Impact of dynamics on cirrus clouds

Peter Spichtinger[1], Fabian Fusina[2], and Andreas Dörnbrack[3]

(1) Institute for Atmospheric Physics, Johannes Gutenberg University, Mainz, Germany
(2) Institute for Atmosphic and Climate Science, ETH Zurich, Zurich, Switzerland
(3) Institute of Atmospheric Physics, German Aerospace Centre (DLR), Wessling, Germany

June 9, 2011

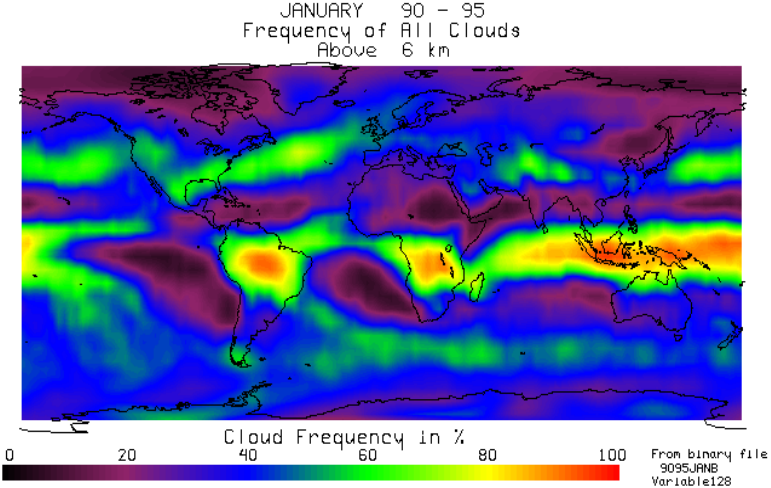
Definition/Motivation

Cirrus cloud: Cloud in the upper troposphere/lowermost stratosphere (temperature $T < 235\,\mathrm{K}$) consisting purely of ice crystals, which have been formed *in situ*

Why should we care about cirrus clouds?

- Cirrus clouds cover about 20-30% of Earth's surface
- Cirrus clouds are important modulators of the radiative budget of the Atmosphere-Earth system

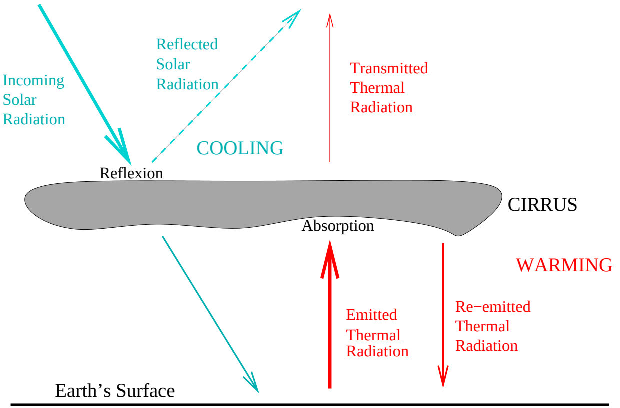
Cirrus cloud cover



Wylie & Menzel, 1999

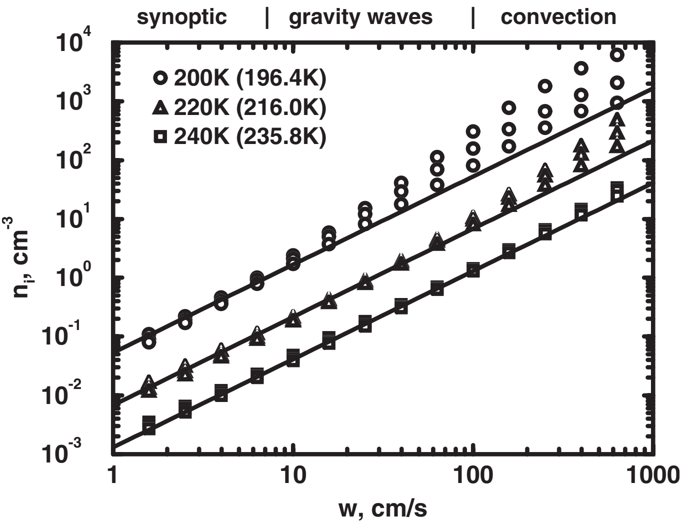
Radiative impact of cirrus clouds

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



A net warming is assumed but not confirmed

Impact of (constant) updrafts on cirrus cloud formation



Kärcher & Lohmann, 2002, JGR

Open questions

- What is the impact of transient changes in the dynamics on cirrus cloud evolution?
- How to investigate the impact of changes in the large-scale dynamics on processes on smaller scales?

