Impact of heterogeneous nucleation on cirrus clouds

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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 clouds are closely related to the tropopause and might influence its structure (see Philipp's talk)

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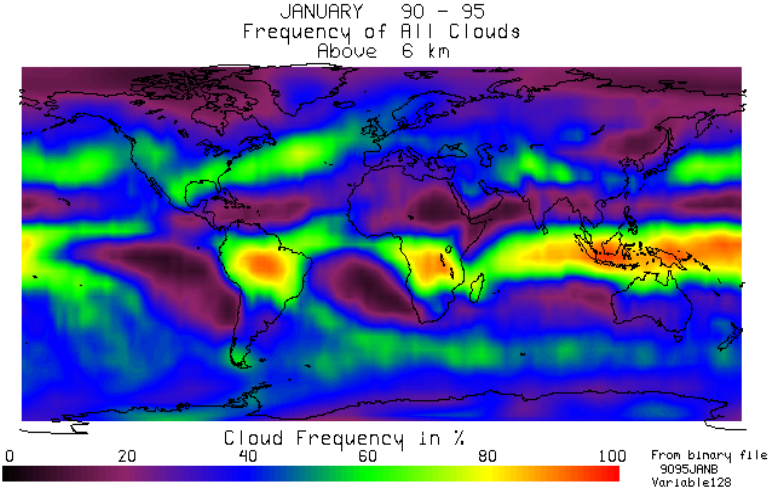
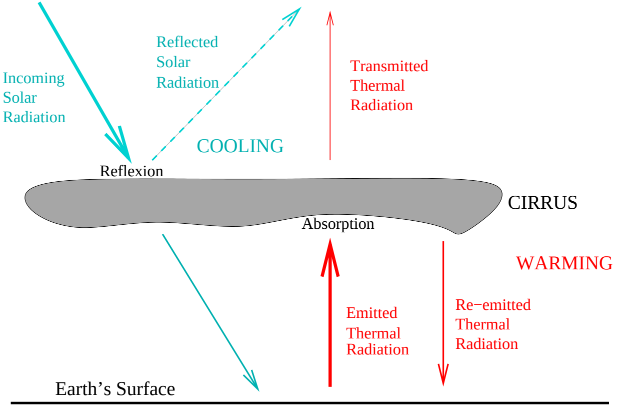
Cirrus cloud cover



