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Cirrus cloud dynamics

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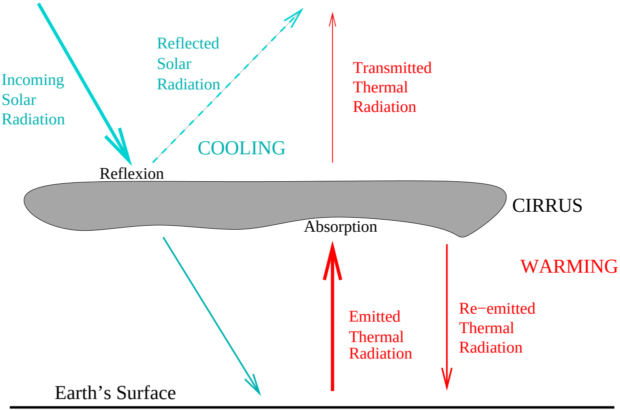
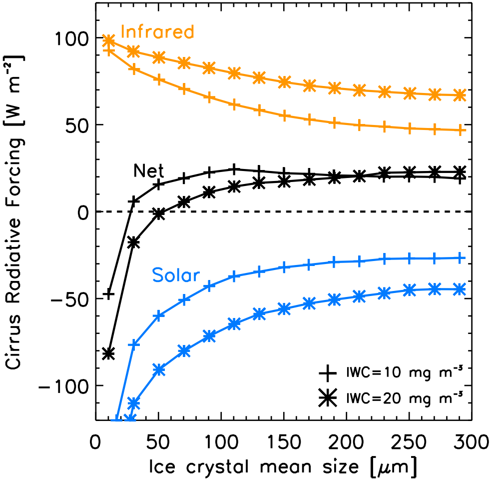
Motivation I

Cirrus clouds are important modulators of Earth's radiation budget:



A net warming is assumed but not confirmed

Motivation I

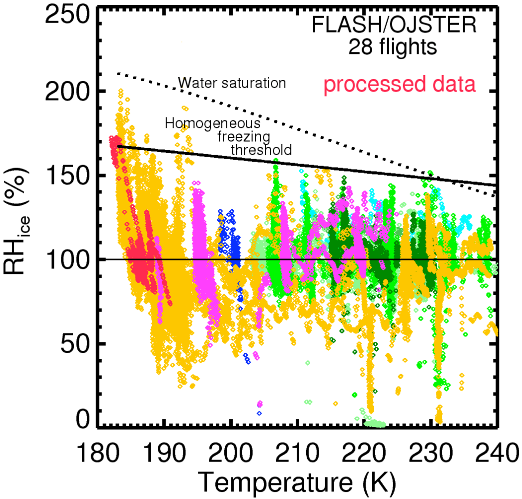


- Net warming and cooling possible
- Transition depends on microphysical properties as ice crystal mass and number concentration
- Ice crystal number concentration depends crucially on local dynamics as shown later

after Zhang et al., 1999, Atmos. Res.

Motivation II

High ice supersaturation inside cirrus clouds



Krämer et al., 2009, ACP

Motivation II

Ice supersaturation puzzle (Peter et al., 2006, Science):

Theory:

- Growing ice crystals deplete ice supersaturation
- Ice supersaturation inside thick cirrus clouds should be removed quickly (thermodynamical equilibrium)

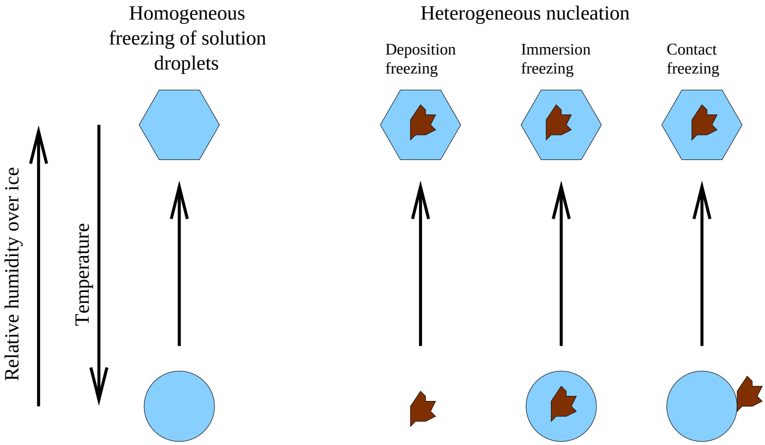
Measurements:

- High ice supersaturation inside cirrus clouds is found with different measurement techniques
- In-cloud supersaturation seems to be persistent for long time

Main topics of this talk

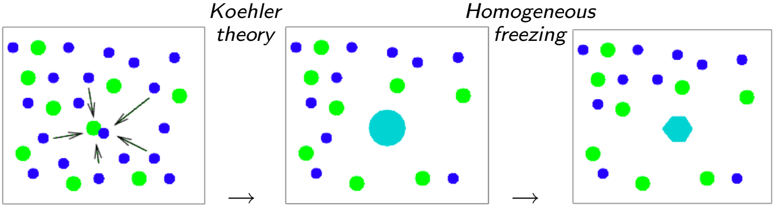
- Is there a feedback of cirrus clouds back to dynamics?
- Can cirrus cloud dynamics explain high ice supersaturation inside extra-tropical cirrus clouds?
- How do heterogeneous ice nuclei change the microphysical and radiative properties of cirrus clouds driven by cirrus cloud dynamics?

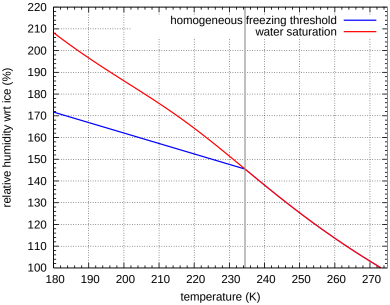
Ice formation at low temperatures ($T < 235\,\mathrm{K}$)



Homogeneous freezing of solution droplets

Aqueous solution droplets from a background aerosol (e.g. H_2SO_4)





Basic processes for changing RHi

Assume an air parcel without exchange to the environment

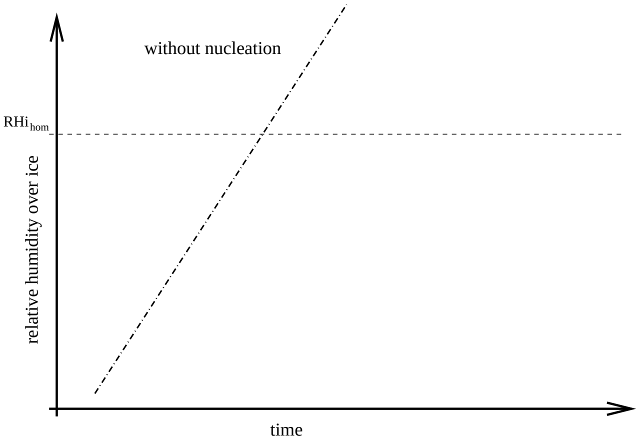
$$RHi = 100\% \frac{p \cdot q}{\epsilon \cdot p_{ice}(T)} \quad (1)$$

$$\frac{dRHi}{dt} = \underbrace{\frac{\partial RHi}{\partial T}\frac{dT}{dt} + \frac{\partial RHi}{\partial p}\frac{dp}{dt}}_{\approx \text{adiabatic expansion}} + \underbrace{\frac{\partial RHi}{\partial q}\frac{dq}{dt}}_{\text{growth}} \quad (2)$$

$$\frac{dq}{dt} = -\frac{dq_c}{dt}, \quad q_c = \text{cloud ice mixing ratio} \quad (3)$$

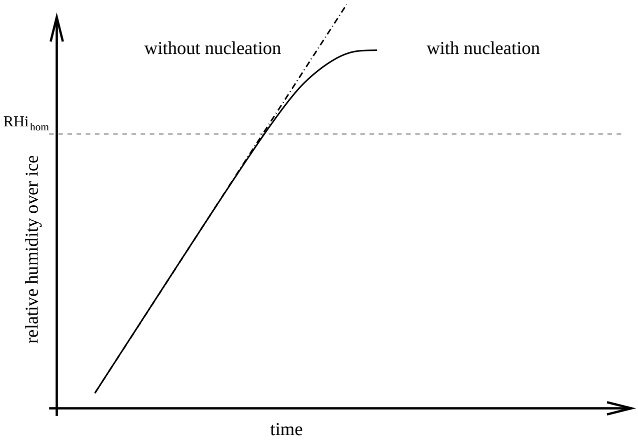
- Adiabatic expansion = cooling: source for supersaturation
- Diffusional growth of ice crystals: sink for supersaturation

Typical freezing events



Competition between cooling (source) and growth (sink)

Typical freezing events



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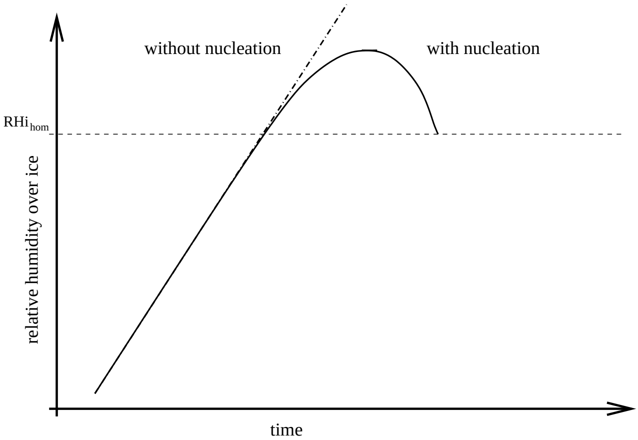

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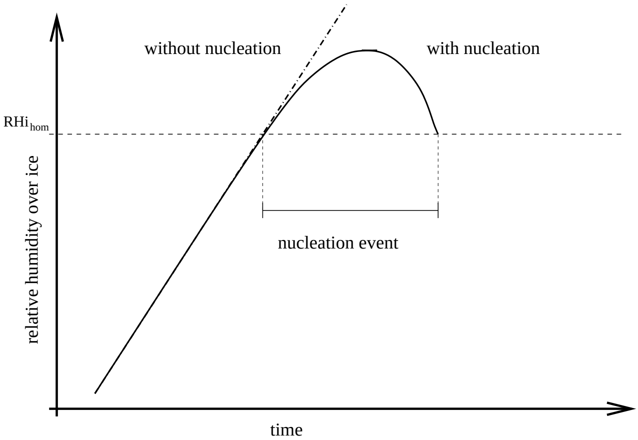
Typical freezing events



