Understanding Ice Crystal Growth, RHI, and the Particle Size Distribution in Cirrus using ARM Measurements and a Cloud Model

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Motivation

- To understand the physical processes that control the observed distributions of:
  - Ice supersaturation (RHI) in cirrus clouds
  - Microphysical properties (PSD, r_{eff}, IWC, N_i)
- Determine if heterogeneous nucleation plays a role in ice formation in the upper troposphere

Outline

- Background
- Model Description
- Case Study Description
- Simulations and comparisons with observations

Aircraft measurements during INCA

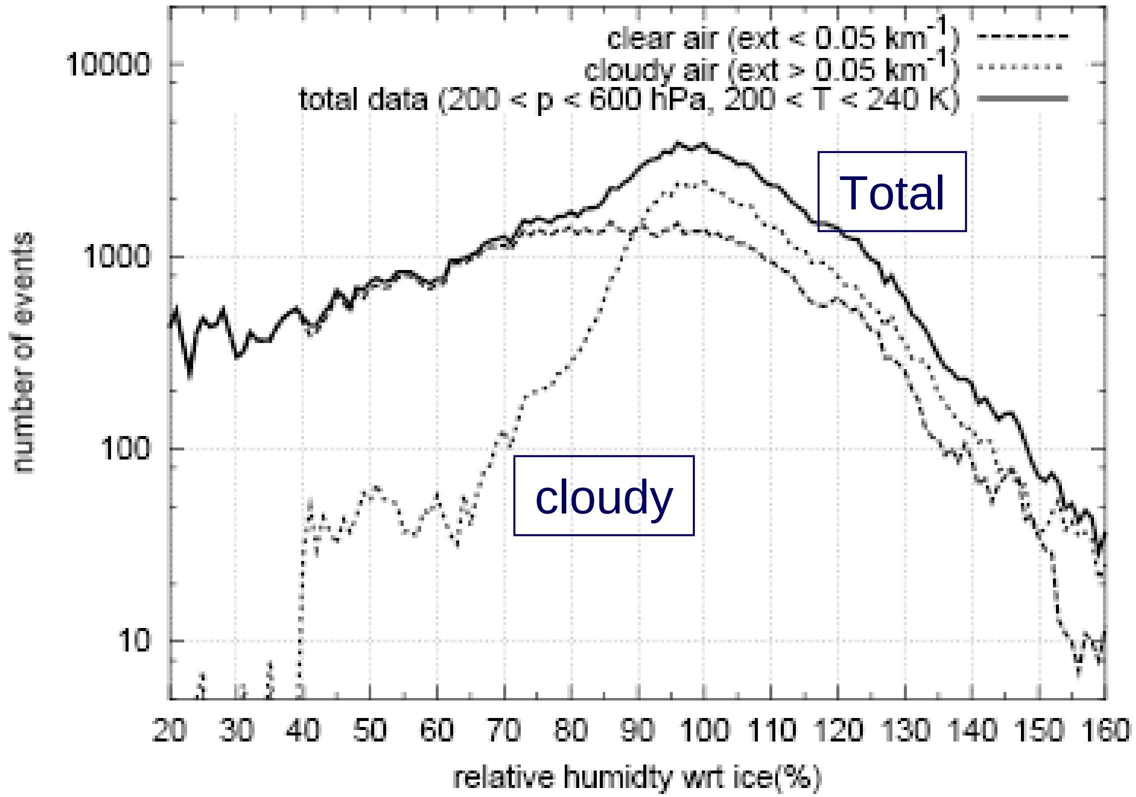


Fig. 1. Statistical distributions (non-normalised) of relative humidity wrt ice inside (dashed line) and outside (dotted line) clouds, and the sum of both (solid line), obtained from INCA measurements. Obviously the bulge in the "sum" distribution originates from measurements inside clouds. It should also be noted that the slopes of the distributions at humidities above ice saturation are similar.

Spichtinger et al. ACP, 2004

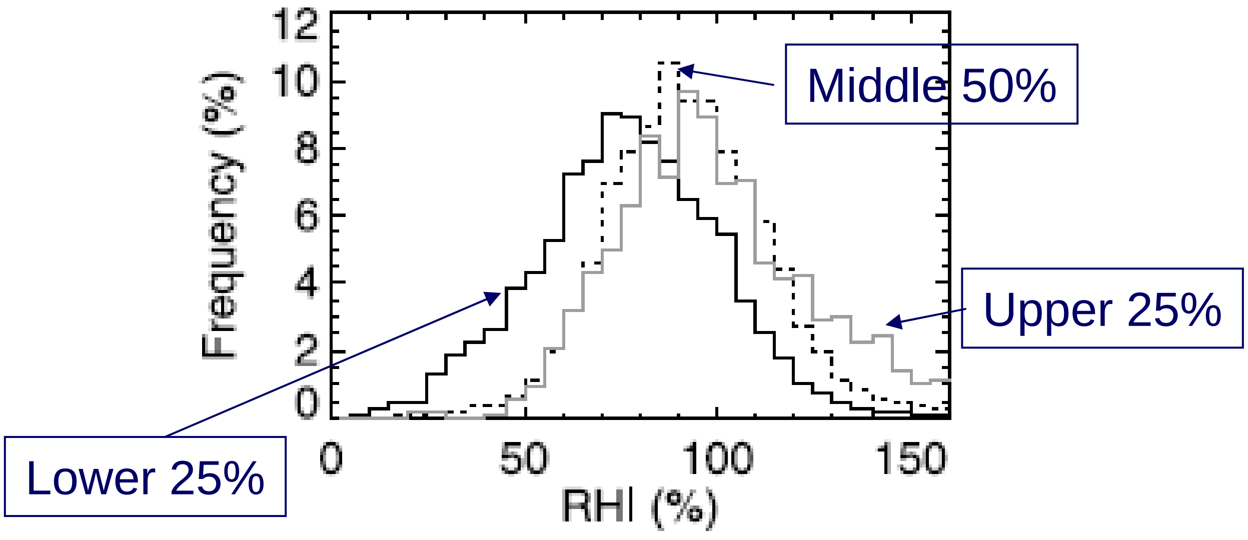


Figure 2. Cloud RHI frequency for 3 different regions in a cloud layer based on percentage of total cloud depth. The lowest 25% is denoted with a solid black line, middle 50% with a dotted line, and upper 25% with a solid grey line.

