University of Victoria

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The Representation of Aerosol Indirect Effects in Global Climate Models

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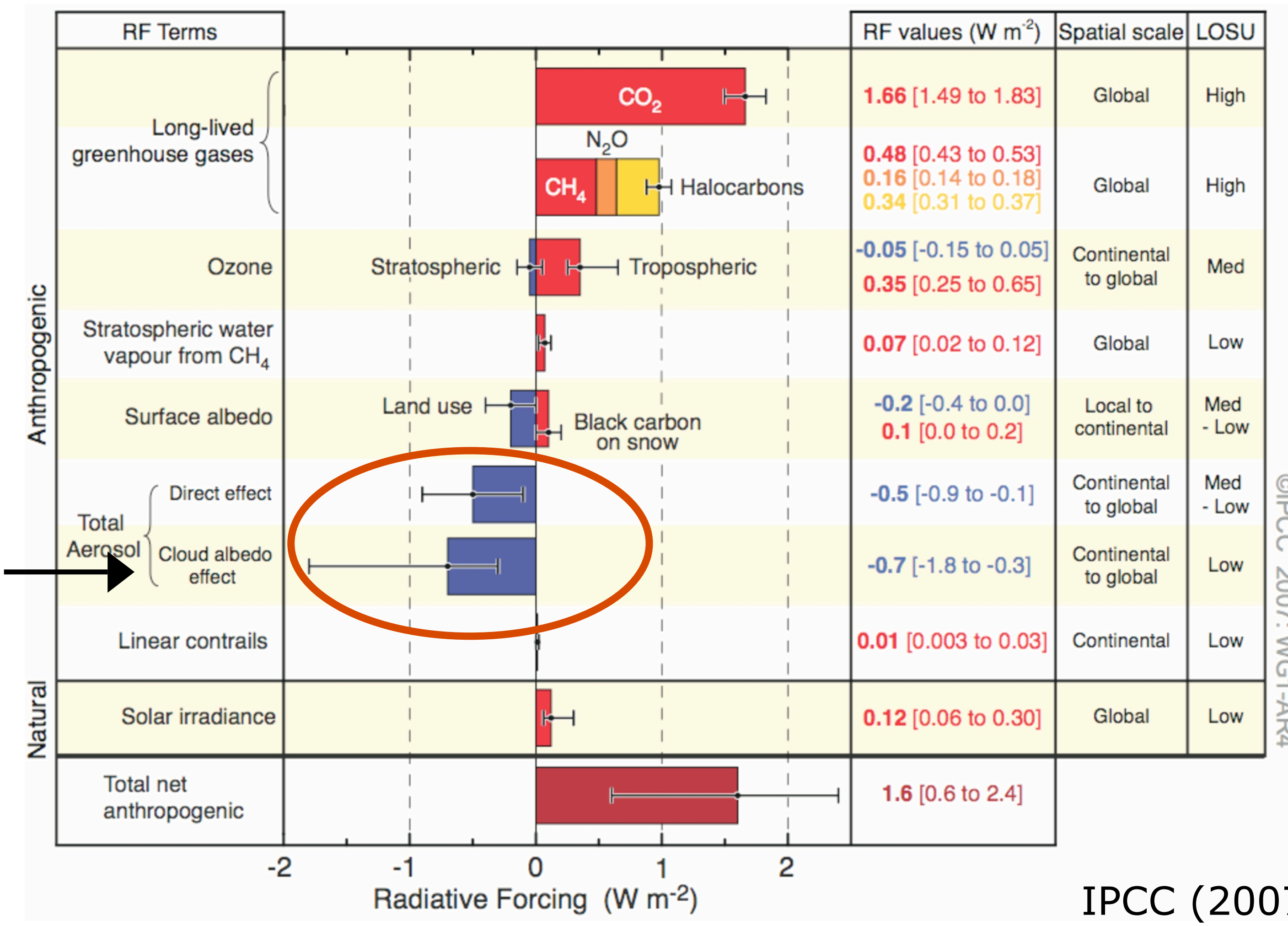
Environment Canada Environnement Canada

Role of Aerosols for Global Climate

Twomey
(1st indirect)
effect



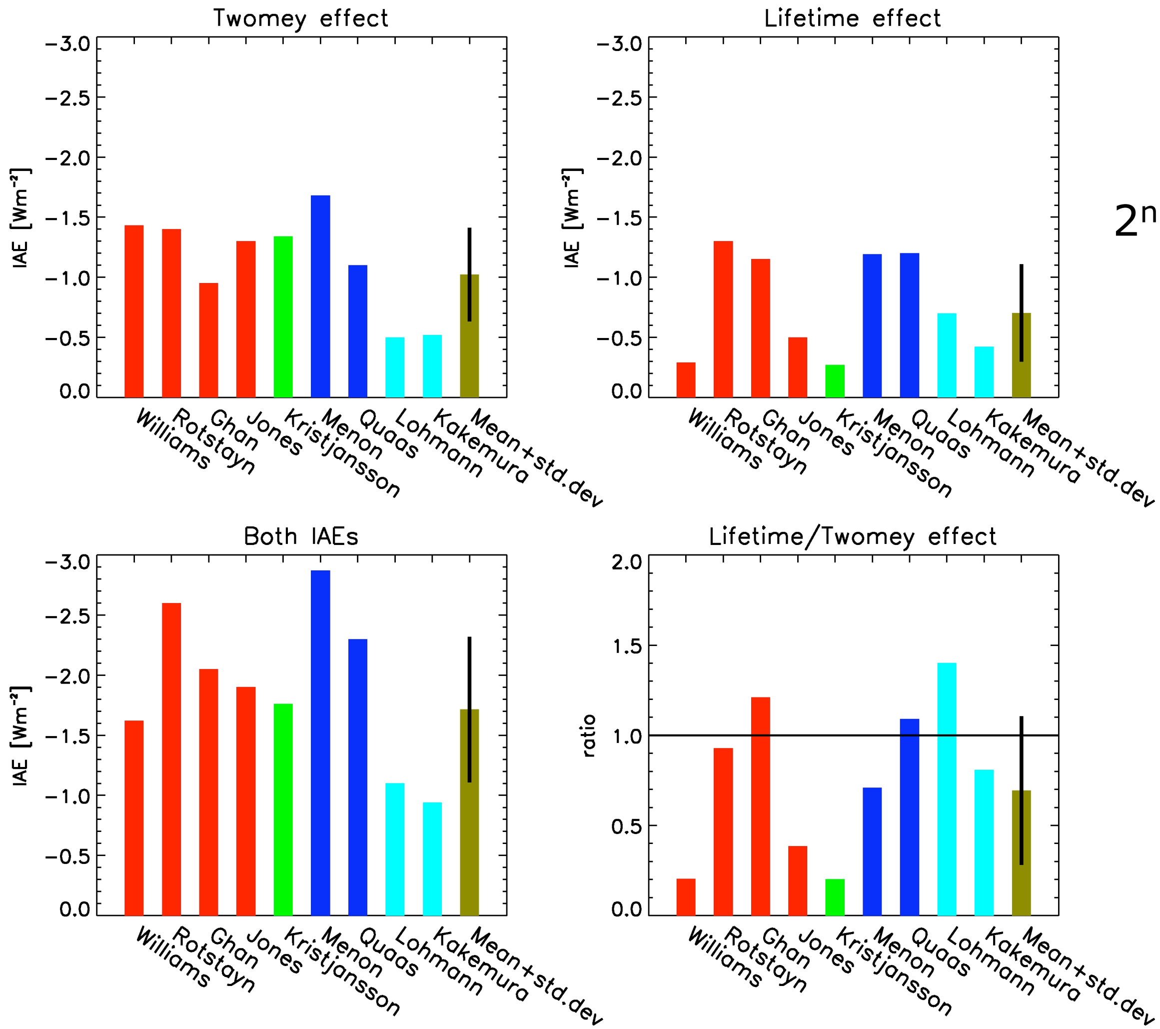
IPCC (2007)

Aerosol Indirect Effects (IE) in GCMs

1st IE

2nd IE

1st + 2nd IE



Lohmann and Feichter, ACP (2005)

Role of Cloud Droplet Number Concentration for Aerosol/Cloud Effects on Radiation