Wylie & Menzel, 1999

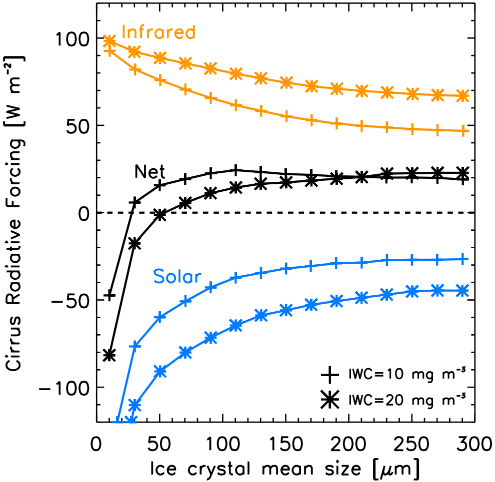
Radiative impact of cirrus clouds

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



A net warming is assumed but not confirmed

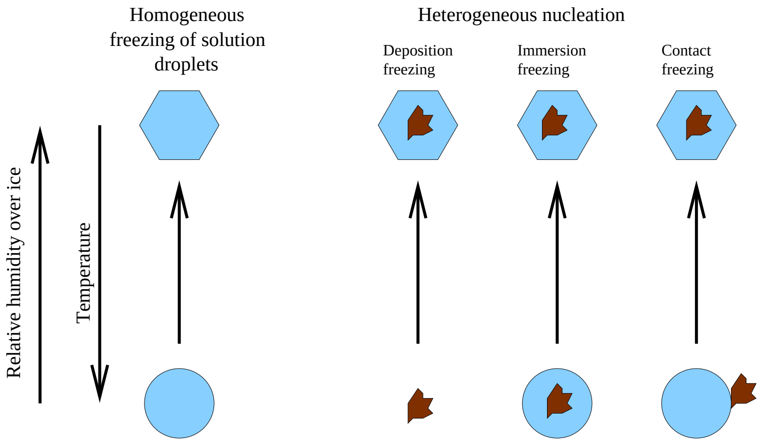
Warming and Cooling is possible



mean size $\sim$ mean mass $=$ IWC/ice crystal number density

Zhang et al., 1999

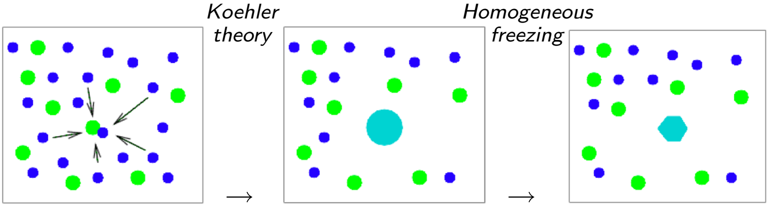
Ice formation mechanisms at cold temperatures ($T < 235$ K)

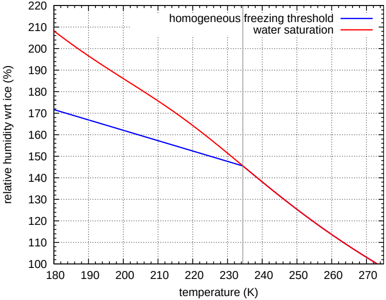


Homogeneous freezing is dominant in terms of number density and depends on local dynamics

Freezing of solution droplets

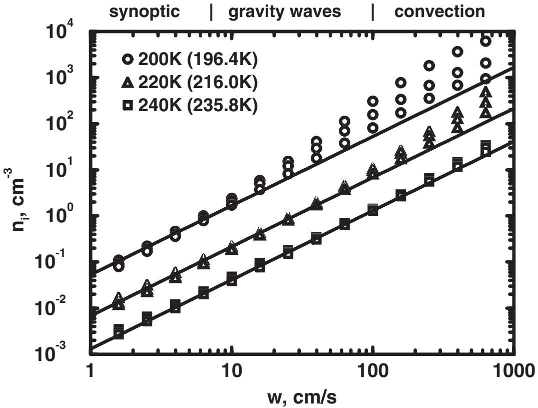
Aqueous solution droplets from a background aerosol (e.g. H_2SO_4)





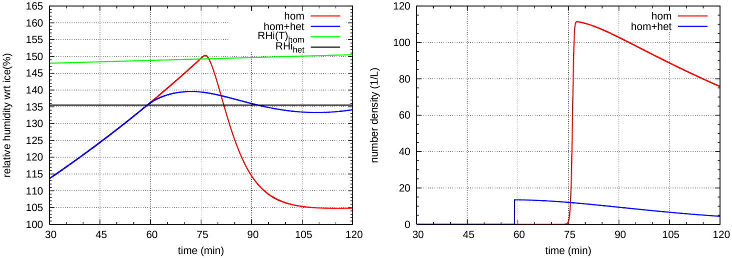
Homogeneous vs. heterogeneous nucleation

- Usually much more crystals form via homogeneous nucleation
- Heterogeneous IN are not very numerous in the tropopause region (usually $N_{IN} \leq 10\,\mathrm{L}^{-1}$)



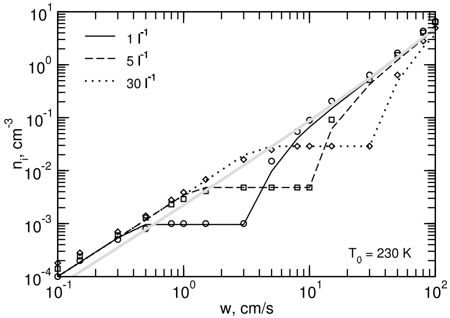
Kärcher & Lohmann, 2002, JGR

Impact of heterogeneously formed ice crystals - part I

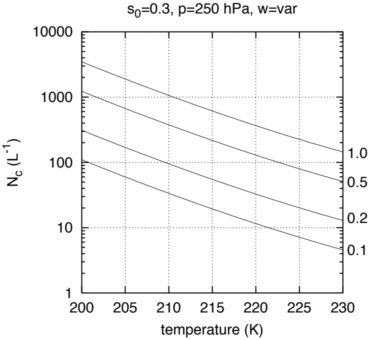


- Heterogeneous nucleation threshold $RHi_{het} = 135.5\,\%$, $N_{IN} = 14\,\mathrm{L}^{-1}$
- Ice crystals stay in box
- Growth by heterogeneously formed ice crystals strong enough to reduce ice supersaturation
- Homogeneous nucleation is suppressed

'negative Twomey effect'



