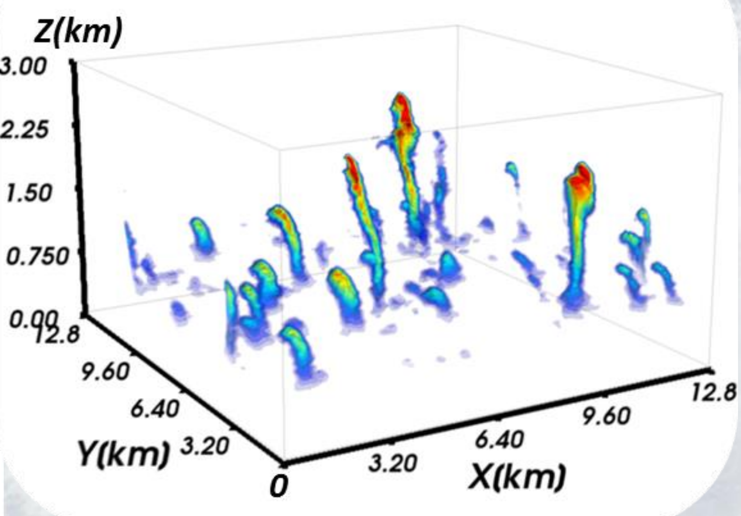
Microphysics of shallow cumulus clouds in LES simulations for testing the new COSMO parametrization



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Thanks to:
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COSMO User Seminar, Offenbach, March 2017

Outline

1. Motivation
2. COSMO new parametrization of SGS cloud properties (for radiation)
3. LES simulations
   A. Simulations design
   B. How should LWC, NC and Reff behave with height?
      - Schematic explanation
   C. Possible parametrization of Reff(z)?
      - Example of simulation results for 5000 CCN cm^{-3}
      - Reff(z) for different simulations
   D. Possible parametrization of averaged LWC(z)?
      - Averaged profiles of LWC, NC and Reff
      - Estimation of averaged LWC profile
4. Next steps

Motivation

- Shallow cumulus are extremely important to radiation budget
- In COSMO these clouds are subgrid, liquid water content in grid points is zero!
- To estimate radiation transfer, we need the optical properties of subgrid clouds
- To calculate them we need the profiles of
    1. Cloud cover (CLC)
    2. Liquid water content (LWC)
    3. Effective radius of droplets (Reff)

- Question: How to estimate 1,2,3 ?
- There are 2 options:
    - Already in the COSMO model (new scheme by U. Blahak):
        - CLC from the relative humidity at a grid point
        - LWC from saturation mixing ratio at a grid point
        - Reff from droplets number concentration (NC) and LWC
    - LES simulation with detailed (Spectral-Bin) microphysics:
        - Simulate shallow cumulus explicitly for different stratifications and aerosols concentrations
        - Average the profiles of CLC, LWC, Reff over space and time to mimic COSMO resolution

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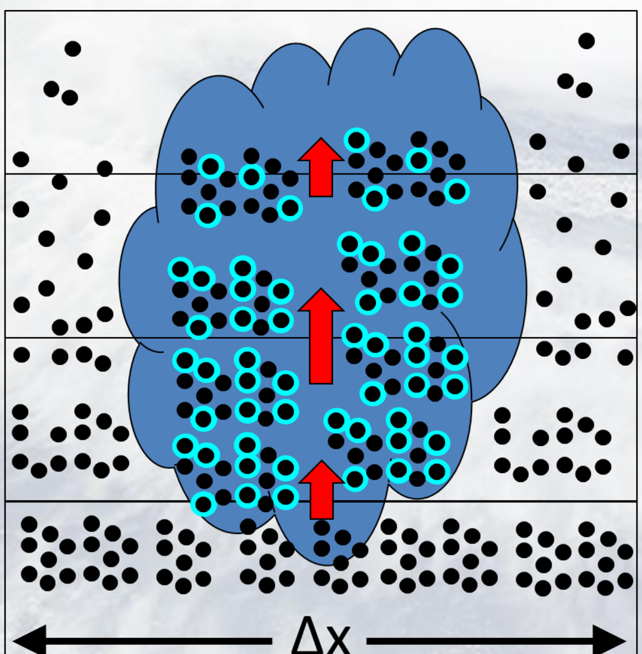
COSMO new scheme (by U. Blahak)

Aerosol concentration clim. profile
(derived from Tegen et al. 1997)

+

Effective updraft speed profile
(including turbulence, radiative cooling and parameterized convection)

Cloud droplets concentration profile
(from Segal & Khain 2006)



Subgrid clouds Liquid Water Content profile
(assuming proportionality to saturation mixing ratio)

Subgrid clouds effective radius profile

$$R_{eff}(z) = \alpha\left(\frac{LWC}{N_c}\right)^{\beta}$$

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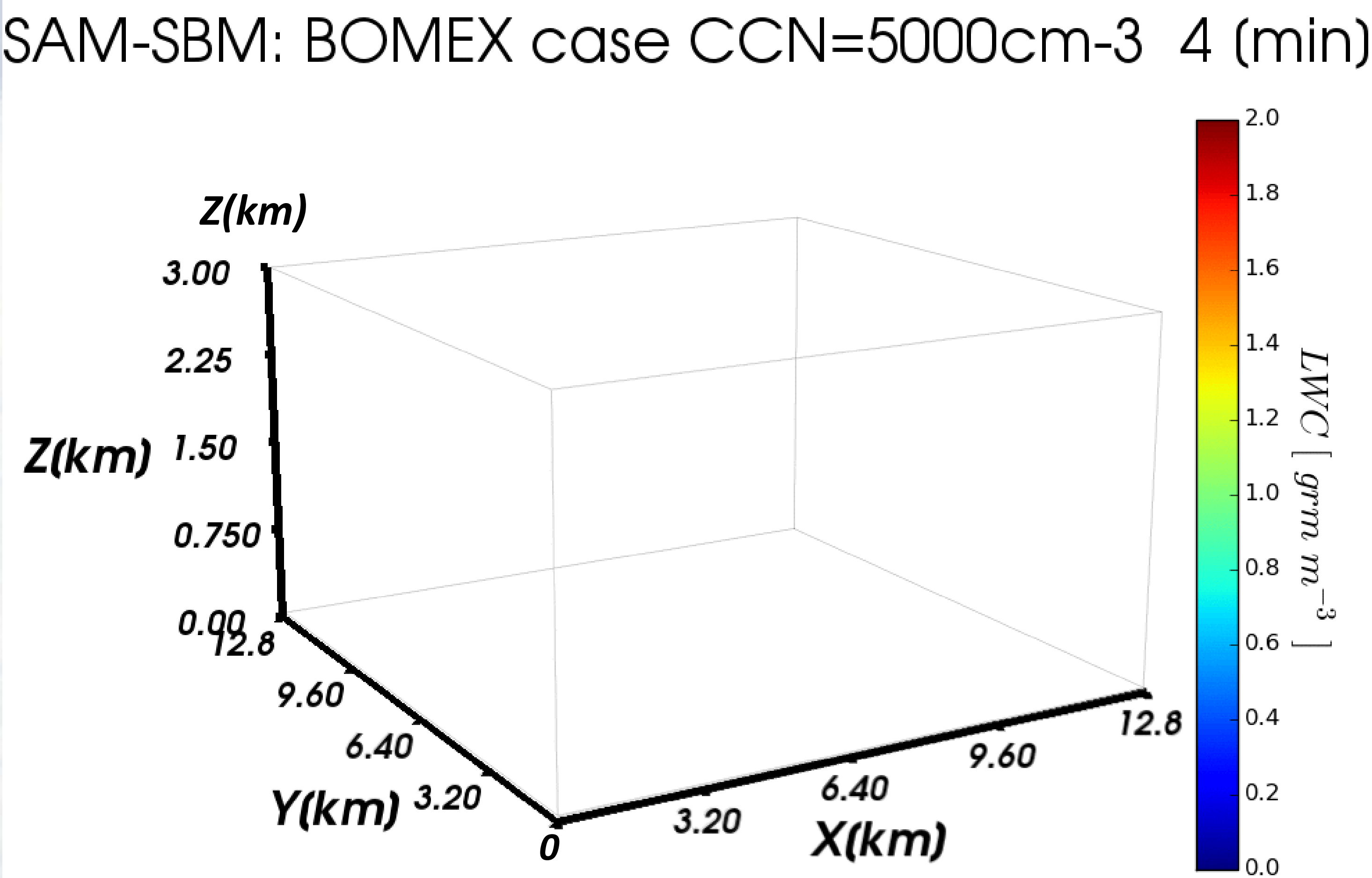
Simulations design

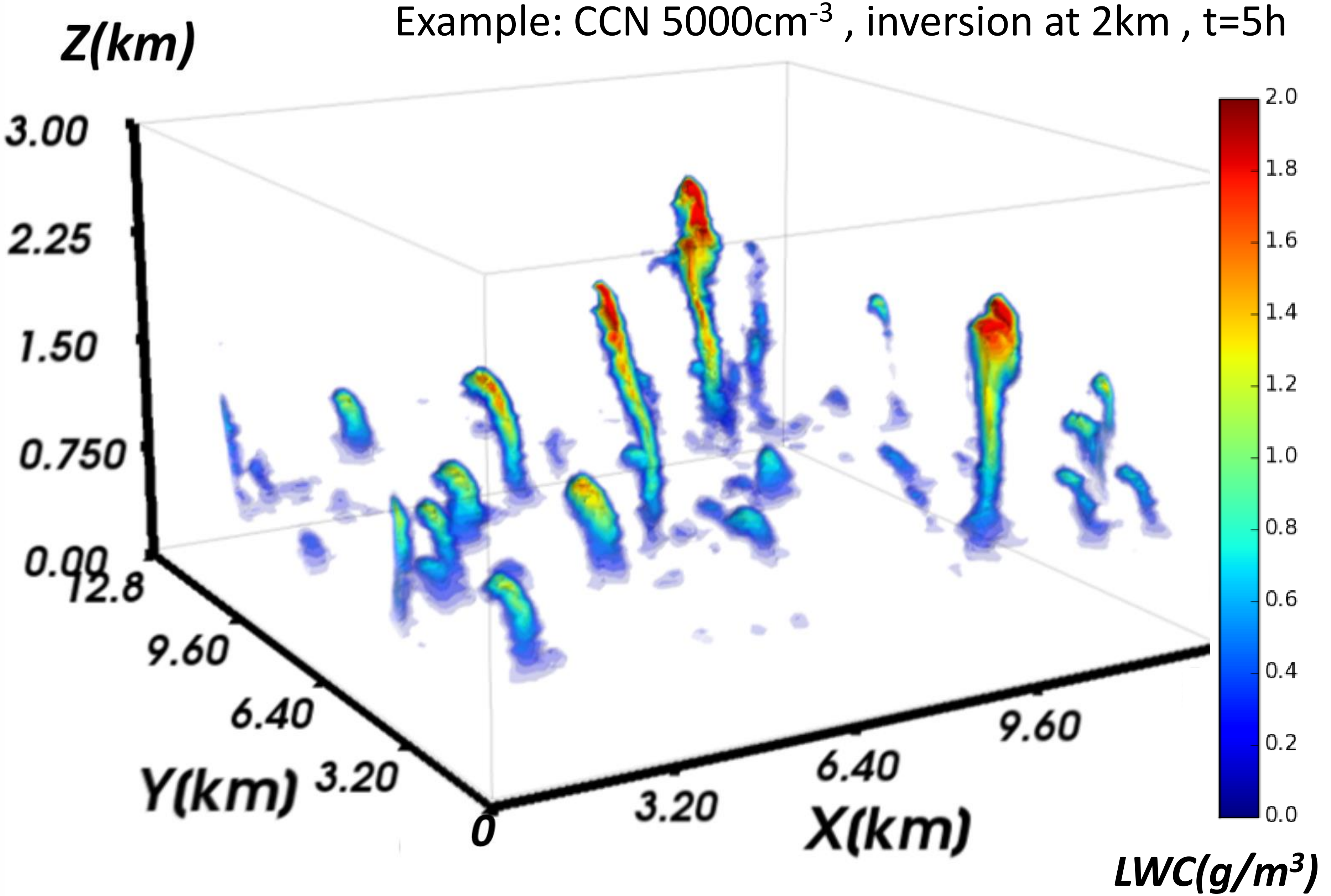
- System for Atmospheric Modelling (SAM) (Khairoutdinov and Randall, 2003) is used to conduct LES simulations (http://rossby.msrc.sunysb.edu/~marat/SAM.html)
- Nonhydrostatic, anelastic, cyclic horiz. boundary conditions, maintaining temp. & moisture gradients at model top
- Microphysics: Spectral-Bin (Khain et al., 2013) with 33 mass bins for drops (radii from 2μm to 3.2mm) to simulate warm processes: droplet nucleation, diffusional growth, collision coalescence, sedimentation, breakup
- Resolution: horiz. 100m, vertical 40m, time step: 1s, runtime: 8h. Domain: 12.8 X 12.8 X 5.1km
- Initial temp. perturbations near the surface at first time step
- Simulated case: Barbados Oceanographic and Meteorological Experiment (BOMEX) (Siebesma et al., 2003) – trade wind cumulus cloud field
- Aerosols: different size distributions (from 100 to 5000 cm^{-3}), where only the large size tails are activated in cumulus