Competition between cooling (source) and growth (sink)

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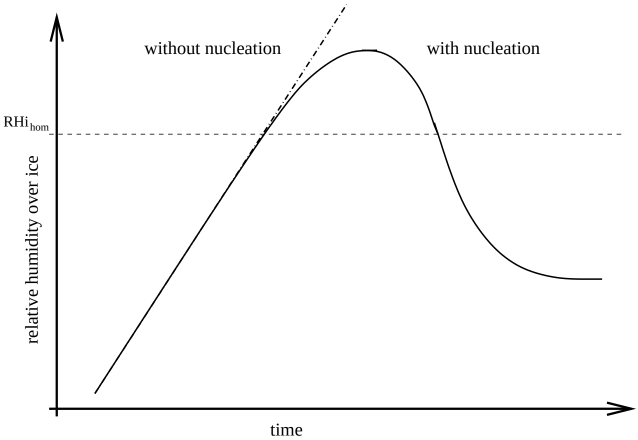
Typical freezing events



Competition between cooling (source) and growth (sink)

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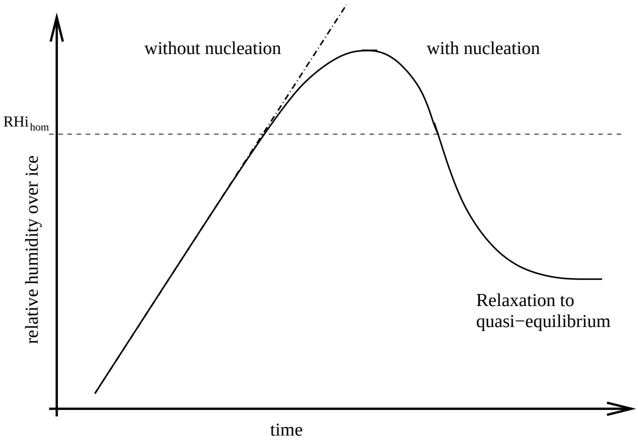
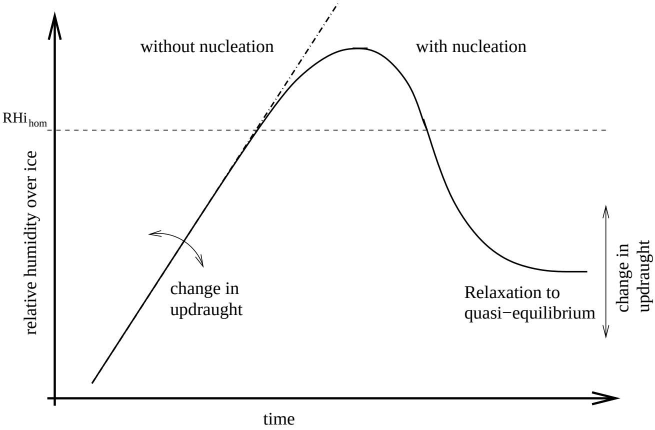


Competition between cooling (source) and growth (sink)

Impact of updraft



Competition between cooling (source) and growth (sink)

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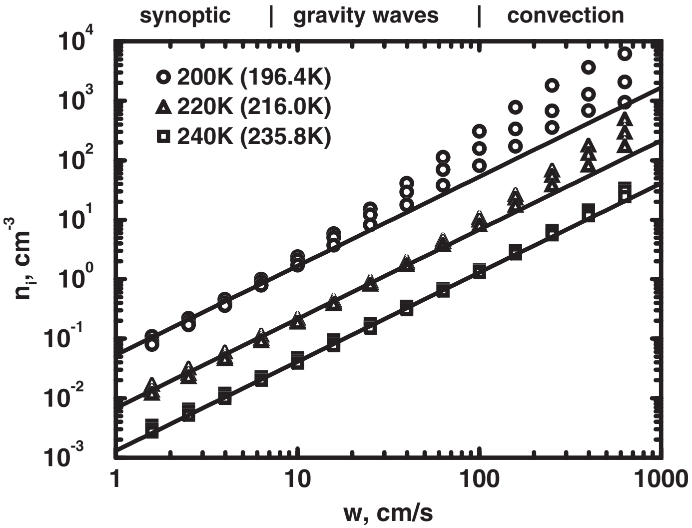
Impact of updraft



Kärcher & Lohmann, 2002, JGR

Feedback on mesoscale dynamics

Setup:

- Ice supersaturated air masses lifted by a constant updraught
- Ice crystal formed in freezing events
- Latent heat release by ice crystal growth

Results:

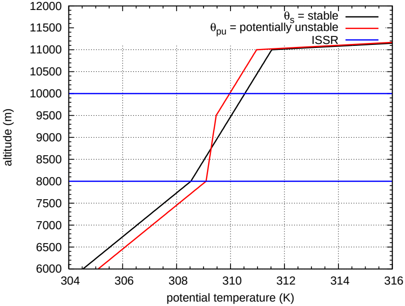
- Convection inside cirrus clouds?
- Impact on local structure?

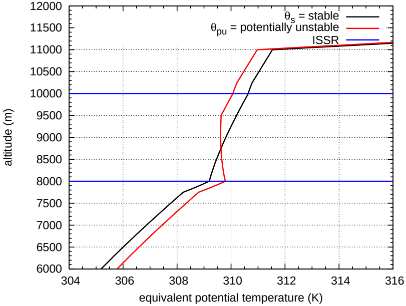
Model description/Setup

- An-elastic non-hydrostatic model EULAG (Prusa et al., 2008)
- Double moment ice microphysics scheme (Spichtinger & Gierens, 2009), including the processes:
  - Ice nucleation
  - Depositional growth/evaporation of ice crystals
  - Sedimentation of ice crystals
- 2D domain:
  - Horizontal extension $L_x = 51.1$ km, $dx = 100$ m, cyclic
  - Vertical extension $4 \leq z \leq 13$ km, $dz = 50$ m
- Constant large-scale lifting of 2D domain: $w = 5\ \mathrm{cm\,s^{-1}}$
- Moderate wind shear $du/dz = 1 \cdot 10^{-3}\ \mathrm{s}^{-1}$
- Saturated layer (RHi=100%) at $8000 \leq z \leq 10000$ m
- Gaussian temperature fluctuations $\sigma_T = 0.05$ K at initialisation

Two thermal stratifications

- Stable profile θ_s
- Potentially unstable profile θ_{pu}



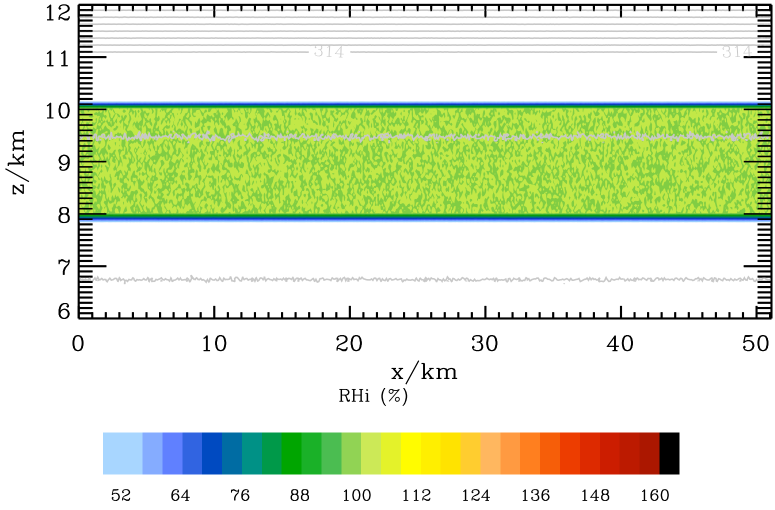


$$\theta = T \cdot \left(\frac{1000\ \text{hPa}}{p}\right)^{\frac{R}{c_p}} \quad ; \quad \theta_e = \theta \cdot \exp\left(\frac{L \cdot q}{c_p \cdot T}\right)$$

potential temperature θ equivalent potential temperature θ_e

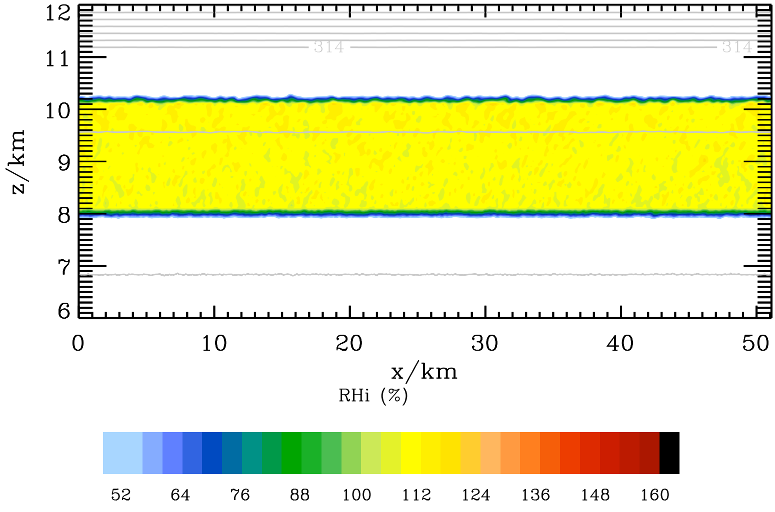
Case: stable θ profile (θ_s)

t= 000 min, black isolines: Ice water content, grey: Isentropes



Case: stable θ profile (θ_s)