Kärcher et al., 2006

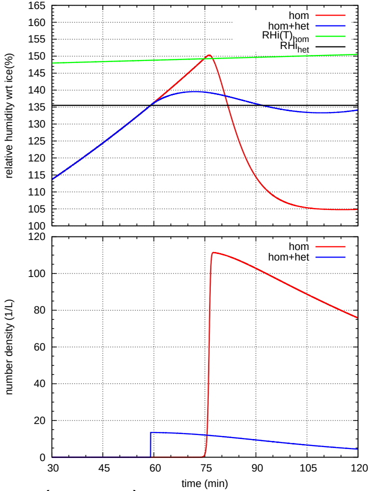


Gierens, 2003

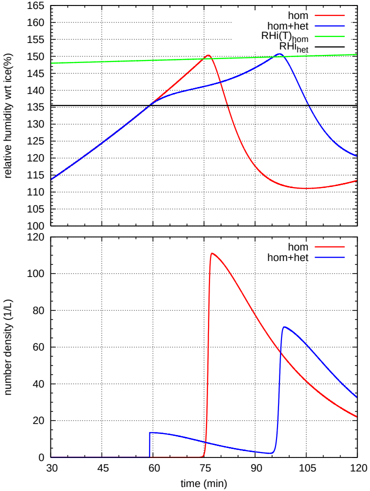
Suppression of homogeneous freezing by previously heterogeneously formed ice crystals

Impact of heterogeneously formed ice crystals - part II

(Implicit) assumption: No sedimentation, but not always realistic



(almost) no sedimentation



sedimentation

Reinvestigating competition of formation mechamisms

'Textbook knowledge':

- Homogeneous nucleation is dominant at low temperatures in terms of ice crystal number concentrations
- Heterogeneous nucleation could modify homogeneous nucleation events at high temperature and/or low vertical velocities
- For high vertical velocities no reasonable impact of heterogeneous nucleation

... is this really true?

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Reinvestigation of these statements via 2D high resolution model simulations, in situations dominated by dynamics (waves) and offline radiation calculations

Basic question for further investigation

Are we able to represent realistic measurements in a wave case with EULAG including our bulk ice microphysics?

If so, then we can use idealized simulations in order to explore the parameter space.

INCA case

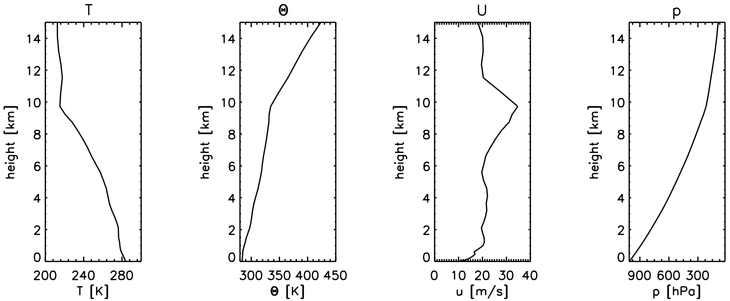
- Extensive flight campaign over midlatitudes of South America in April 2000
- Instrumentation for measuring ice clouds (particles and environmental fields)
- One case was dedicated to wave clouds (Andes)

EULAG for cirrus clouds

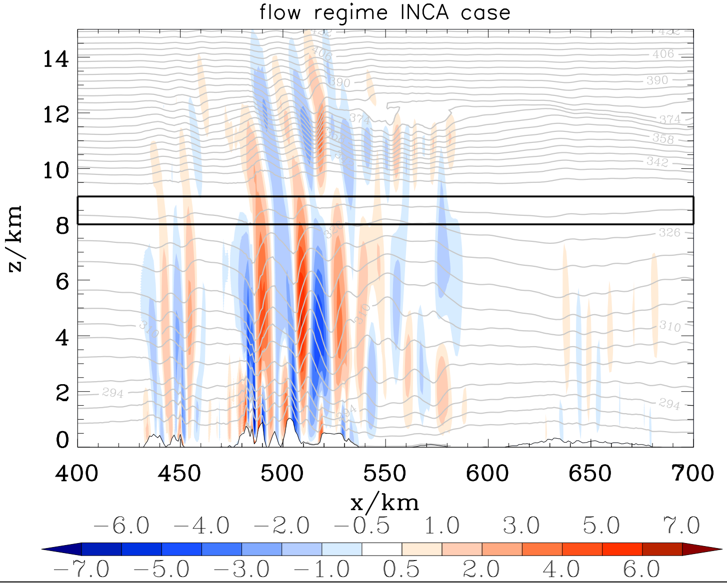
- An-elastic non-hydrostatic model EULAG (Prusa et al., 2008)
- Double moment ice microphysics scheme (Spichtinger & Gierens, 2009), including the processes:
  - Ice nucleation (homogeneous/heterogeneous)
  - Depositional growth/evaporation of ice crystals
  - Sedimentation of ice crystals
- Horizontal resolution: $\Delta x = 250\,\mathrm{m}$
- Vertical resolution: $\Delta z = 50\,\mathrm{m}$