Cloud Droplet Effective Radius

Cloud Liquid Water Content

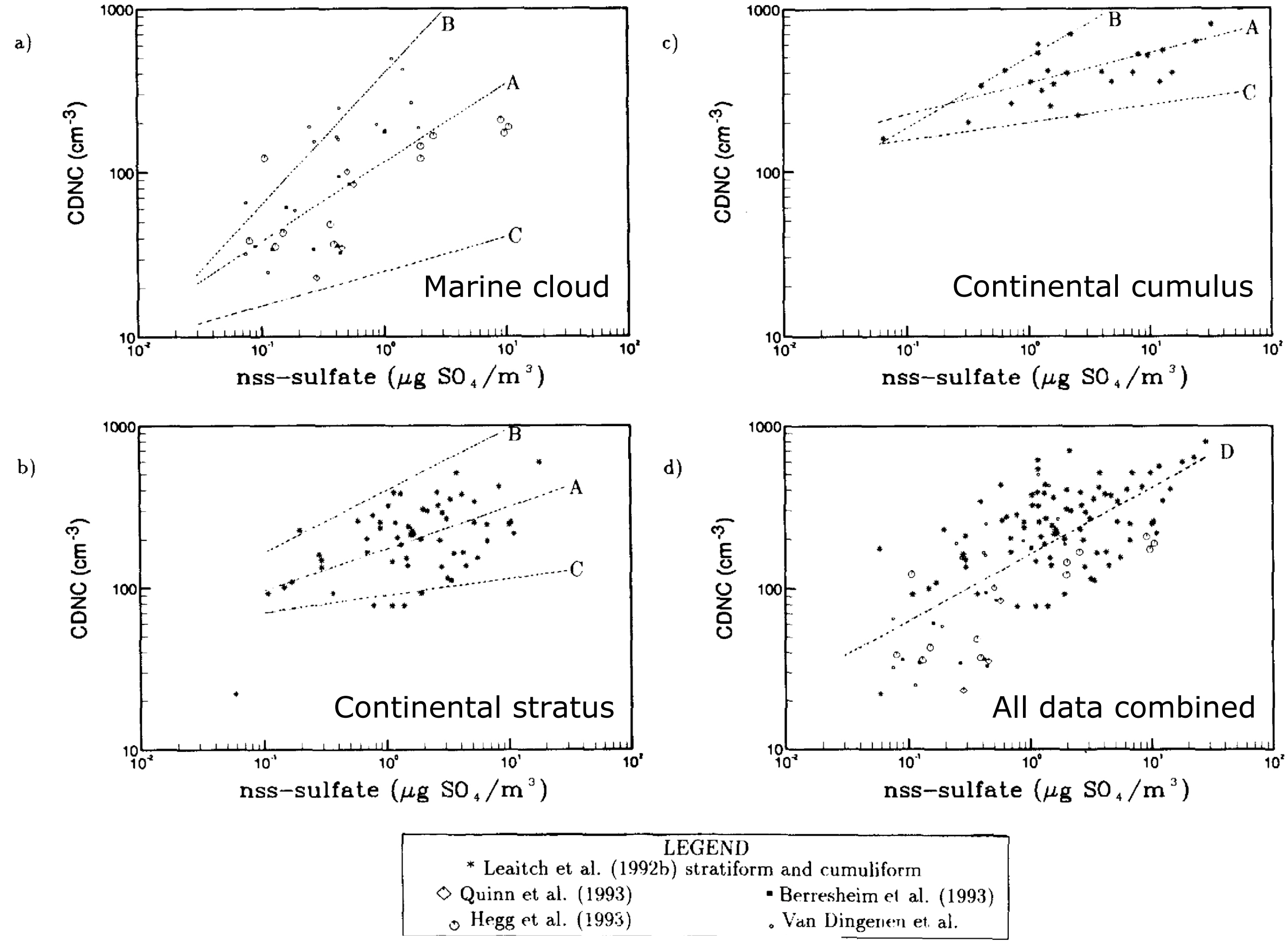
$$r_{eff} = \frac{\int r^3 \, n(r) \, dr}{\int r^2 \, n(r) \, dr} = \beta \left(\frac{3 \, LWC}{4\pi \, \rho_w \, N_c} \right)^{1/3}$$

Spectral Shape Factor

Cloud Droplet Number Concentration (CDNC)

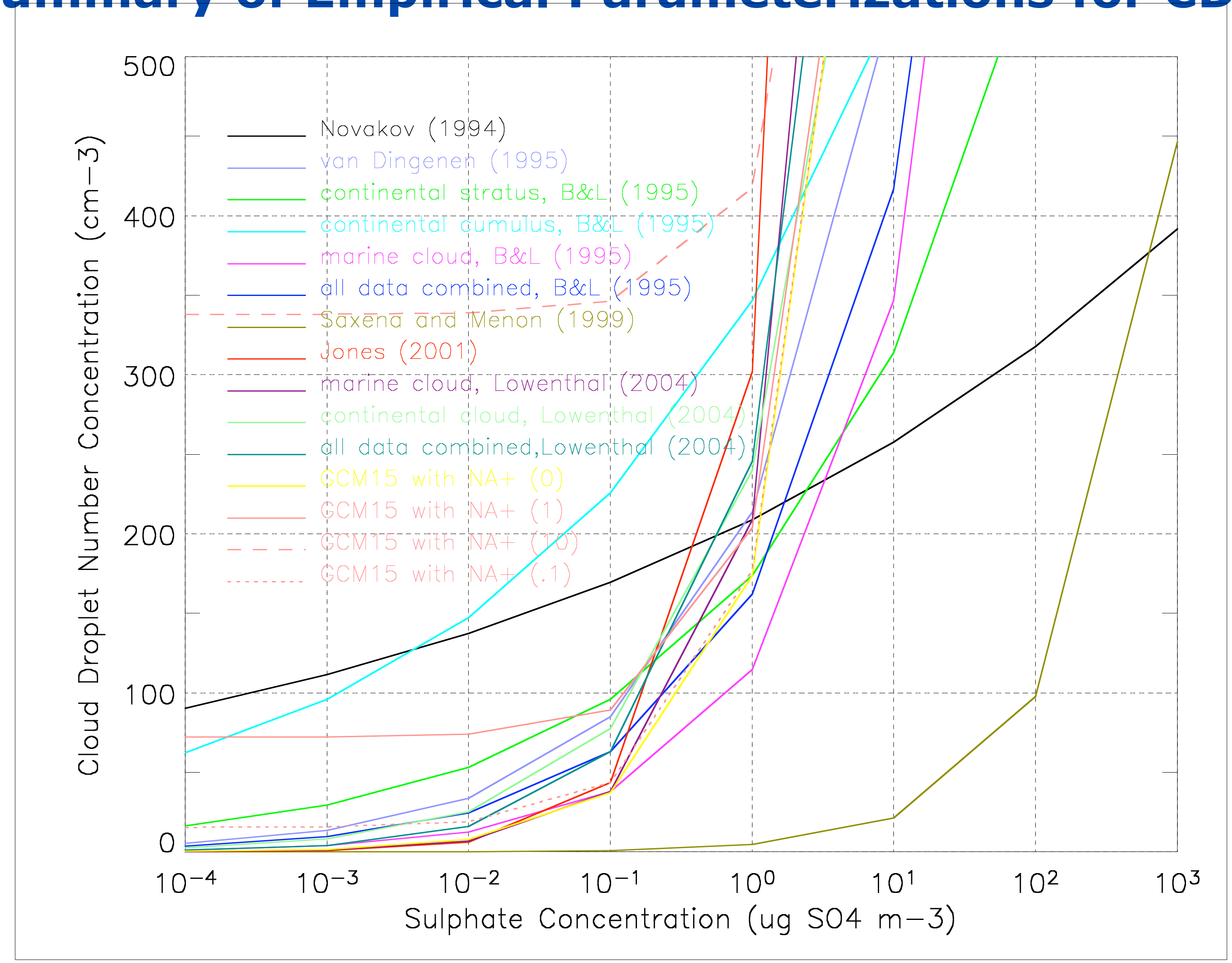
Twomey effect
(1st indirect effect, cloud albedo effect):
Aerosol ↗ N_c ↗ r_{eff} ↘

An Empirical Parameterization for Cloud Droplet Number Concentration (CDNC)

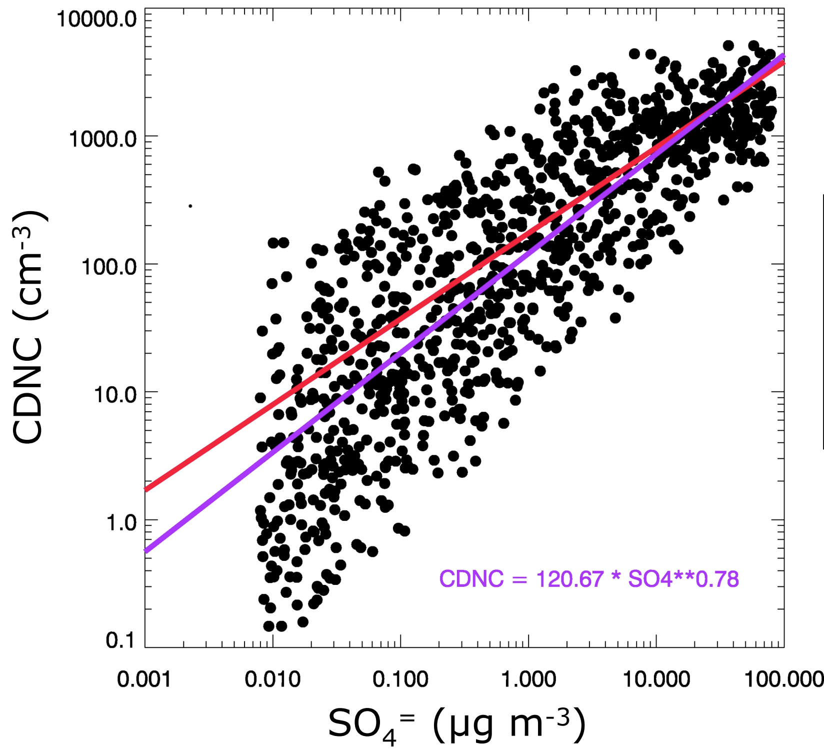


Boucher and Lohmann (1995)

Summary of Empirical Parameterizations for CDNC



Adiabatic Parcel Model Simulations



Large scatter in CDNC caused by differences in size distributions for given $SO_4^{=}$ concentration