t= 030 min, black isolines: Ice water content, grey: Isentropes



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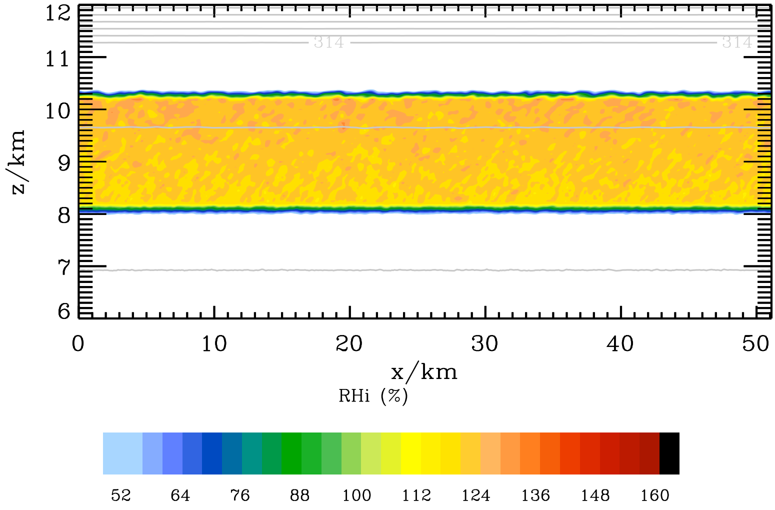
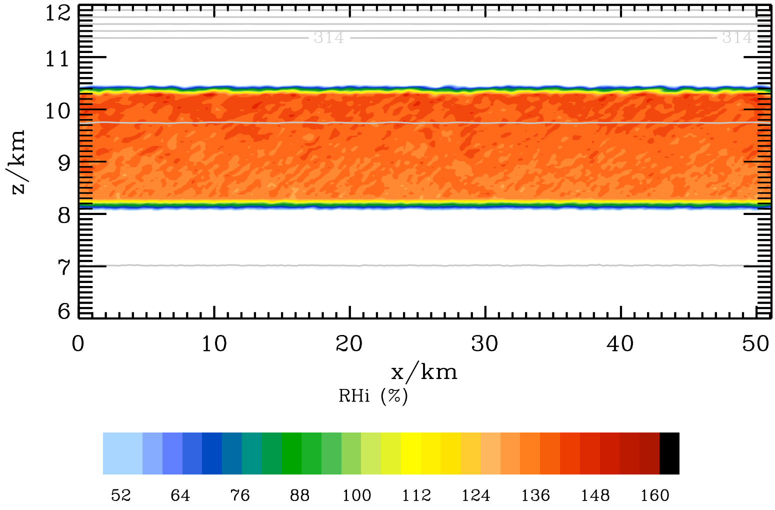
Case: stable θ profile (θ_s)

t= 060 min, black isolines: Ice water content, grey: Isentropes



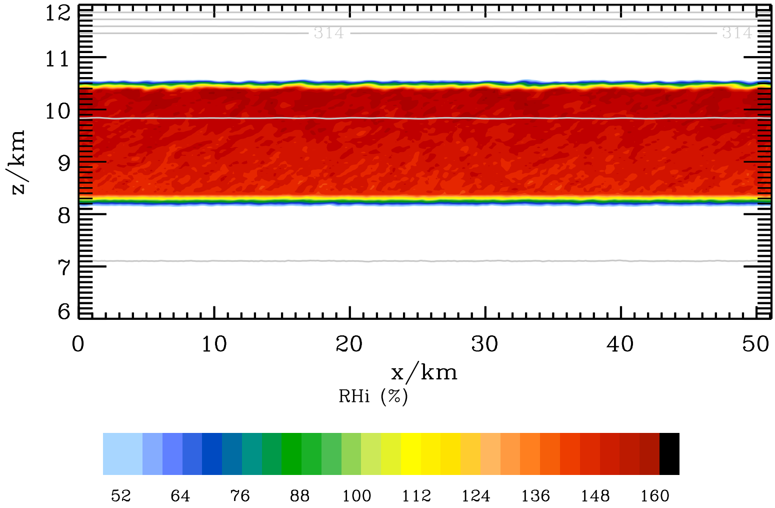
Case: stable θ profile (θ_s)

t= 090 min, black isolines: Ice water content, grey: Isentropes



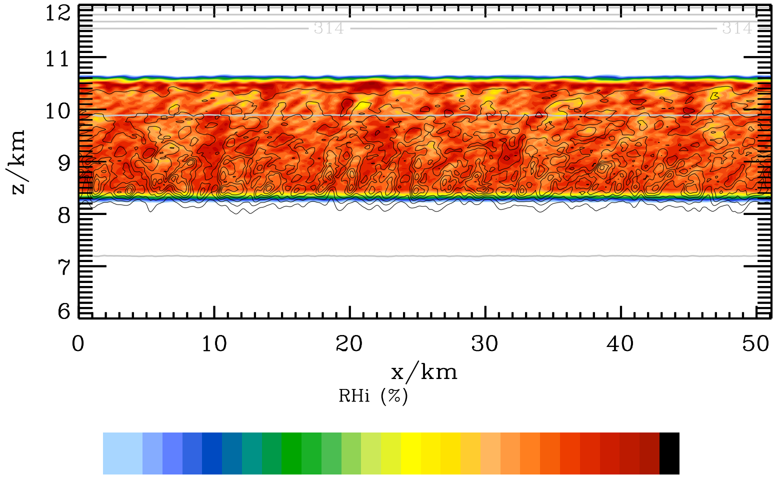
Case: stable θ profile (θ_s)

t= 120 min, black isolines: Ice water content, grey: Isentropes



Case: stable θ profile (θ_s)

t= 150 min, black isolines: Ice water content, grey: Isentropes



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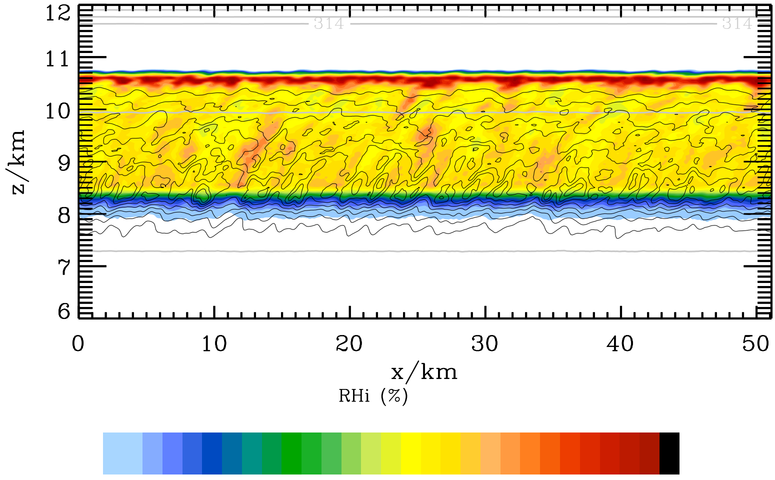
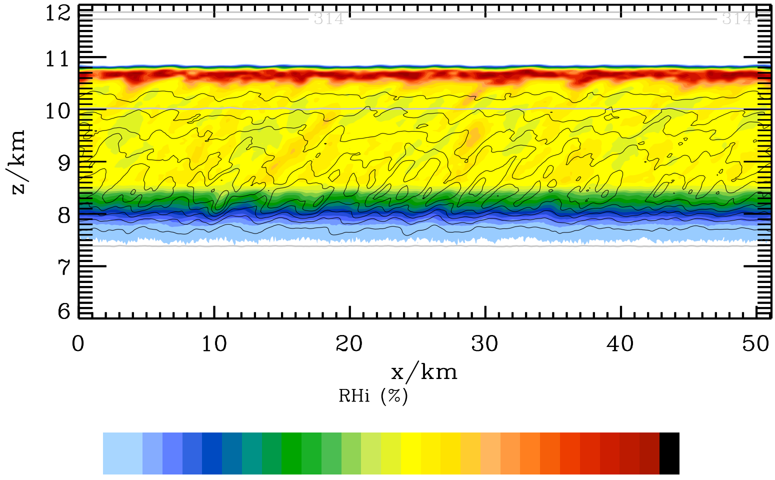
Case: stable θ profile (θ_s)

t= 180 min, black isolines: Ice water content, grey: Isentropes



Case: stable θ profile (θ_s)

t= 210 min, black isolines: Ice water content, grey: Isentropes



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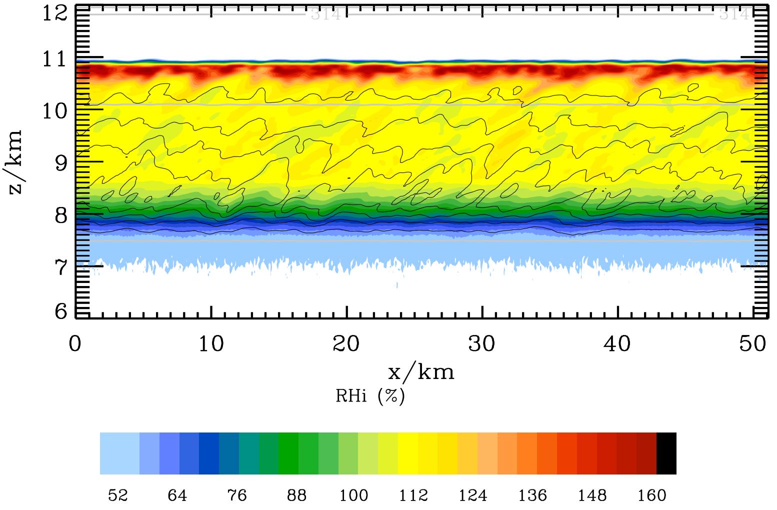
Case: stable θ profile (θ_s)

t= 240 min, black isolines: Ice water content, grey: Isentropes



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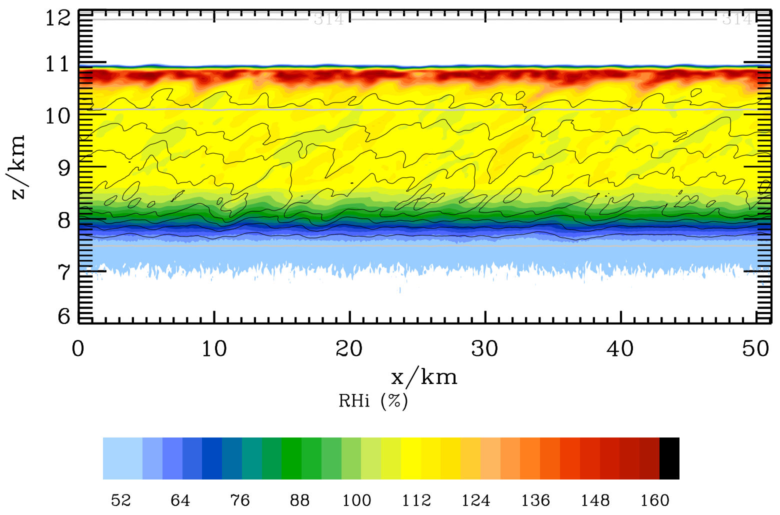