Outline:

- New method for time-dependent ambient states in anelastic equations (in the EULAG model)
- Investigation of orographic waves with changing wind on
  1. resolved dynamics
  2. cirrus cloud properties

Derivation of anelastic equations I

Start: Horizontally homogeneous hydrostatic background state of the Boussinesq expansion around a constant stability profile satisfying

$$\partial p_b/\partial z = -g\,\rho_b \tag{1}$$

and via linearising the pressure gradient we end with the anelastic equations:

$$\nabla\cdot(\rho_b\,\mathbf{u}) = 0 \tag{2}$$

$$\frac{d\mathbf{u}}{dt} = -\nabla\left(\frac{p - p_b}{\rho_b}\right) + g\frac{\Theta - \Theta_b}{\Theta_b}\,\mathbf{k} - 2\,\boldsymbol{\Omega}\times\mathbf{u} \tag{3}$$

$$\frac{d\Theta}{dt} = 0 \tag{4}$$

with $\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla$.

Derivation of anelastic equations II

In EULAG we solve the entropy equation in the form

$$\frac{d\Theta'}{dt} = -\mathbf{u} \cdot \nabla\Theta_e \tag{5}$$

for a given environmental state Θ_e, where $\Theta' = \Theta - \Theta_e$ and $\Theta_e(\mathbf{x})$ is a given environmental (or ambient) state suitable for the considered problem.

In a next step, we derive the perturbation form of the equations by subtracting a known environmental (or ambient) state $\mathbf{u}_e$ from the momentum balance.

Derivation of anelastic equations III

It is assumed that the environmental variables $\mathbf{u}_e$ satisfies the balance equations as follows:

$$\nabla \cdot (\rho_b \mathbf{u}_e) = 0 \tag{6}$$

$$\frac{d_e \mathbf{u}_e}{dt} = -\nabla \left(\frac{p_e - p_b}{\rho_b} \right) + g \frac{\Theta_e - \Theta_b}{\Theta_b} \mathbf{k} - 2\,\mathbf{\Omega} \times \mathbf{u}_e, \tag{7}$$

with $\frac{d_e}{dt} = \frac{\partial}{\partial t} + \mathbf{u}_e \cdot \nabla$.
Usually, a stable situation is assumed, i.e.

$$0 = -\nabla \left(\frac{p_e - p_b}{\rho_b} \right) + g \frac{\Theta_e - \Theta_b}{\Theta_b} \mathbf{k} - 2\,\mathbf{\Omega} \times \mathbf{u}_e \tag{8}$$

Derivation of anelastic equations IV

We end with the following equations:

$$\frac{d\mathbf{u}}{dt} = -\nabla\left(\frac{p'}{\rho_b}\right) + g\frac{\Theta'}{\Theta_b}\mathbf{k} - 2\,\mathbf{\Omega}\times\mathbf{u}' + \frac{d_e\mathbf{u}_e}{dt} \tag{9}$$

$$\frac{d\Theta'}{dt} = -\mathbf{u}\cdot\nabla\Theta_e, \tag{10}$$

where the primed quantities are determined as $\psi' = \psi - \psi_e$ with $\psi = u, v, w, \Theta, p$.

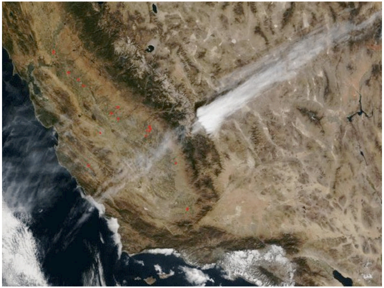
Note the occurrence of the term $\frac{d_e\mathbf{u}_e}{dt}$ as a forcing term on the right side of the momentum equation.

