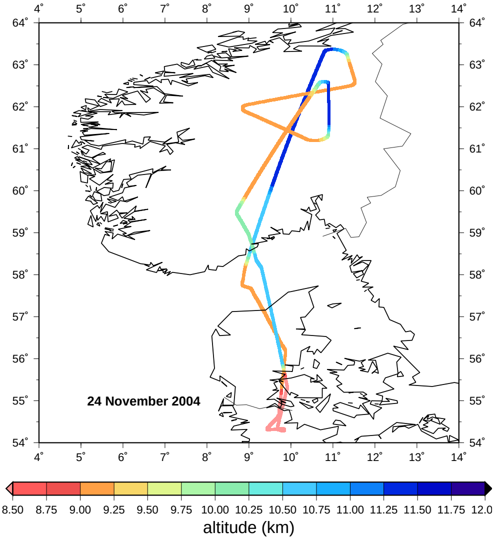
Three regimes:

- Few heterogeneous IN: Only few heterogeneous IN (up to about 10 L^{-1}): Homogeneous nucleation occurs over the whole depth of the cloud
- Medium number of IN (about 10/20 L^{-1}): Heterogeneous nucleation disturbs subsequent homogeneous nucleation; ice supersaturation inside the cirrus cloud possible.
- Large number of IN (50 L^{-1} and more): The cloud is completely dominated by heterogeneously formed ice.

High (and persistent) supersaturation inside cirrus possible

Motivation: CIRRUS II campaign

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



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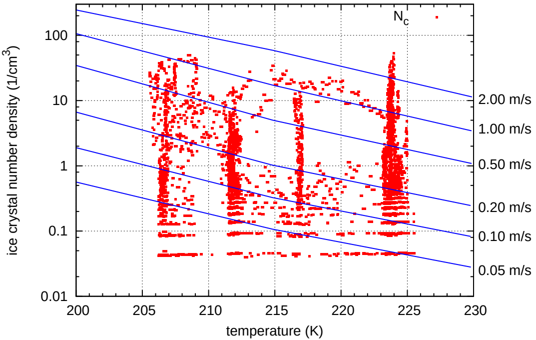
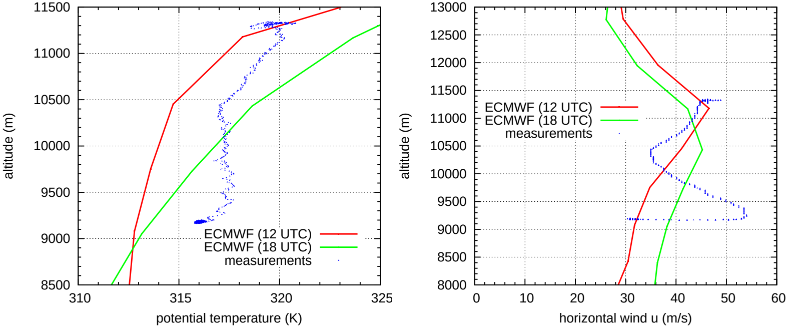
Motivation: CIRRUS II campaign

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 ...

Vertical profile in ascent



⇒ Idealized model study using almost exclusively ECMWF fields

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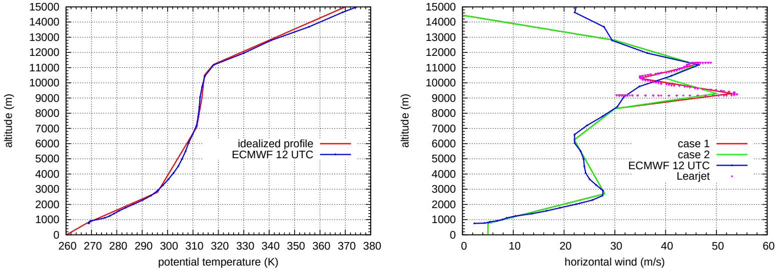
First series of simulations

- 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 trajectory calculations)

General setup (2D)

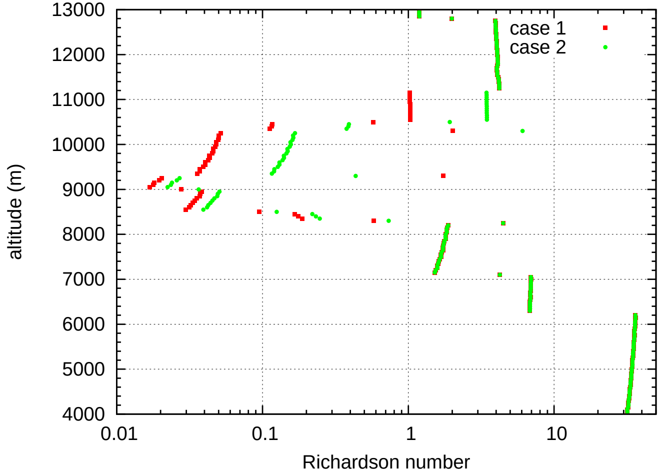
Profiles of potential temperature and horizontal wind:



In general two cases with different wind profiles.