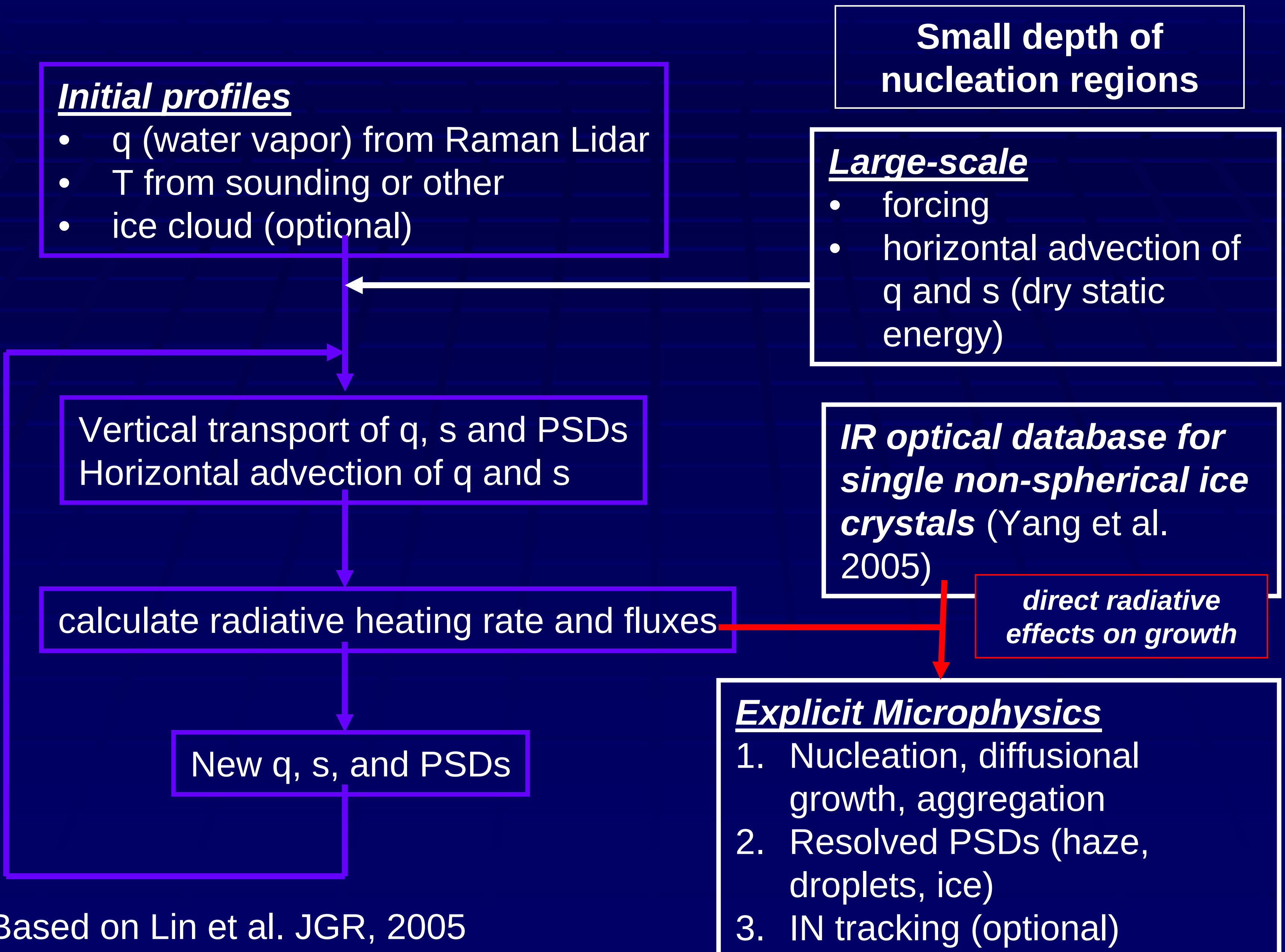
Comstock, Ackerman, & Turner GRL, 2004

ARM Raman Lidar Measurements

Particle Size Distribution In Cirrus

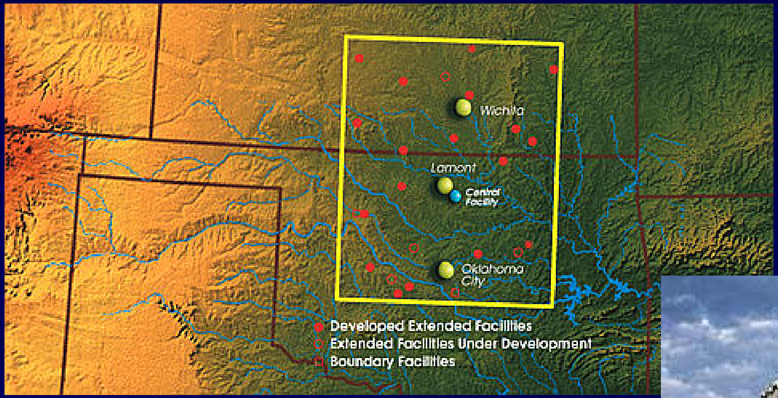
- Contribution of small particles to cirrus PSD
  - *In situ* probes may overestimate the contribution of small crystals (shattering)
  - Discrepancy between radar & lidar measurements near cloud top indicates presence of small crystals in nucleation zone
- Models have trouble reproducing the observed PSD
  - Presence of large particles near cloud top indicate that crystals are growing too fast