Model setup

1. 2D Cirrus cloud model:
    - Anelastic/non-hydrostatic model EULAG (Prusa et al., 2008)
    - Consistent two-moment bulk microphysics for cold temperature regime ($T < 235\,\mathrm{K}$; Spichtinger & Gierens, 2009):
        - Nucleation (homogeneous/heterogeneous)
        - Diffusional growth/evaporation
        - Sedimentation
        - Arbitrary many classes of ice, discriminated by formation
        - 1-1-relationship between background aerosol and ice crystals

    here: pure homogeneous nucleation
2. Transient ambient states (as derived above) included

Orographic cirrus clouds

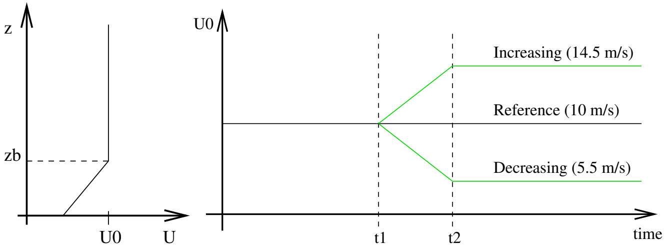


Setup for orographic waves

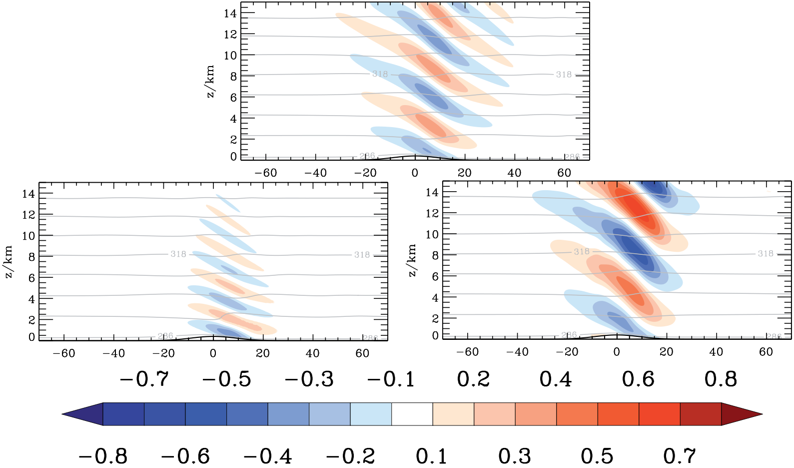
- 2D domain: 307 km$\times$ 20 km (resolution: dx=200 m, dz=50 m)
- Sponge layer at $z = 15\,\text{km}$ for absorbing gravity waves in order to avoid reflections
- Simulation time: $t_{tot} = 480$ min, time step: $dt = 2\ s$
- Potential temperature profile with constant Brunt-Vaisala frequency $N = 0.0115\,\mathrm{s}^{-1}$
- Gaussian-shaped mountain with height 400 m and halfwidth $b = 12.5\,\text{km}$
- Ice supersaturated layer between 8 and 11 km.

Setup for orographic waves

- non-transient simulations: $u_0 = 5.5/10/14.5\,\mathrm{m\,s^{-1}}$
- transient simulations: horizontal wind changes linearly within 60 min
  (a) increasing wind from $u_0 = 10\,\mathrm{m\,s^{-1}}$ to $u_0 = 14.5\,\mathrm{m\,s^{-1}}$
  (b) decreasing wind from $u_0 = 10\,\mathrm{m\,s^{-1}}$ to $u_0 = 5.5\,\mathrm{m\,s^{-1}}$