Setup for simulations

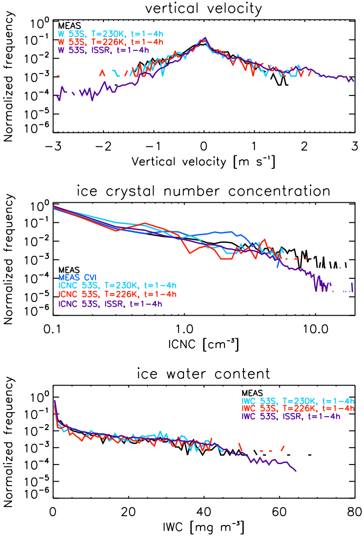
- 2D section (mostly Westerly winds) through the Andes
- Vertical profiles (temperature/pressure/wind) from ECMWF analyses
- Humidity profiles estimated to be close to in situ measurements



Vertical velocity (m/s) and potential temperature (K)



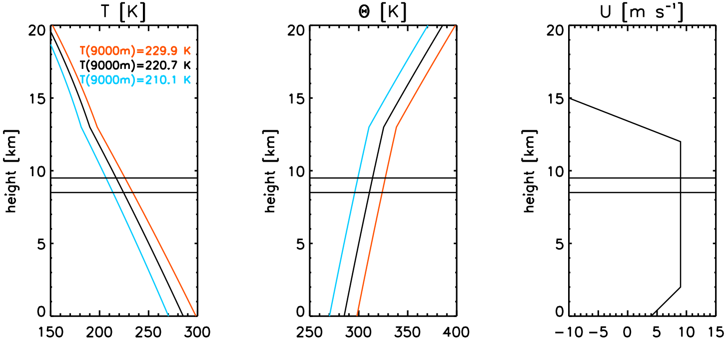
Measurements vs. simulations



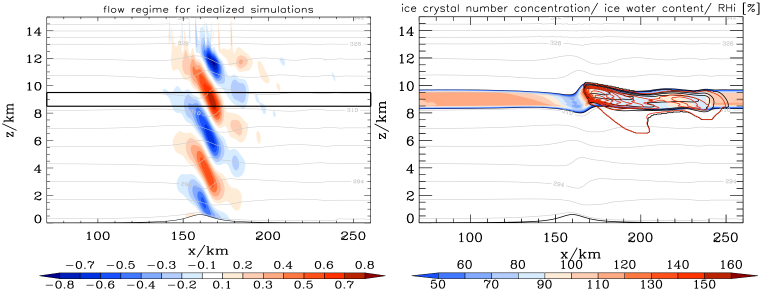
Joos et al., 2009

Idealized setup

- Bell shaped mountain $H(x) = \frac{h_0}{1+\left(\frac{x}{a}\right)^2}$, $h_0 = 600\,\mathrm{m}$, $a = 10\,\mathrm{km}$
- Supersaturation layer at $8.5 \leq z \leq 9.5\,\mathrm{km}$, $RHi = 120\%$
- Vertical profiles with constant Brunt-Vaisala frequency $N = 0.009\,\mathrm{s}^{-1}$
- Shift in profiles for warmer/colder temperatures by $\pm 10\,\mathrm{K}$



Reference case - flow regime and microphysics



- Quasi-hydrostatic wave, some small reflection at tropopause
- Vertical velocities in the range $-0.75 \leq w \leq 0.75\,\mathrm{m\,s^{-1}}$
- Now runs with no homogeneous and prescribed heterogeneous IN concentrations ($5/10/50\,\mathrm{L^{-1}}$, nucleation threshold $RHi_{het} = 130\%$)