Flowchart: 1D model (<10m) driven by large scale forcing data



Based on Lin et al. JGR, 2005

ARM Southern Great Plains (SGP) Site

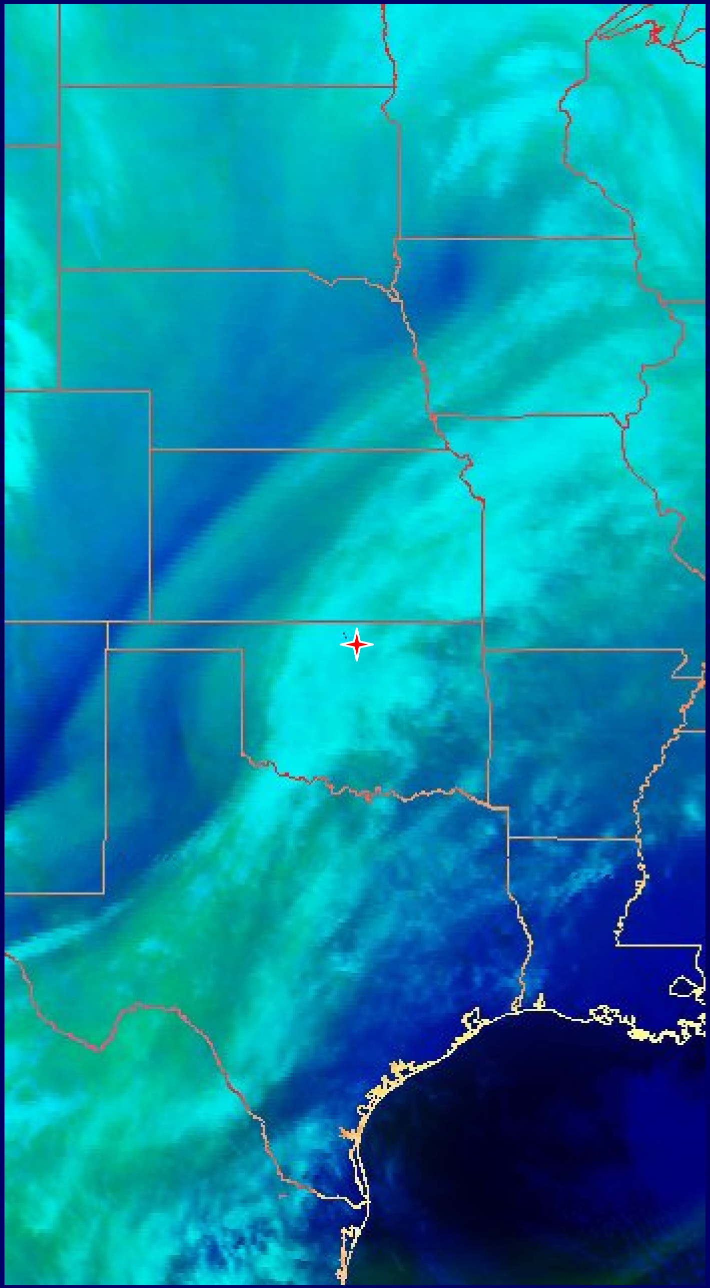


MMCR 35 GHz

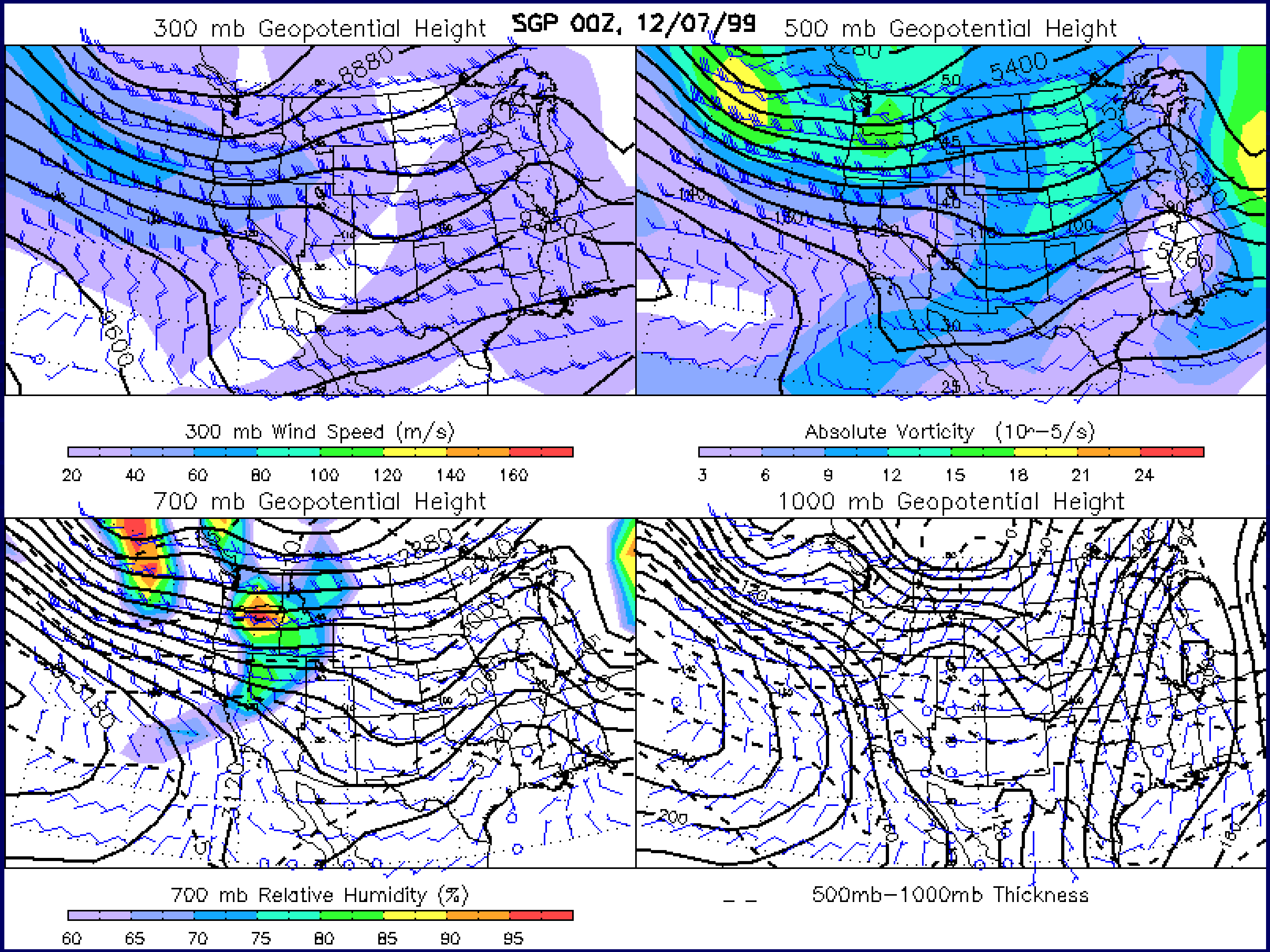
Raman Lidar
Extinction (387 nm)
Water Vapor (408 nm)
Depolarization (355 nm)

Case Study:
ARM SGP
7 Dec1999

GOES8 Composite Image
0455 UTC



NCEP Reanalysis



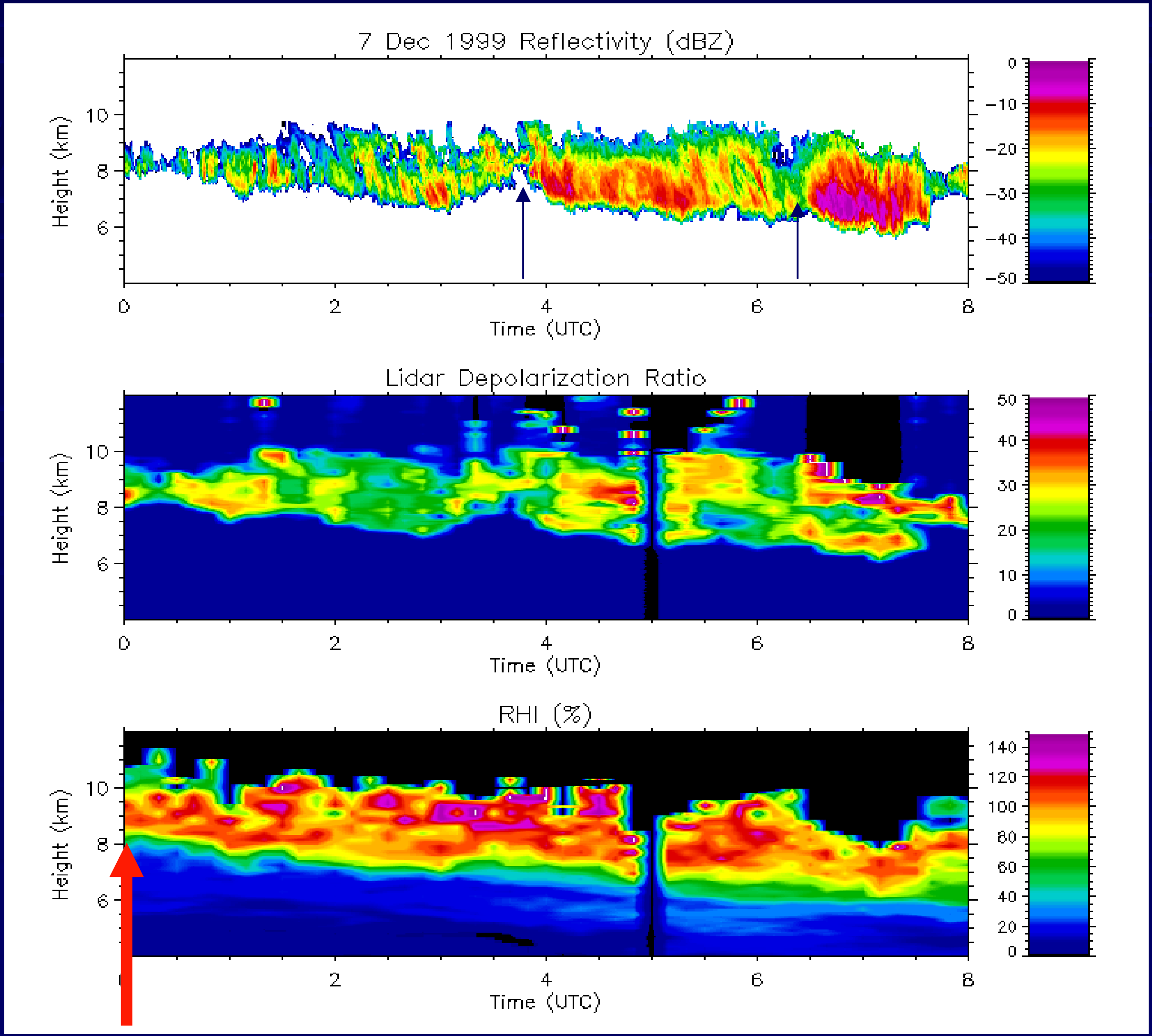
Courtesy Jay Mace http://www.met.utah.edu/mace/homepages/research/archive/archive.html