Kelvin-Helmholtz instability

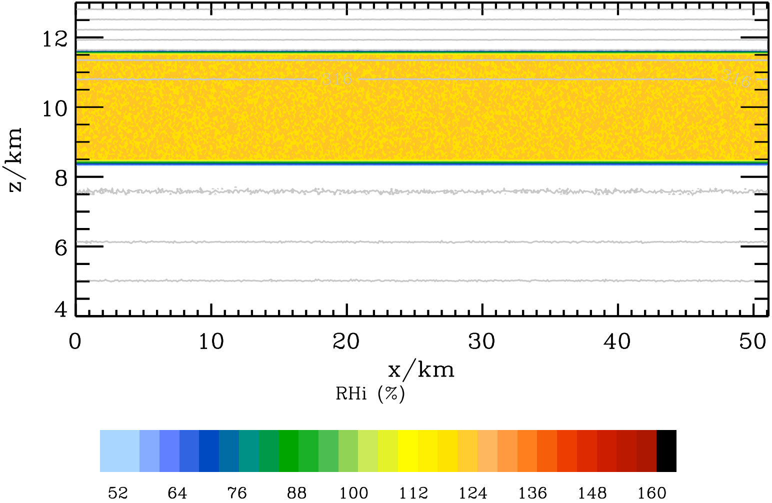
Initial conditions: Richardson Number for case 1 & 2