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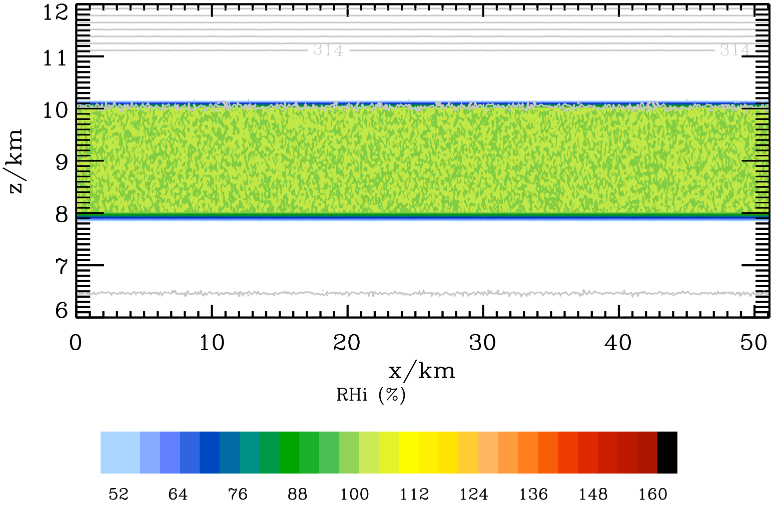
Case: potentially unstable θ profile (θ_{pu})

t= 000 min, black isolines: Ice water content, grey: Isentropes



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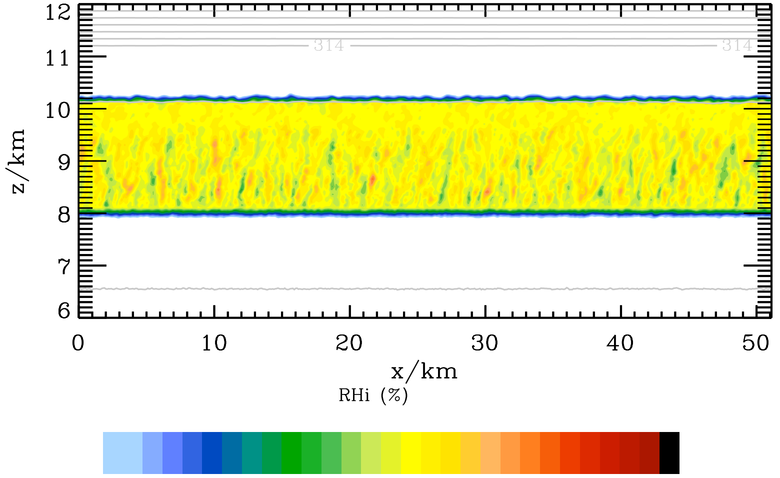

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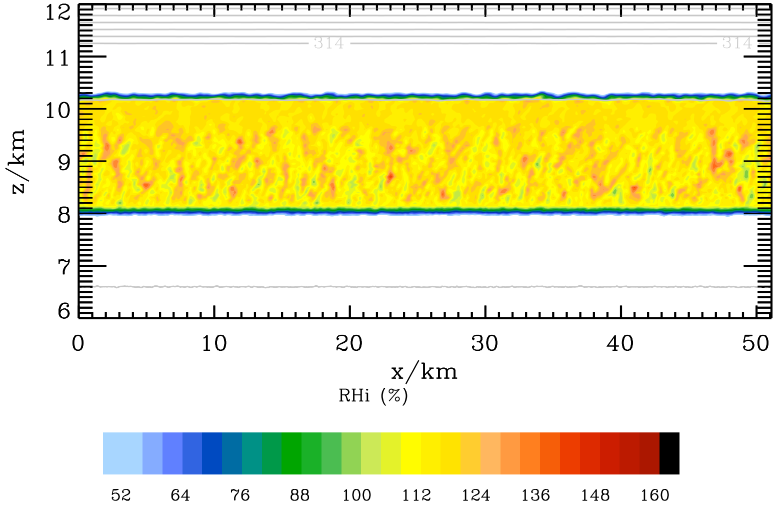
Case: potentially unstable θ profile (θ_{pu})

t= 045 min, black isolines: Ice water content, grey: Isentropes



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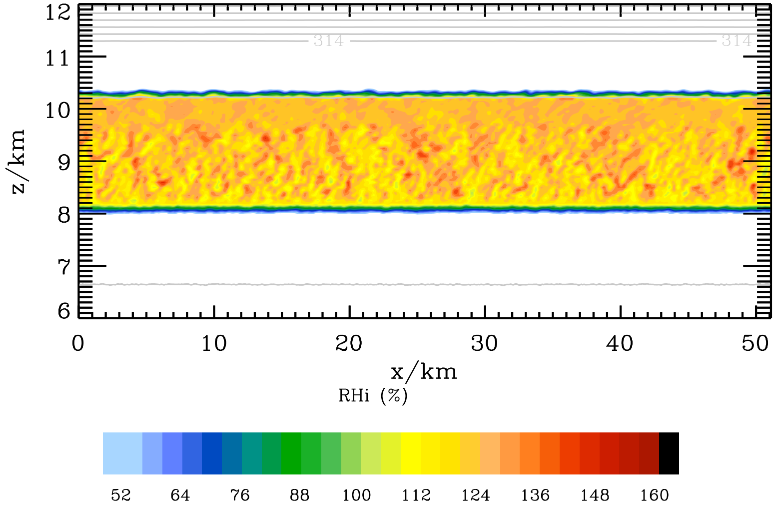
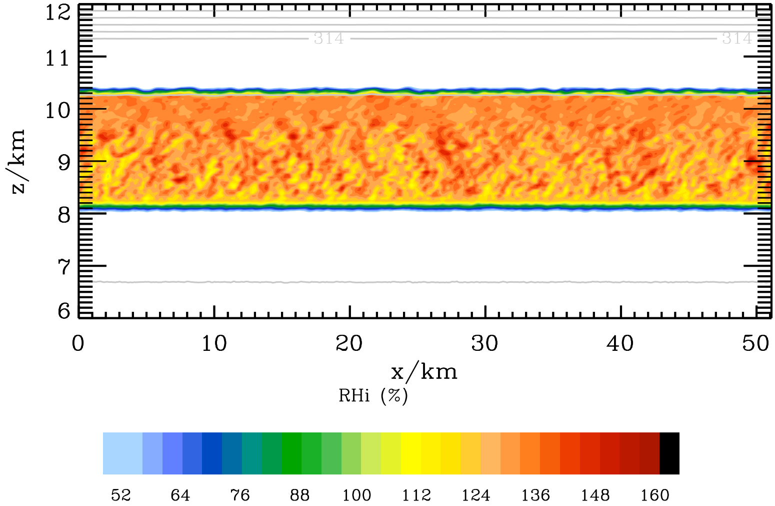
t= 060 min, black isolines: Ice water content, grey: Isentropes



Case: potentially unstable θ profile (θ_{pu})

t= 075 min, black isolines: Ice water content, grey: Isentropes



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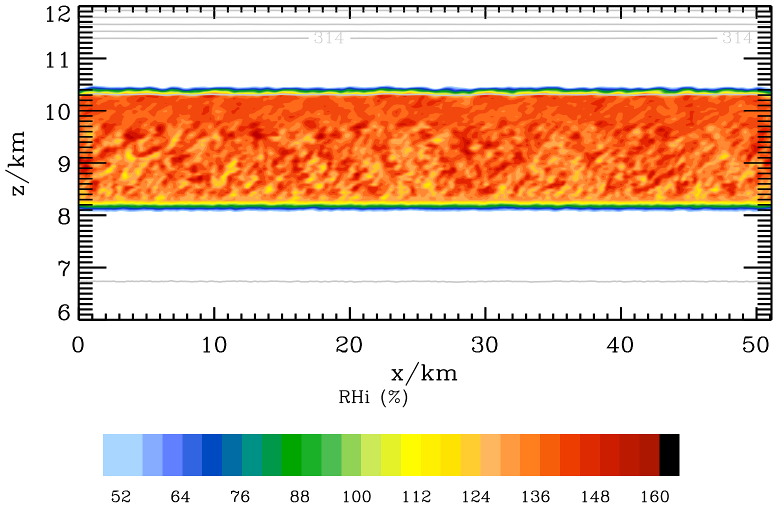
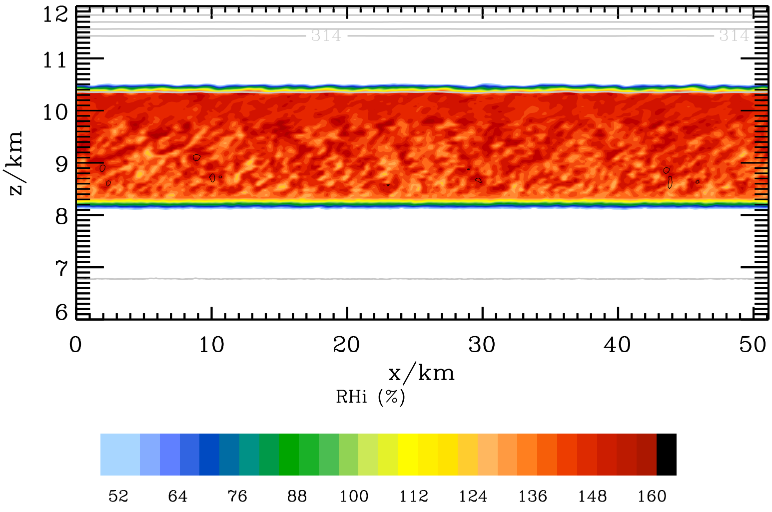
Case: potentially unstable θ profile (θ_{pu})