Shallow cumulus simulations



Shallow cumulus simulations

Example: CCN 5000cm^{-3} , inversion at 2km , t=5h



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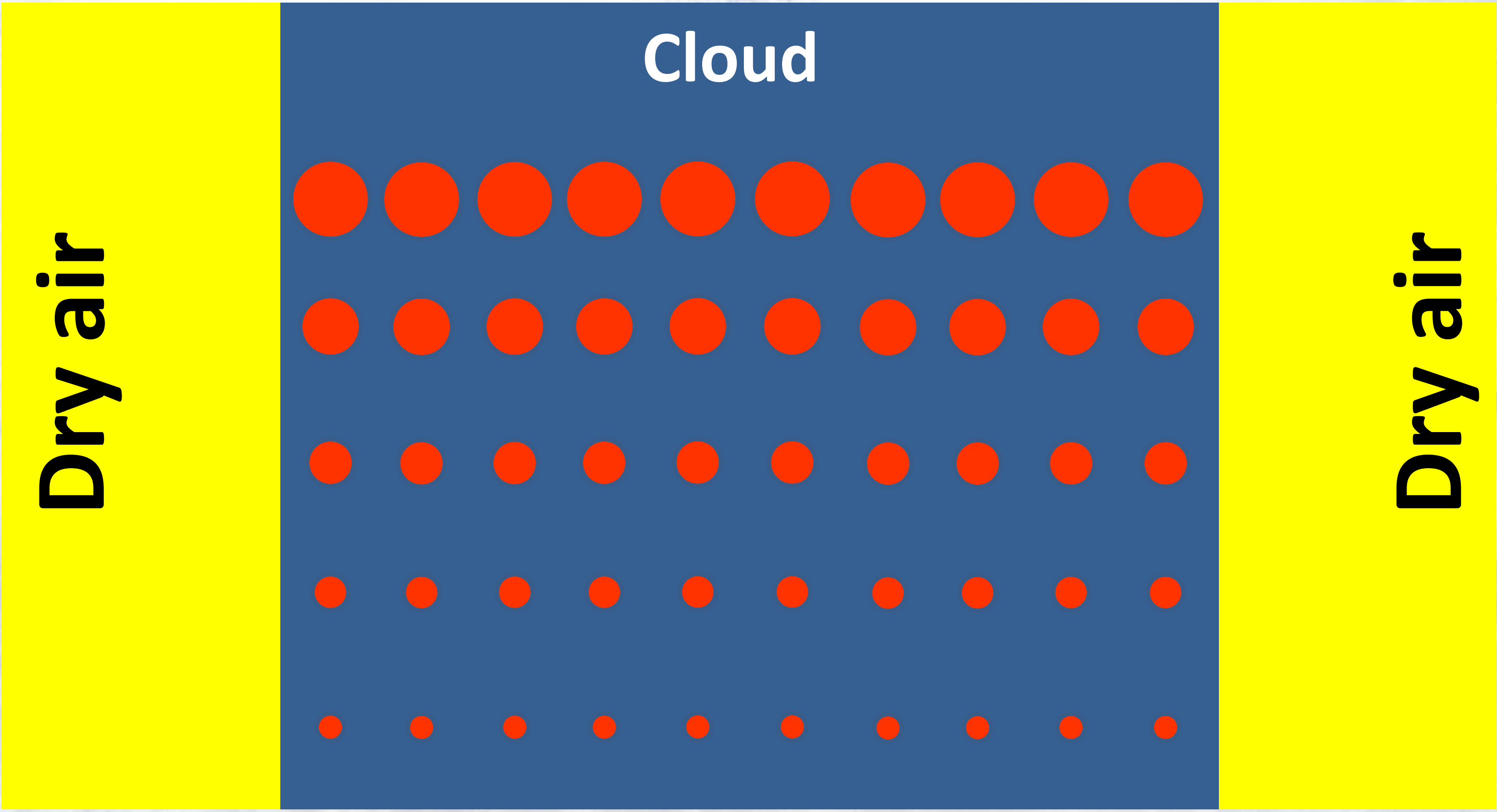
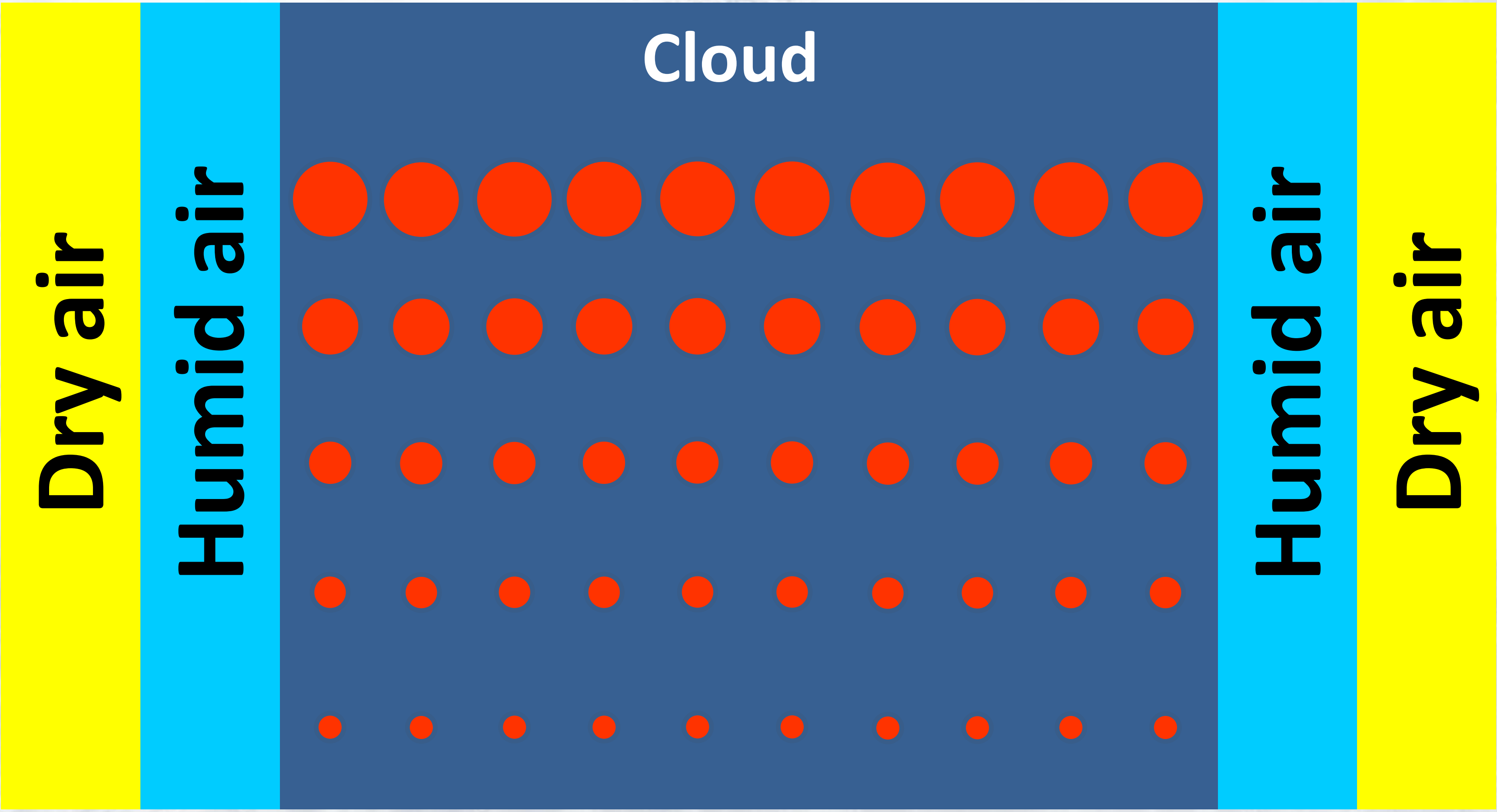
1. Assume no mixing with surrounding