Conditionally unstable in the vertical range $8500 \leq z \leq 10500$ m

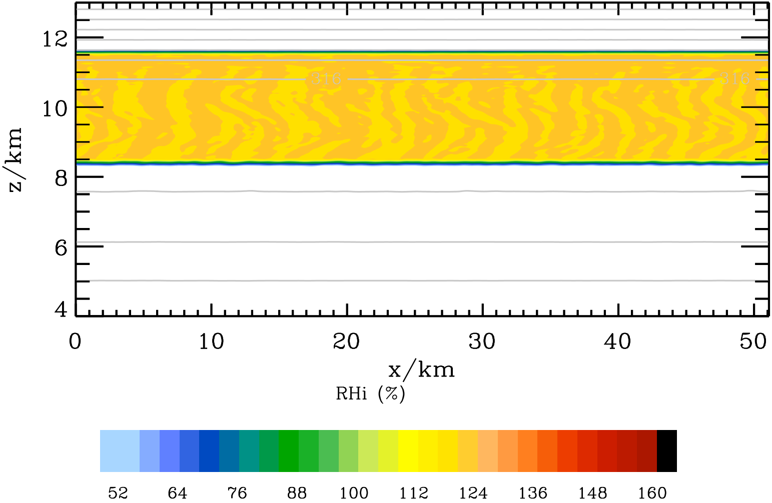
Case 1, without lifting

t= 000 min



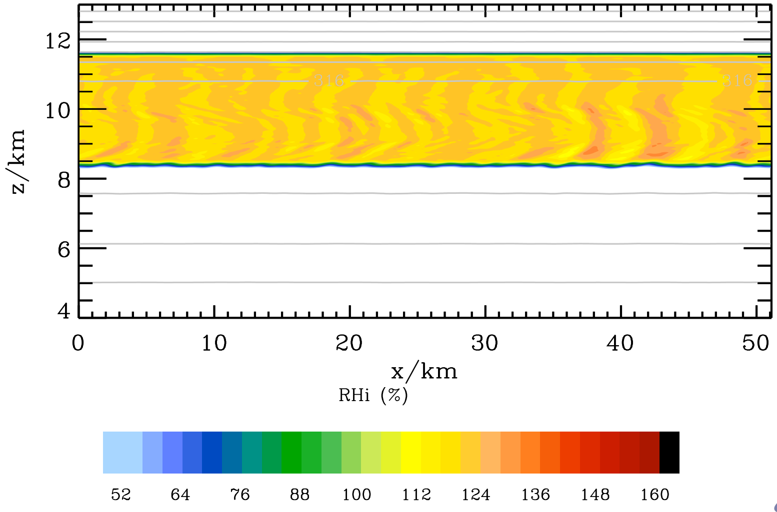
Case 1, without lifting

t= 010 min



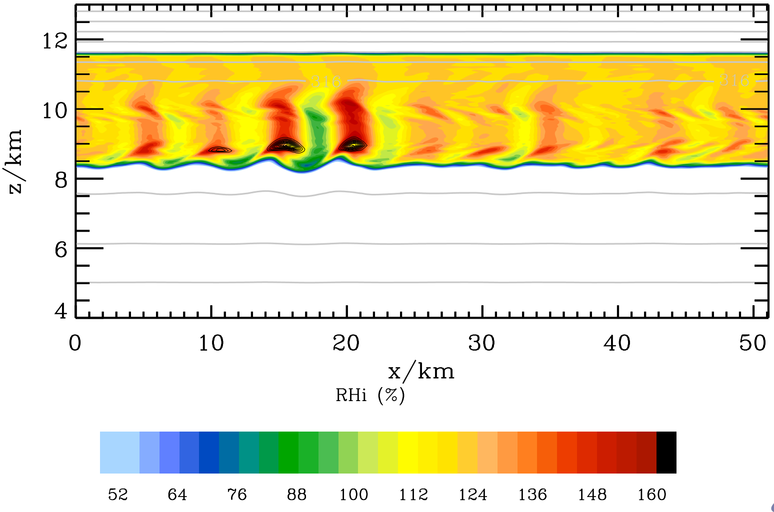
Case 1, without lifting

t= 020 min



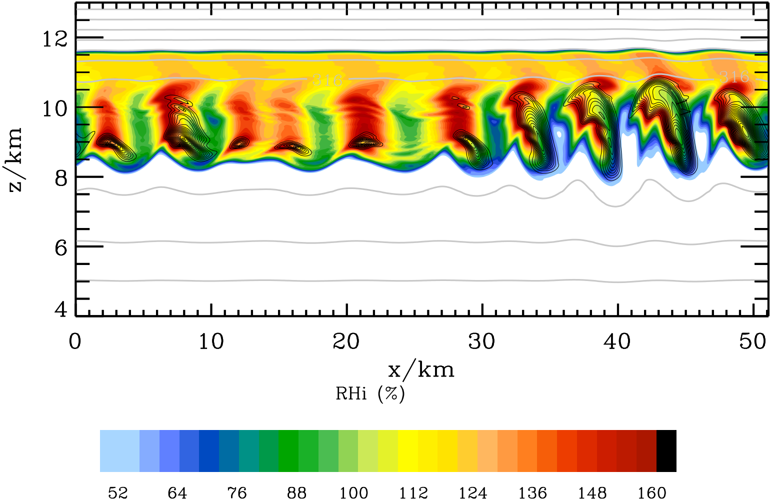
Case 1, without lifting

t= 030 min



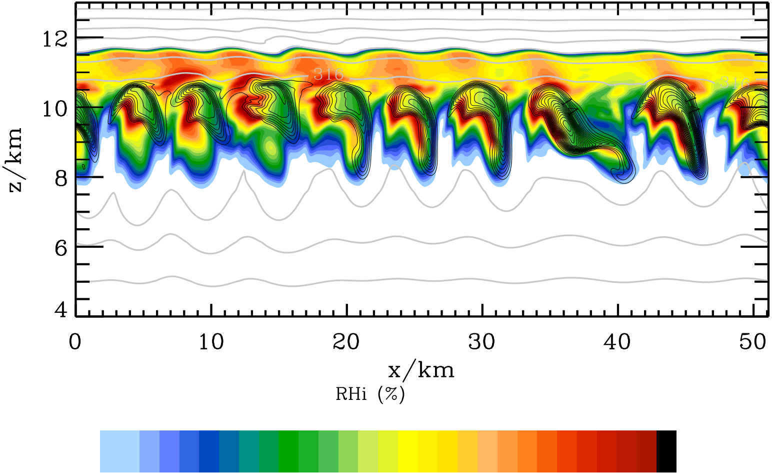
Case 1, without lifting

t= 040 min



Case 1, without lifting

t= 050 min



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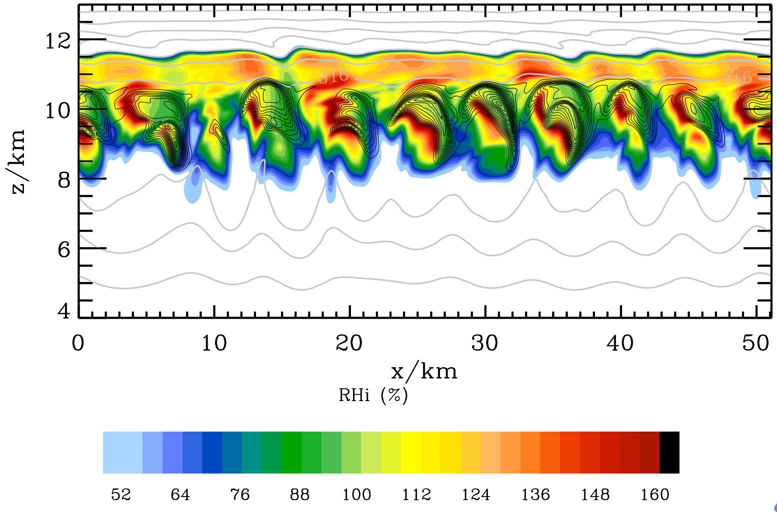
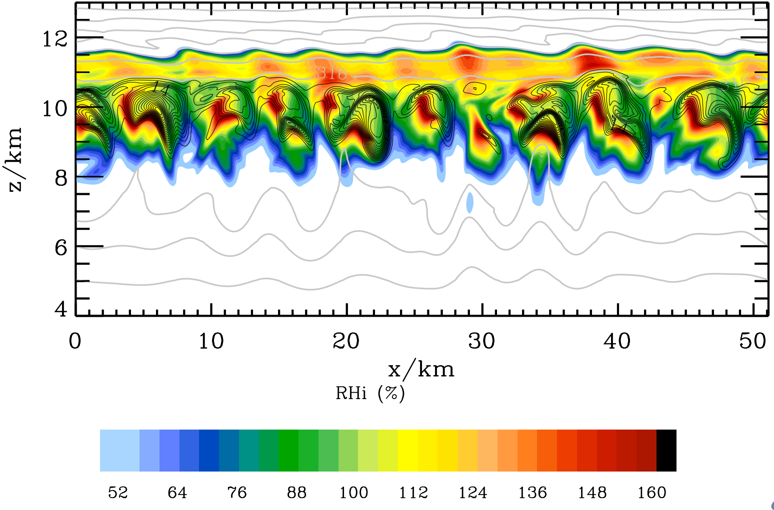
Case 1, without lifting