t= 090 min, black isolines: Ice water content, grey: Isentropes



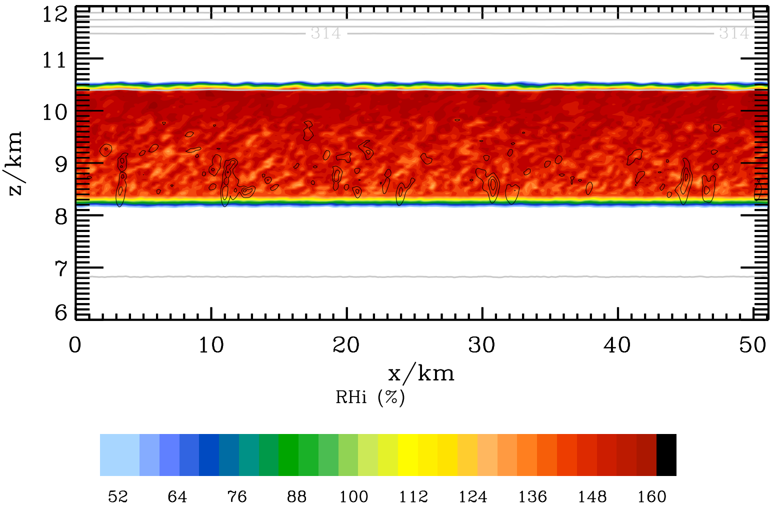
Case: potentially unstable θ profile (θ_{pu})

t= 105 min, black isolines: Ice water content, grey: Isentropes



Case: potentially unstable θ profile (θ_{pu})

t= 120 min, black isolines: Ice water content, grey: Isentropes



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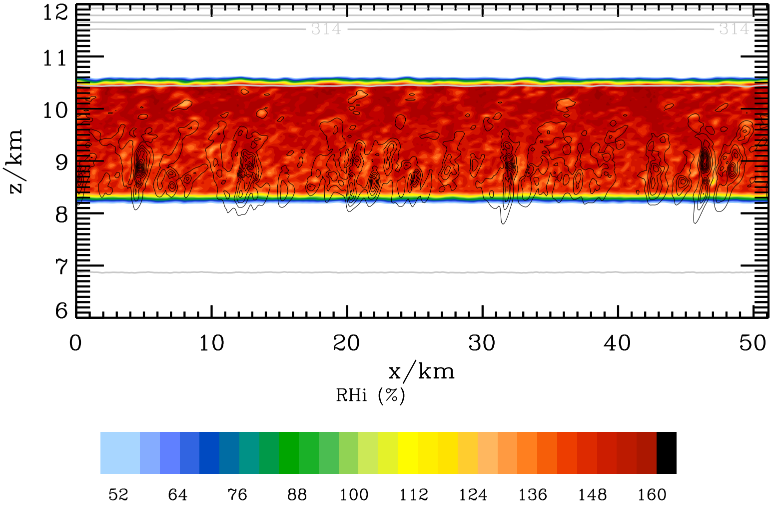
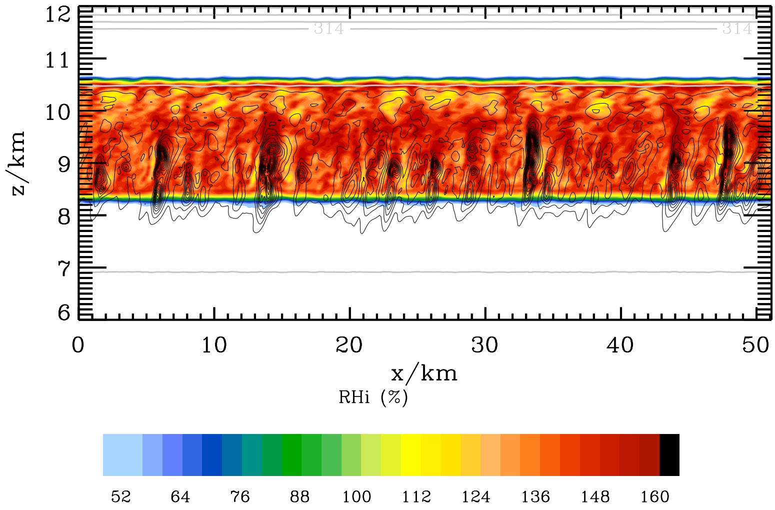
Case: potentially unstable θ profile (θ_{pu})

t= 135 min, black isolines: Ice water content, grey: Isentropes



Case: potentially unstable θ profile (θ_{pu})

t= 150 min, black isolines: Ice water content, grey: Isentropes



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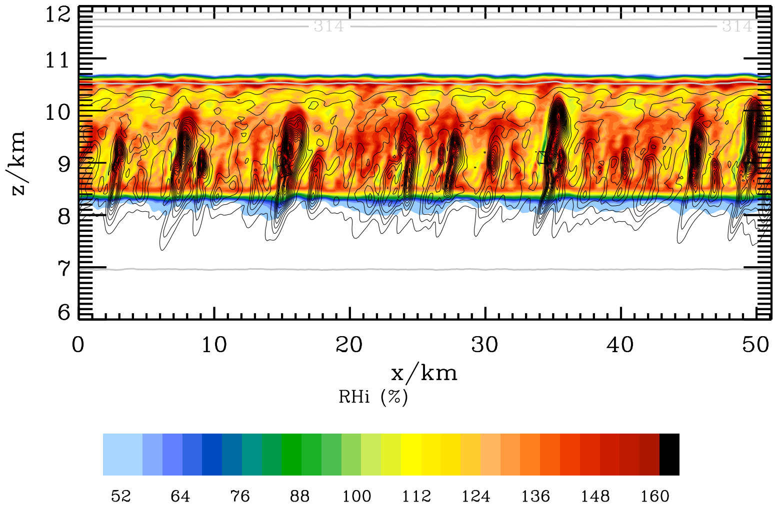
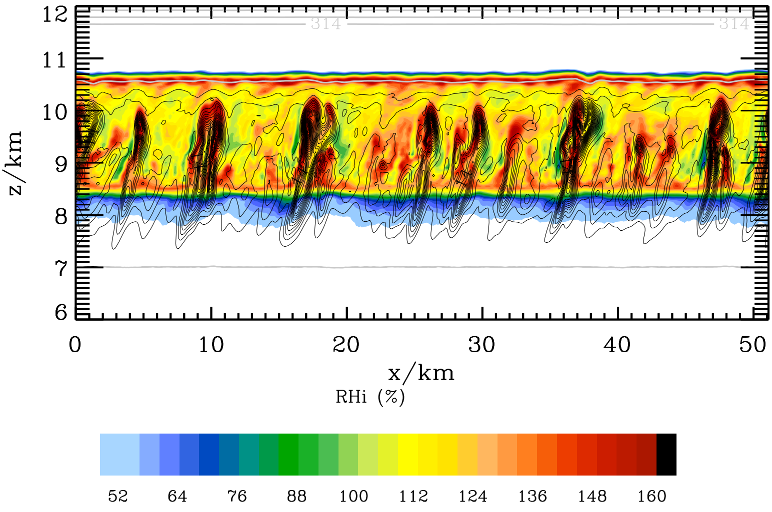
Case: potentially unstable θ profile (θ_{pu})

t= 165 min, black isolines: Ice water content, grey: Isentropes



Case: potentially unstable θ profile (θ_{pu})

t= 180 min, black isolines: Ice water content, grey: Isentropes



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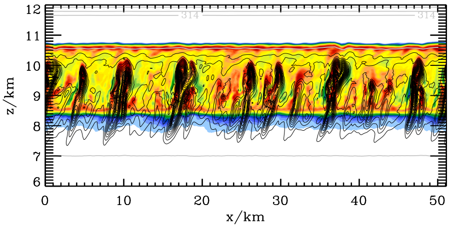
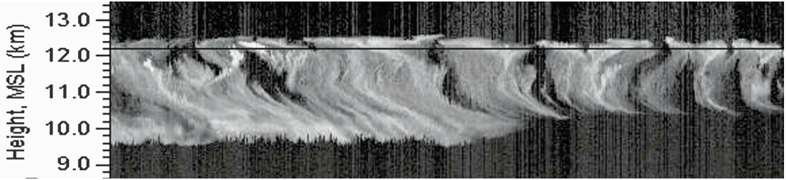
Case: potentially unstable θ profile (θ_{pu})

Simulations vs. observations (LIDAR)



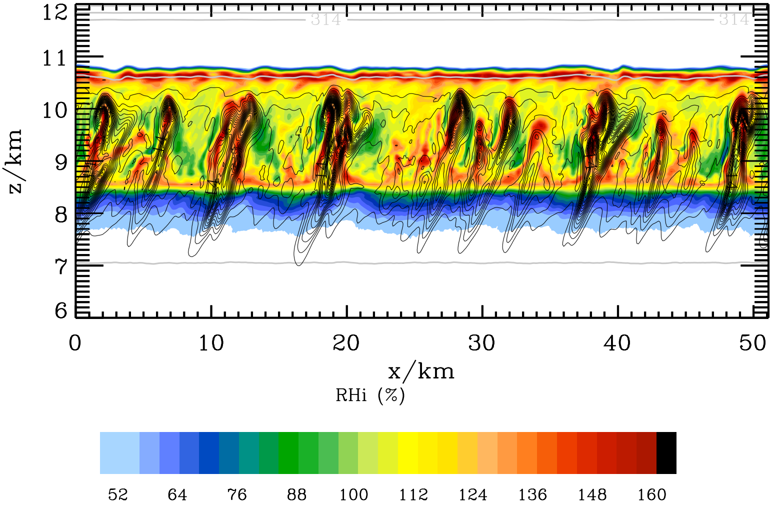


← about 100 km →

Sassen et al., 2007, JAS

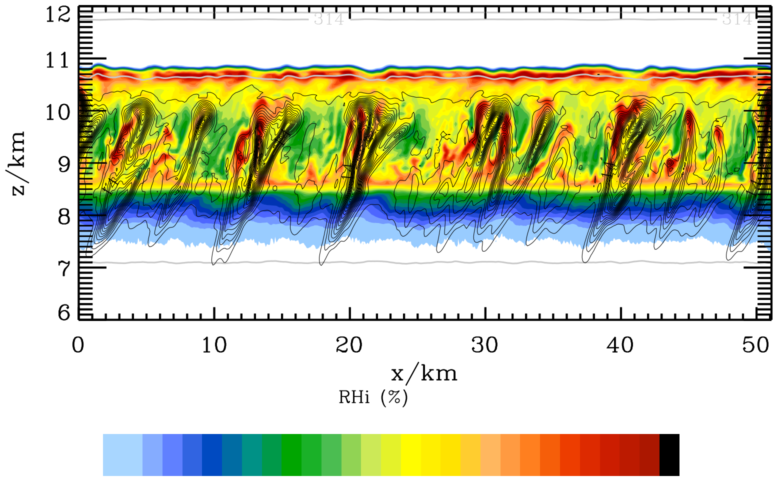
Case: potentially unstable θ profile (θ_{pu})