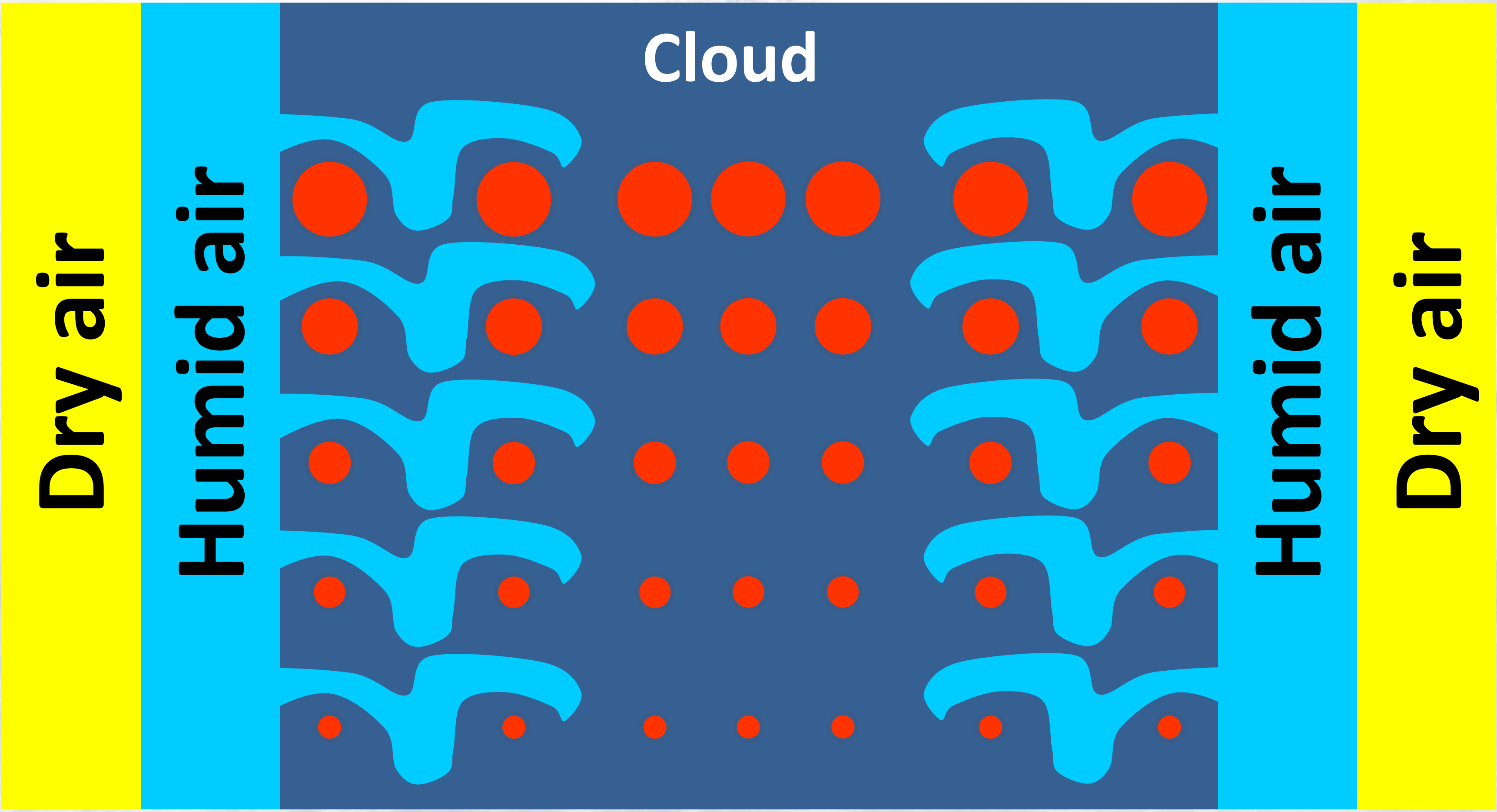
- The droplets are growing with height (diffusional growth)
- The number concentration stays similar with height
- *Each droplet represents size distribution !



2. Air close to the cloud is very humid



3. Entrainment leads to decreasing droplets concentration, keeping their size ~constant



4. Neglecting the dissipation at cloud top…

Height dependence?

LWC – increase with height

NC – stay more or less constant

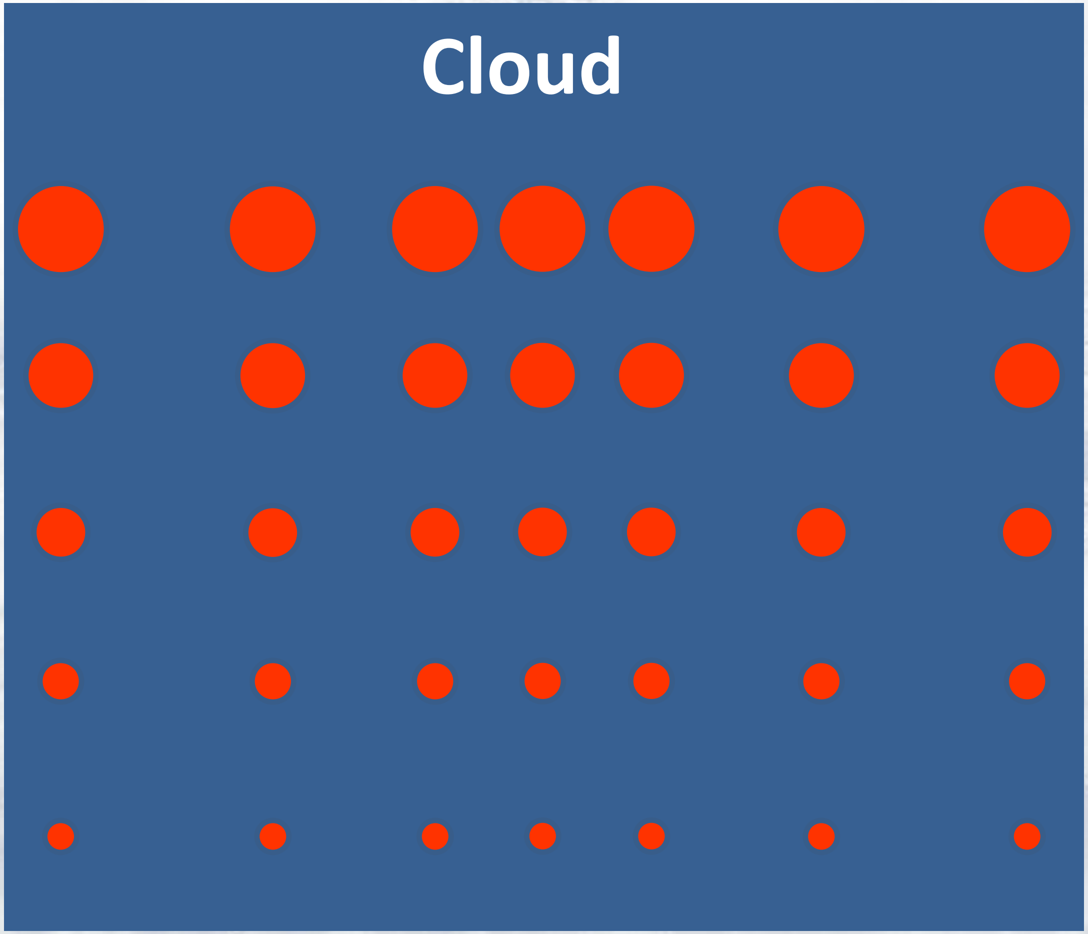
Reff – increase with height

Horizontal dependence?

LWC – big variation

NC – big variation

Reff – small variation



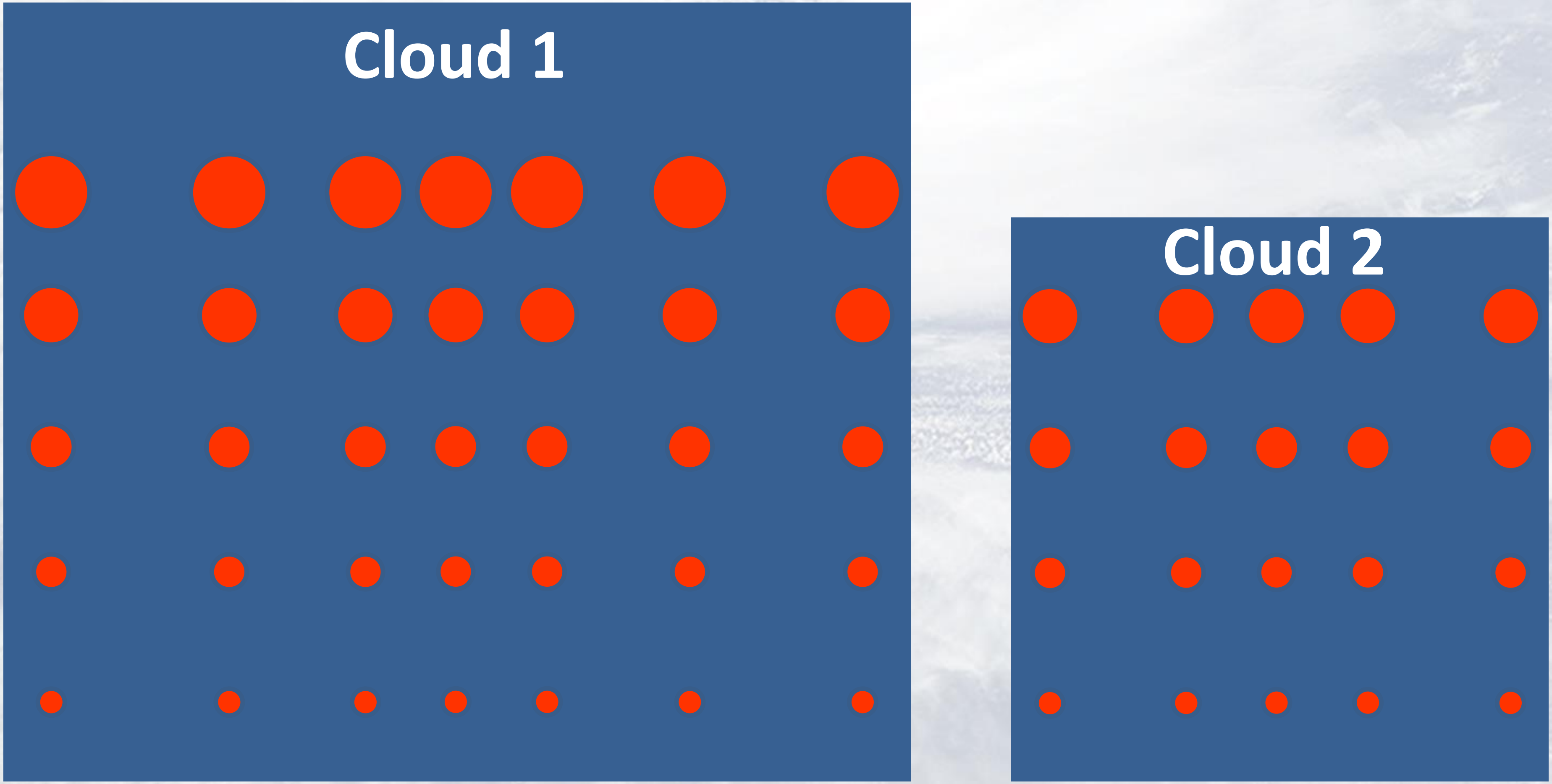
On average over many cloudy grid-points?

Height dependence?

LWC – increase with height
NC – stay more or less constant
Reff – increase with height

Horizontal dependence?