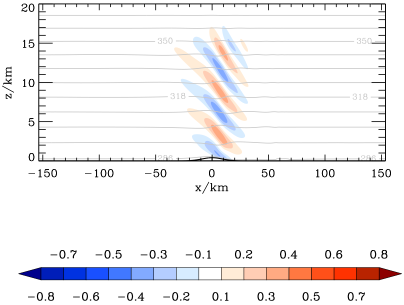


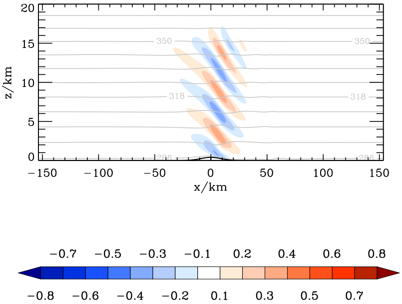
Reference cases



Transient cases

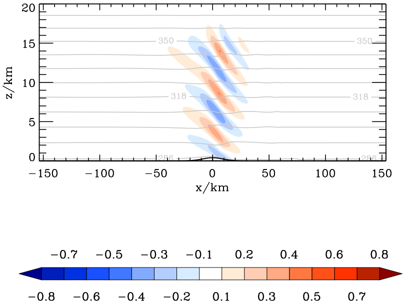
t=180 min

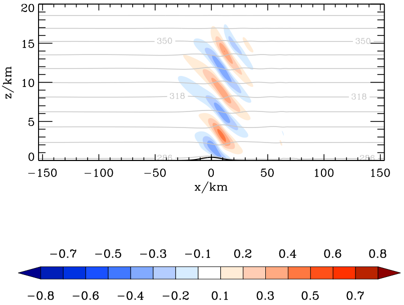




Transient cases

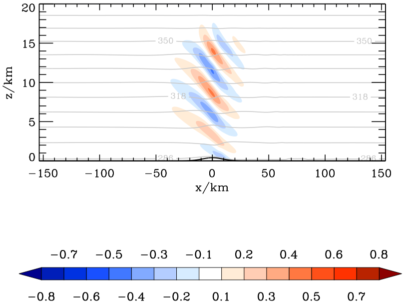
t=200 min

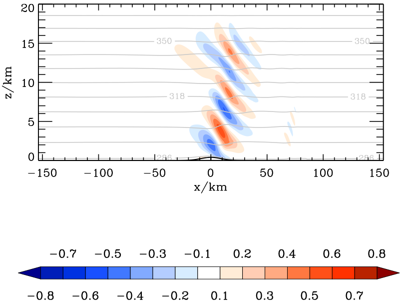




Transient cases

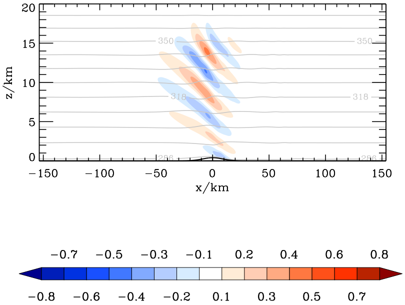
t=220 min

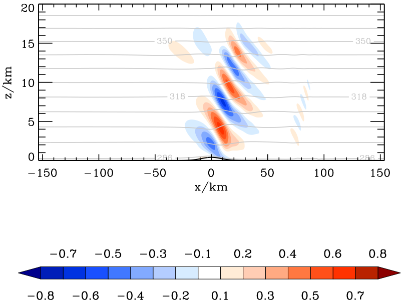




Transient cases

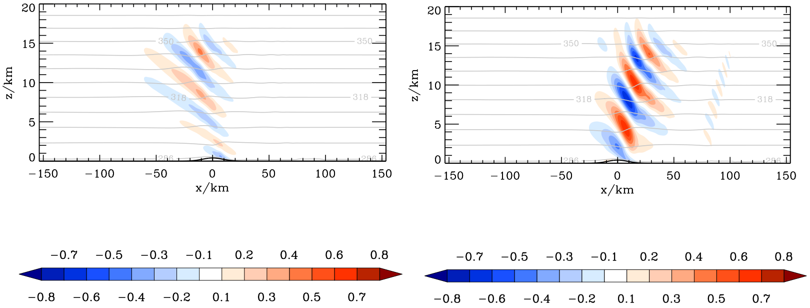
t=240 min





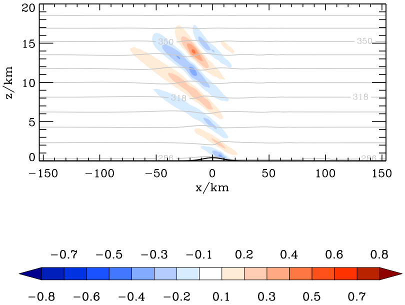
Transient cases

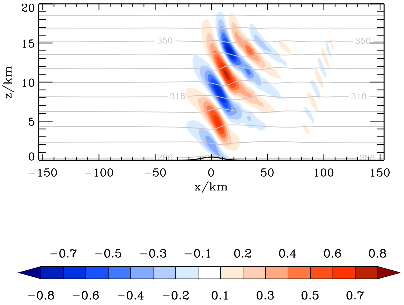