Observations: 7 December 1999

Radar Reflectivity

Lidar Depolarization Ratio

Raman Lidar + Merged Sonde

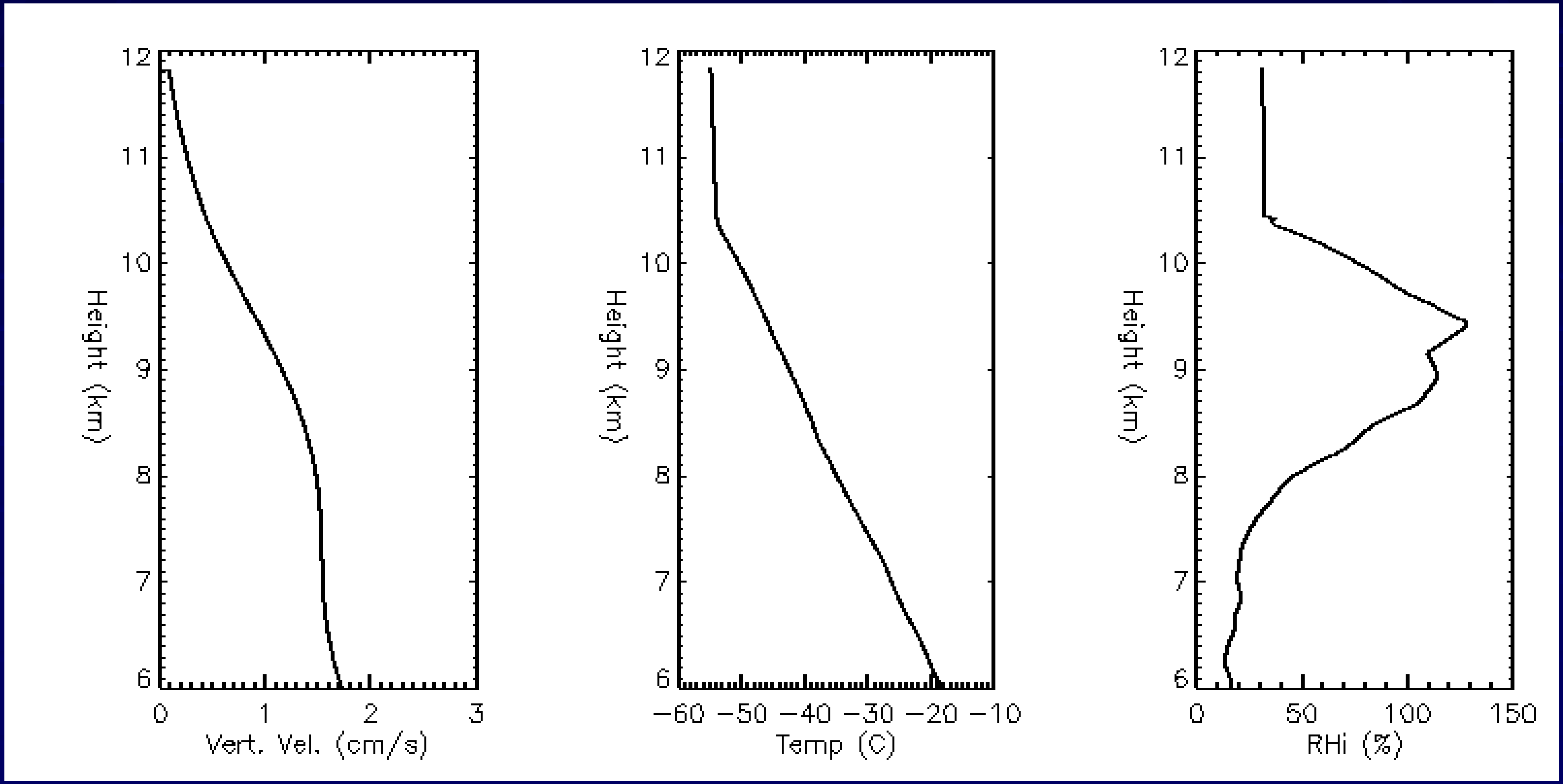


0000 UTC

Control Run

- The control run will have the following characteristics:
  - Homogeneous nucleation only
  - Deposition Coeff = 1.0
  - Vertical velocity: forcing dataset
  - Temperature from Radiosonde
  - Water vapor from Raman lidar at 0000 UTC
  - Radiation turned on
  - Aggregation turned off
  - Particle shape = columns