LWC – big variation
NC – big variation
Reff – small variation



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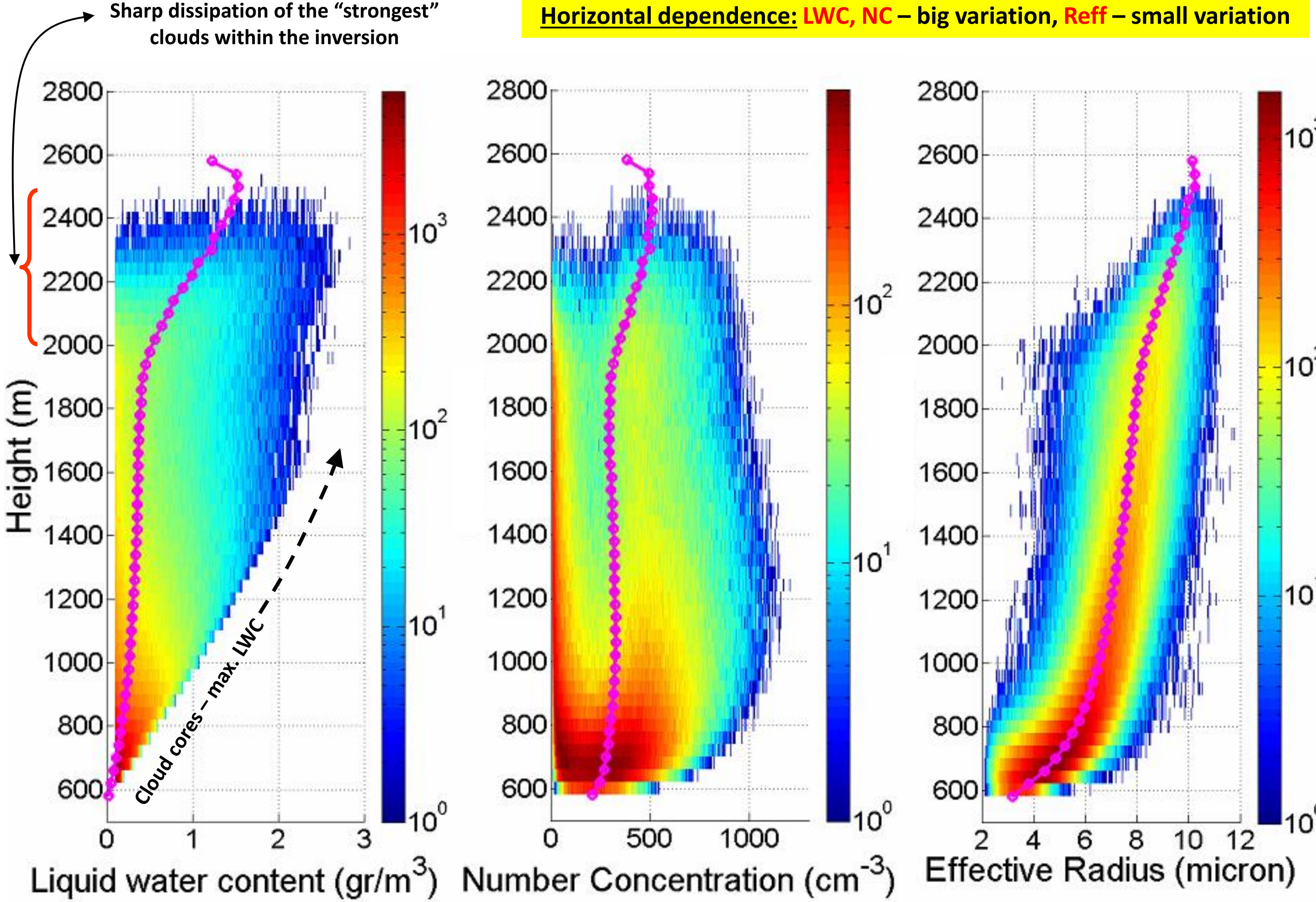
Example of simulation results for 5000 CCN cm^{-3} :

scatter over all grid points and times

— Averaged (over space and time) **profiles**

color: number of grid points (log scale)

<u>Horizontal dependence:</u> LWC, NC – big variation, Reff – small variation



Possible parametrization of the Effective Radius ?

Everywhere in the cloud:

$$LWC(z) = \frac{4\pi\rho_w}{3} NC(z) \left(\frac{R_{eff}(z)}{1.08}\right)^3$$

Specifically, in cloud core:

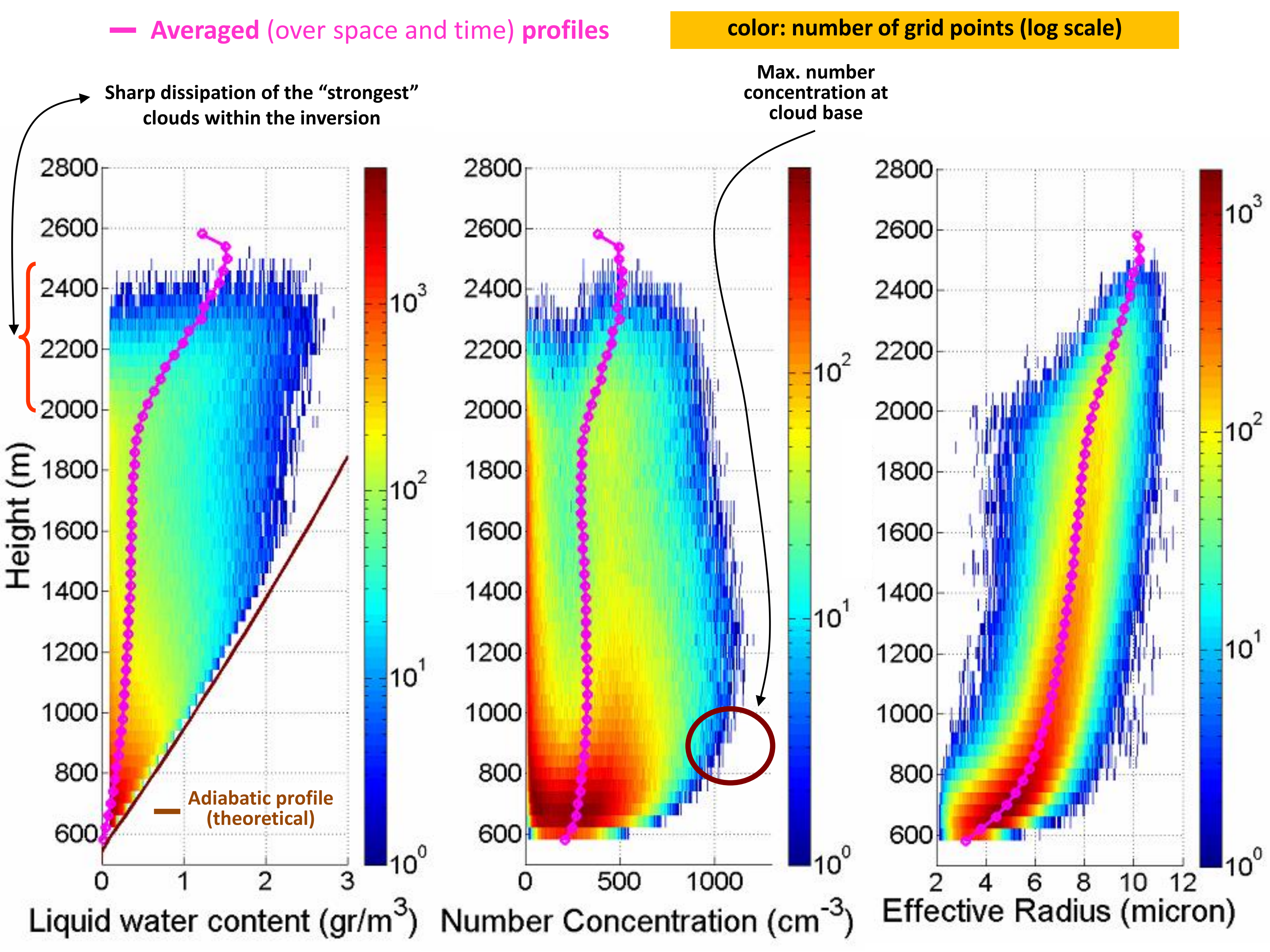
$LWC(z) \approx LWC_{adiab}(z)$

$\mathrm{NC}(z) \approx const \approx NC_{cloud\ base}$

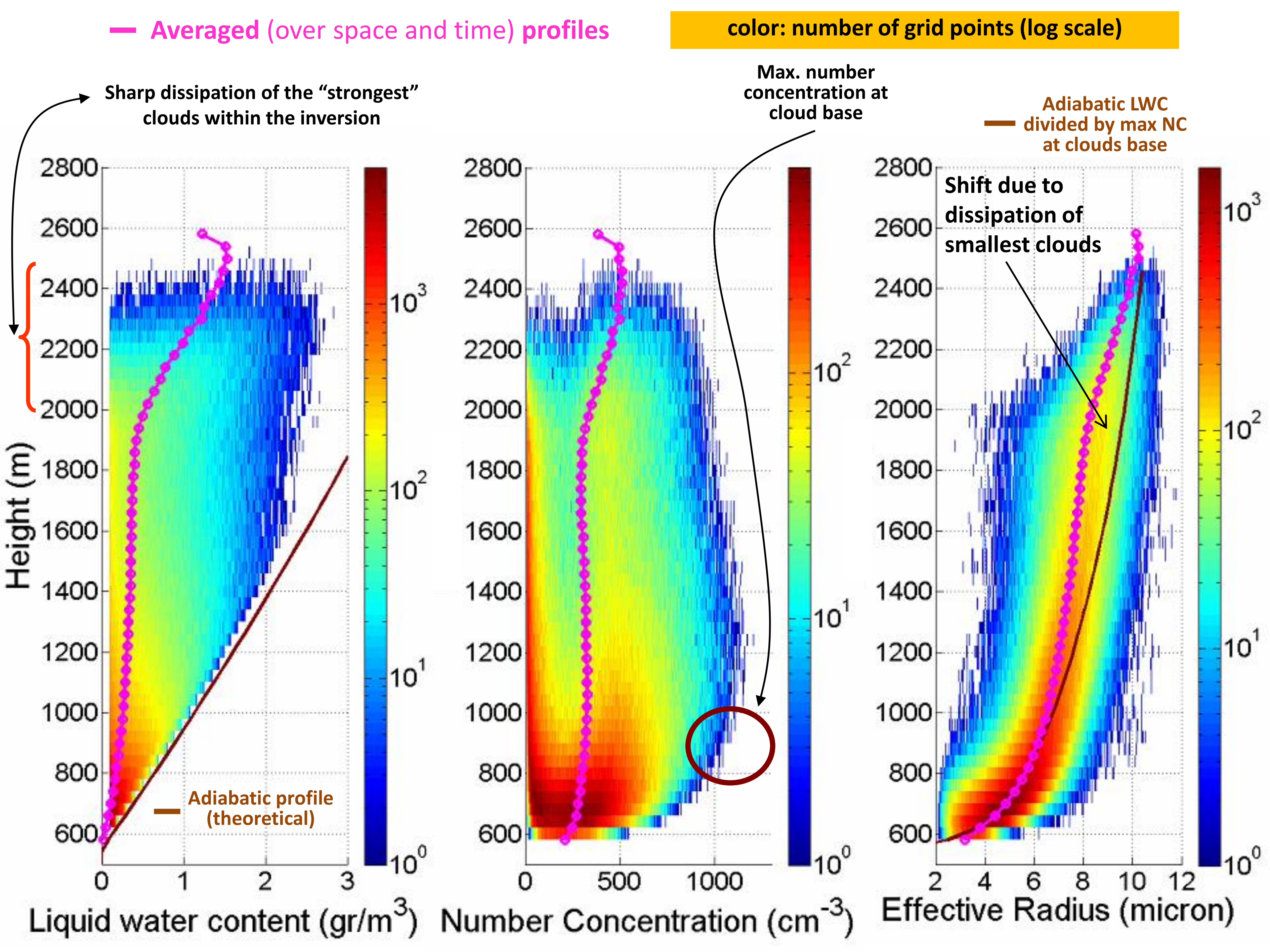
from Segal & Khain 2006

$\mathrm{Reff}(z) \approx \overline{\mathrm{Reff}(z)}$

$$\Rightarrow \quad \overline{R_{eff}(z)} \approx 1.08 \left(\frac{LWC_{adiab}(z)}{\frac{4\pi\rho_w}{3} NC_{cloud\ base}}\right)^{1/3}$$