t= 060 min



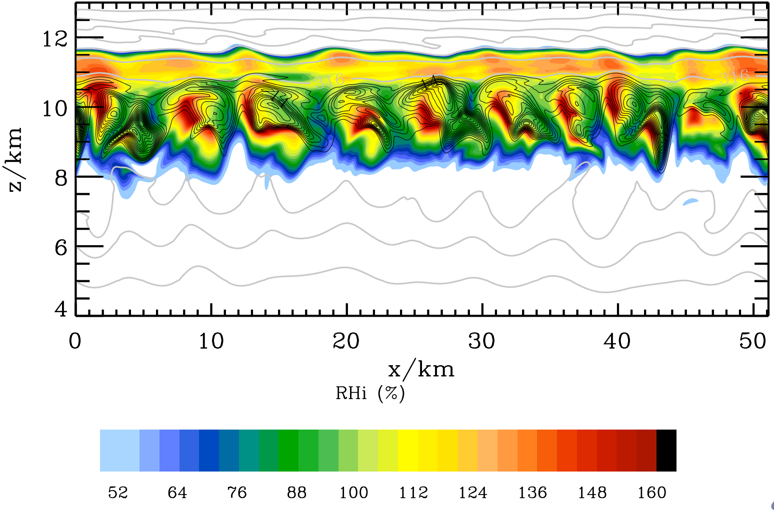
Case 1, without lifting

t= 070 min



Case 1, without lifting

t= 080 min



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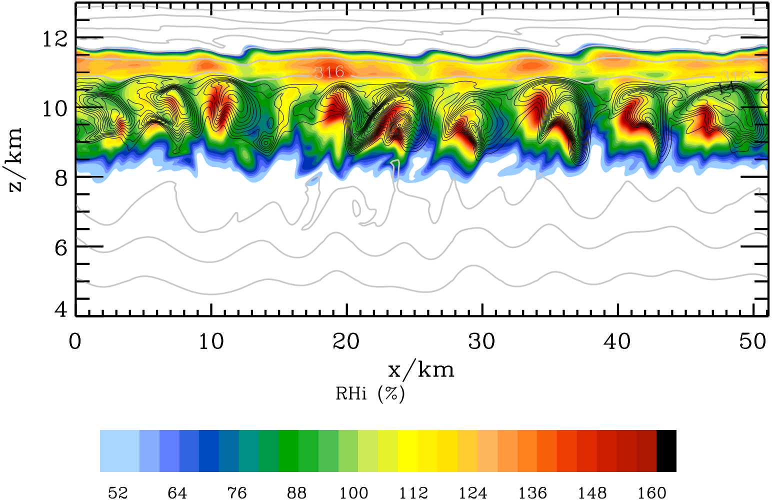
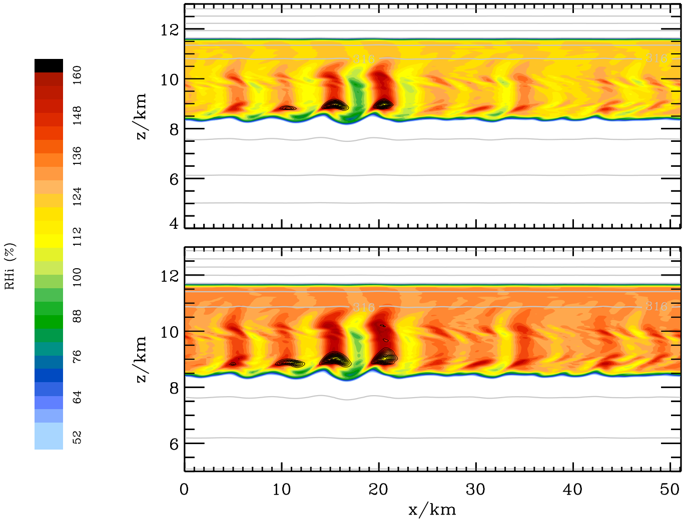
Case 1, without lifting