t= 195 min, black isolines: Ice water content, grey: Isentropes



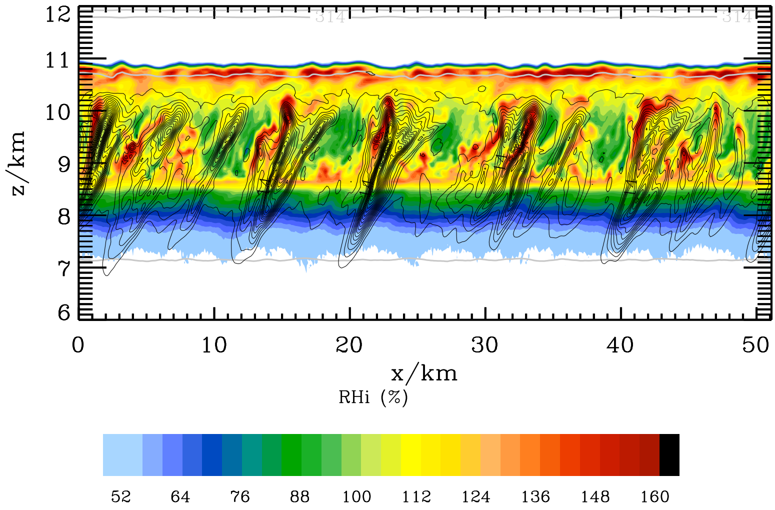
Case: potentially unstable θ profile (θ_{pu})

t= 210 min, black isolines: Ice water content, grey: Isentropes



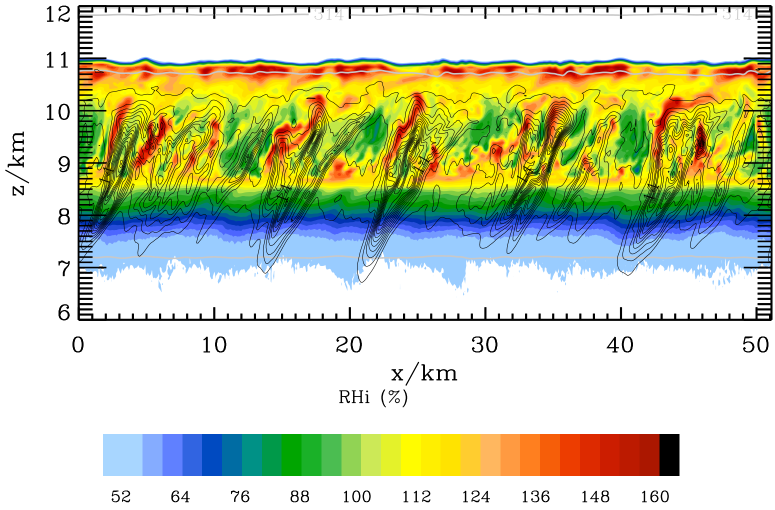
Case: potentially unstable θ profile (θ_{pu})

t= 225 min, black isolines: Ice water content, grey: Isentropes



Case: potentially unstable θ profile (θ_{pu})

t= 240 min, black isolines: Ice water content, grey: Isentropes



Stable vs. potentially unstable case

Stable case:

- Constant updraught dominant
- Layer cloud formed

Potentially unstable case:

- Small eddies trigger ice nucleation in small areas
- Latent heat release (crystal growth) leads to updraught
- Convective cells form and rise up to level of neutral buoyancy
- Outside the cells a layer cloud forms
- Patchy structure inside a cirrostratus (fall streaks)

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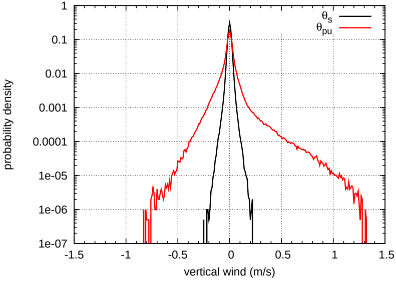
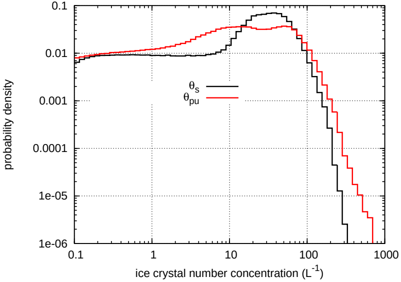
Impact of convection on dynamics and microphysics

Dynamics



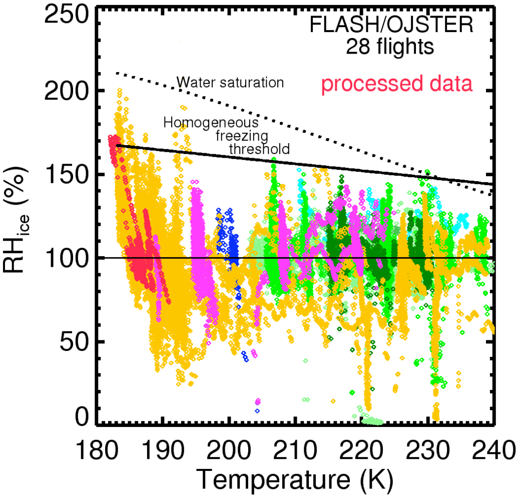
Microphysics



Potentially unstable vs. stable:

- More vigorous local dynamics triggered by convective cells: Higher vertical velocities
- Higher ice crystal number concentrations triggered by stronger updraughts

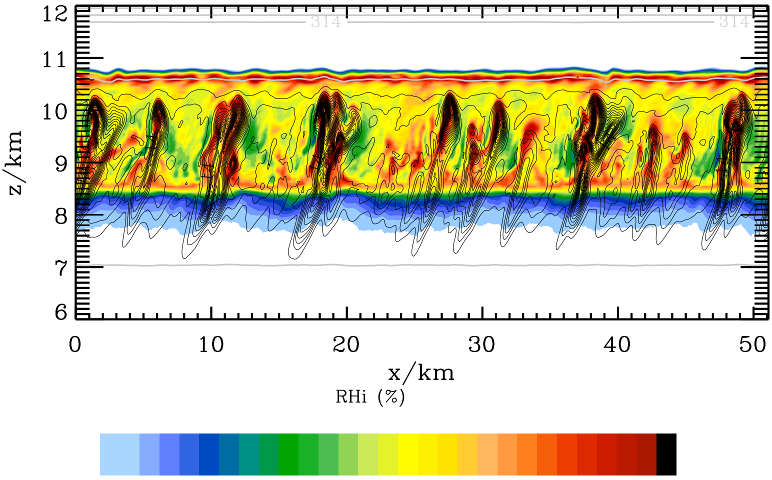
Ice supersaturation inside cirrus clouds



Can cirrus cloud dynamics explain in-cloud ice supersaturation?

Horizontal sections, profile θ_u

t=190 min, horizontal section at $z \sim 9800$ m



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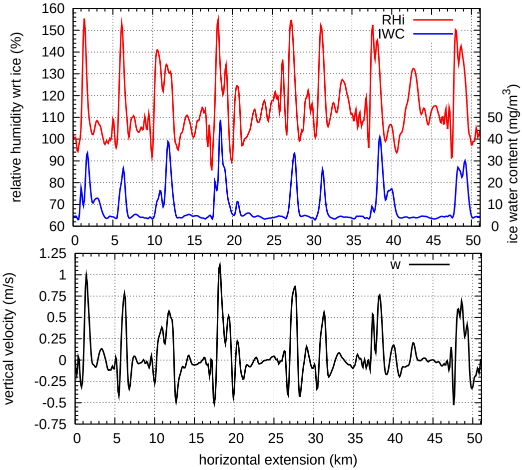
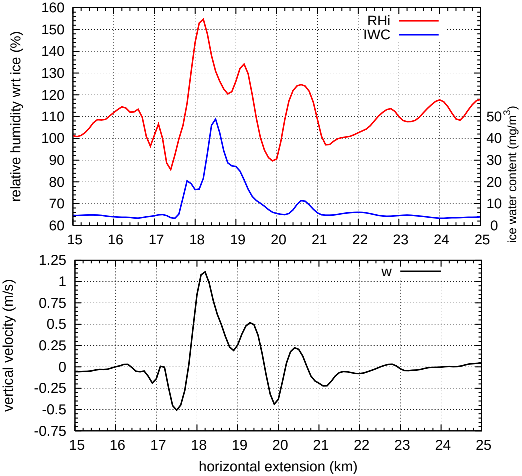
Horizontal sections at $z \sim 9800$ m ("aircraft")



In regions with high ice crystal mass/number concentration: occurrence of large ice supersaturation (RHi $\sim 150 - 155\%$)

Horizontal sections at $z \sim 9800$ m ("aircraft")

Zoom on $15 \leq x \leq 25$ km:



Ice supersaturation inside cirrus

- Convective cells form their own updraughts due to latent heat release
- Persistent vertical velocity is source for ice supersaturation
- At high vertical velocities cooling (increase of RHi) dominates over growth (decrease of RHi)

High ice supersaturation inside cirrus maintained via convection

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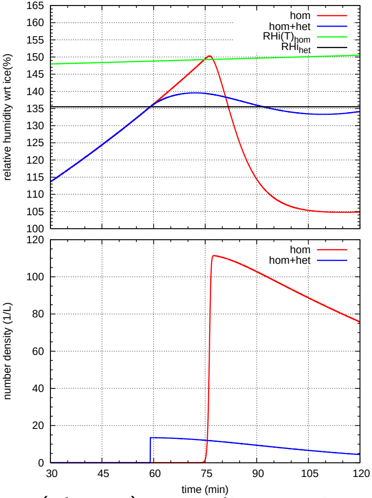
Ice supersaturation inside cirrus