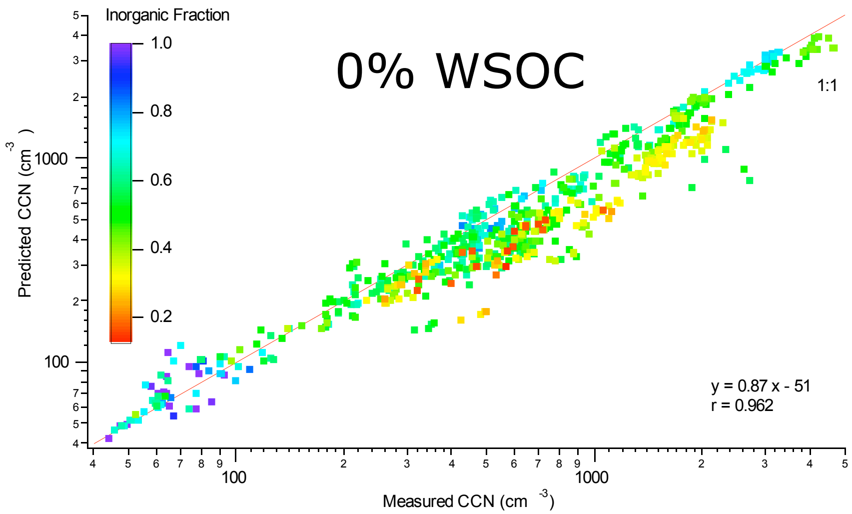
Red line:
GCM4 parameterization
(Ma and von Salzen, submitted to ACP)

Dry aerosol mass: 0.01 – 100 µg m^{-3}
Mode radius: 0.01 – 0.1 µm
Variance: 1.2 – 2.2

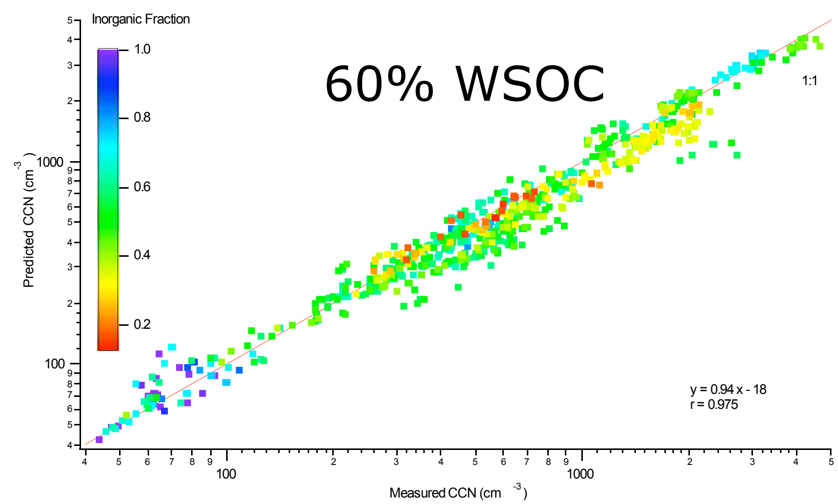
Updraft velocity: 1 m s^{-1}
Cloud depth: 1000 m

CCN Observations for Water Soluble Organic Carbon Aerosol

Predicted vs. measured CCN for different assumptions about water-solubility of organic carbon

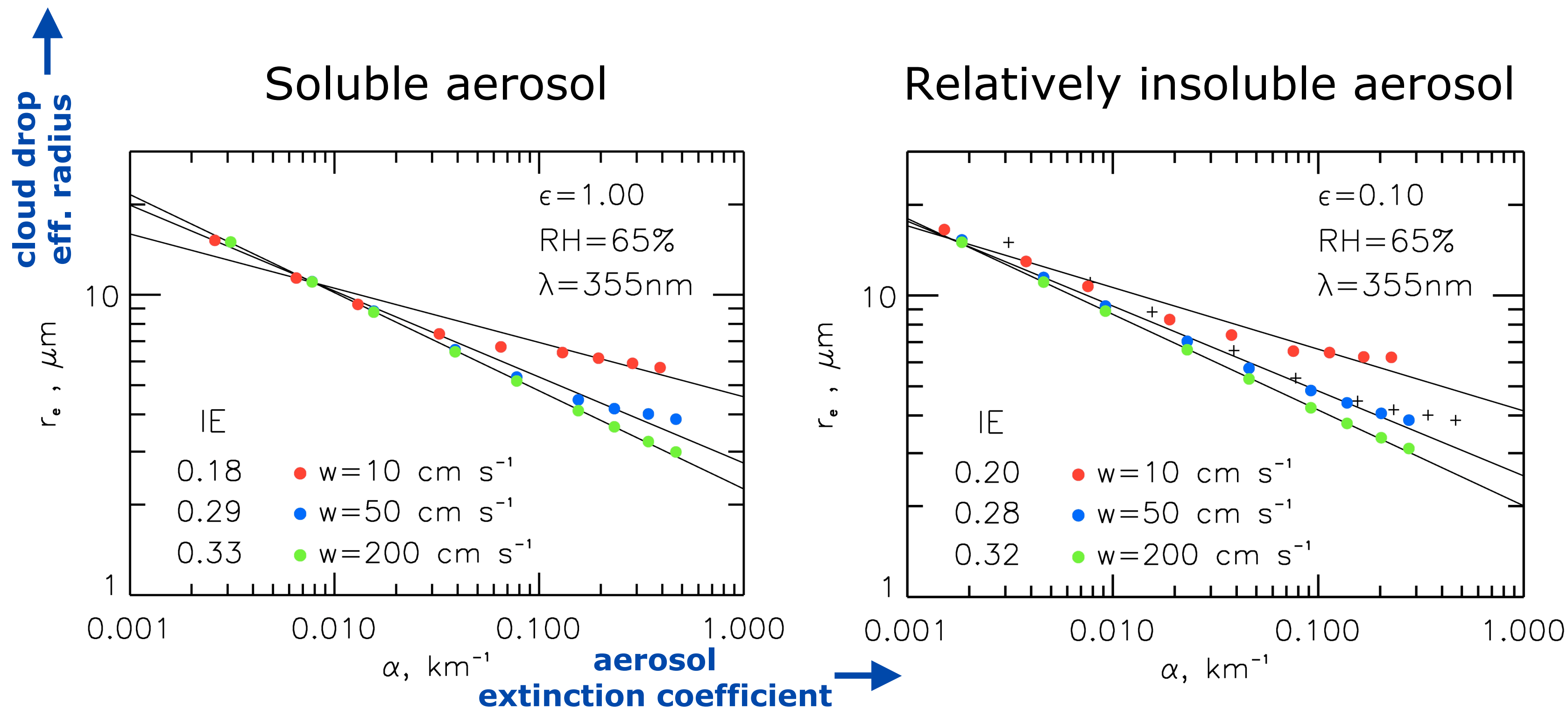


Courtesy: Abbatt and Leaitch



Systematic effects of organic material on CCN concentrations

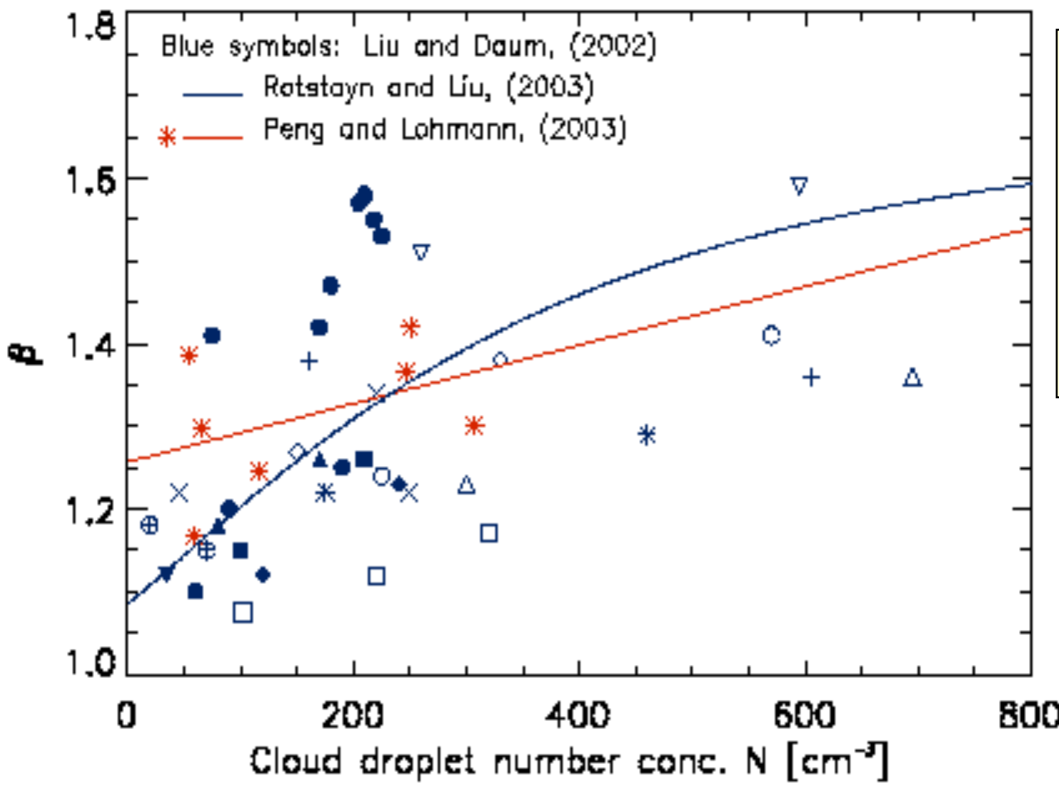
Cloud Updraft Velocities



Feingold (2003)

Aerosol indirect effects are linked to cloud dynamical processes and therefore depend on cloud type

Yet Another Cause of Uncertainty: Dispersion Effect



$r_{eff} = \beta\ (LWC/CDNC)^{1/3}$ is used in GCMs to account for the aerosol dispersion effect.
(Rotstayn and Liu, 2003
Peng and Lohmann, 2003)

$\beta = f(CDNC)$ is derived based on field studies (Liu and Daum, 2000)

Peng and Lohmann (2003): Including the dispersion effect reduces the simulated indirect aerosol effect from –1.4 W m^{-2} (const. β) to –1.2 W m^{-2} ($\beta(N_l)$)

Looking Ahead to the Future:
First Principles Based Parameterizations in GCMs

First Principles Based Parameterizations of CDNC

- Abdul-Razzak and Ghan (2000), Nenes and Seinfeld (2003).
- Realistic dependencies of CDNC on aerosol size and chemical composition.
- **Assumption:** Adiabatically ascending parcels of air.
- **Key parameters:** Dry aerosol size distribution and cloud updraft velocity.
- **Approach:** Provide approximate solution of droplet growth equation for condensation under equilibrium conditions for water vapour, based on Köhler theory.
- **Diagnosis of CDNC** as fraction of activated aerosol at maximum supersaturation. No direct information available on dispersion effect and cloud droplet size.