t= 090 min



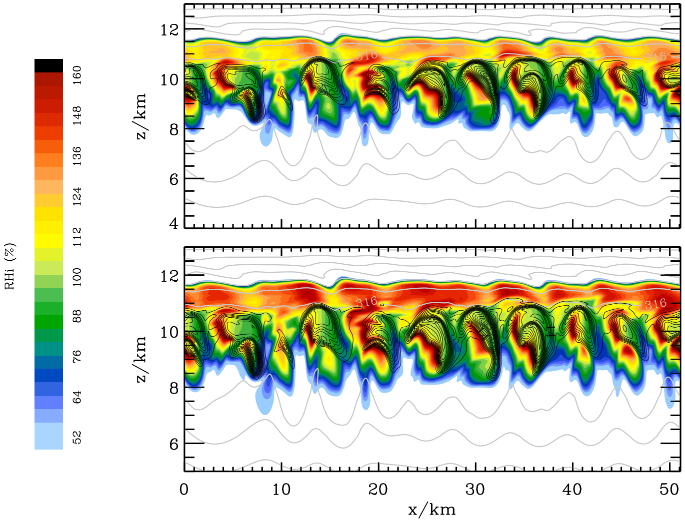
comparison without/with lifting

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



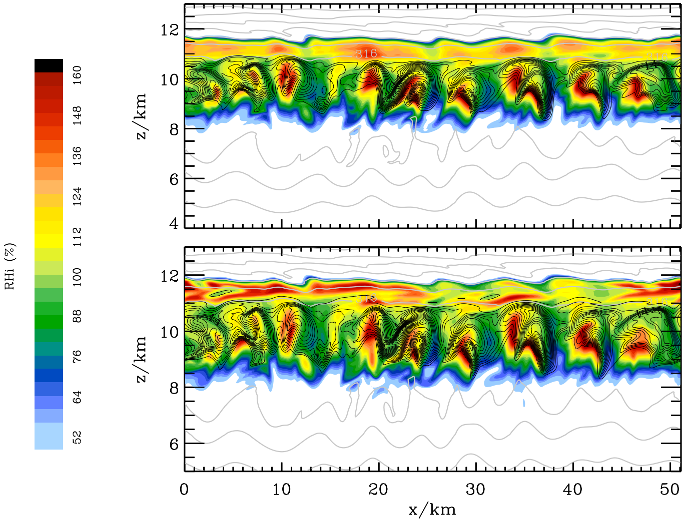
comparison without/with lifting

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



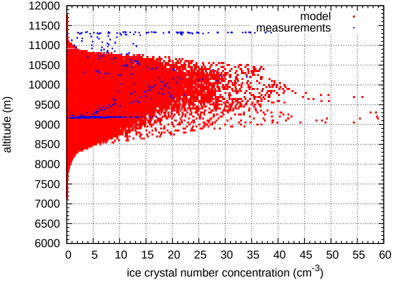
comparison without/with lifting

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

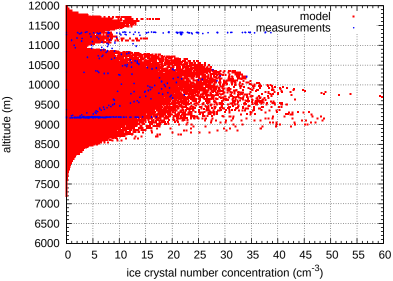


Ice crystal number concentrations

$w = 0\ \mathrm{cm\,s^{-1}}$

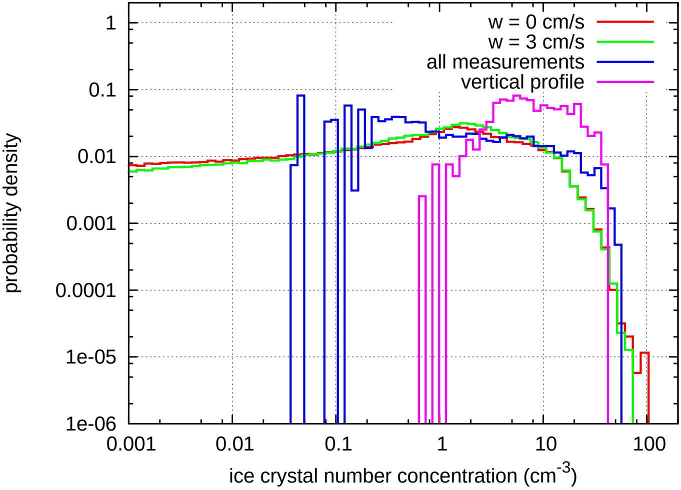


$w = 3\ \mathrm{cm\,s^{-1}}$



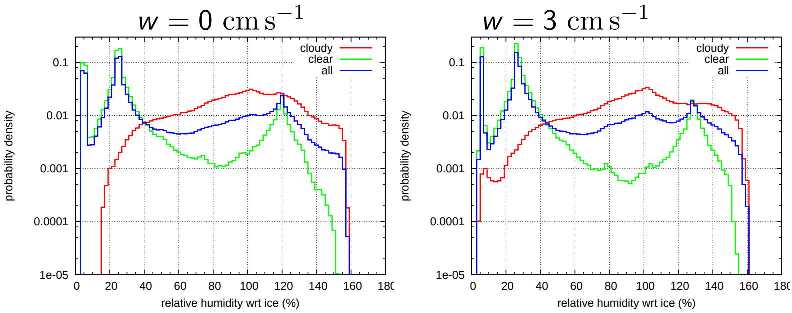
Statistics

Ice crystal number concentration distributions:



Statistics

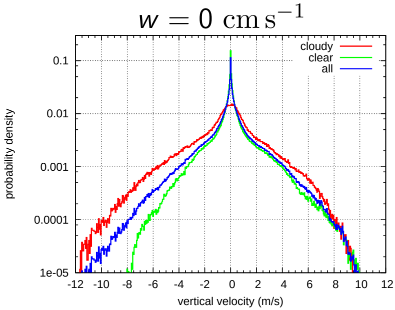
Relative humidity distributions:

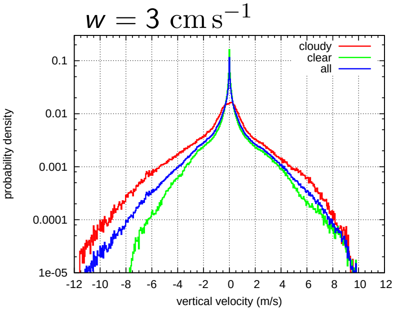


High ice supersaturation inside cirrus cloud possible.

Statistics

Vertical velocity distributions:





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Summary

- New ice microphysics scheme for EULAG (Spichtinger and Gierens, ACPD, 2008a)
- Modification of homogeneous nucleation by heterogeneous IN leads to high and persistent ice supersaturation inside cirrus clouds (Spichtinger and Gierens, ACPD, 2008b)
- Kelvin–Helmholtz instabilities could explain high ice crystal number densities in CIRRUS II case, i.e. no artificial enhancement but real (Spichtinger et al., in prep.)
- Dynamics and aerosols can crucially influence cirrus cloud properties (ice crystal number density, relative humidity inside cirrus, ...)

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The End

Thank you for your attention

Homogeneous nucleation

- lognormal size distribution of background aerosol droplets (sulfuric acid) with initial modal radius/mass and fixed geometric standard deviation σ_a
- Due to Koehler's theory: Size distribution of $\mathrm{H_2O/H_2SO_4}$ solution droplets (radius r_d), depending on environmental conditions (T, RH)
- Amount of newly nucleated ice crystals per time step Δt calculated using nucleation rates $J(a_w, T)$ (Koop et al., 2000):

$$\Delta N_i = N_a \cdot \int_0^\infty f(r_d)(1 - \exp(-JV_d\Delta t))dr_d, \qquad (15)$$

N_a=available background aerosol number density, V_d=droplet volume

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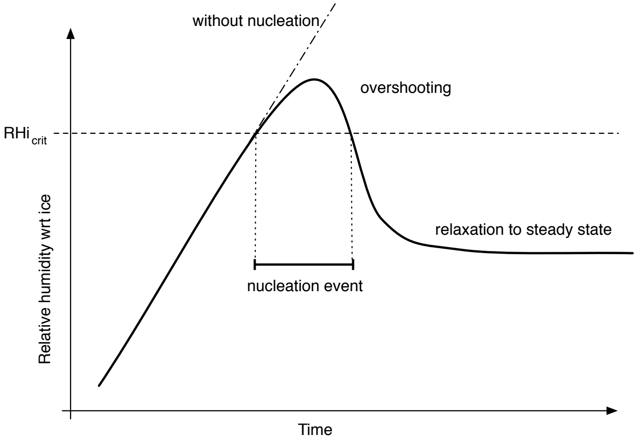
Homogeneous nucleation