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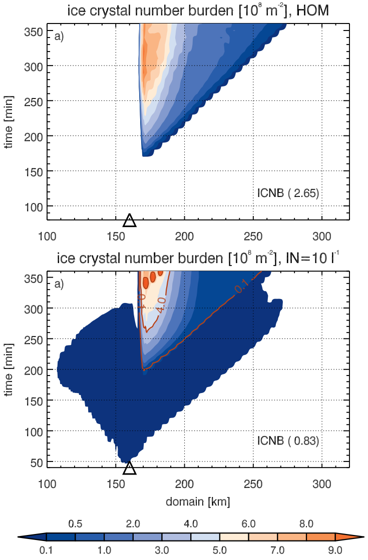
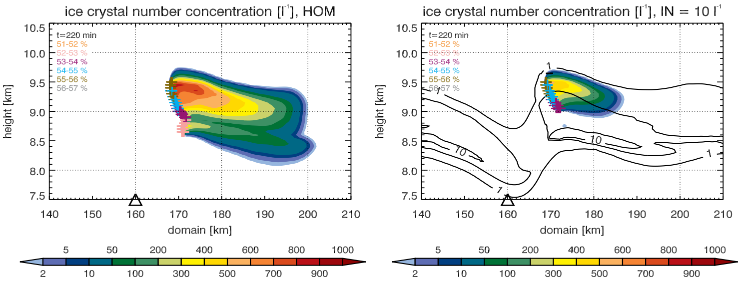
Time evolution - homogeneous vs. 10 IN



Zoom into microphysics



- In homogeneous case nucleation over broader vertical range
- Heterogeneous nucleation leads to suppression of homogeneous nucleation

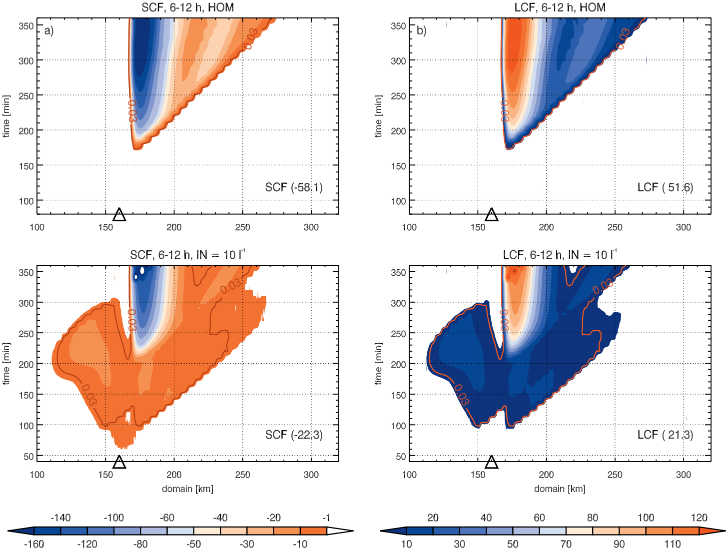
Radiation calculations

- Offline calculation for the output using a radiation transfer model (Liou and Fu, 1993)
- 6 Bands in solar spectrum, 12 bands in IR spectrum
- Radiation conditions of equinox (i.e. 20th of March)
- Earth's albedo $= 0.3$
- Different local time ranges: $6 - 12$LT and $12 - 18$LT
- Output: optical depth (for $0.2 \leq \lambda \leq 2\,\mu$m), short wave and longwave radiative fluxes at top of atmosphere (TOA)
- Investigation in terms of cloud radiative forcing:

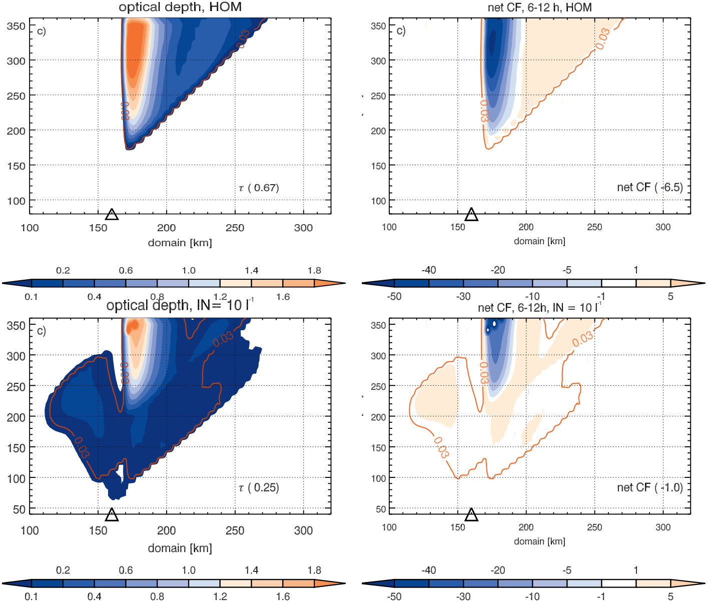
$$CF_{range} = F_{range,clear} - F_{range,cloudy} \quad (1)$$

for each range and for all together (net cloud forcing)