Averaged (over space and time) profiles
color: number of grid points (log scale)
Sharp dissipation of the "strongest" clouds within the inversion
Max. number concentration at cloud base
Adiabatic profile (theoretical)
Height (m)
Liquid water content (gr/m3)
Number Concentration (cm-3)
Effective Radius (micron)



Averaged (over space and time) profiles
color: number of grid points (log scale)
Sharp dissipation of the "strongest" clouds within the inversion
Max. number concentration at cloud base
Adiabatic LWC divided by max NC at clouds base
Shift due to dissipation of smallest clouds
Adiabatic profile (theoretical)
Height (m)
Liquid water content (gr/m^3)
Number Concentration (cm^{-3})
Effective Radius (micron)

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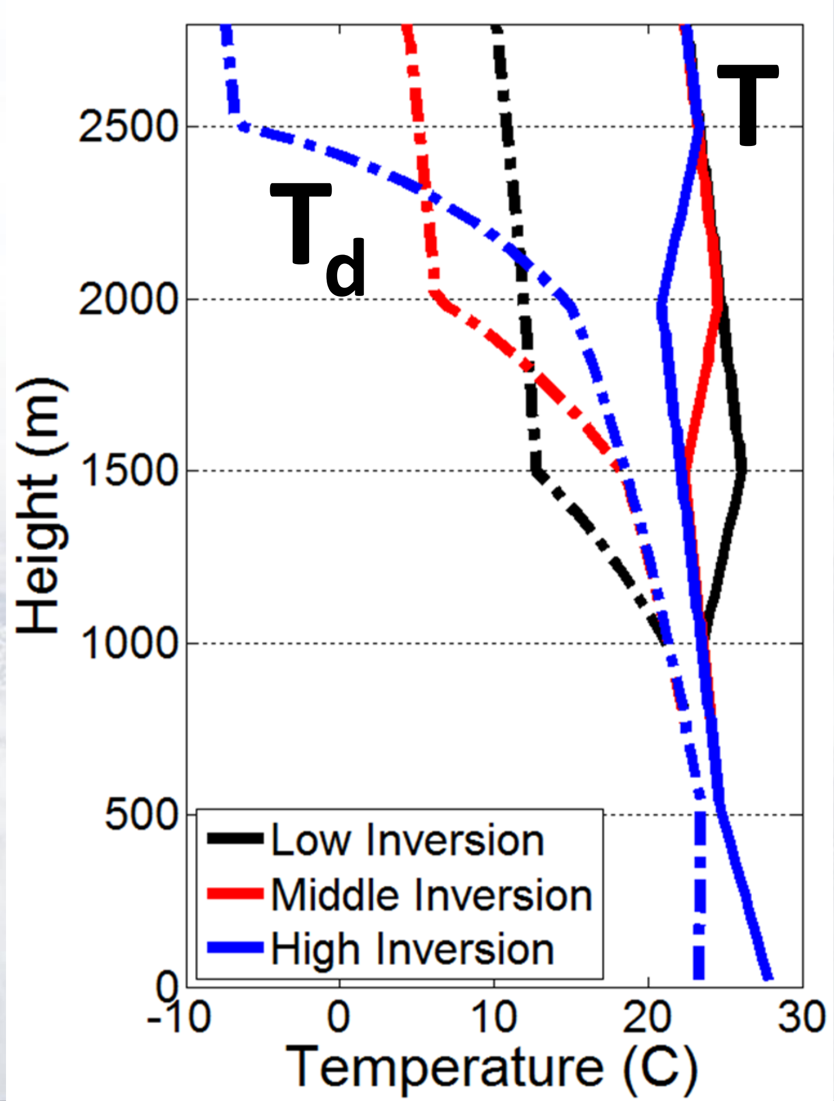
Simulations at different conditions

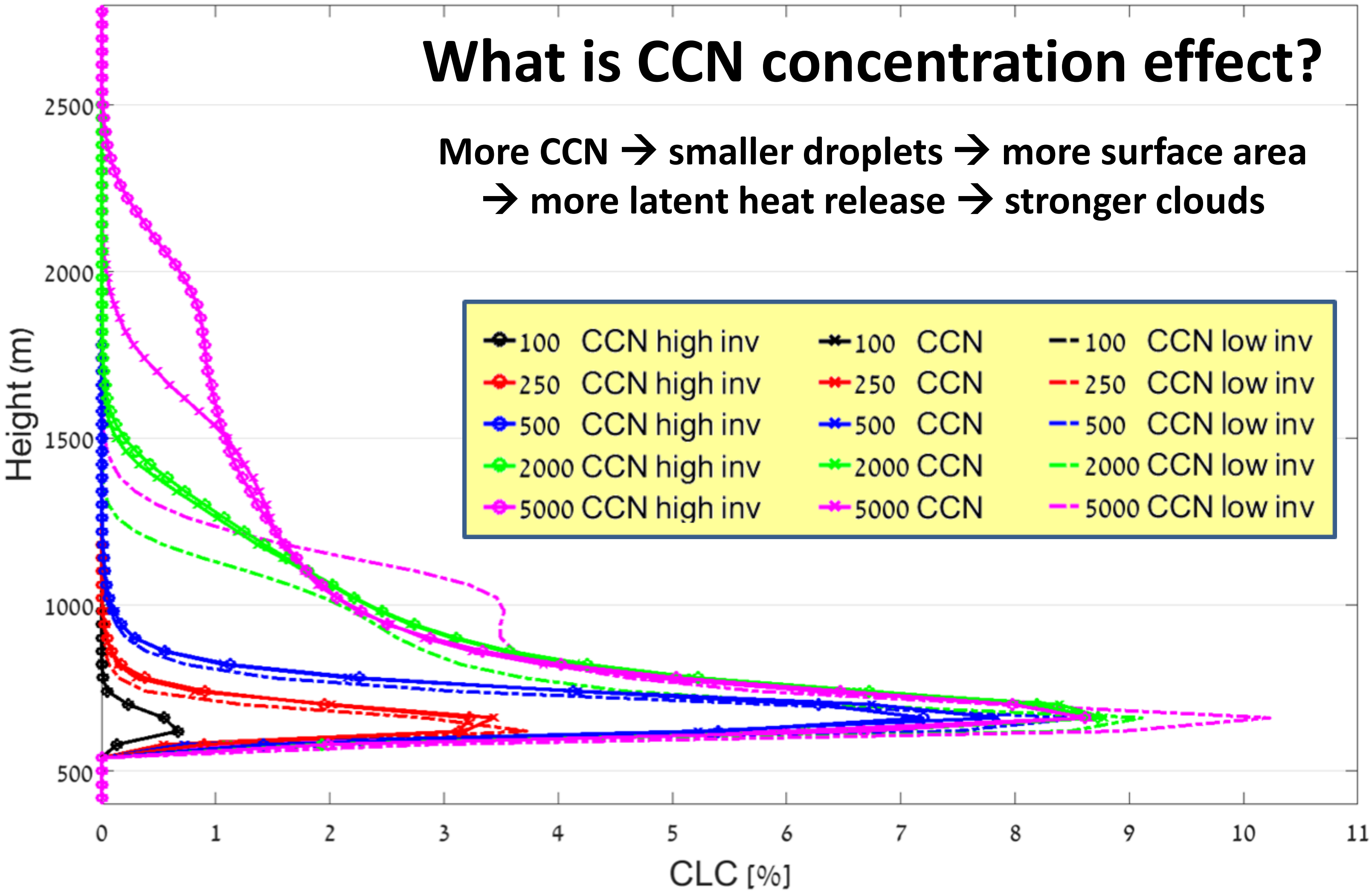
- **CCN concentrations of 100, 250, 500, 2000, 5000 cm^{-3}**

  (Only the tails of the CCN distributions are activated)

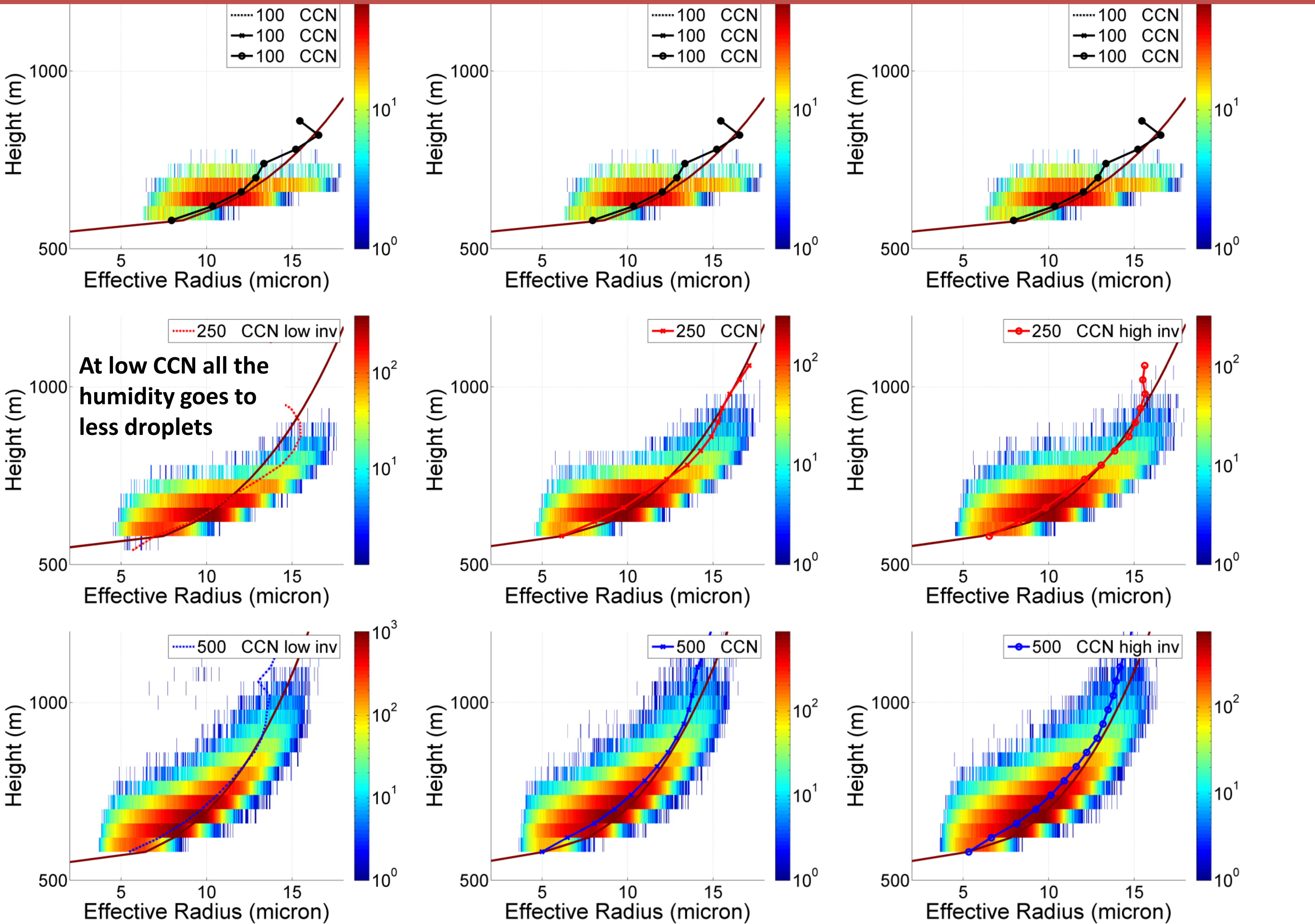
- **3 different stratifications (inversion at 1000m, 1500m, 2000m)**