Initial Profiles



Factors controlling ice number concentration and particle growth

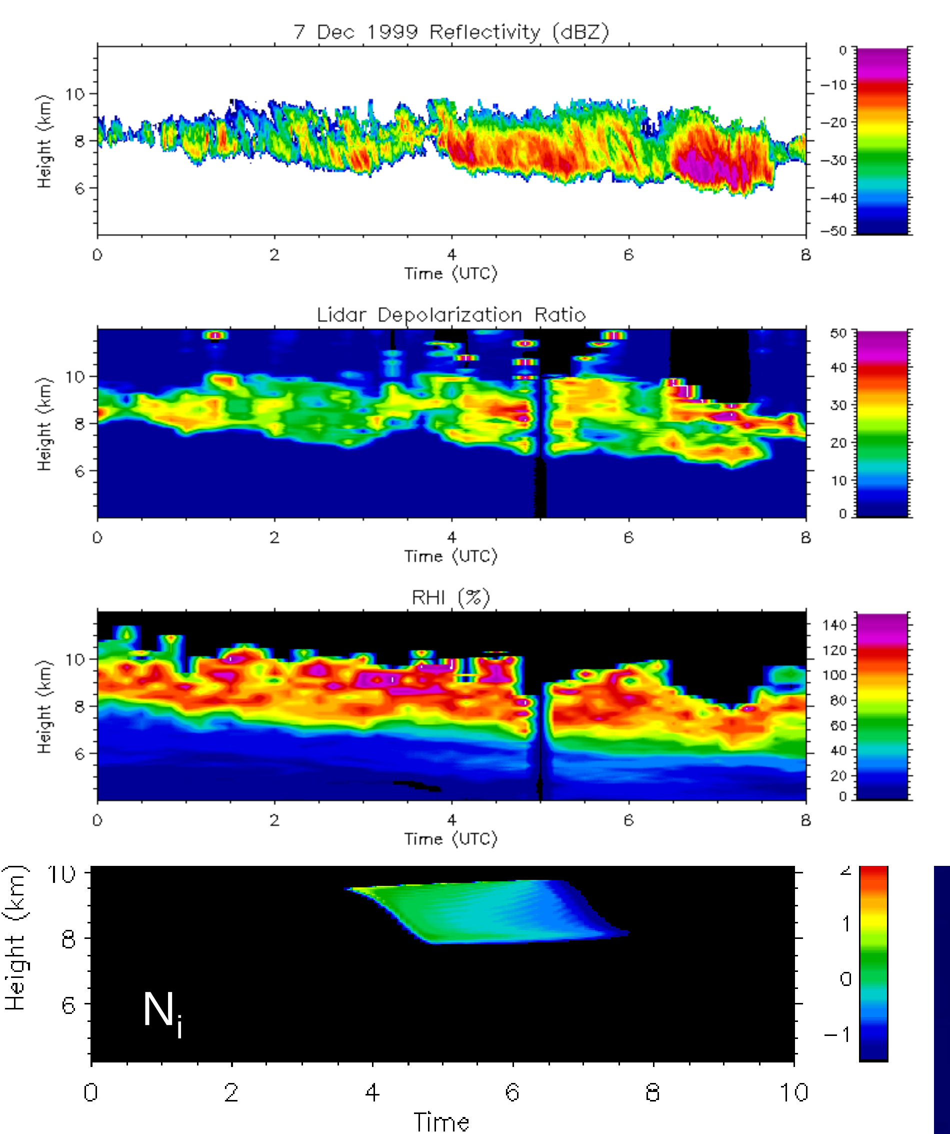
- Nucleation mechanism: clouds that form by heterogeneous nucleation will have smaller Num. Conc. than those that form by homogeneous nuc. (DeMott et al. 1997)
- Deposition coefficient: small values retard the growth of ice crystals, causing large increases in the number concentrations of ice and particles are overall smaller in the cloud (Gierens et al. 2003; Magee et al 2006).
- Vertical velocity (w): increased w substantially increases the number conc. and IWC
- Initial RHI profile: larger initial RHI has only small effects on the frequency distribution of the number concentration
- Turbulence: Will broaden the PSD; generate more medium to large particles (Gu and Liou 2000)

The Role of Deposition Coefficient in Ice Crystal Growth

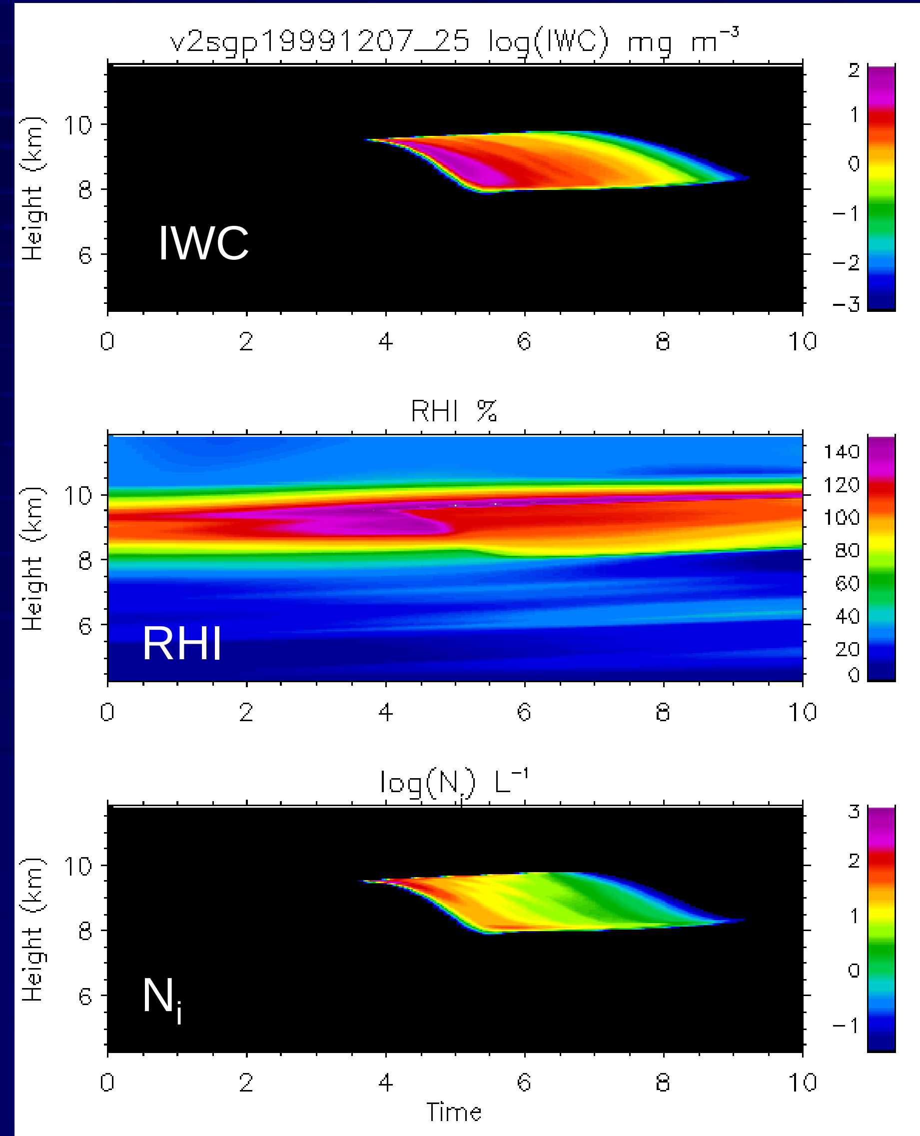
$$\frac{dm}{dt} = \frac{4\pi C(S_i - 1)}{\left[\left(\frac{L_S}{R_v T} - 1\right)\frac{L_S}{KT} + \frac{R_v T}{e_i(T) D}\right]}$$

- Growth efficiency driven by ice vapor pressure and diffusion term
- α_D represents the fraction of water molecules that come in contact with the ice crystal surface and are integrated into the crystal lattice
- α_D often assumed to be 1.0 – Crystals uptake moisture and grow quickly
- New laboratory measurements at -50 C show that α_D~0.006 (Magee et al. 2006)