What About Real Clouds?

Shallow Cumulus

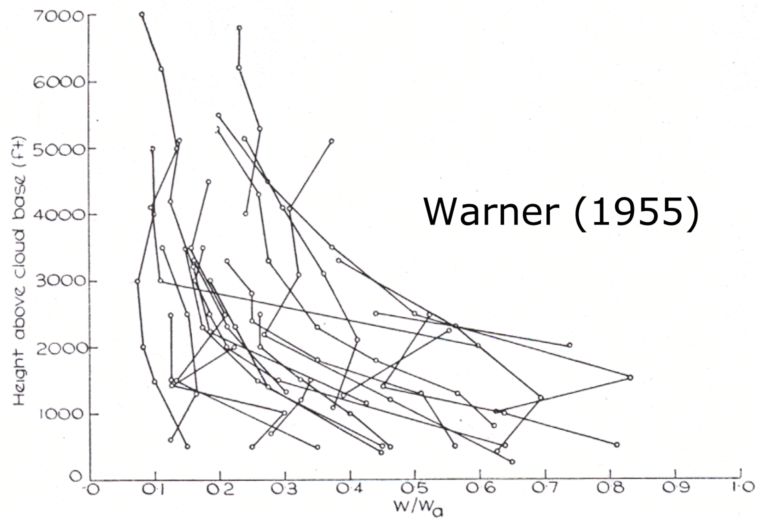
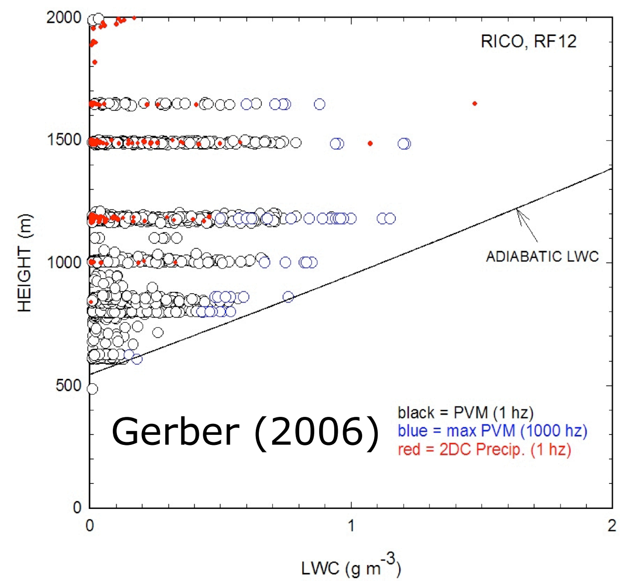


Fig. 7. Ratio of observed liquid water content to adiabatic value versus height above base.



Overwhelming evidence for non-adiabatic conditions in clouds from observations: **Implications for cloud droplets?**

A Prognostic Approach for Cloud Droplet Nucleation: Droplet Growth Equation and Köhler Theory

droplet radius

supersaturation in ambient air

supersaturation at droplet surface

$$R_p \frac{dR_p}{dt} = \frac{s - s_p}{C}$$

$$s_p = \underbrace{\frac{A}{R_p}}_{\text{curvature (Kelvin) term}} - \underbrace{\frac{B}{R_p^3}}_{\text{solute (Raoult) term}}$$

$$A = \frac{2M_w \sigma_w}{RT\rho_w} \;, \; B = \frac{3M_w \nu m_s}{4\pi\rho_w M_s \left[1 + \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{\rho_s}{\rho_u}\right)\right]} \;, \; C = \frac{\rho_w RT}{e_* D_v' M_w} + \frac{L_v \rho_w}{k_a' T}\left(\frac{L_v M_w}{RT} - 1\right)$$

A Prognostic Approach for Cloud Droplet Nucleation: Generalized Droplet Growth Equation (GDGE)

For quasi-steady supersaturation:

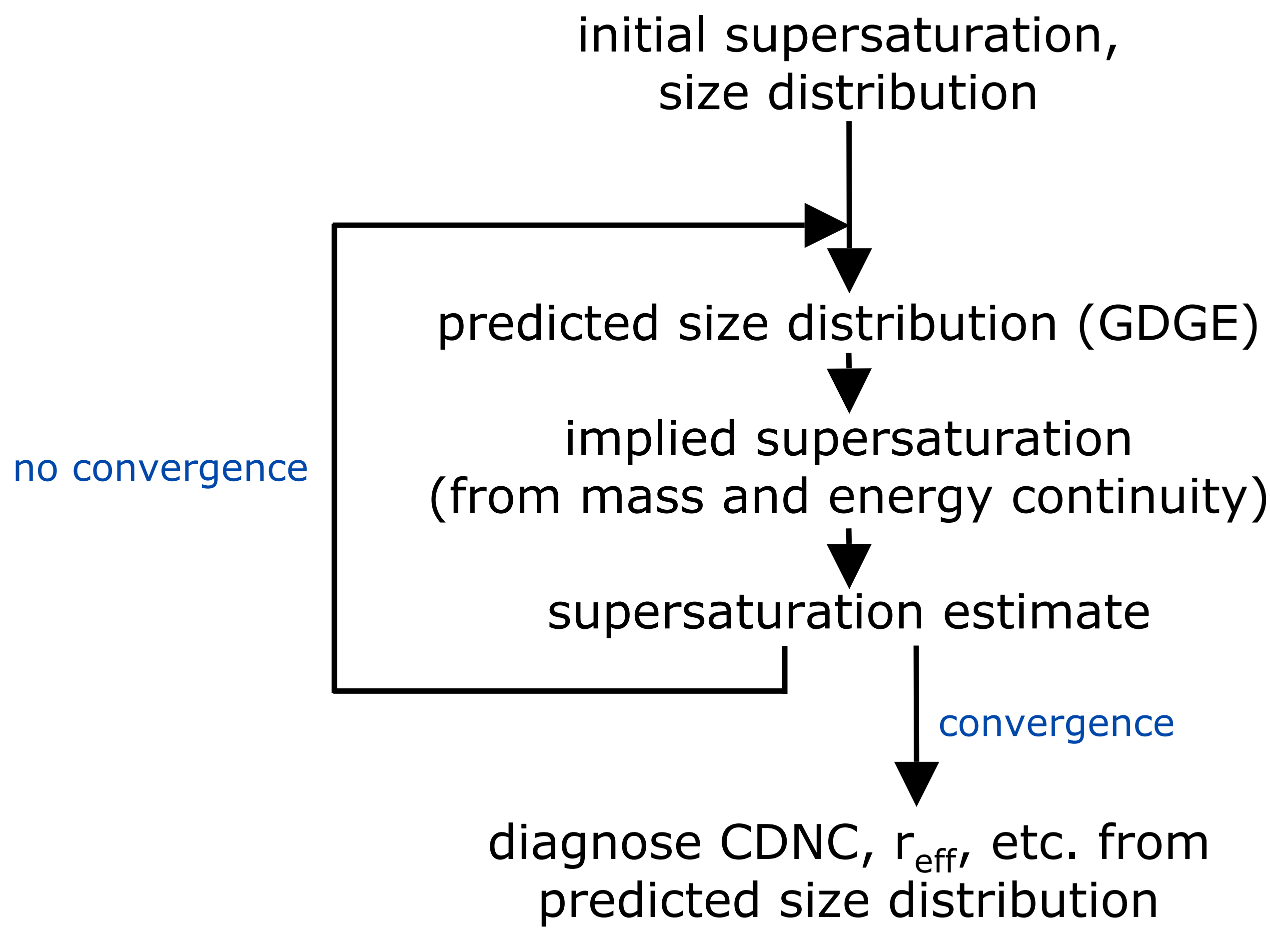
$$\frac{dR_p}{dt} \rightarrow \boxed{\frac{dx}{du} = \delta - \hat{B}\left(\frac{F}{\sqrt{x}} - \frac{1}{x^{3/2}}\right)}$$

$x = \dfrac{R_p^2}{2}$ =generalized droplet size, $u = \dfrac{|s|t}{C}$ =generalized time

$$\hat{B} = \frac{B}{2^{3/2}|s|} \quad , \quad F = \frac{2A}{B} \quad , \quad \delta = \frac{s}{|s|}$$