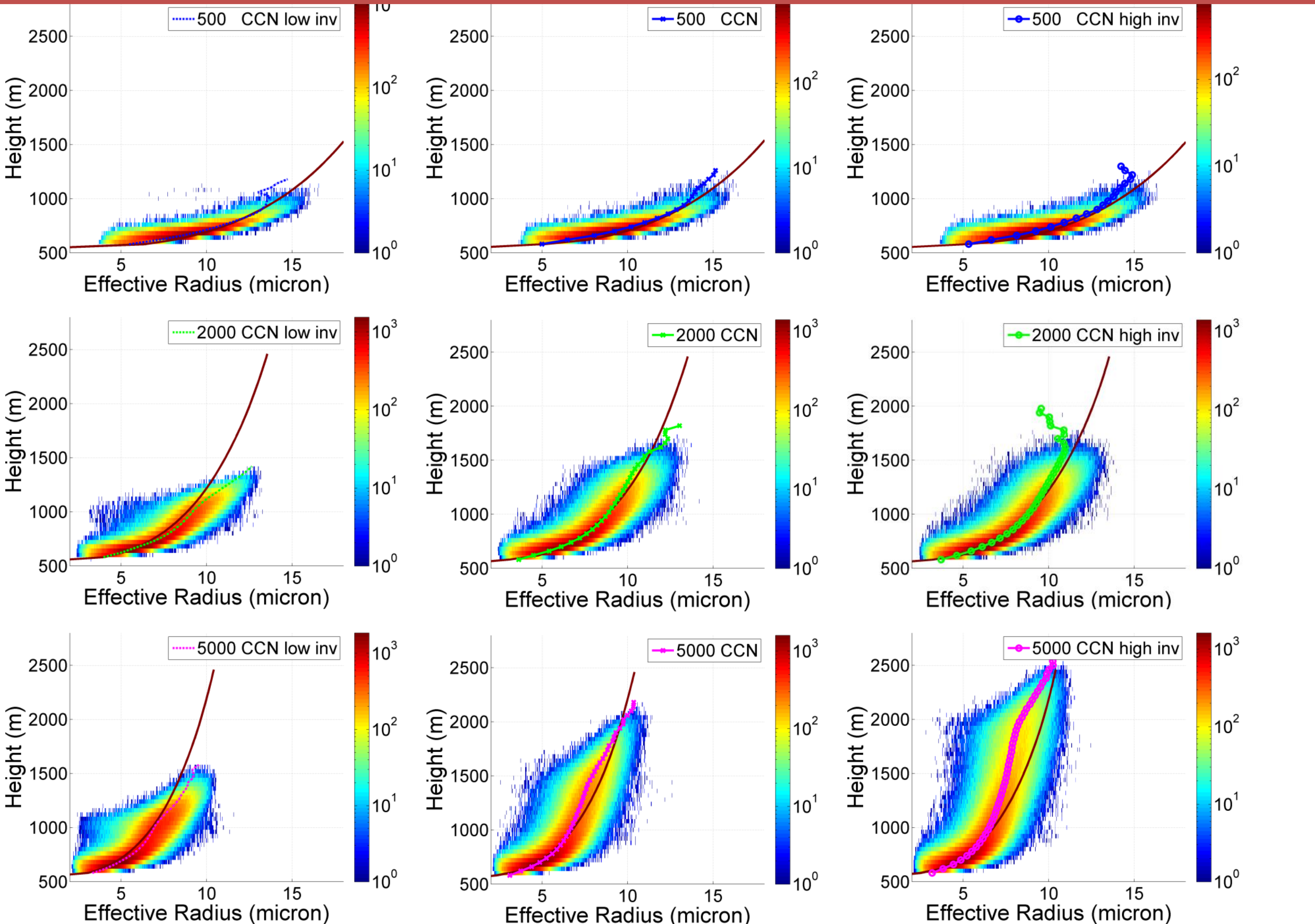
Cloud Cover averaged profiles



Effective radius profiles for low CCN concentrations



Effective radius profiles for high CCN concentrations



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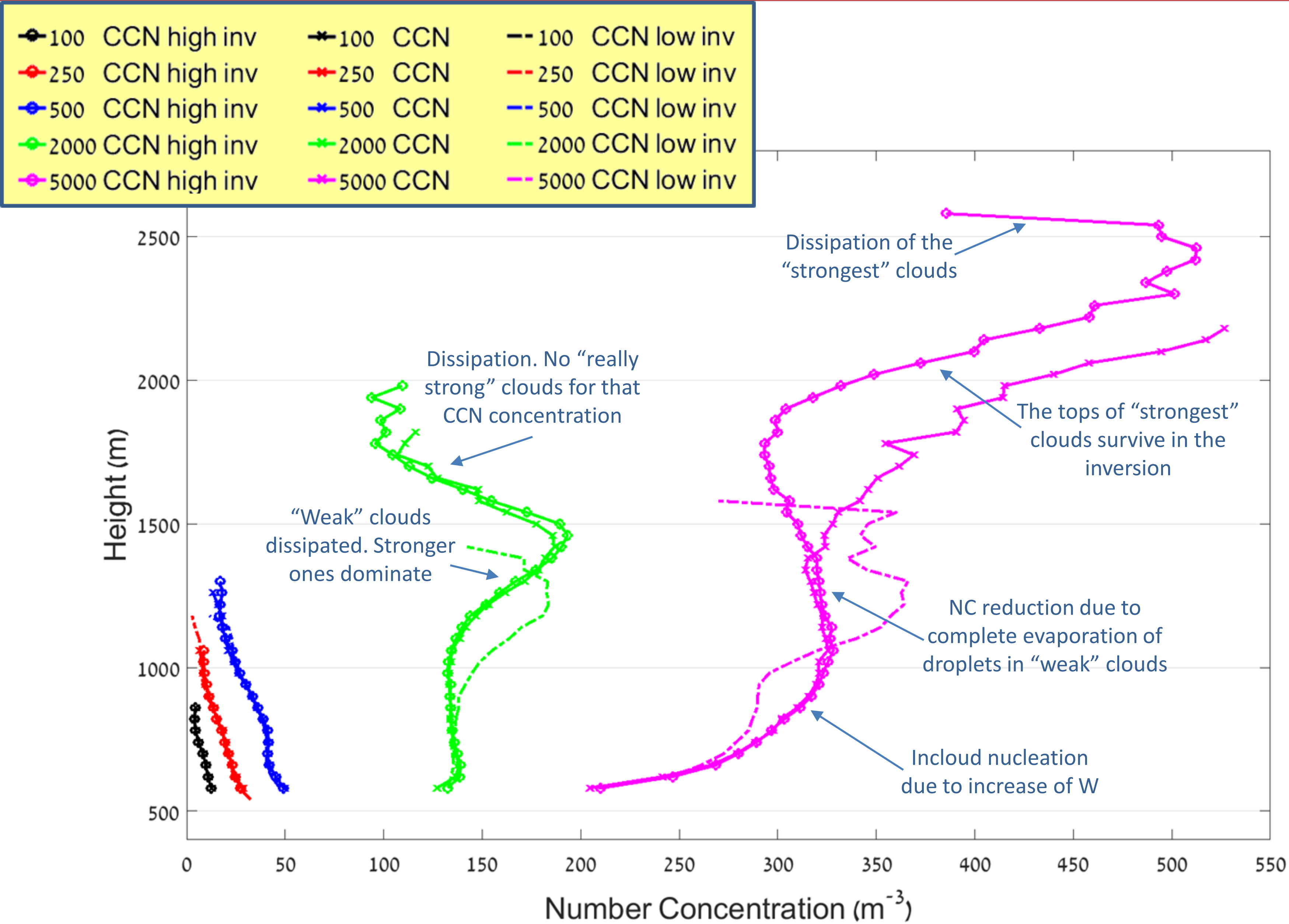
Suppose we are able to estimate averaged Reff profile from given stratification and CCN concentration

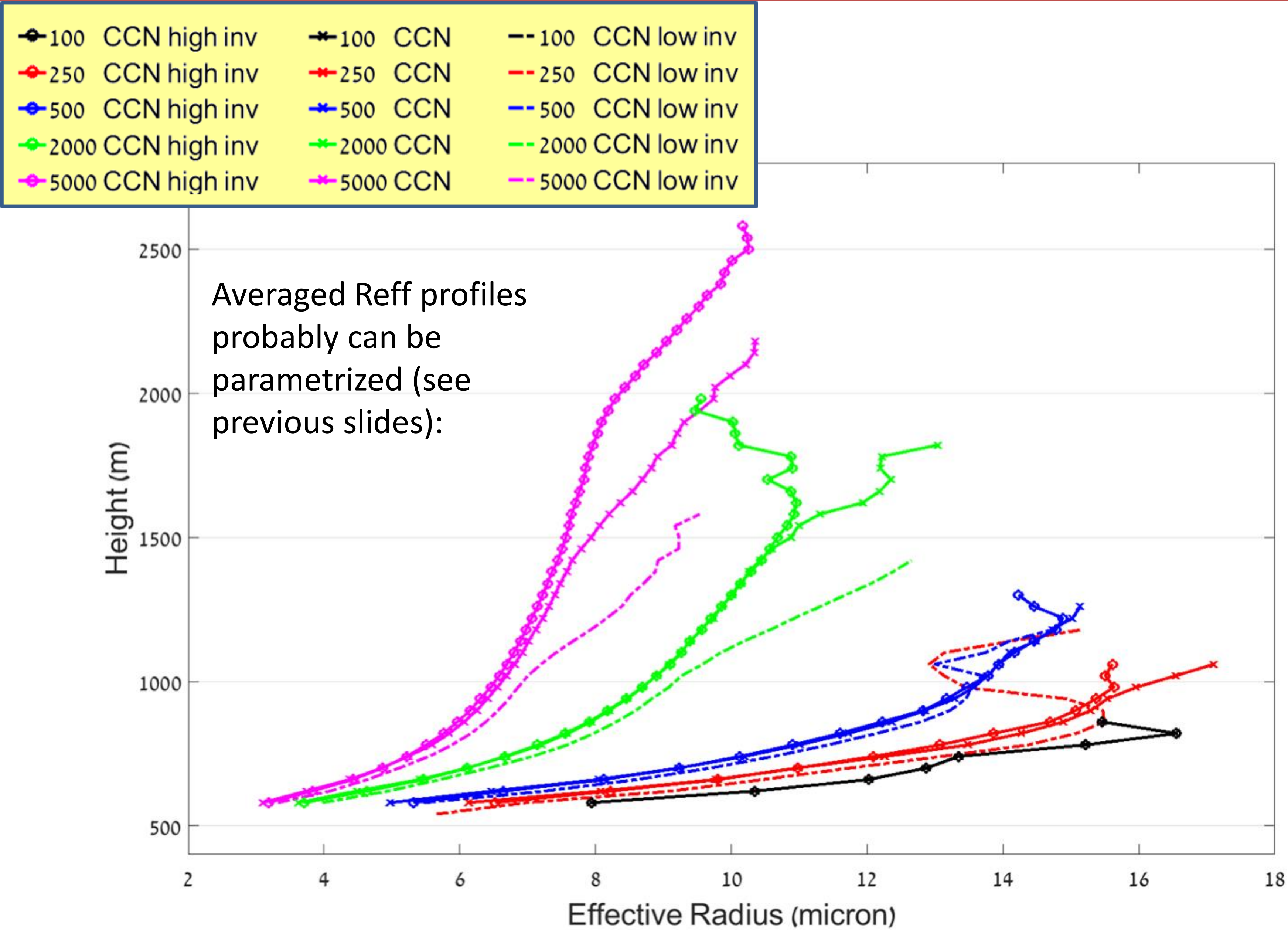
What about averaged LWC profile?