t=260 min



Transient cases

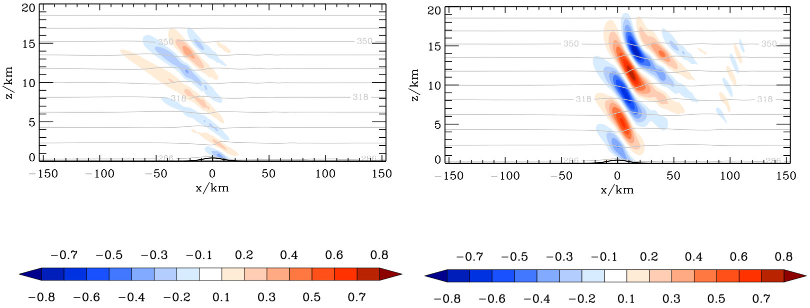
t=280 min





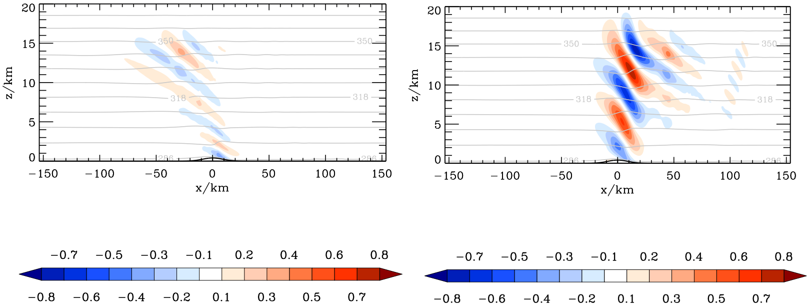
Transient cases

t=300 min



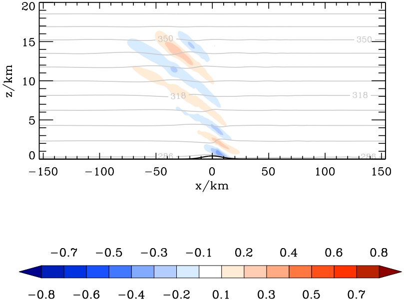
Transient cases

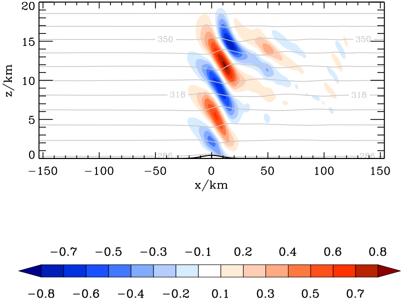
t=320 min



Transient cases

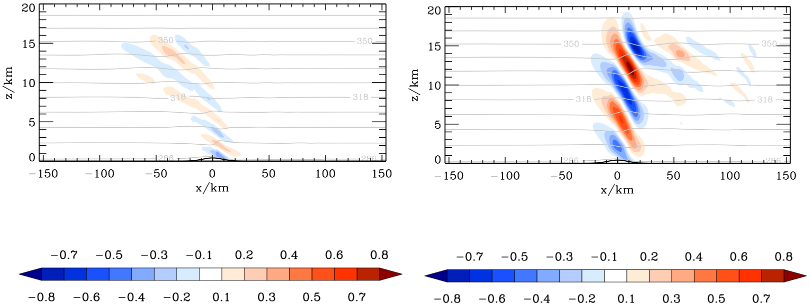
t=340 min





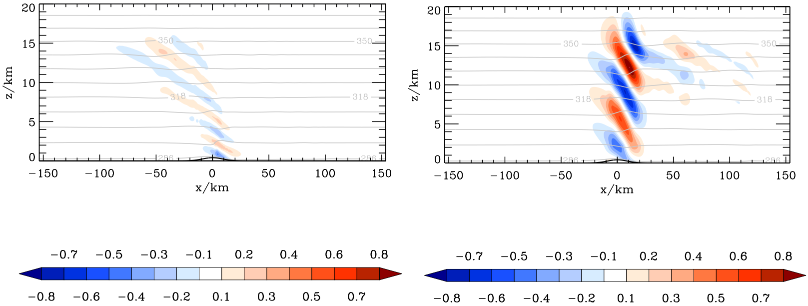
Transient cases

t=360 min



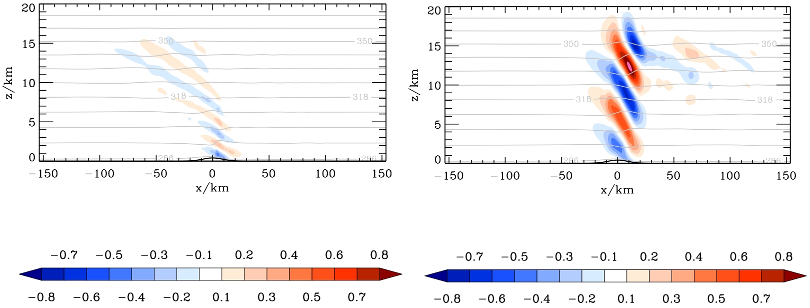
Transient cases

t=380 min



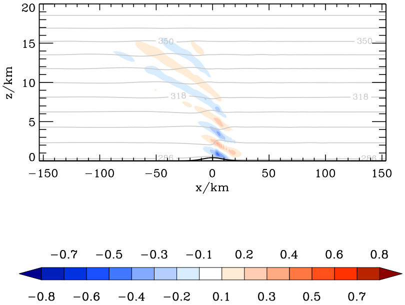
Transient cases

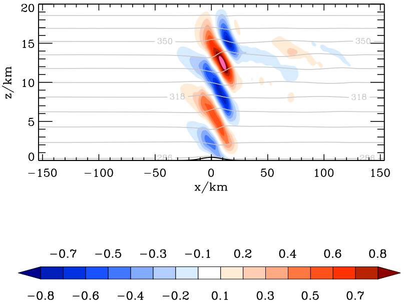
t=400 min



Transient cases

t=420 min