Look-up tables for solutions of the GDGE are available for applications in GCMs

A Prognostic Approach for Cloud Droplet Nucleation: Basic Algorithm

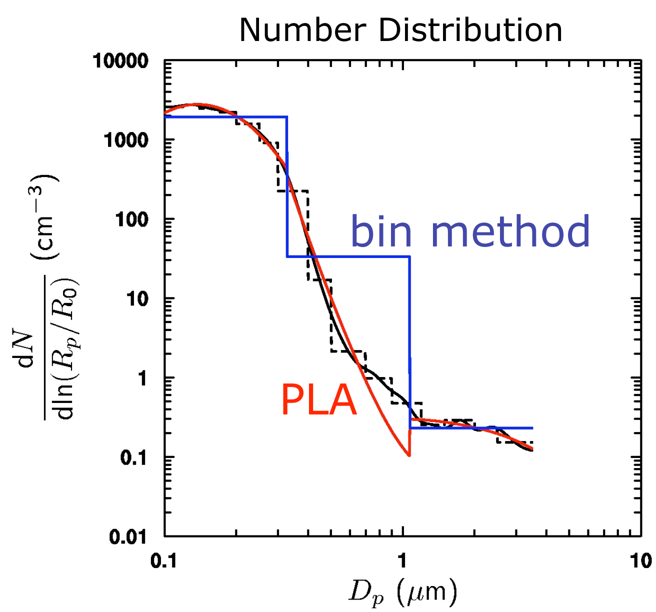


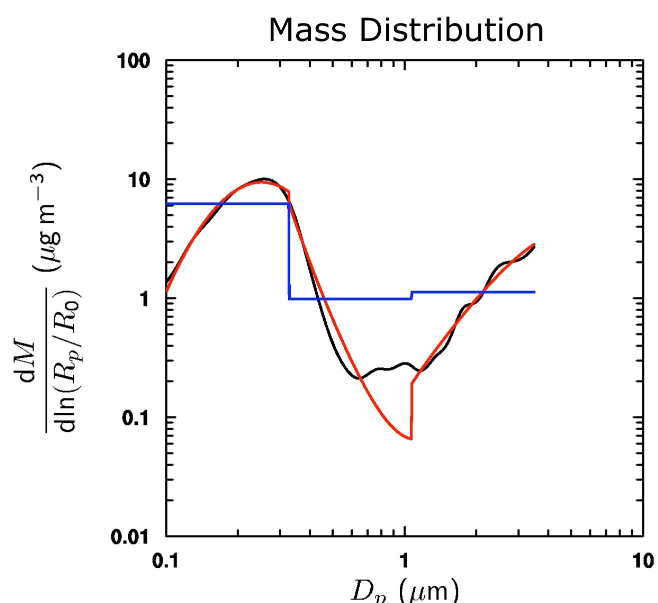
Piecewise Log-normal Approximation (PLA)

Representation of aerosol number distribution:

[illegible]

for section boundaries at $\varphi_{i\pm1/2} = \ln(R_{i\pm1/2} / R_0)$.

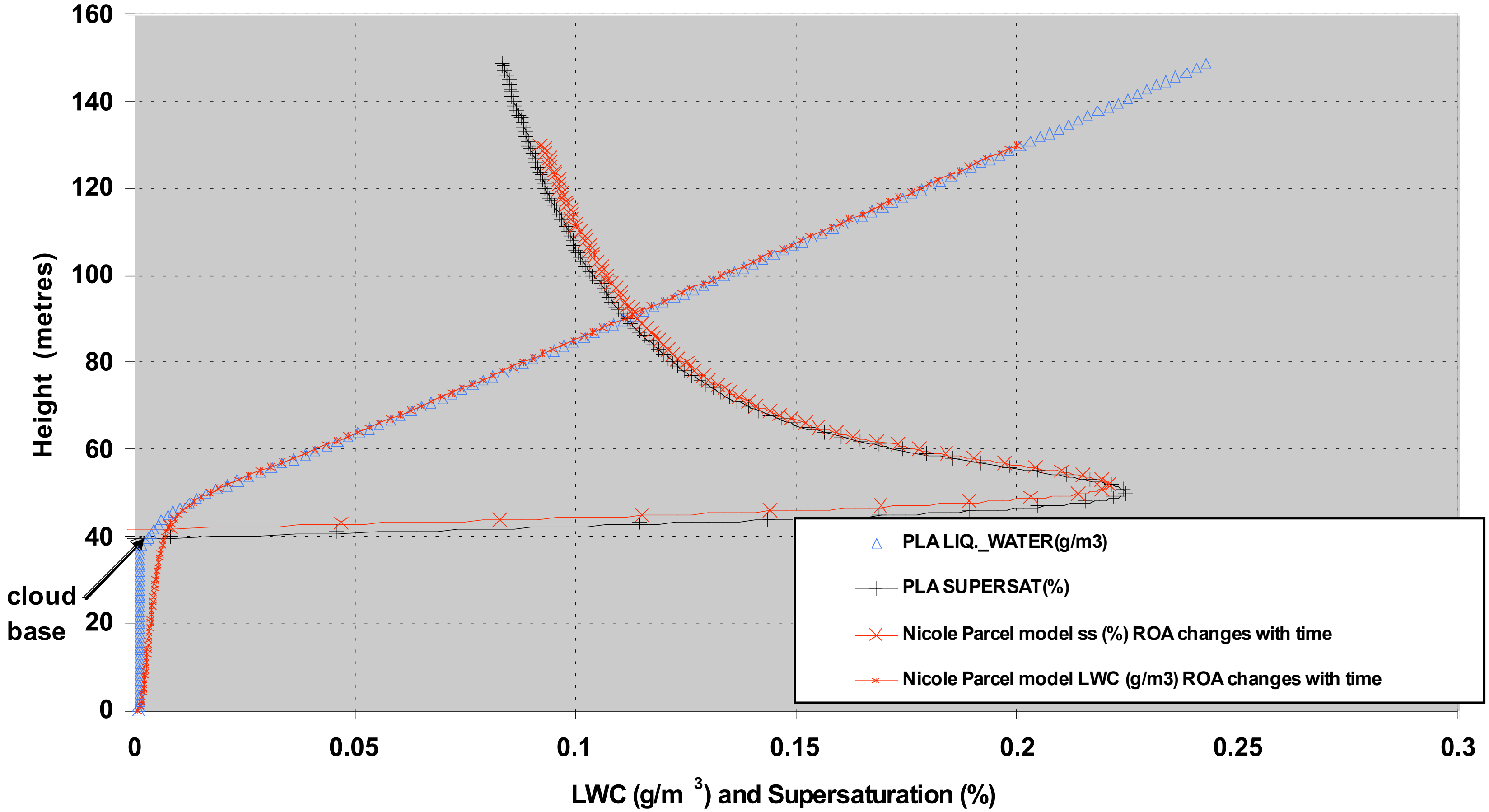




von Salzen (2006)

Comparisons with Detailed Parcel Model …in Progress

Courtesy: Nicole Shantz



GCM Simulation of Cloud Droplet Nucleation in Shallow Cumulus Clouds

Mixing in Shallow Cumulus: The Mixing Line

Linear mixing for cloud properties (e.g. total water, liquid water static energy)

$$\boxed{\chi = f\,\chi_e + (1-f)\,\chi_c} \qquad f = 0\ldots1$$

Cloud Environment   Cloud core

Mixing fraction probability distribution $p(f)$

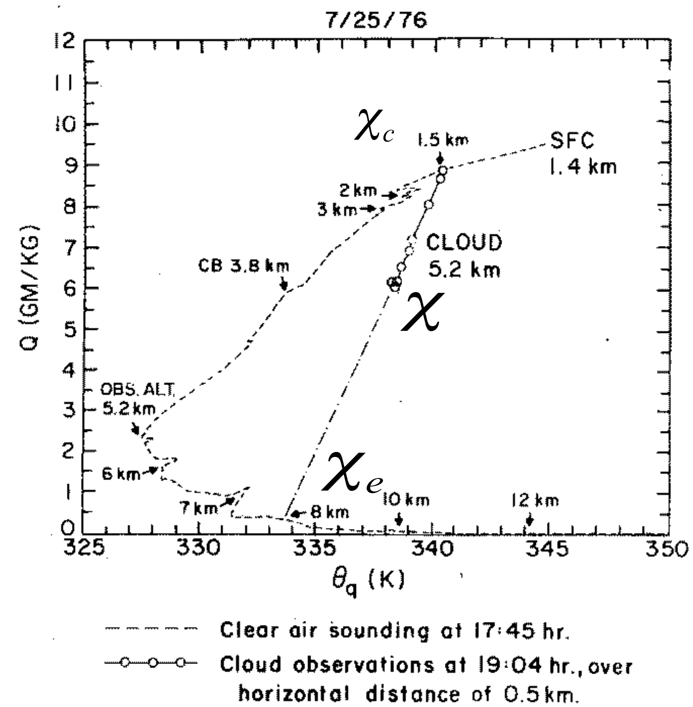


FIG. 4. Comparisons of the total mixing ratio Q and the wet equivalent potential temperature θ_q computed from data collected inside a growing cumulus cloud with Q and θ_q values of a representative sounding. The dashed line refers to the sounding; the points connected by lines represent the in-cloud observations. The data correspond to the first half-kilometer shown in Fig. 3. Air with the observed properties could have been formed by mixing air from the surface levels with air from ~8 km as indicated by the dot-dashed line. The observation level was 5.2 km (−2°C). Cloud base (CB) was at 3.8 km.