(assuming averaged profile is what we need)

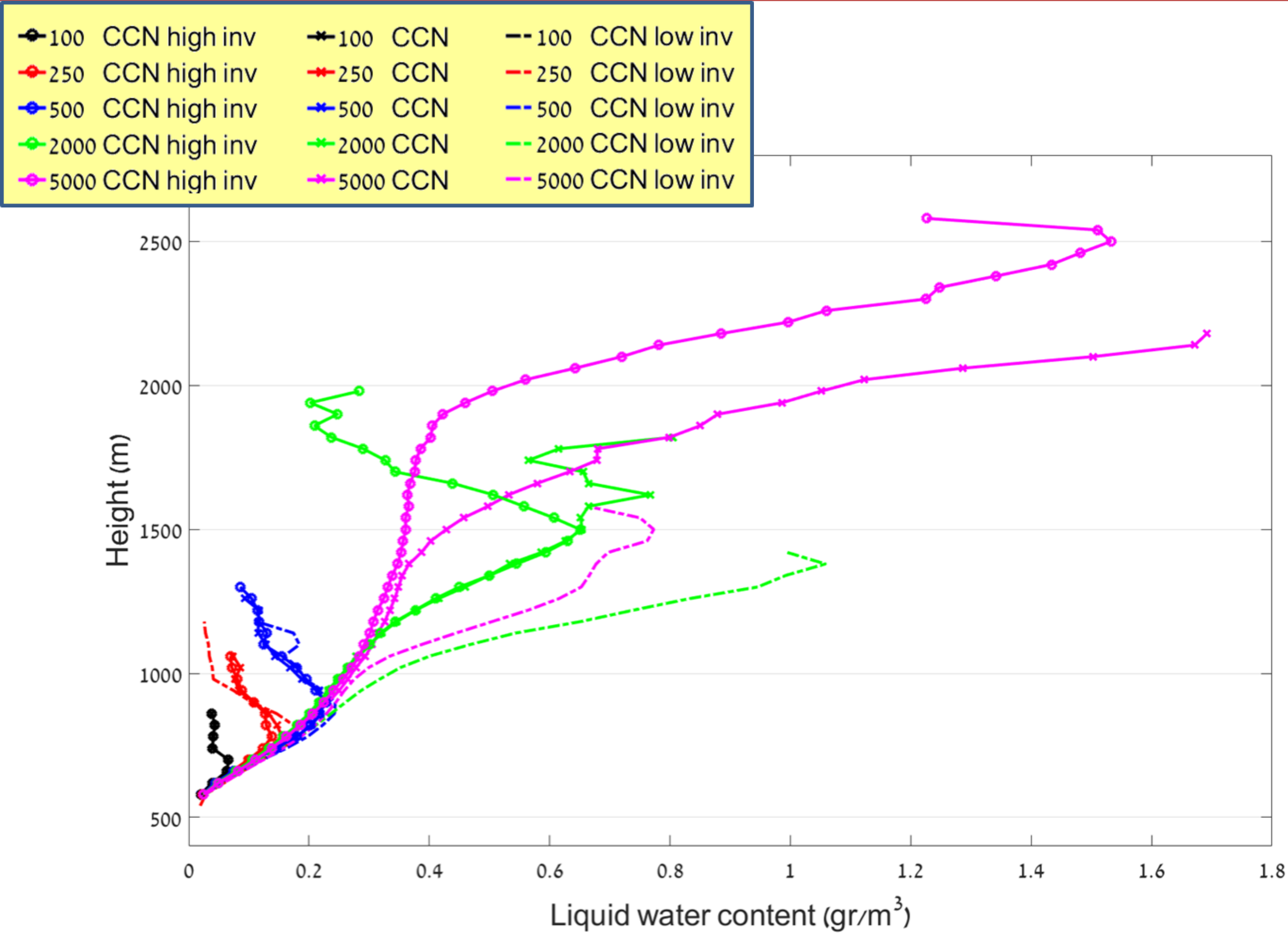
Number Concentration averaged profiles



Effective Radius averaged profiles



Liquid Water Content averaged profiles



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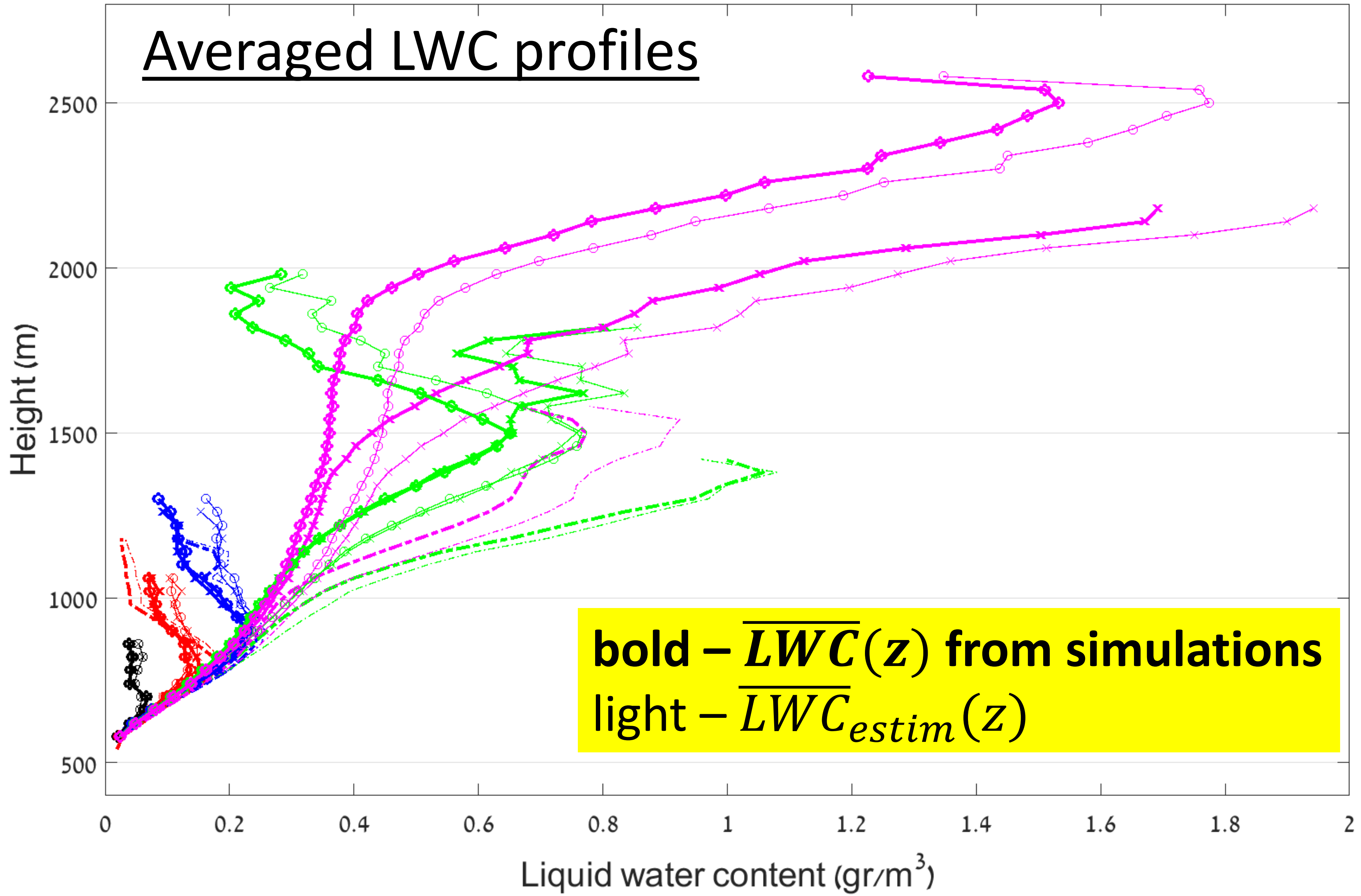
Estimation of averaged LWC profile

$$\overline{LWC}(z) = \frac{4\pi\rho_w}{3}\overline{NC(z)\left(\frac{R_{eff}(z)}{1.08}\right)^3} \overset{?}{\approx} \underbrace{\frac{4\pi\rho_w}{3}\overline{NC}\left(\frac{\overline{R_{eff}}}{1.08}\right)^3}_{\overline{LWC}_{estim}(z)}$$

Let's check this assumption…

Estimation of averaged LWC profile



Estimation of averaged LWC profile

The assumption works …

$$\overline{LWC}(z) \approx \frac{4\pi\rho_w}{3}\overline{NC}\left(\frac{\overline{R_{eff}}}{1.08}\right)^3$$

So, how to parametrize $\overline{\boldsymbol{LWC}}_{\boldsymbol{estim}}(\boldsymbol{z})$?

<u>We need:</u>

$\overline{R_{eff}}(z)$ - Have already (see previous slides)

$\dfrac{\overline{NC}(z)}{NC_{cloud\ base}}$ - Probably can be parametrized … ?

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Next Steps

- SAM :
  - Only the tail of aerosols size distributions is currently activated → Investigate for other typical aerosol distributions
  - Investigate for other temperature/humidity profiles, also different surface fluxes
  - Should we perform ***weighted*** averaging of LWC and Reff profiles over space?
- COSMO :
  - Perform idealized COSMO simulations with similar sounding profiles and aerosol concentrations to those used in SAM
- Validation:
  - Compare profiles of subgrid COSMO Reff, NC, LWC, CLC with those obtained in SAM
- Alternative parametrization ?
  - Analyze the possibility to set up an alternative parametrization:

Profiles of temperature, humidity and aerosol concentration → Look-up table → Profiles of subgrid CLC, Reff, LWC

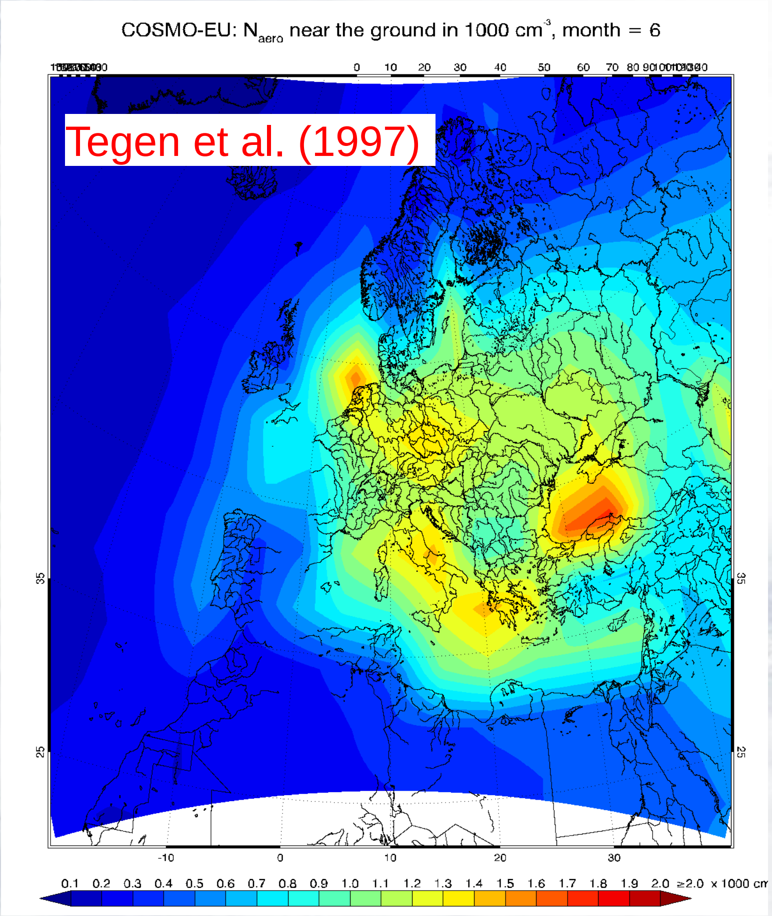
Thank you!

Uli's parametrization:

Option 2: Tegen / Segal & Khain

- icloud_num_type_rad = 2
  - Cloud nuclei profile $n_{CN}(z)$ is estimated from Tegen aerosols
  - Activation of n_{CN} to n_{CCN} is estimated from Segal & Khain (2006) parameterization based on the estimated vertical velocity at cloud base
  - n_C is assumed equal to n_{CCN}

$n_{CN}(x,y,z)$ from Tegen aerosol climatology



- Tegen climatology is for opt. thickn. τ of 5 aerosol types: **sea salt, sulfuric acid, other organics, black carbon and dust**, where the black carbon is already contained in the „other organics".
- Assumptions about spec. extinction coefficient β_{ext}, modal radii, aerosol bulk density and soluble fraction η lead to total N_{CN} number per area. Assumption of an exponentially decreasing vertical profile (in terms of mass fraction!) leads to 3D CN concentrations:

$$N_{CN} = \sum_{i=1}^{4} \frac{3\,\tau_i\,\eta_i}{4\pi\,\beta_{ext,i}\,\bar{r}^3_{mode,i}\,\rho_{bulk,i}}$$

$$N_{CN} = \int_0^{z_{max}} n_{CN}(z)\,\rho_0(z)\,dz$$

$$\rho_0(z) = \rho_{00}\,\exp\left(-\ln 2\,\frac{z}{\Delta z_{\rho,1/2}}\right)$$

	i	η	β_{ext}	$\bar{r}_{mode}$	ρ_{bulk}
			$m^2\,kg^{-1}$	µm	$kg\,m^{-3}$
dust	1	0.1	1500	1.0	3000
organics	2	0.9	8000	0.08	2000
SO_4	3	1	8000	0.08	2000
sea salt	4	0.9	200	0.5	3000

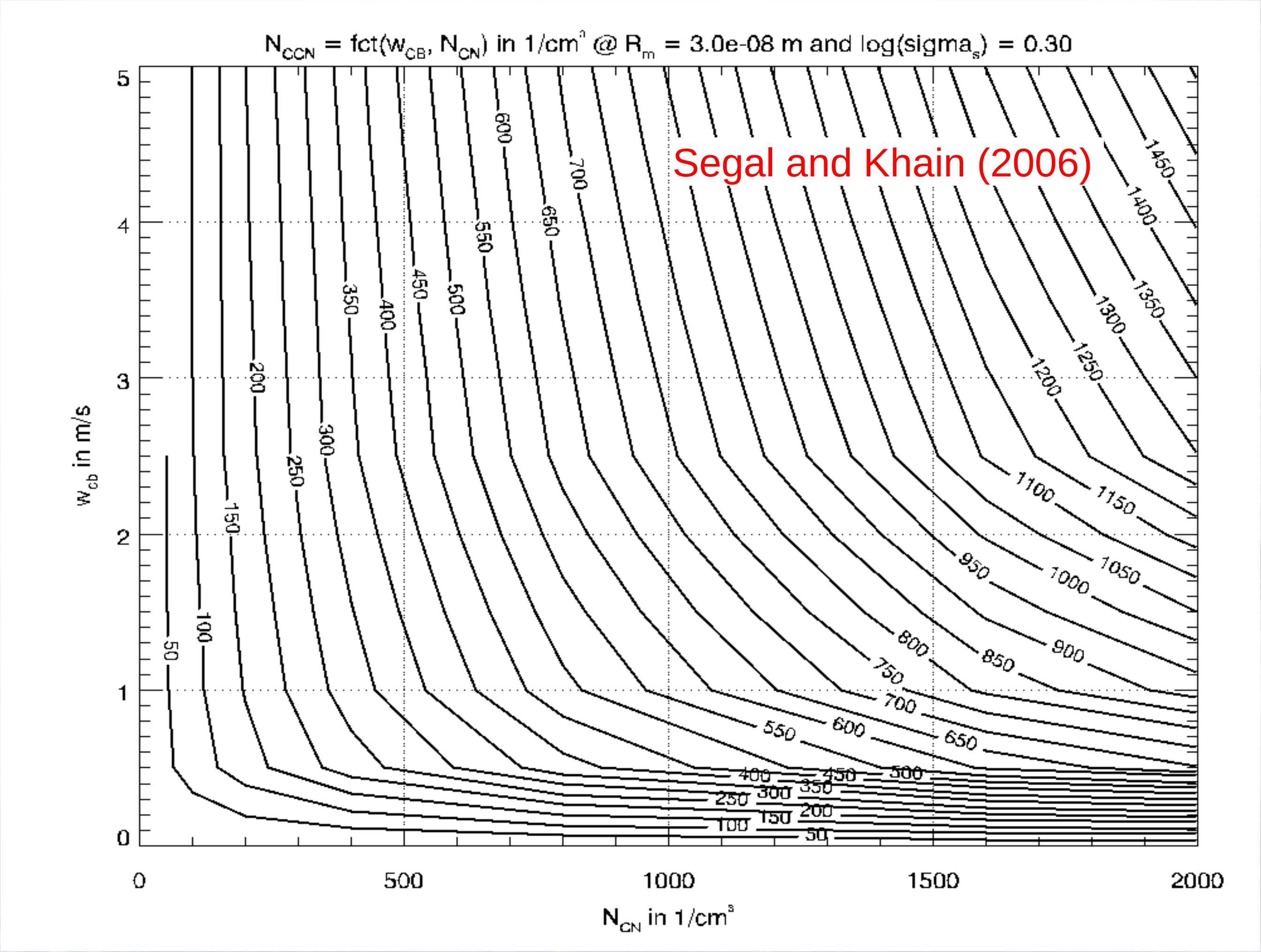
$$n_{CN}(z) = n_{CN,0}\begin{cases}\exp\left(-\frac{z-z_0}{\Delta z_{1/e}}\right) & \text{if } z > z_0 \\ 1 & \text{else}\end{cases} \qquad [\mathrm{kg}^{-1}]$$

$$\Rightarrow n_{CN,0} = N_{CN}\left\{\rho_0(z_0)\left[\frac{\Delta z_{\rho,1/2}}{\ln 2}\left(\exp\left(\ln 2\,\frac{z_0}{\Delta z_{\rho,1/2}}\right)-1\right) + \Delta z_{eff,1/e}\left(1-\exp\left(\frac{z_0-z_{max}}{\Delta z_{eff,1/e}}\right)\right)\right]\right\}^{-1}$$

$$\text{with } \Delta z_{eff,1/e} = \left(\frac{1}{\Delta z_{1/e}} + \frac{\ln 2}{\Delta z_{\rho,1/2}}\right)^{-1}$$

$n_{CCN}(x,y,z)$ from Tegen / Segal & Khain

… + Updraft-based activation parameterization of n_{CCN}:



$n_{CCN}(x,y,z)$ from Tegen / Segal & Khain

- Parameterized after Segal and Khain (2006) as function of n_{CN} and w_{cb} at cloud base, where mean radius and width of an assumed log-normal aerosol distribution is assumed constant (2D lookup tables)
  - In „active" clouds ($w_{nuc} > w_{cb,min}$ and $q_c > 0$ or clc_con > 0 over several adjacent height layers), activation is at cloud base and n_{CN} decreases exponentially above cloud base (→ autoconversion, accreation).
  - All other grid points: derive n_c from lookup table based on local n_{CN} and w_{nuc}
  - Let $n_{CCN,SK}$ be the lookup table, then:

$$n_C(z) = \begin{cases} n_{CCN,SK}\Big(n_{CN}(z_{cb}), w_{nuc}(z_{cb})\Big)\ \exp\left(-\frac{z-z_{cb}}{\Delta z_{a,1/e}}\right) & \text{if } w \geq w_{cb,min} \ \wedge\ q_C(z) > 0 \ \wedge\ z \geq z_{cb} \\ n_{CCN,SK}\Big(n_{CN}(z), \max[w_{nuc}(z), w_{cb,min}]\Big) & \text{else} \end{cases} \qquad [\mathrm{kg}^{-1}]$$

  - Effective updraft speed w_{nuc} for nucleation, including turbulence, radiative cooling an parameterized convection:

$$w_{eff} = \overline{w} + 0.7\sqrt{\frac{2\,TKE}{6}} - \frac{c_p}{g}\frac{\partial T}{\partial t}\bigg|_{\text{radiation}}$$

$$w_{nuc} = \max\left[\, w_{eff}\,,\, w^* \,\right]$$

$$w^* = \left(-g\, z_{topcon}\frac{\overline{w'\Theta'_{v,S}}}{\Theta_{v,S}}\right)^{1/3} \quad \text{(convective velocity scale after Deardorff)}$$

    - z_{top_con}: PBL height as determined from $\Theta_v < \Theta_{v,surf}$+0.5 K, or upper bound of lowest continuous „clc_con" layer