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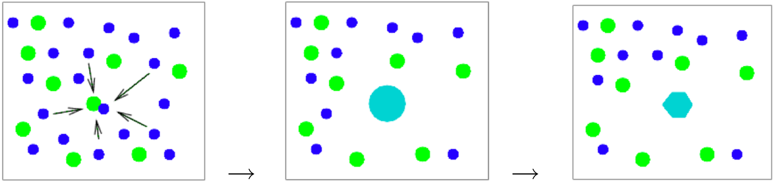
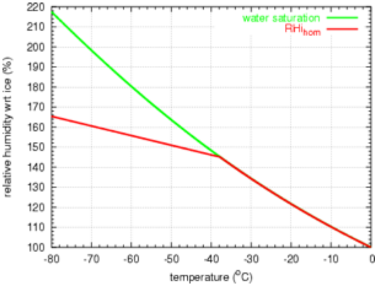
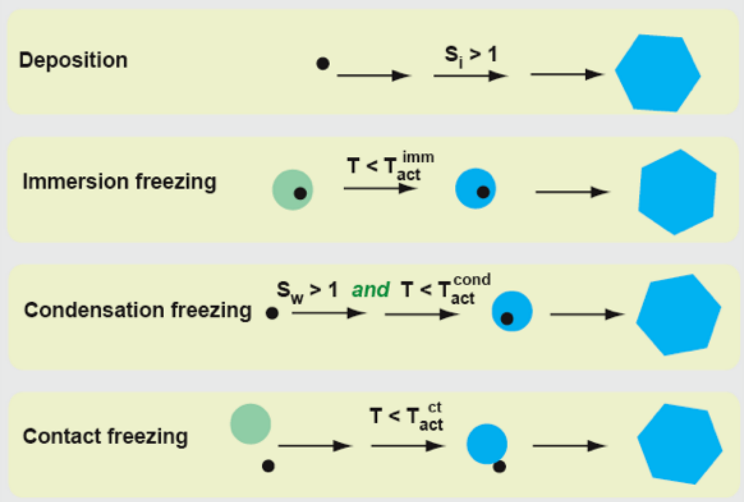
Ice nucleation I





By surpassing a nucleation threshold (depending on droplet size and temperature) spontaneous freezing set in. Remark: nucleation rates vary over several orders of magnitudes.

Ice nucleation II



Aerosol properties important ...

Cirrus cloud projects at ETH Zurich

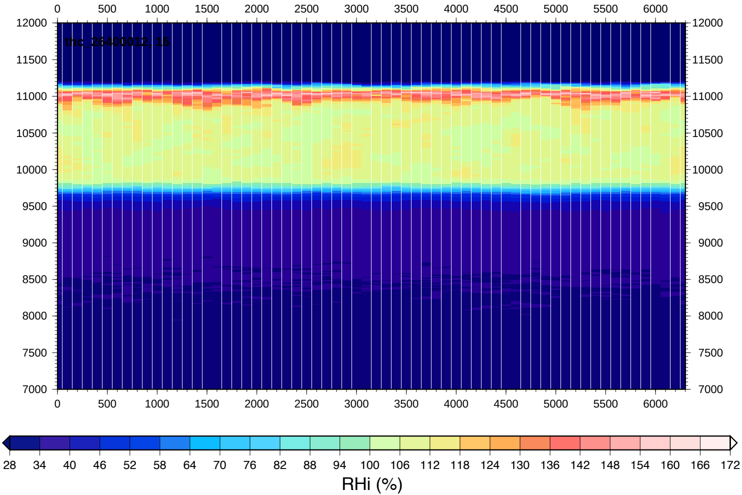
EULAG projects

- Cirrus and turbulence (Spichtinger & Smolarkiewicz)
- Orographic cirrus clouds (Joos & Spichtinger)
- Cirrus clouds, radiation and smallscale dynamics (Fusina & Spichtinger)
- Multiscale modelling of cirrus clouds (Fusina & Spichtinger)

Further boxmodel studies and GCM projects

2D relative humidity fields

$t = 150$ min, $N_a = 00\mathrm{L}^{-1}$



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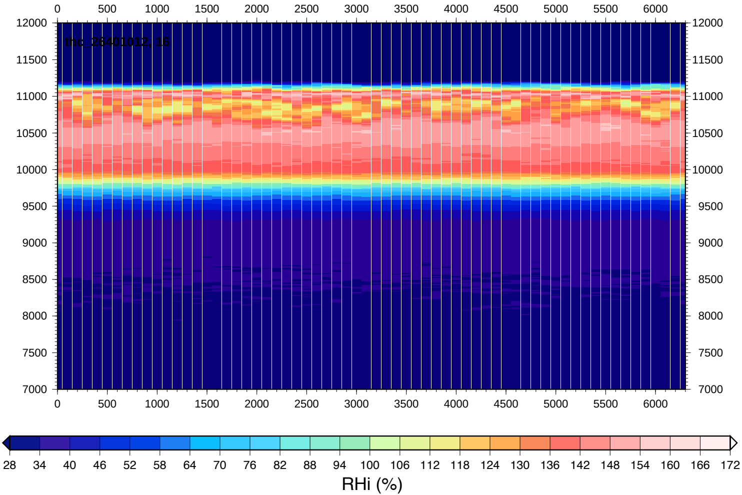
2D relative humidity fields