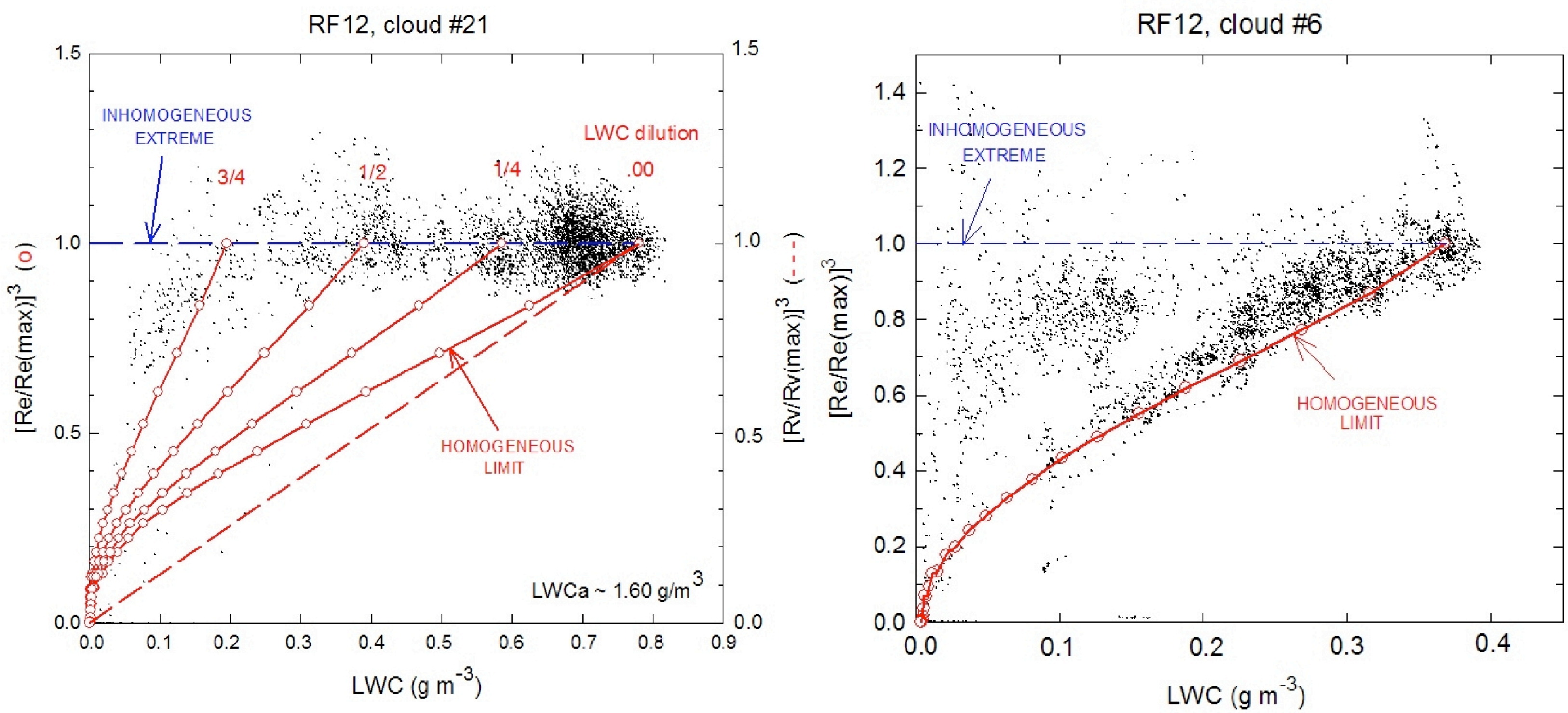
Paluch (1979)

Mixing in Shallow Cumulus: Implications for Cloud Droplets

- **Relevant time scales**:
  - $\tau_e=(1/R)(d R/d t)$ Droplet evaporation time scale
  - $\tau_t=(L^2/\varepsilon)^{1/3}$ Turbulent mixing time scale
- **Homogeneous mixing**: $\tau_e >> \tau_t$, Efficient turbulent mixing means that droplets are exposed to the same humidity and temperature. Sizes of individual droplets are reduced by evaporation. Spectral broadening from mixing line.
- **Extremely inhomogeneous mixing**: $\tau_t >> \tau_e$, Filaments of cloudy and non-cloudy air. Droplets inside and outside filaments experience different environmental conditions and may either have nearly adiabatic sizes or evaporate completely. Little spectral broadening, relatively large cloud droplets.

Cloud Droplet Sizes in RICO Shallow Cumulus

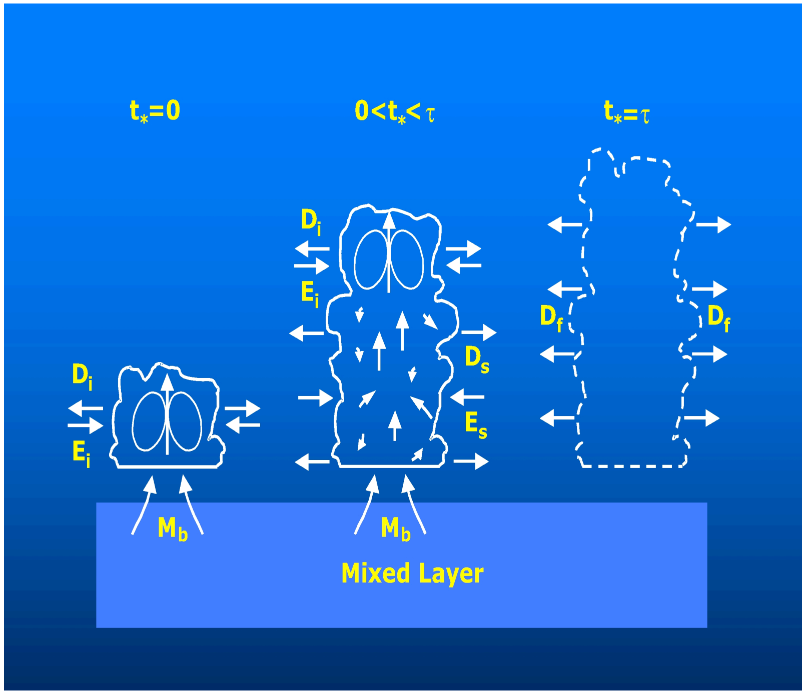
Inhomogeneous mixing   Homogeneous mixing



Gerber, 12th AMS Conference on Cloud Physics, Madison, 2006

Parameterization of Shallow Convection in CCCma AGCM4

- Based on continuity equations for mass, energy, and vertical momentum
- Idealized cumulus lifecycle with variable cloud top heights
- Lateral and cloud-top mixing processes
- Non-homogenous clouds: Probability distributions of cloud properties
- Simple warm microphysics (no precipitation processes)
- Suitable for cloud droplet nucleation parameterizations



von Salzen and McFarlane (2002)
von Salzen et al. (2005)

GCM Sensitivity Experiments for Shallow Convection

- Combination of new approach for cloud droplet nucleation with shallow cumulus parameterization to test effects of different assumptions about mixing between cloud core and environment on cloud droplets.
- Prognostic calculation of vertical profiles of cloud droplet size distributions for cloud core conditions. Parameterization of droplet size for mixed cloudy air.
- Prognostic sulphate and sea salt aerosol size distributions based on PLA approach (simplified):

  $SO_4^=$: Binary homogeneous nucleation H_2SO_4/H_2O; Condensation of H_2SO_4, NH_3, H_2O; gravitational settling; cloud removal; in-cloud production (bulk); transport

  Sea salt: Ocean production (Lewis and Schwartz, 2004); gravitational settling; cloud removal; transport

- No feedbacks of simulated cloud droplets on climate yet.

GCM Sensitivity Experiments for Shallow Convection

- **HOM: Homogeneous mixing:** Variable cloud liquid water content and droplet concentration (mixing line)

$$\mathrm{LWC} = \mathrm{LWC_c} + \frac{d\,\mathrm{LWC}}{df} f$$

$$\mathrm{CDNC} = \mathrm{CDNC_c} + \frac{d\,\mathrm{CDNC}}{df} f$$

Mean cloud properties

$$\langle \mathrm{CDNC} \rangle = \int_{f=0}^{1} \mathrm{CDNC}\; p(f)\, df$$

$$\langle r_{eff} \rangle = \beta \int_{f=0}^{1} (\mathrm{LWC/CDNC})^{1/3}\; p(f)\, df$$

- **INHOM: Extremely inhomogeneous mixing:** Adiabatic, cloud-core conditions for cloud droplet size