Fast Growth Dep = 1.0

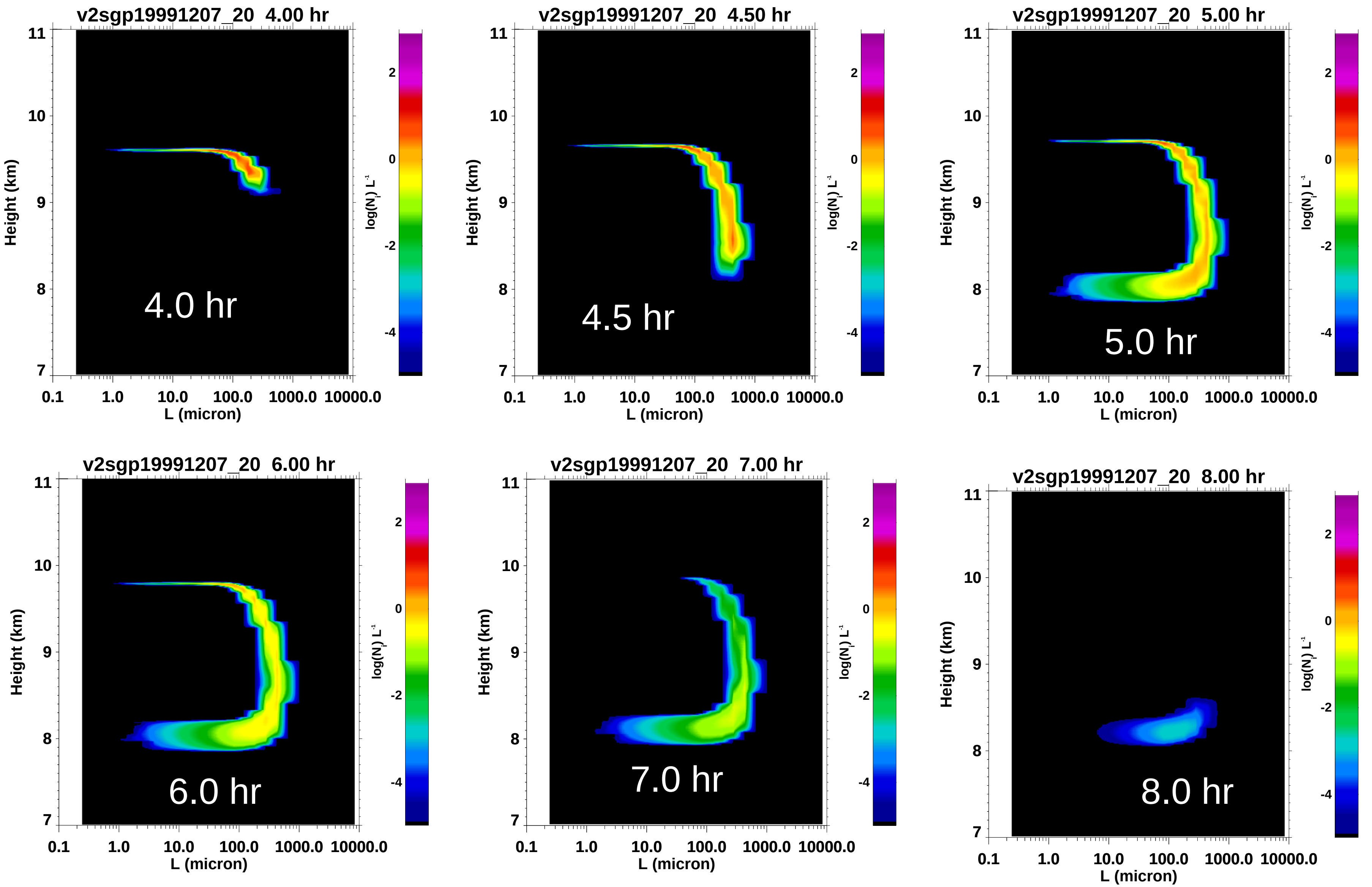


Slow Growth Dep = 0.006



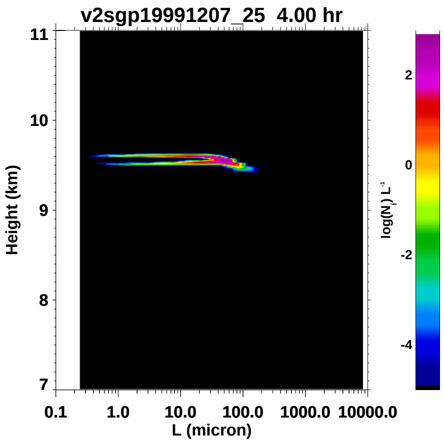
Homogeneous nucleation

Particle Size Distribution: Control Run

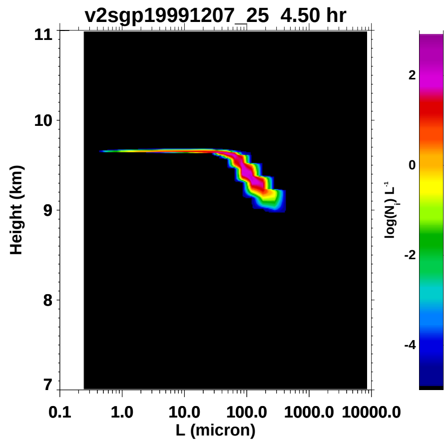


Homogeneous nucleation; DepCoef=1.0

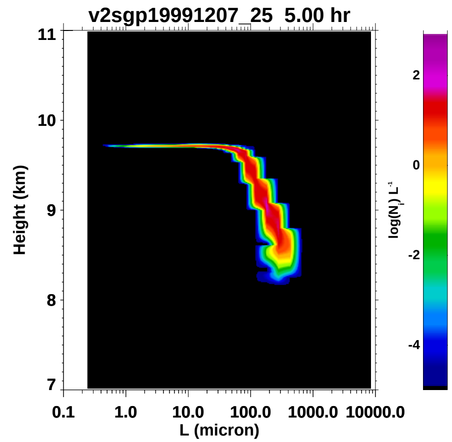
Same as Control Run but for Deposition Coef=0.006
Homogeneous Nucleation Only



4.0 hr



4.5 hr



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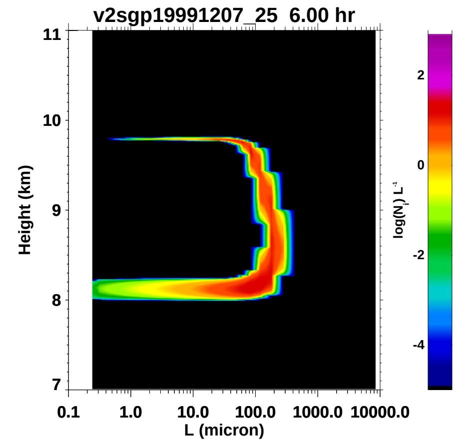
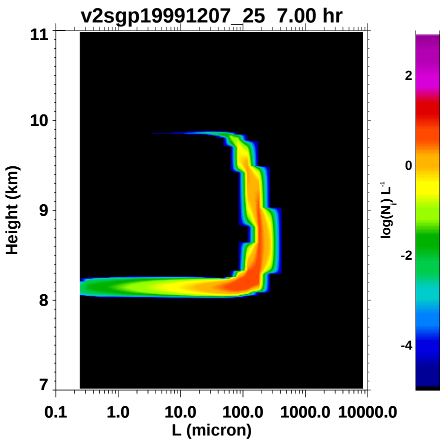
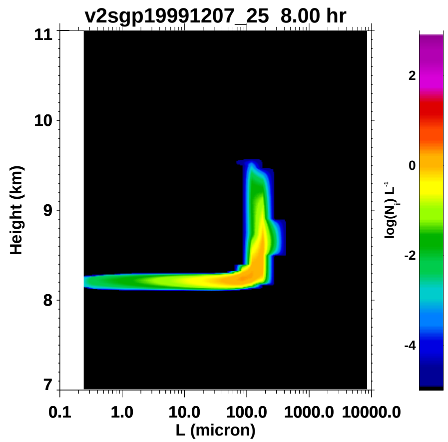