$t = 150$ min, $N_a = 10\mathrm{L}^{-1}$



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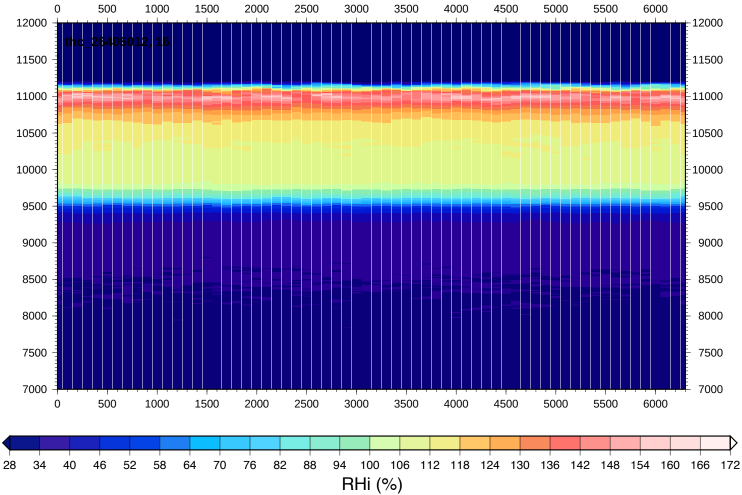
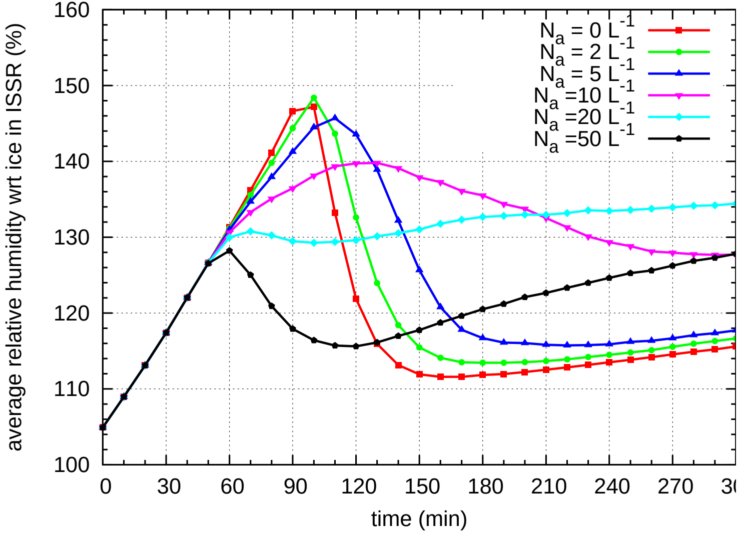
2D relative humidity fields

$t = 150$ min, $N_a = 50\mathrm{L}^{-1}$

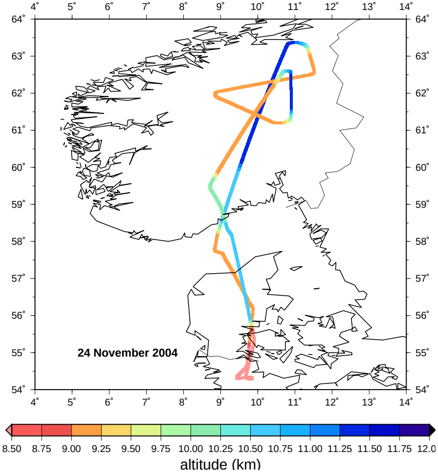


mean relative humidity $\geq 100\%$



orographic waves???

Remember flight pattern over Norway:



What about flow over mountains? orographic waves?

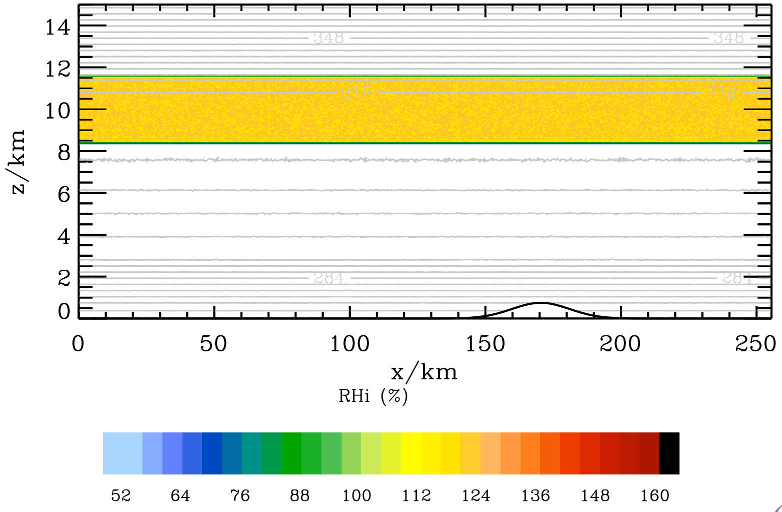
Second series of simulations

- 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.