$$\langle \mathrm{CDNC} \rangle = \int_{f=0}^{1} \mathrm{CDNC}\; p(f)\, df$$

$$\langle r_{eff} \rangle = \beta\, (\mathrm{LWC_c/CDNC_c})^{1/3}$$

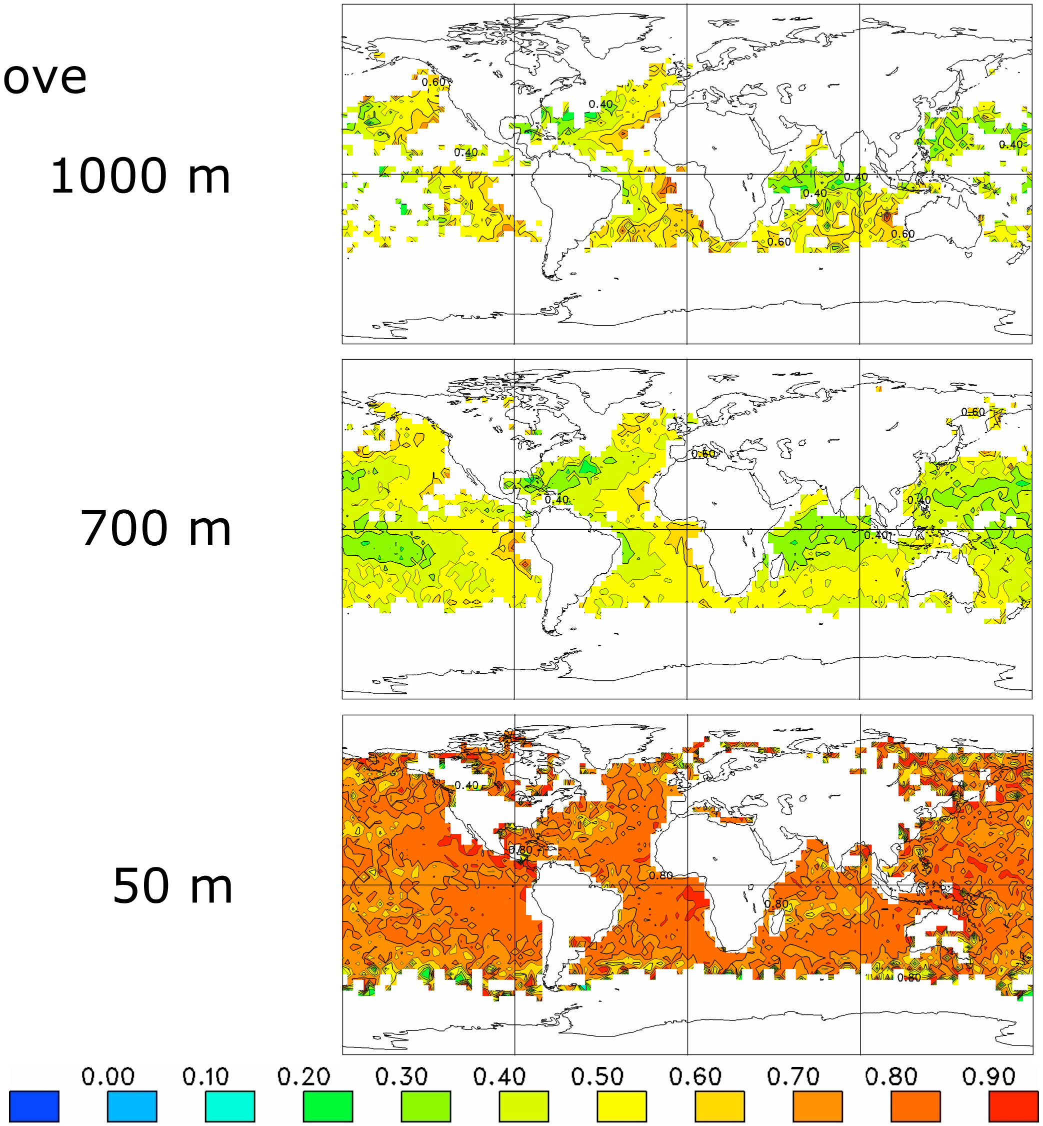
Adiabatic Fraction in Simulated Shallow Cumulus (JJA)

Distance above cloud base:

1000 m

700 m

50 m

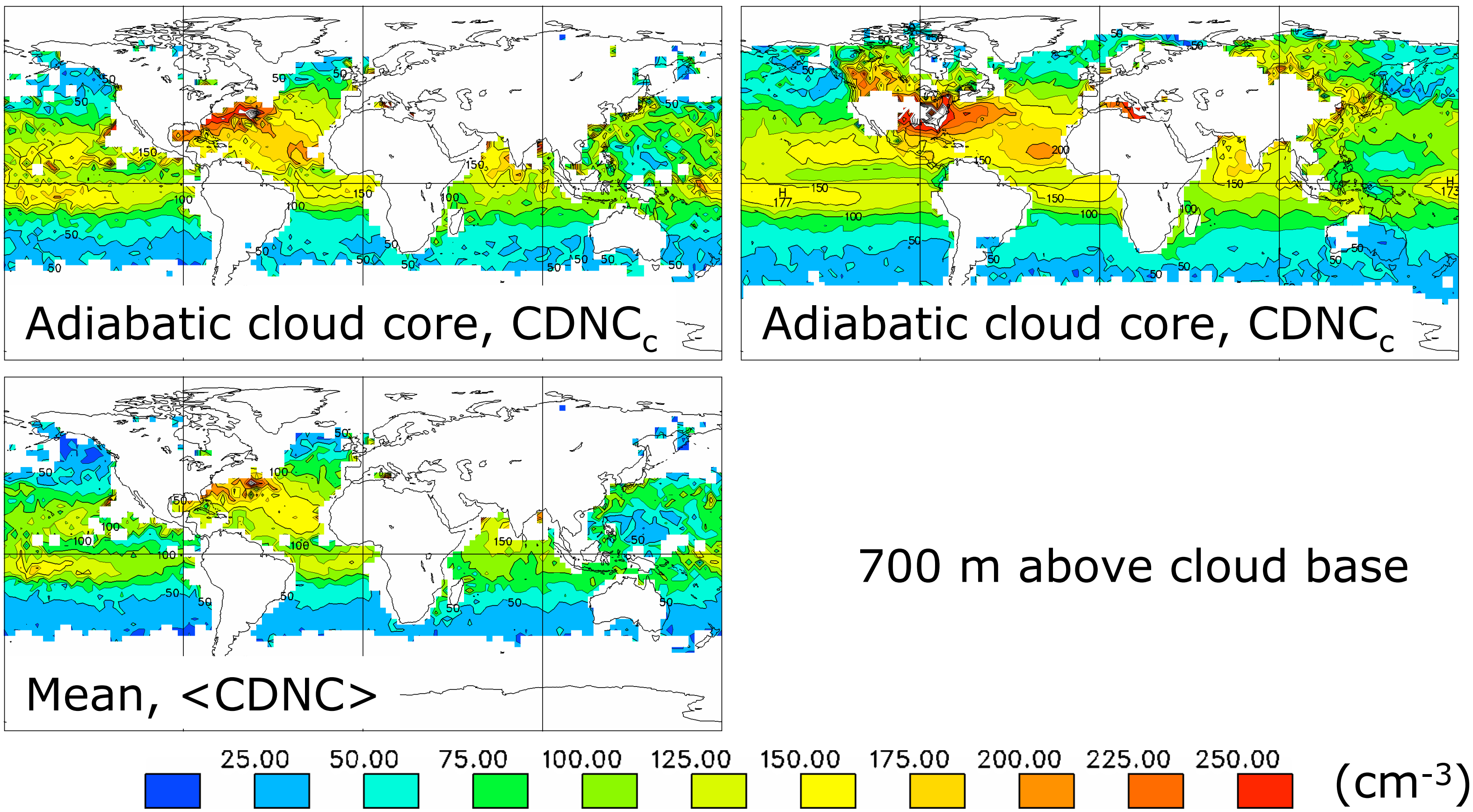


$$\frac{LWC}{LWC_a}$$

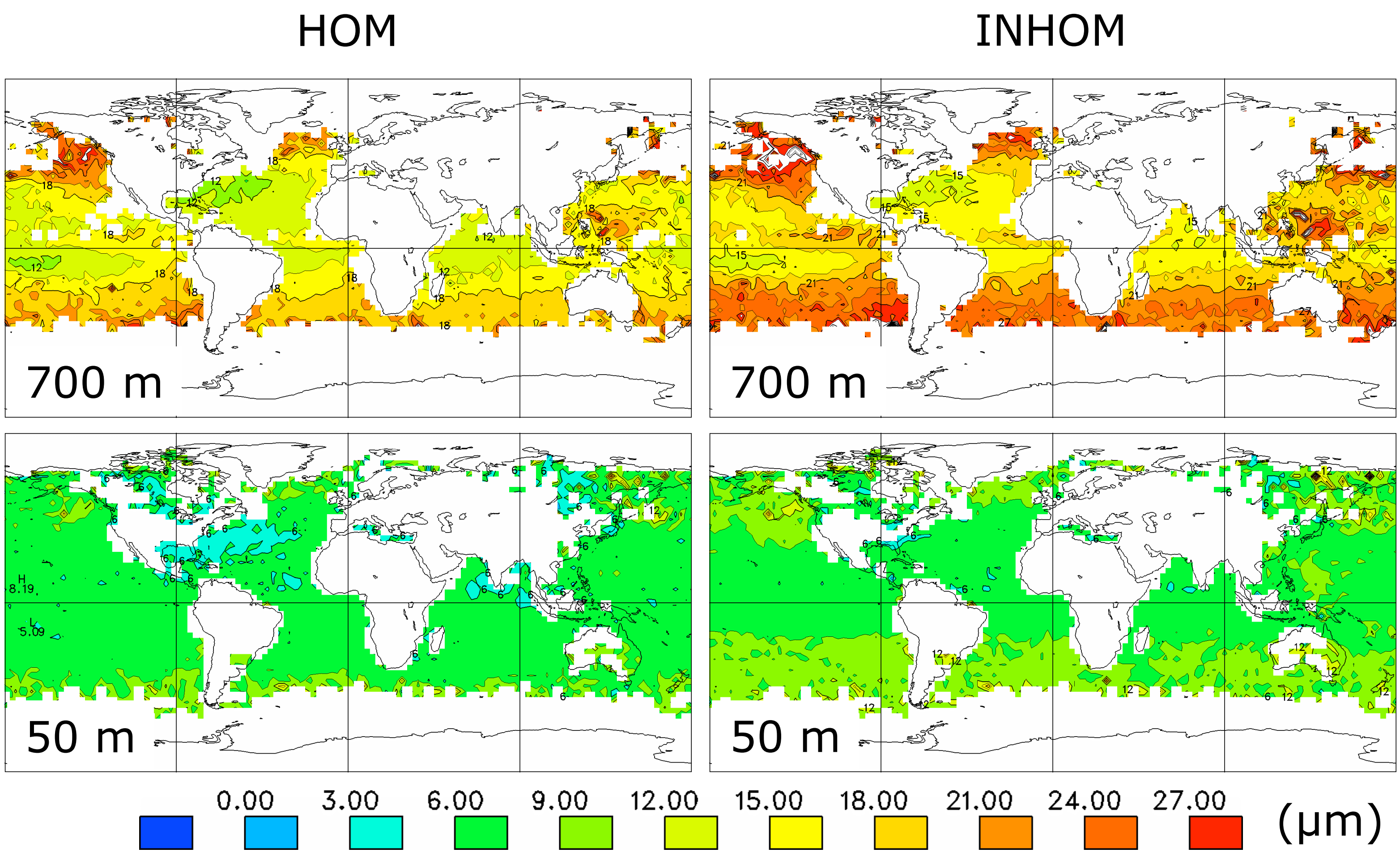
Cloud Droplet Number Concentration (JJA)