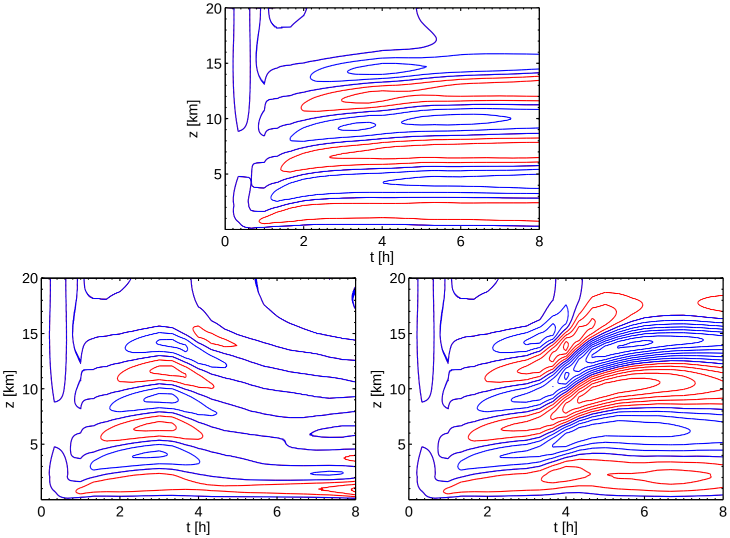




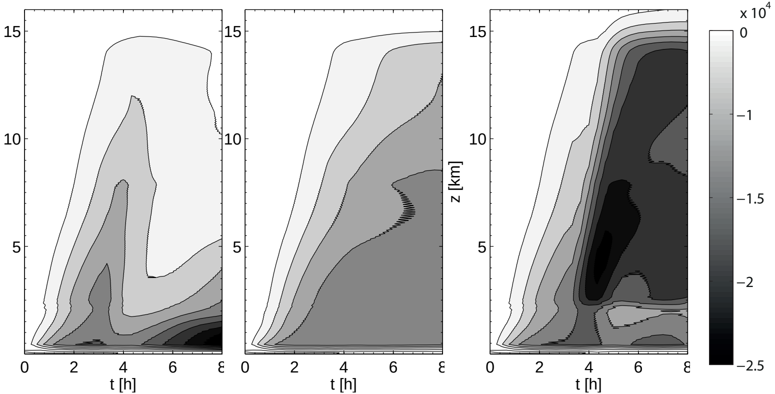
Travelling wave packets

- Reference case: Stationary, hydrostatic wave with intrinsic horizontal phase velocity of $c_I = -u_0$, i.e. total horizontal phase velocity $c_h = c_I + u_0 = 0$
- Transient cases:
  - Wave packets emitted at an earlier time step have intrinsic phase velocity $c_I \neq -u_0$, compared to actual background velocity u_0.
  - Wave packets are not stationary anymore, because $c_h \neq 0$, travelling upstream (decreasing case) or downstream (increasing case)
  - Interference of wave packets possible