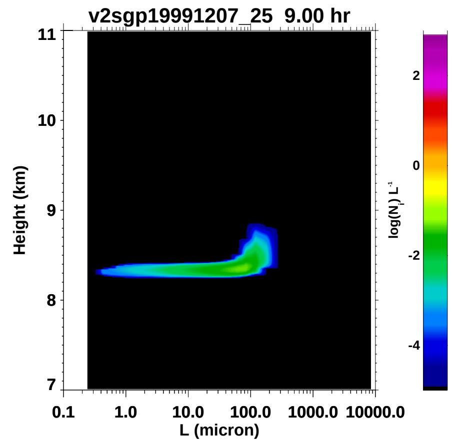
6.0 hr



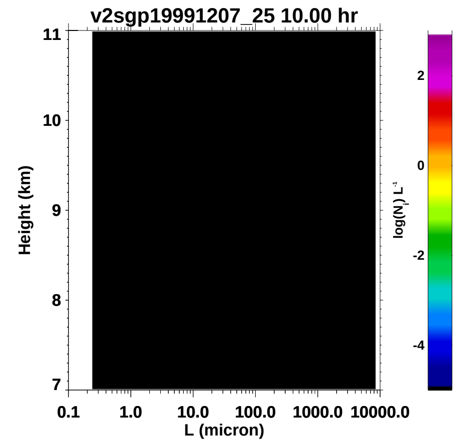
7.0 hr



8.0 hr

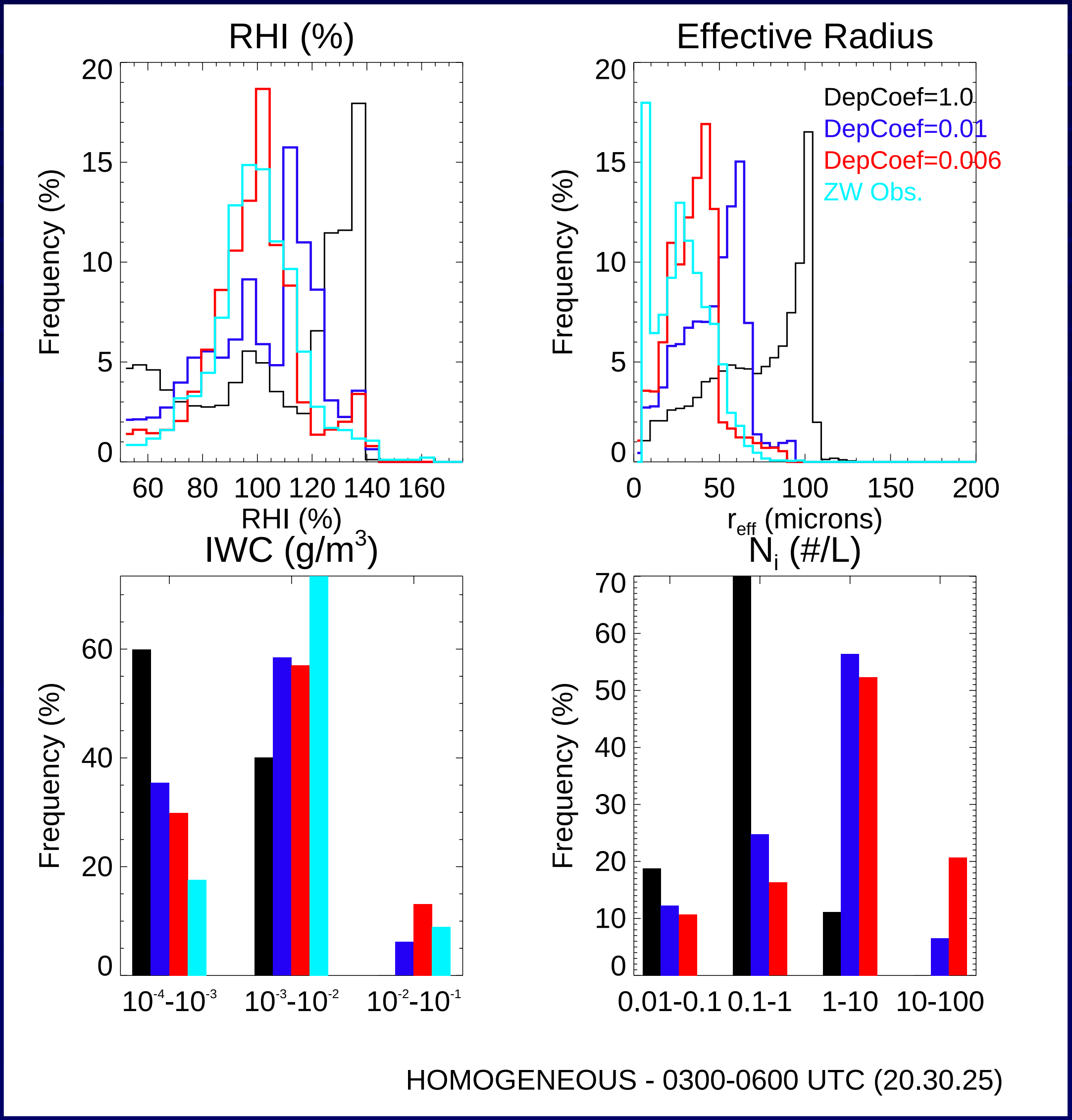


9.0 hr



10.0 hr

Frequency distributions of RHI, r_{eff}, IWC, and Ice Number concentration compared with observations



RHI: Note that PDF of RHI for Dep=1.0 and 0.01 is skewed large; For Dep=0.006 mode of PDF matches obs

R_{eff}: Again, for large DepCoef, r_{eff} is skewed to large particles. PDF shape is consistent for Dep=0.006