- Convective cells form their own updraughts due to latent heat release
- Persistent vertical velocity is source for ice supersaturation
- At high vertical velocities cooling (increase of RHi) dominates over growth (decrease of RHi)

High ice supersaturation inside cirrus maintained via convection

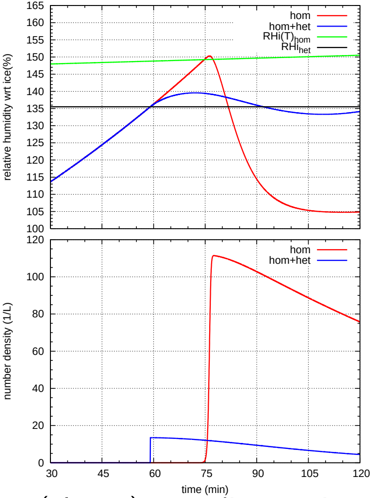
- Convective cells have a short lifetime
- Ice supersaturation inside cirrus is transient phenomenon

Impact of heterogeneously formed ice crystals

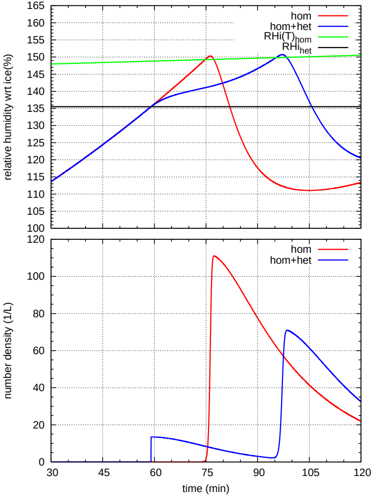


(almost) no sedimentation

Impact of heterogeneously formed ice crystals



(almost) no sedimentation



sedimentation

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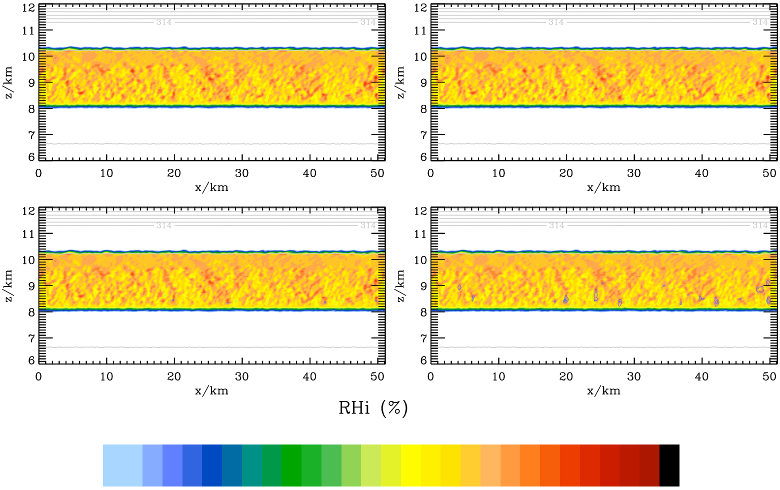
Initial conditions

- Homogeneous nucleation as usual
- Heterogeneous nucleation with fixed nucleation threshold ($RHi_{het} = 130\,\%$)
- Variation of heterogeneous IN: $N_{IN} = 5/10/50\,\mathrm{L}^{-1}$

HOM vs. HOM/HET ($5/10/50\,\mathrm{L}^{-1}$)

t=60 min



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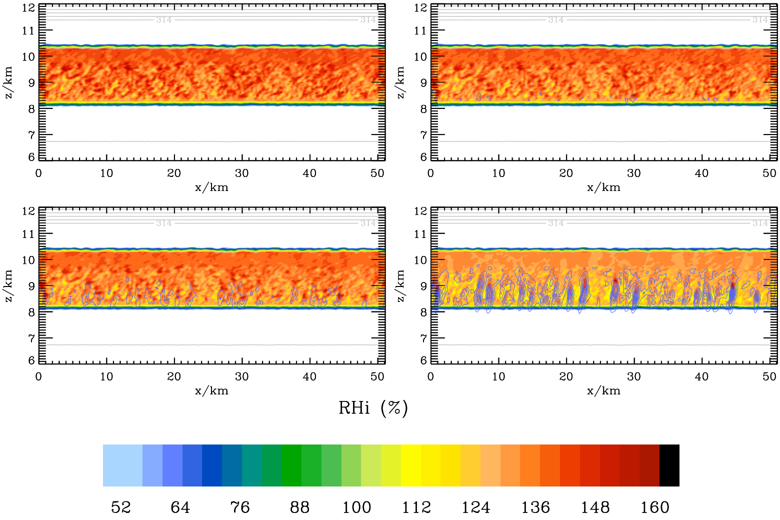
HOM vs. HOM/HET ($5/10/50\,\mathrm{L}^{-1}$)

t=90 min



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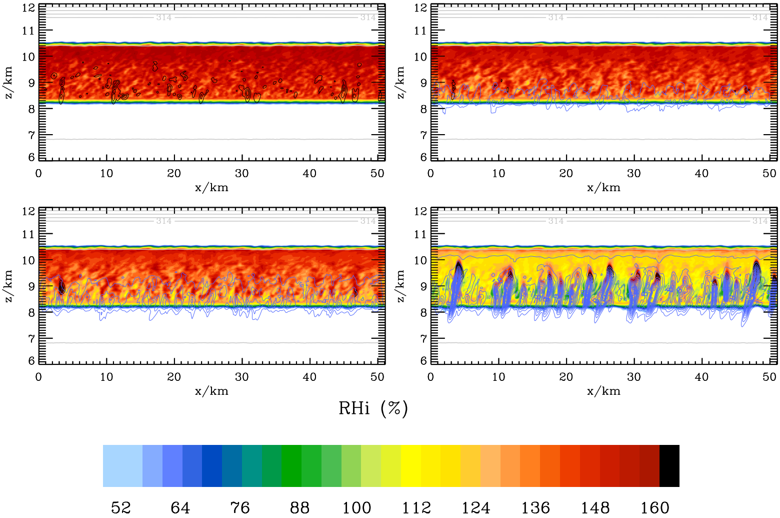
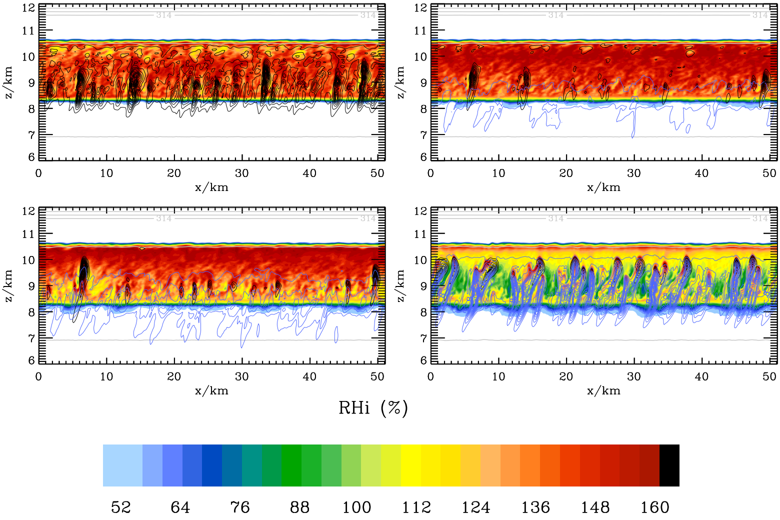
HOM vs. HOM/HET $(5/10/50\,\mathrm{L}^{-1})$

t=120 min



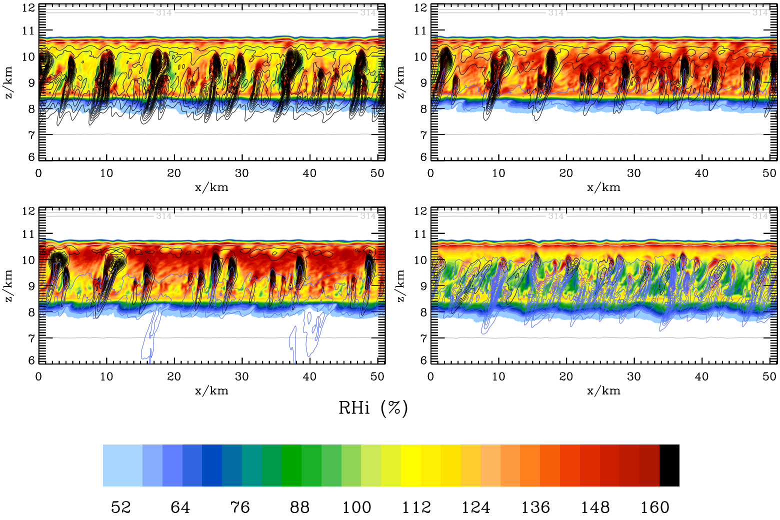
HOM vs. HOM/HET ($5/10/50\,\mathrm{L}^{-1}$)

t=150 min



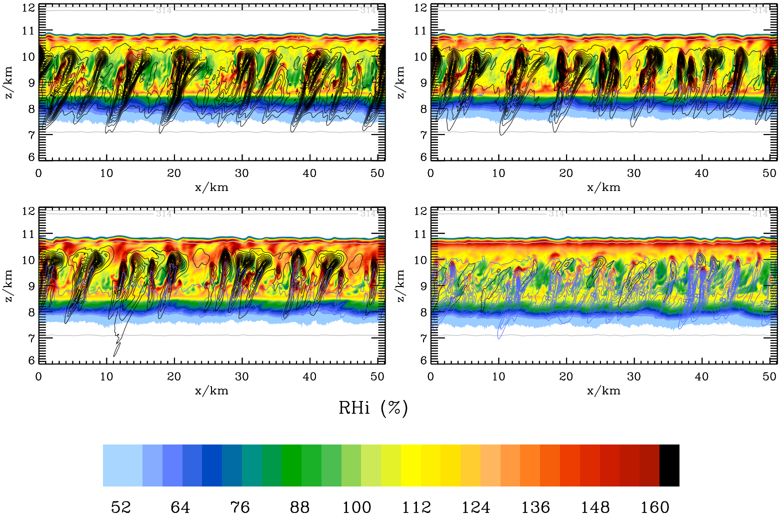
HOM vs. HOM/HET ($5/10/50\,\mathrm{L}^{-1}$)