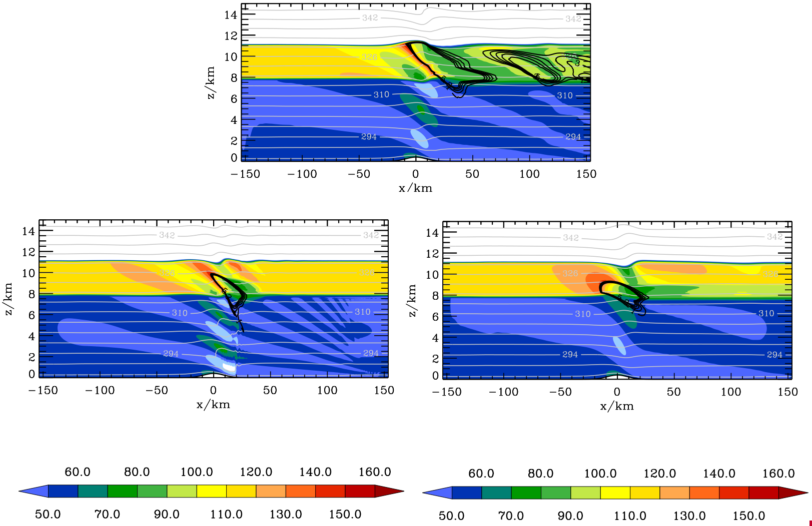
Vertical section of vertical velocity/time evolution