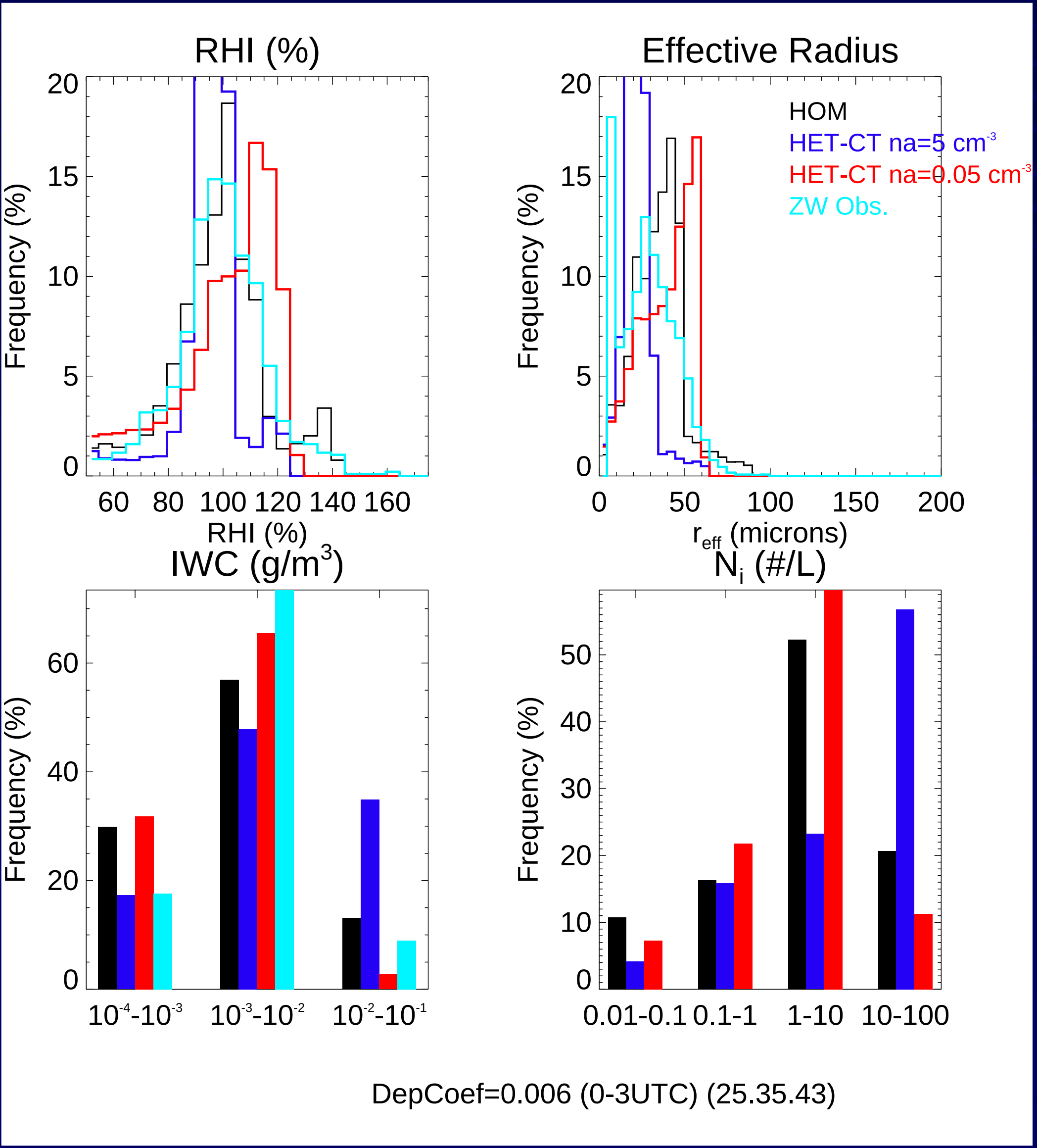
IWC: Note that when particles are larger (black line) IWC is smaller and number concentrations are smaller

N_i: No observations for comparison but recall numbers like 10—100 per liter is typical for midlatitude cirrus from the literature

Obs: Courtesy Zhien Wang

Heterogeneous Nucleation; Varying Aerosol (IN) concentration

Deposition Coef = 0.006



N_a=0.05 cm^{-3} "typical" UT value (DeMott et al. 1997)

N_a=5 cm^{-3} dirty UT

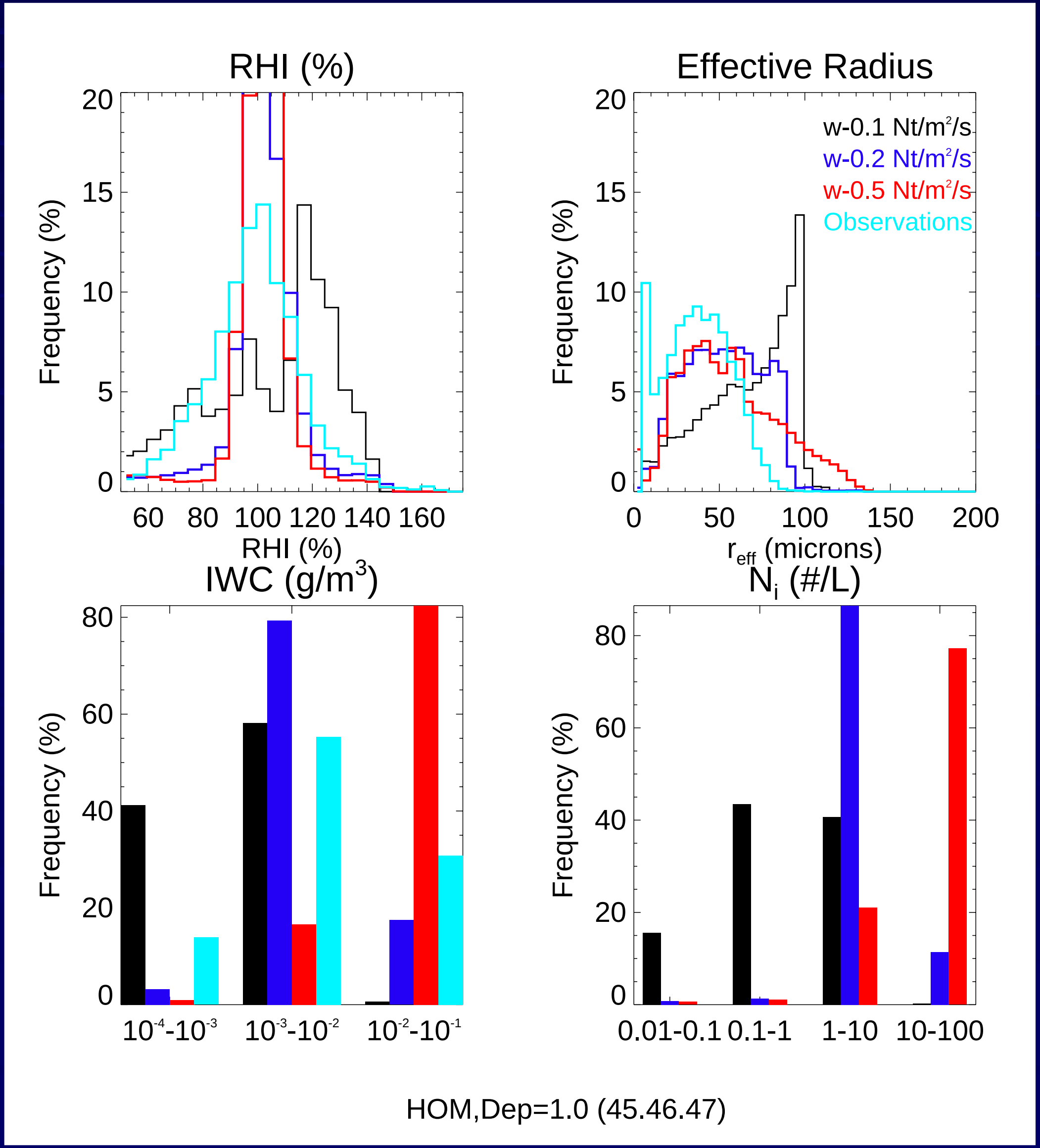
RHI: Larger for smaller N_a

R_{eff}: Larger for smaller N_a; narrow PDF for larger N_a

N_i: number conc are similar to HOM case with typical N_a

Homogeneous Nucleation; Deposition = 1.0

Varying Vertical Velocity



Vertical velocity profile is constant with values 3, 5, and 15 cm s^{-1}

Results are much less consistent with observations when only omega is perturbed.

RHI: Peak RHI is similar for larger omega

r_{eff} : Has a broader distribution for larger omega, which is more consistent with observations.

Summary

- Simulations using α_D=1.0
  - Overestimate RHI and r_{eff}
  - Underestimate IWC
- Slower particle growth (α_D=0.006) produces results more consistent with observations.
  - Larger number conc. of small-medium sized particles reduces RHI in lower parts of cloud due to larger total surface area taking up water vapor.
  - Produces fewer larger particles and larger IWC
- Particle Size Distribution
  - Small particles only in nucleation & sublimation zones
  - No bimodal distribution
- Heterogeneous nucleation
  - For “typical” UT ice nuclei, is less consistent with obs.