t=180 min



HOM vs. HOM/HET $(5/10/50\,\mathrm{L}^{-1})$

t=210 min



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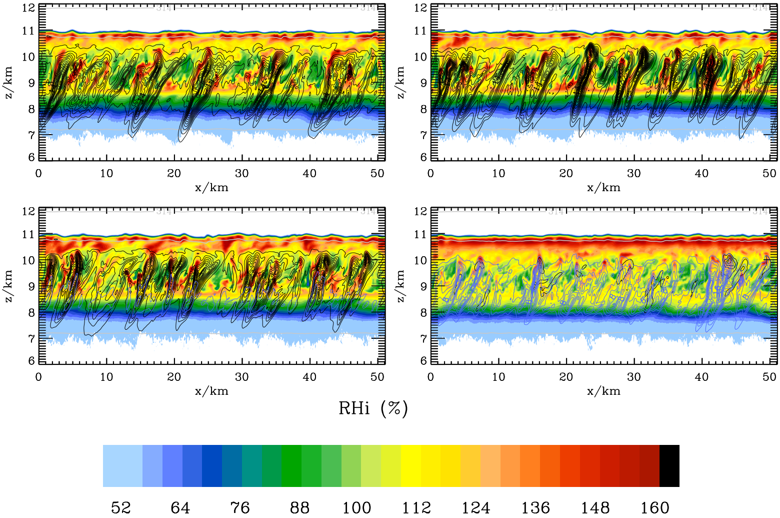
HOM vs. HOM/HET ($5/10/50\,\mathrm{L}^{-1}$)

t=240 min



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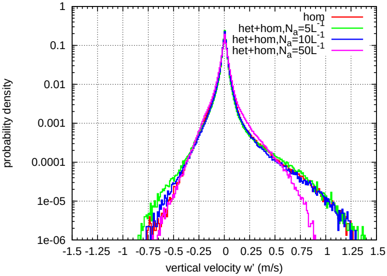
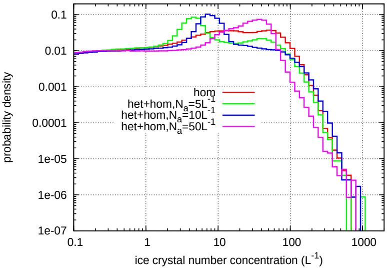
Impact of het. nucleation on dynamics and microphysics

Dynamics

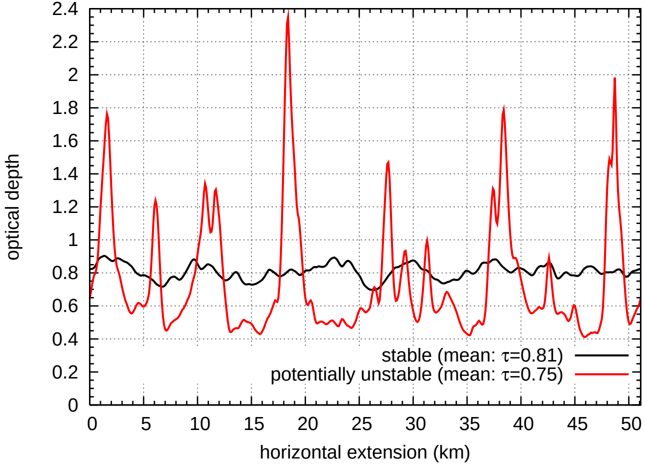


Microphysics



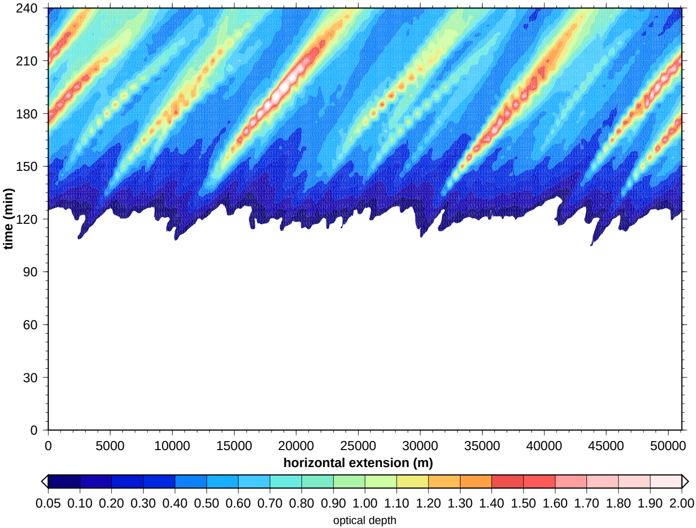
- Almost no change in dynamics (only for high aerosol loading)
- Shift at low ice crystal number concentrations
- Only small changes for high ice crystal number concentrations

Optical thickness – patchy cirrus cloud



Source for uncertainties in radiative forcing for cirrus clouds

Optical depth - homogeneous nucleation



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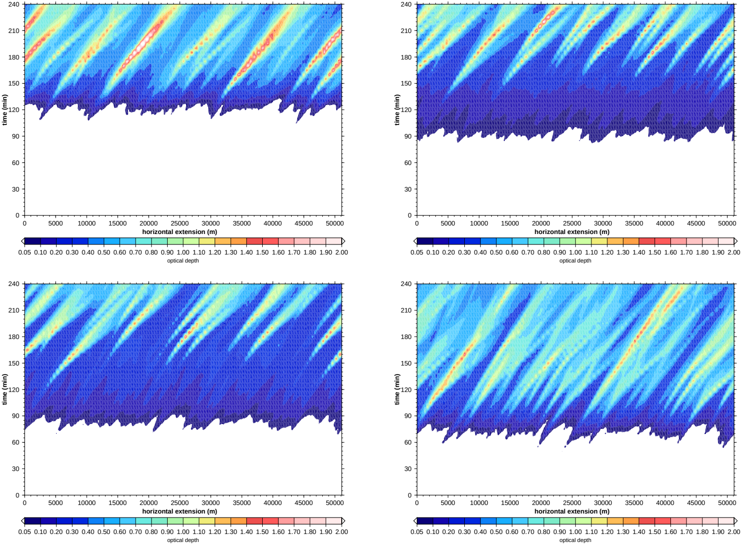
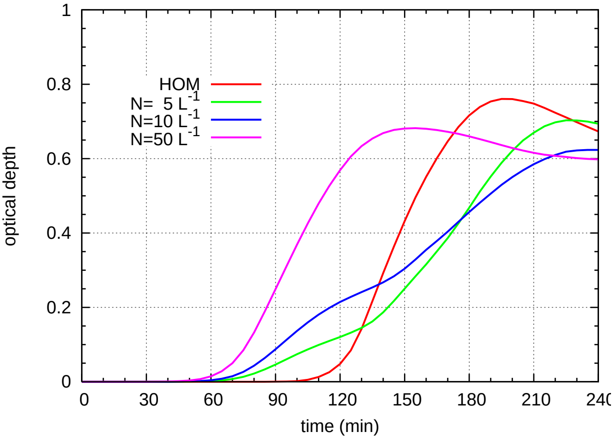
Optical depth - HOM vs. HOM/HET ($5/10/50\,\mathrm{L}^{-1}$)



Mean optical depth



Impact of het. nucleation on radiation

- Clouds appear earlier (het. nucleation at $RHi = 130\%$)
- Heterogeneous nucleation lead to weaker cells and less optical depth
- Many heterogeneous ice nuclei lead to a more uniform coverage of optical depth

Summary

- Cirrus cloud formation can feedback to mesoscale dynamics (analogon to classical cloud dynamics)
- Cirrus cloud convection leads to cell/fallstreak structure within a layer cirrus cloud
- Cirrus cloud convection can maintain ice supersaturation inside cirrus clouds
- Strong differences in dynamics and microphysics for stable/unstabe case
- Impact of heterogeneous nucleation on dynamics/microphysics/radiation

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Outlook

- Investigation of realistic cases of cirrus cloud convection
- Theoretical description of cirrus cloud convection
- Three dimensional simulations of cirrus cloud convection

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Thank you for your attention!

Model description

Basis: Multiscale non-hydrostatic, an-elastic model EULAG (Smolarkiewicz and Margolin, 1997)

Recently developed bulk ice microphysics scheme for the low temperature range ($T < -38^{\circ}$C) including:

- Nucleation
- Deposition growth/evaporation
- Sedimentation

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

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

Spichtinger & Gierens, 2009, Part 1a

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 ($\alpha = 0.5$):

$$\frac{dm}{dt} \approx a \cdot m^b \cdot \left(1 - \exp\left(-(m/m_0)^\gamma\right)\right) \tag{4}$$

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:

$$\frac{dq_c}{dt} \approx a \cdot \mu_b[m] \cdot \left(1 - \exp\left(-(\overline{m}/(m_0 \cdot \chi))^\gamma\right)\right) \tag{5}$$

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, $v_{t,m}, v_{t,n}$):

$$q_c \cdot v_{t,m} = \int_0^\infty f(m)\ m\ v_t(m)\ dm \qquad (6)$$

$$N_c \cdot v_{t,n} = \int_0^\infty f(m)\ v_t(m)\ dm \qquad (7)$$

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

$$\frac{v_t}{v_0} = \alpha \cdot \left(\frac{m}{m_0}\right)^\beta, \quad v_0, m_0 \text{ unit velocity/mass} \qquad (8)$$

and derive the following formulas for the terminal velocities:

$$v_{t,n} = v_0 \cdot \frac{\alpha}{m_0^\beta} \cdot \frac{\mu_\beta[m]}{\mu_0[m]} \qquad (9)$$

$$v_{t,m} = v_0 \cdot \frac{\alpha}{m_0^\beta} \cdot \frac{\mu_{\beta+1}[m]}{\mu_1[m]} \qquad (10)$$

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