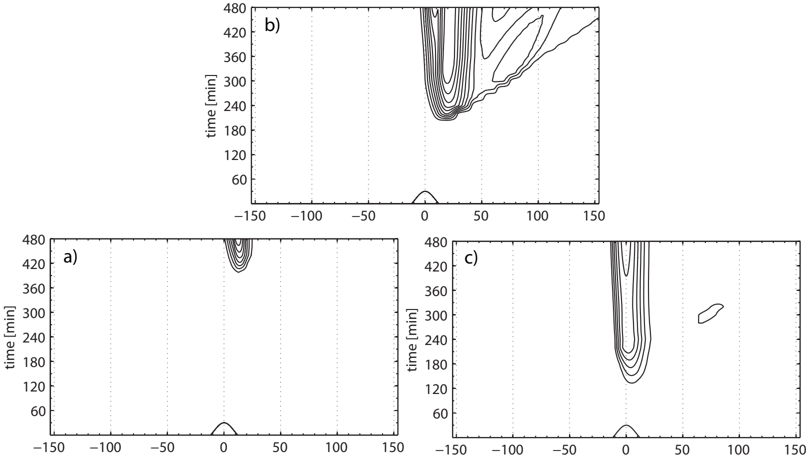
Momentum flux/time evolution



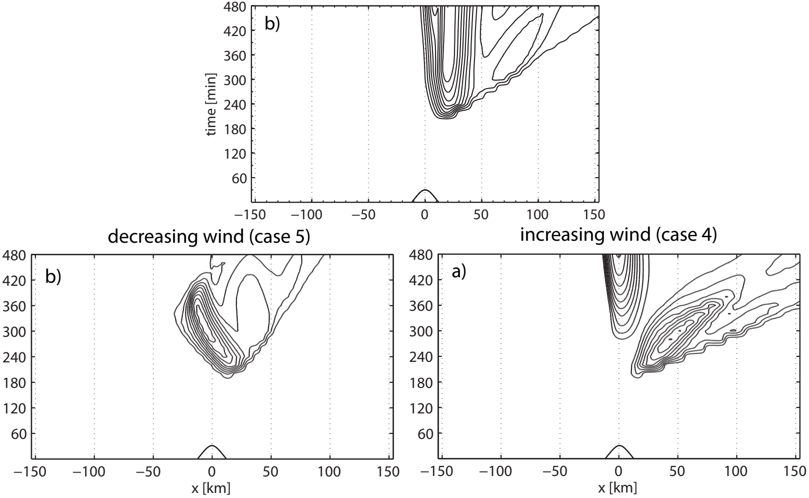
Cirrus clouds



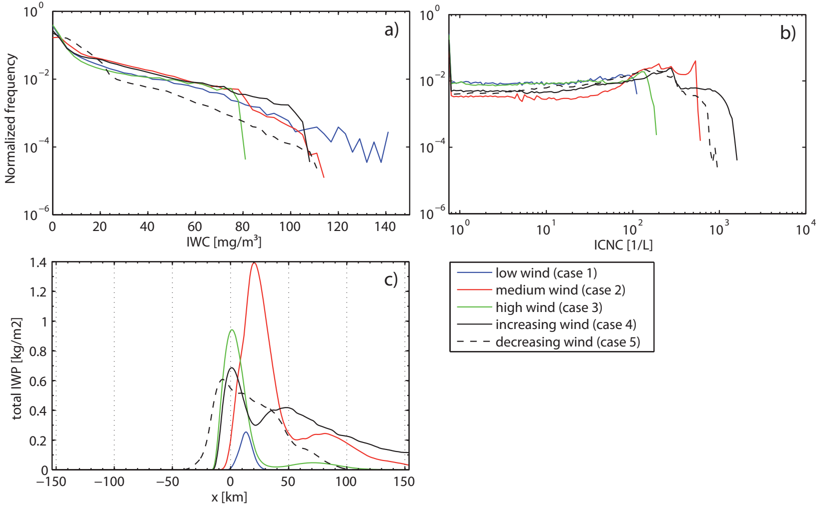
Ice water path/reference cases



Ice water path/transient cases



Cloud properties



Summary/Dynamics

- New scheme for handling time-dependent large-scale flows and their impact on smaller scales.
- First application for time-dependent stratified flows over mountains
- Time-dependent flows leads to strong changes in the gravity wave patterns (vertical velocity, vertical position of updraught/downdraught regions)
- Interaction of wave packets excited under different large-scale flows leads to non-linear effects
  - Vertical velocities after transition are smaller/larger than in the comparable steady state simulations
  - momentum flux shows maxima/minima during transition

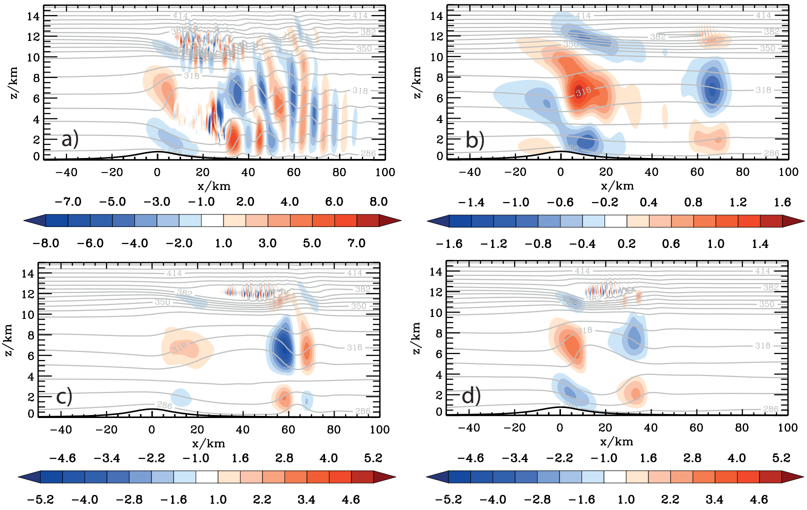
Summary/Impact on cirrus clouds

- Horizontal displacement of clouds due to horizontally shifted wave packets
- Pronounced changes in ice water path
- Small changes in ice crystal number concentrations

Outlook

- Other flow regimes for flow over mountain
- Change in potential temperature
- Three-dimensional simulations
- Realistic large-scale flow from analyses/other model output
- Comparisons with measurements (?)

Outlook


a)
b)
c)
d)
z/km
x/km
−7.0 −5.0 −3.0 −1.0 2.0 4.0 6.0 8.0
−8.0 −6.0 −4.0 −2.0 1.0 3.0 5.0 7.0
−1.4 −1.0 −0.6 −0.2 0.4 0.8 1.2 1.6
−1.6 −1.2 −0.8 −0.4 0.2 0.6 1.0 1.4
−4.6 −3.4 −2.2 −1.0 1.6 2.8 4.0 5.2
−5.2 −4.0 −2.8 −1.6 1.0 2.2 3.4 4.6

Outlook

Thank you for your attention!