New approach for cloud droplet nucleation

Nenes and Seinfeld (2003) (modified for PLA method)



Mean Cloud Droplet Effective Radius (JJA)



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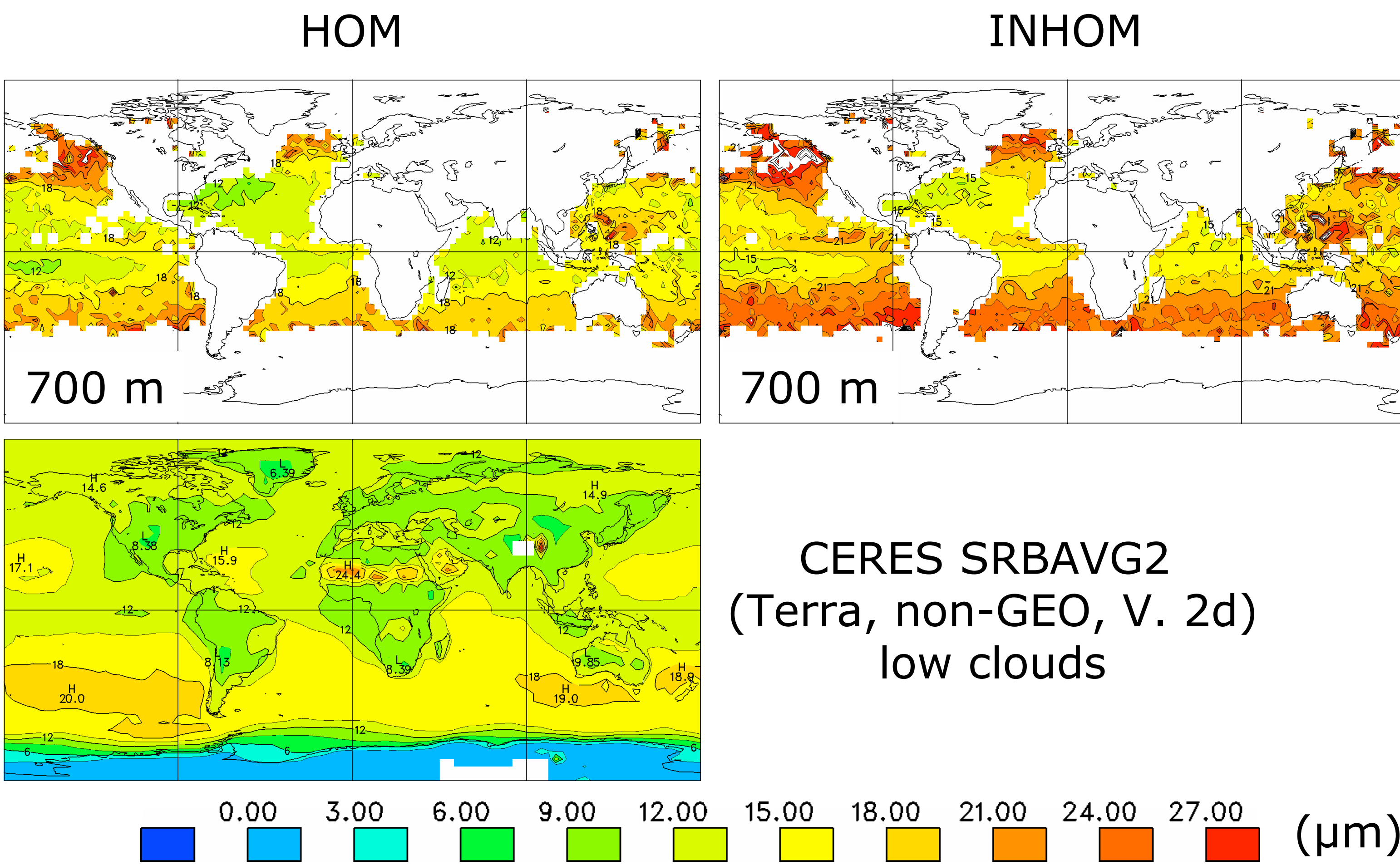
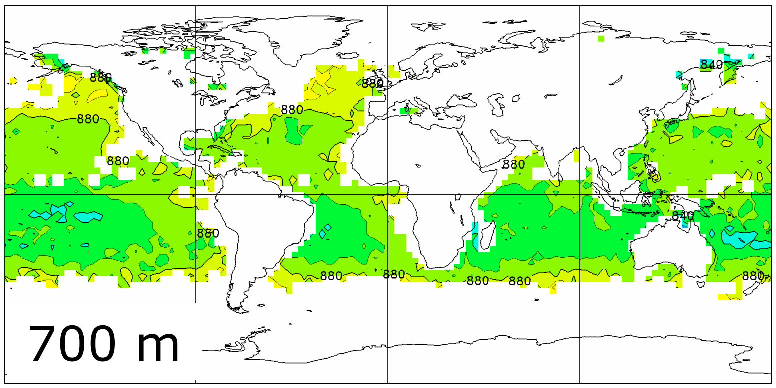
Mean Cloud Droplet Effective Radius (JJA)

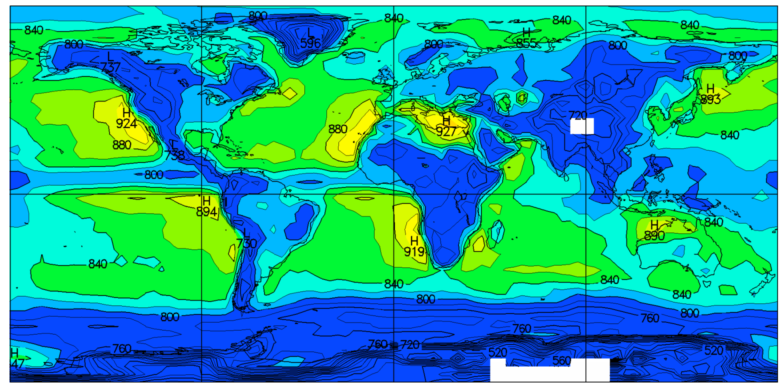


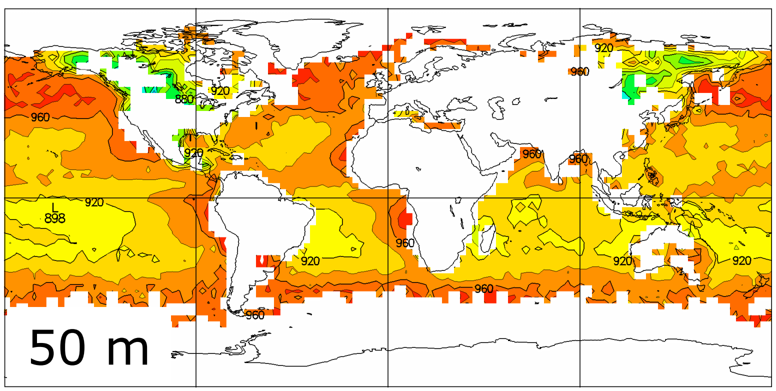
Cloud Top Pressure (JJA)

GCM
Shallow convection

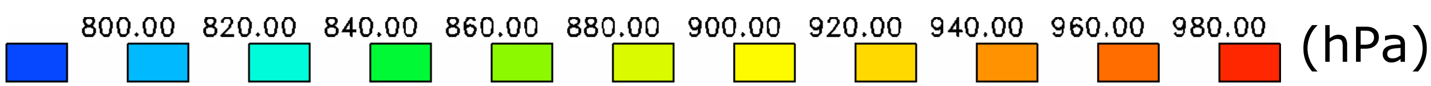
CERES SRBAVG2
(Terra, non-GEO, V. 2d)
low clouds







How to compare results for r_{eff} for variable cloud tops and different types of clouds?



Conclusions

- Empirically based parameterizations of CDNC and aerosol indirect effects are inherently uncertain in GCMs.
- Currently available first principles based parameterizations of CDNC are considerably more realistic but assumptions of adiabatic conditions and steady updrafts are not yet fully evaluated.
- GCM simulations for simplified aerosol cycles give evidence for sensitivity of shallow cumulus cloud droplet sizes to entrainment mixing assumptions.
- Role of shallow cumulus cloud droplet sizes for radiation and climate still needs to be addressed in GCM.
- Future GCM studies for stratiform clouds, including fog.
- Ideally, studies of cloud droplet size should distinguish between different types of clouds and cloud vertical extend (e.g. cloud-type specific diagnostics from CERES for model validation? Field experiment comparisons?).

The End