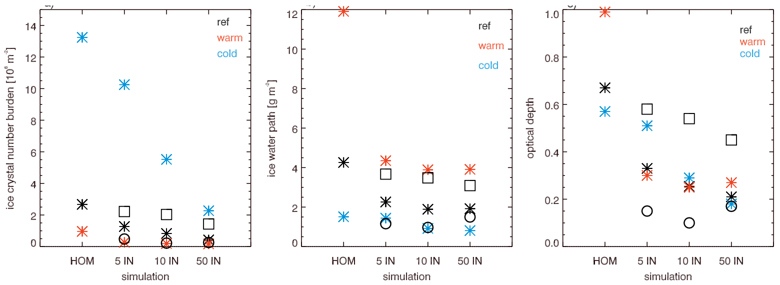
Short wave and long wave forcing (6-12 LT)



Optical depth and net forcing (6-12 LT)

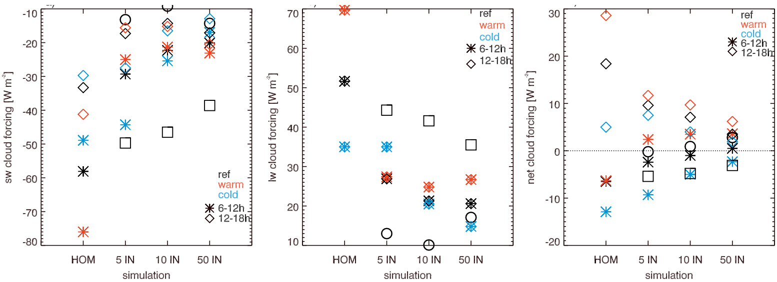


Summary for all simulations



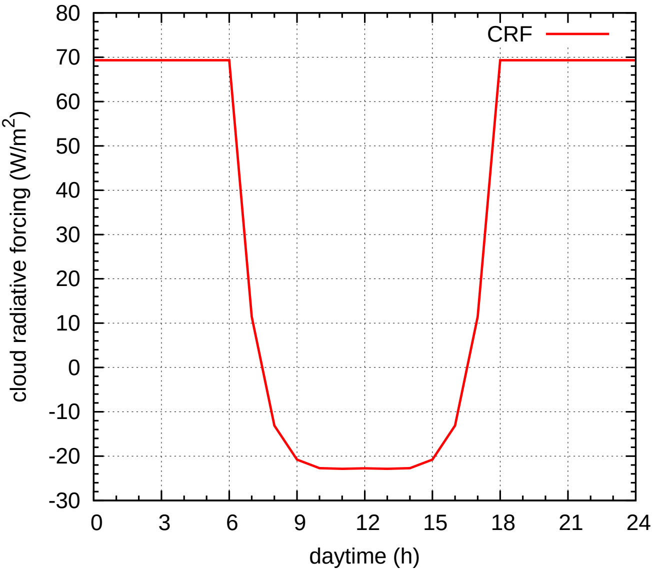
- Decrease in ice crystal number concentration and ice water path with in creasing IN concentrations
- Optical depth is depending non-linear on number and mass concentration, thus complicated; decrease in optical depth with increasing IN concentrations
- Strong temperature dependence (ice & mass concentration)

Summary for all simulations



- Short wave forcing depends on local time, stronger for 6-12 LT
- Short wave forcing (cooling effect) and long wave forcing (warming) decreases in strength with increasing IN concentrations
- Net cloud forcing descreases in strength with increasing IN concentrations

Impact of local time (equinox)



Summary

- Cirrus and ice supersaturation occur frequently in the tropopause region
- Heterogeneous nucleation can influence formation of ice crystals by homogeneous nucleation also in high velocity regime
- Strong impact of heterogeneous vs. homogeneous nucleation on radiative properties of orographic cirrus clouds

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Future work

- More radiative transfer calculations for other daytimes
- Same strategy for convective cirrus clouds (see Philipp's talk)
- Further calculation in 3D and with online radiation scheme

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Thank you for your attention!