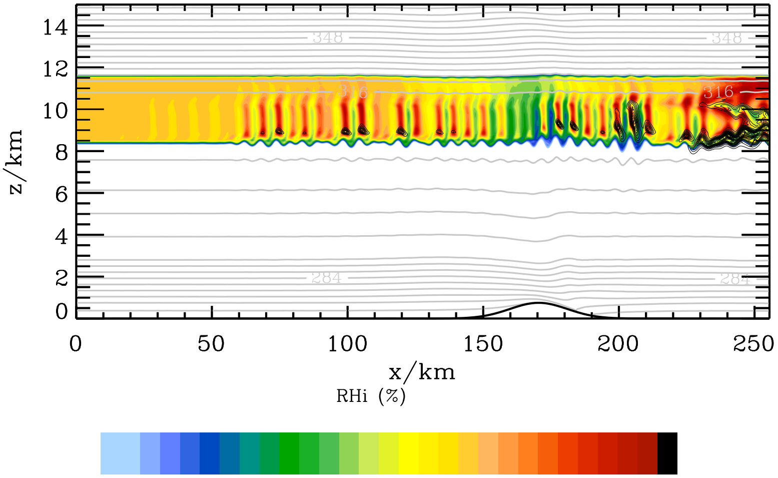
Case 1

t= 000 min



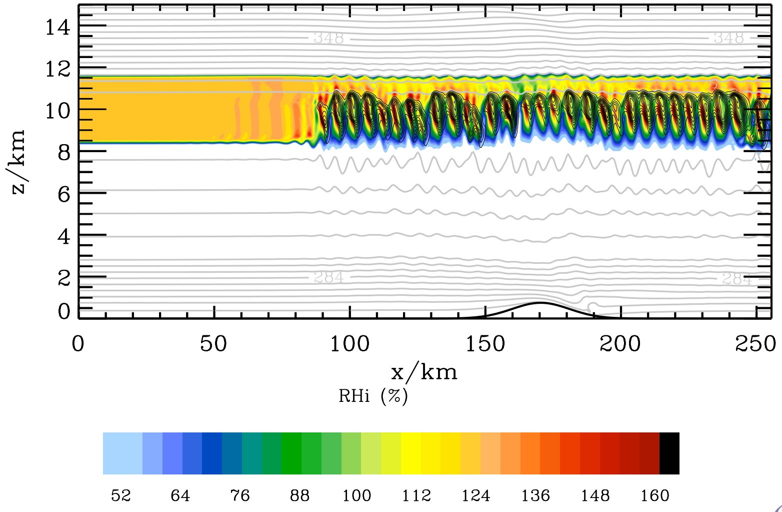
Case 1

t= 030 min



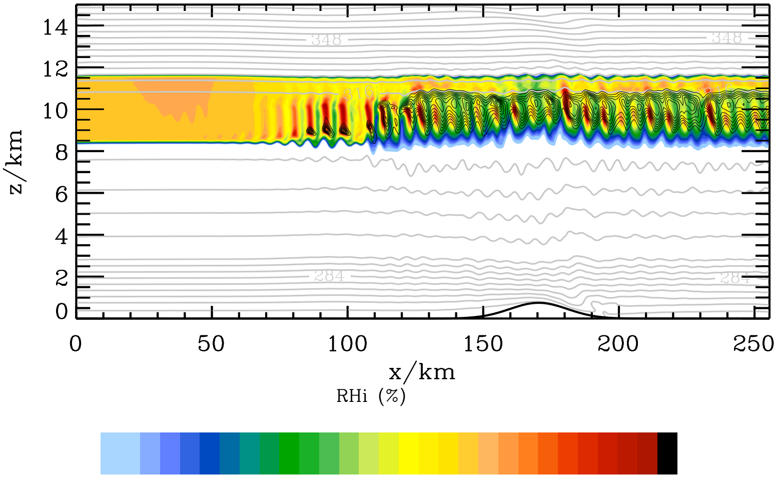
Case 1

t= 045 min



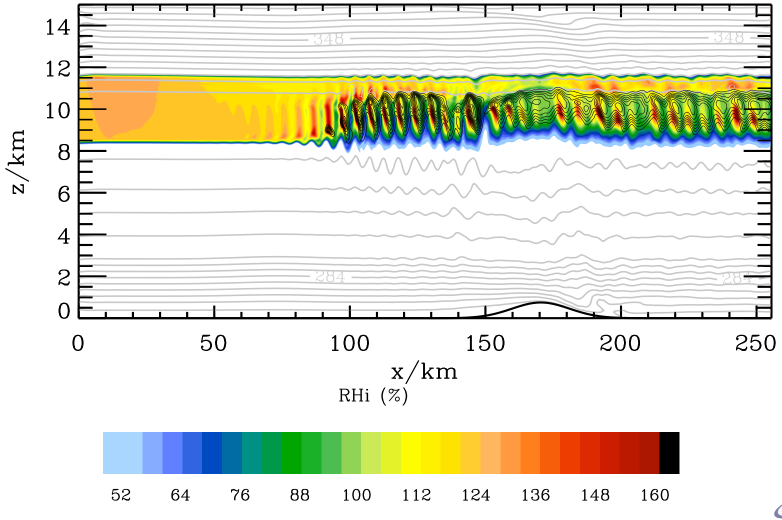
Case 1

t= 060 min



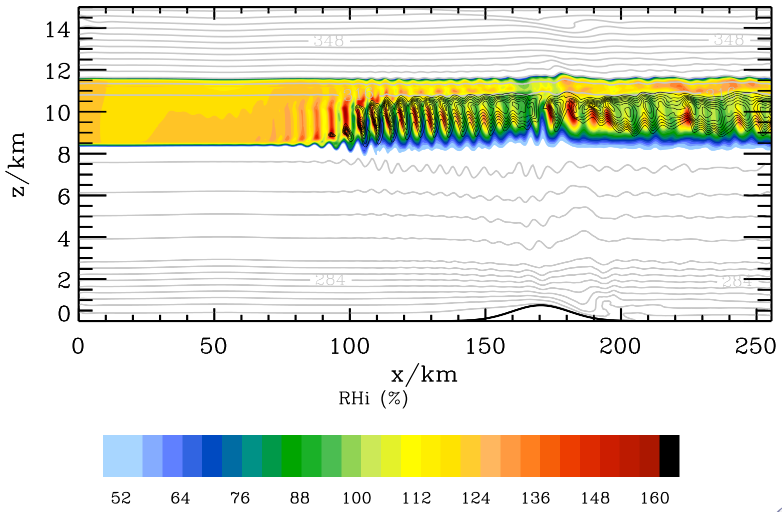
Case 1

t= 075 min



Case 1

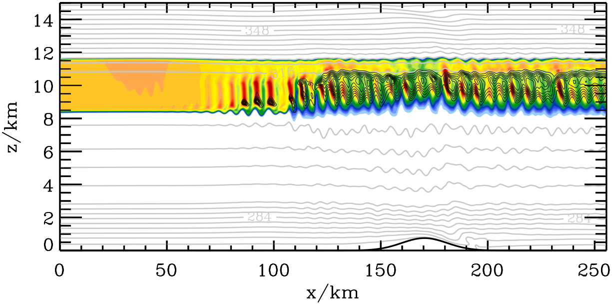
t= 090 min



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)



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Statistics

Ice crystal number concentration distributions: