A HYBRID BULK-BIN APPROACH TO MODEL WARM-RAIN PROCESSES

(work in progress in Toulouse)

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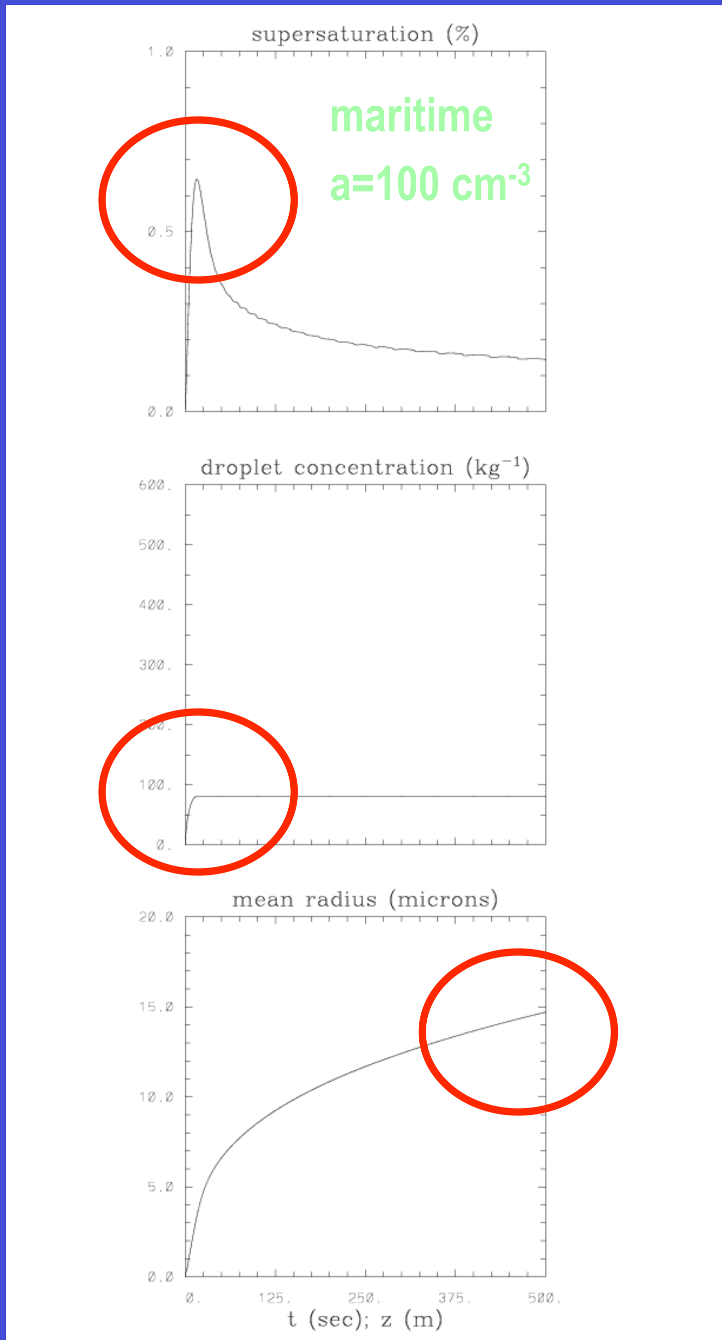
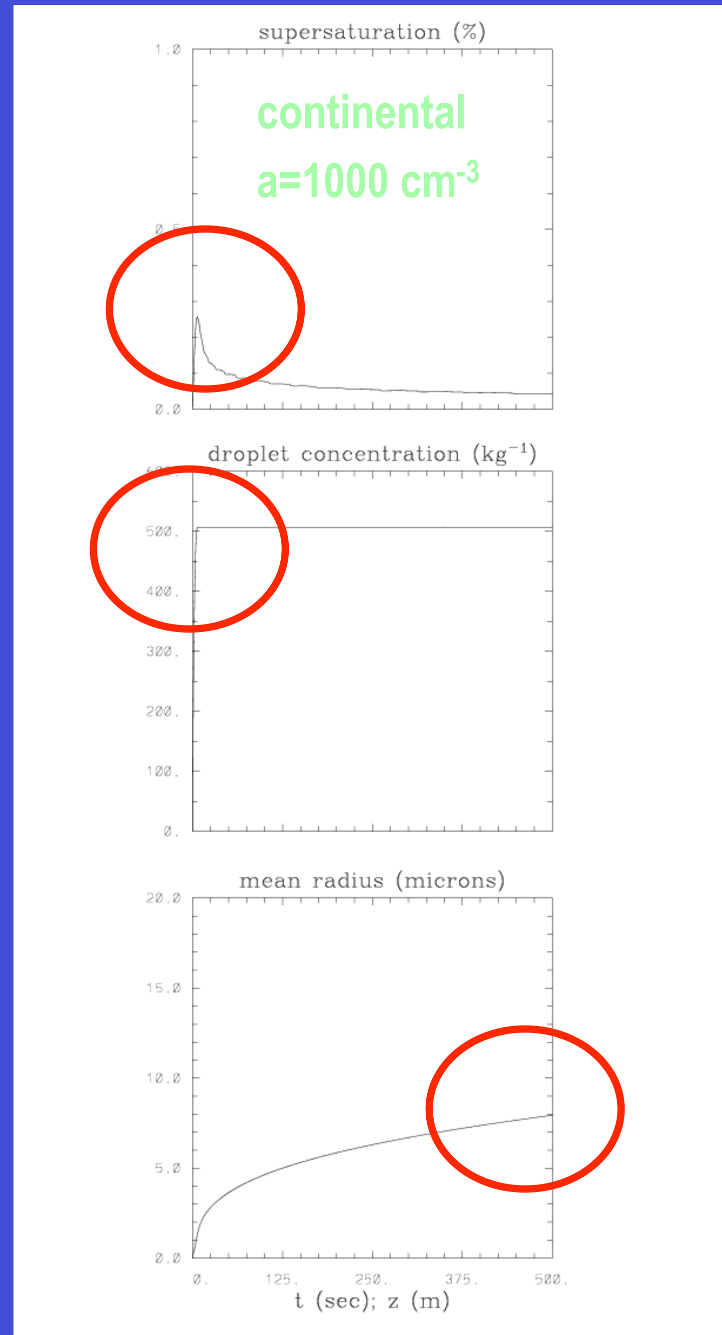
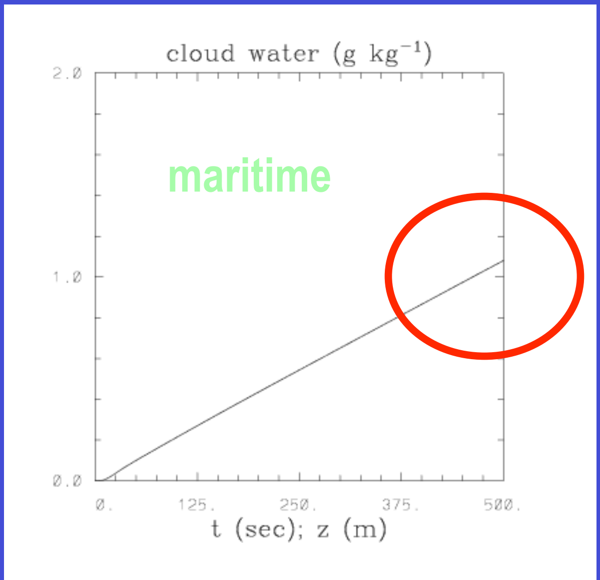
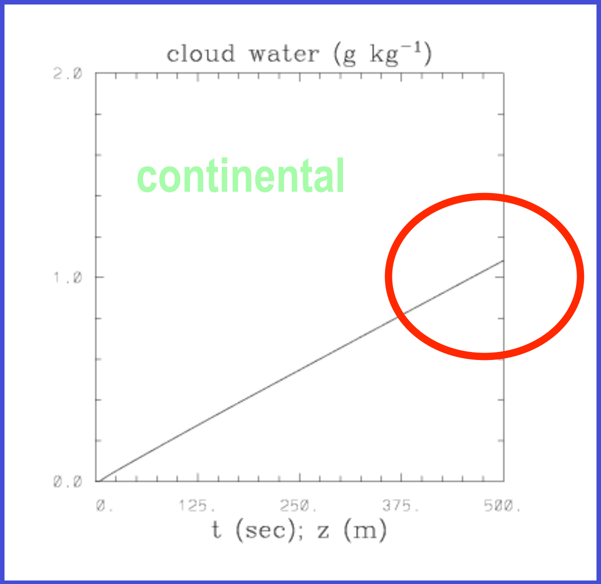


supersaturation (%)
maritime
a=100 cm-3
droplet concentration (kg-1)
mean radius (microns)
t (sec); z (m)



supersaturation (%)
continental
a=1000 cm-3
droplet concentration (kg-1)
mean radius (microns)
t (sec); z (m)


cloud water (g kg^{-1})
maritime
2.0
1.0
0.0
0.
125.
250.
375.
500.
t (sec); z (m)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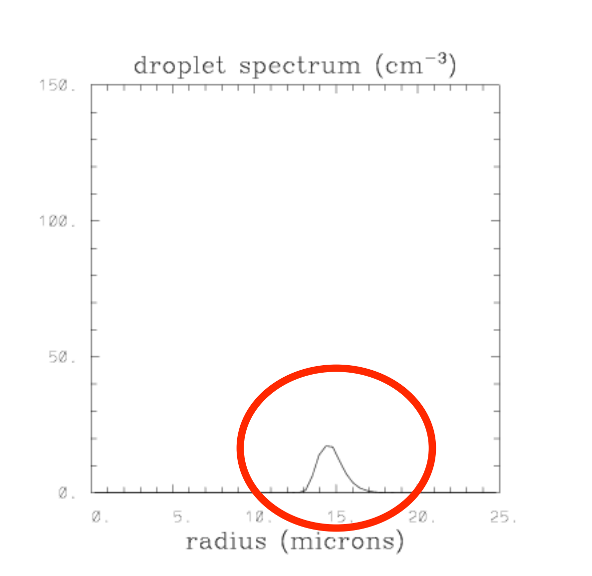
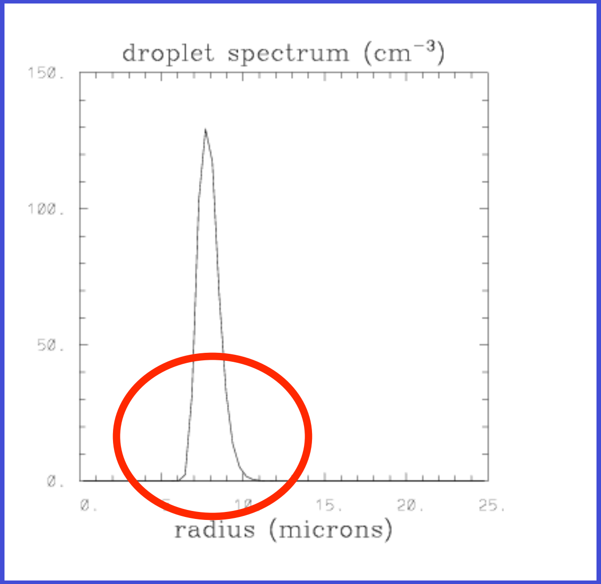

droplet spectrum (cm^{-3})
150.
100.
50.
0.
0.
5.
10.
15.
20.
25.
radius (microns)


droplet spectrum (cm^{-3})
150.
100.
50.
0.
0.
10.
15.
20.
25.
radius (microns)

Supersaturation prediction is not needed for droplet growth; it is only needed for the activation…

… so if we have activation parameterization, why bother predicting supersaturation?

This is starting point for the hybrid bulk-bin approach: we predict spectral evolution of the activation spectrum, adjusting always to water saturation inside the cloud.

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Bin model: we predict S, then calculate droplet growth/evaporation (change of the spectrum); this gives condensation rate.

Hybrid model: we predict condensation rate from saturation adjustment, then calculate evolution of the droplet spectrum.

$$\frac{\partial \theta}{\partial t} + \frac{1}{\rho_o}\nabla \cdot (\rho_o \mathbf{u}\theta) = \frac{L_v}{\Pi c_p}(C - E) + D_\theta \ ,$$

$$\frac{\partial q_v}{\partial t} + \frac{1}{\rho_o}\nabla \cdot (\rho_o \mathbf{u} q_v) = -C + E + D_v \ ,$$

$$\frac{\partial f}{\partial t} + \frac{1}{\rho_o}\nabla \cdot (\rho_o \mathbf{u} f) + \frac{\partial}{\partial r}\left(\frac{dr}{dt} f\right) = \left(\frac{\partial f}{\partial t}\right)_{act} + \left(\frac{\partial f}{\partial t}\right)_{coal} + D_f$$

C – condensation rate from saturation adjustment.
Applied only to cloud droplet part of the spectrum (say, below 40 microns).

E – drizzle/rain evaporation rate.
Applied only to drizzle/rain part of the spectrum.

NOTE: C=0 when E≠0.

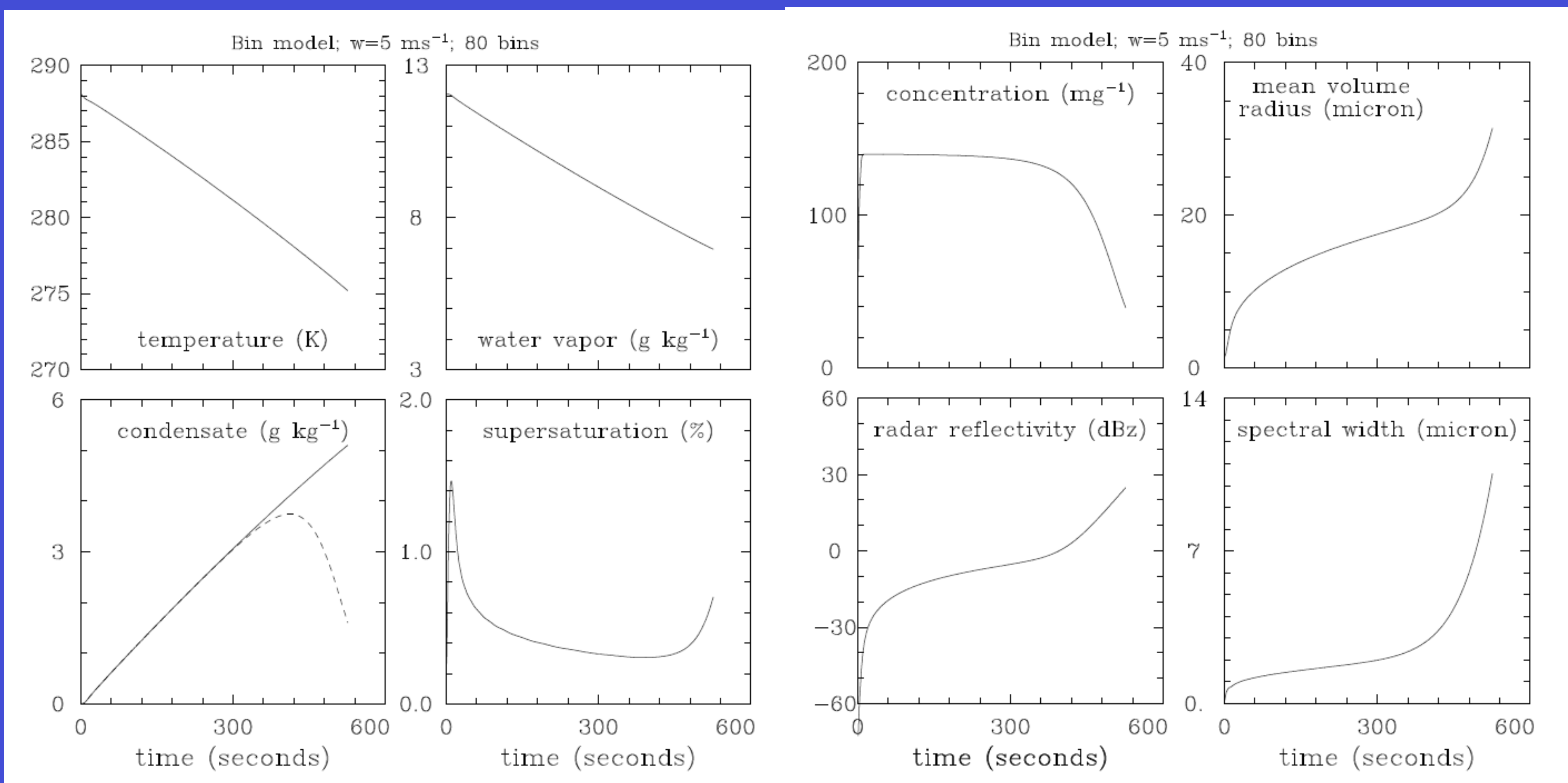
Q: How to derive spectral change given the known condensation rate?

A: Through the "bogus supersaturation" approach!

$$C = 4\,\pi\rho_w A S^* \sum_{i=1}^{N_C} f^{(i)}\,\Delta r^{(i)}\,r^{(i)}$$

N_c – last class for cloud water

Adiabatic parcel simulations:
bin model results (maritime conditions, w=5 m/s):



Evolution of the difference between bin and bulk-bin models (lower right panel shows supersaturation in the bulk-bin model):

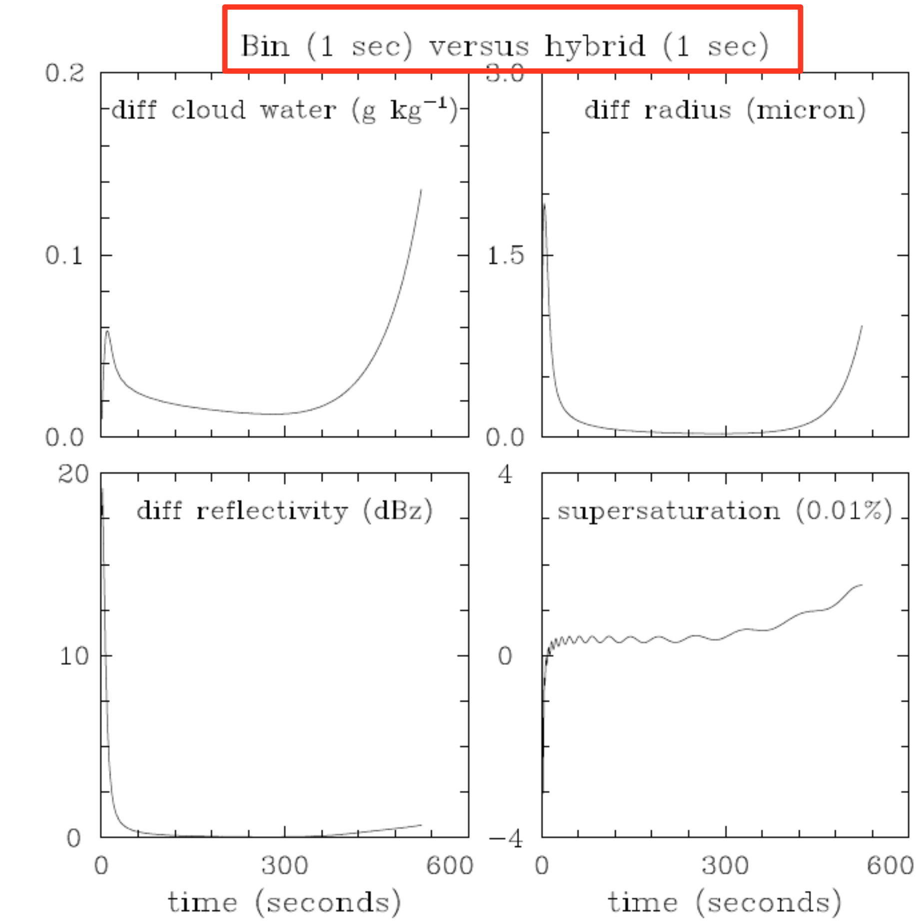


Figure 4: Evolution of the differences between the bin and hybrid bulk-bin simulations with 1 sec time step for the adiabatic parcel simulations as in Fig. 1, 2 and 3. The panels show the difference in the cloud water, mean volume radius, and radar reflectivity. The bottom right panel shows the evolution of the supersaturation in the hybrid scheme; the scale on the vertical axis is in units of 0.01%. See text for details.

Evolution of the difference between bin and bulk-bin models (lower right panel shows supersaturation in the bulk-bin model):

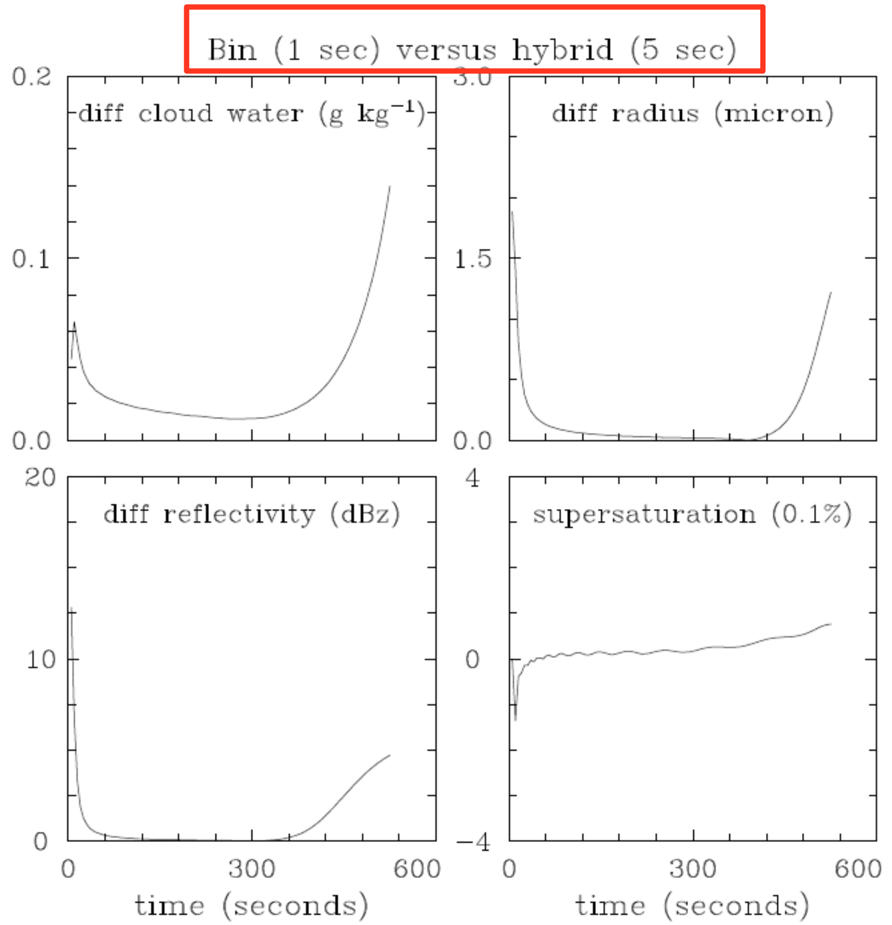


Figure 5: As Fig. 4, but for the hynrid bulk-bin scheme using 5 sec time step. Note a different scale for the supersaturation plot (the unit is 0.1%).

Application to the multidimensional framework (condensation only).

Traditional approach versus invariant-variable approach

$$\frac{\partial \rho_o \theta}{\partial t} + \nabla \cdot (\rho_o \theta \mathbf{u}) = \rho_o \frac{L\bar{\theta}}{c_p \bar{T}} C_d$$

$$\frac{\partial \rho_o q_v}{\partial t} + \nabla \cdot (\rho_o q_v \mathbf{u}) = -\rho_o C_d$$

$$\frac{\partial \rho_o q_c}{\partial t} + \nabla \cdot (\rho_o q_c \mathbf{u}) = \rho_o C_d,$$

$$\frac{\partial \rho_o \theta_I}{\partial t} + \nabla \cdot (\rho_o \theta_I \mathbf{u}) = 0$$

$$\frac{\partial \rho_o q}{\partial t} + \nabla \cdot (\rho_o q \mathbf{u}) = 0,$$

The key issue: numerical problems near the cloud-environment boundaries

Klaassen and Clark *JAS* 1985 (bulk model)

Grabowski *JAS* 1989 (bin model)

Kogan et al. *JAS* 1995 (bin model)

Grabowski and Smolarkiewicz *MWR* 1990 (bulk model)

Stevens et al. *MWR* 1996 (2-moment scheme)

Grabowski and Morrison *MWR* 2008 (2-moment scheme)

1D advection-condensation (and advection-condensation-mixing) problem (Grabowski and Smolarkiewicz *MWR* 1990)

quasi-analytic solution

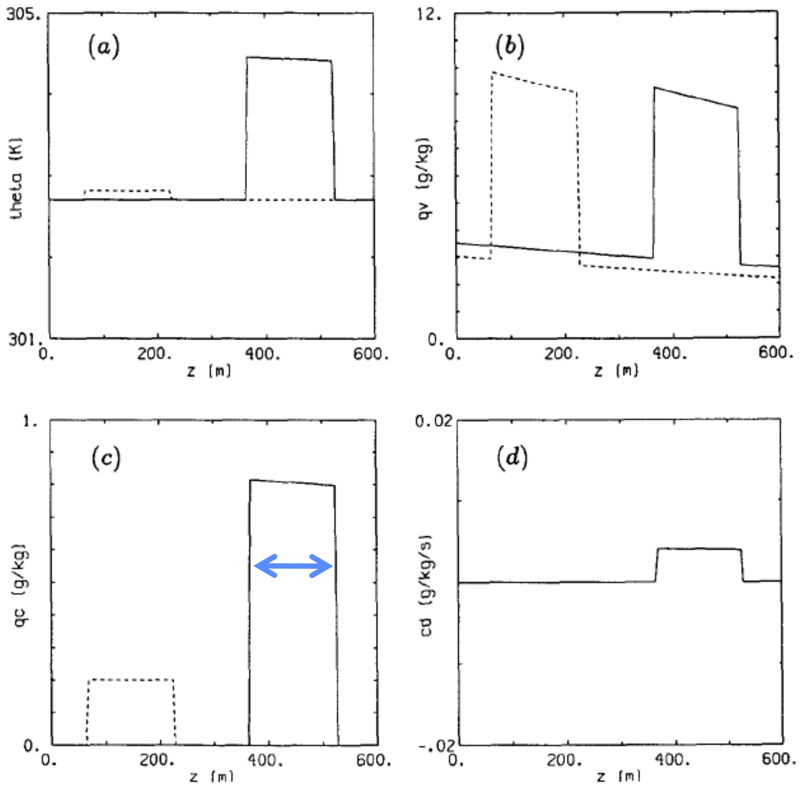


FIG. 1. Analytic solution for the one-dimensional, idealized advection–condensation problem. The dashed and the solid lines represent, respectively, initial conditions and final results for the potential temperature (a), the water vapor mixing ratio (b), the cloud water mixing ratio (c), and the condensation rate (d).

iord=2 monotone MPDATA

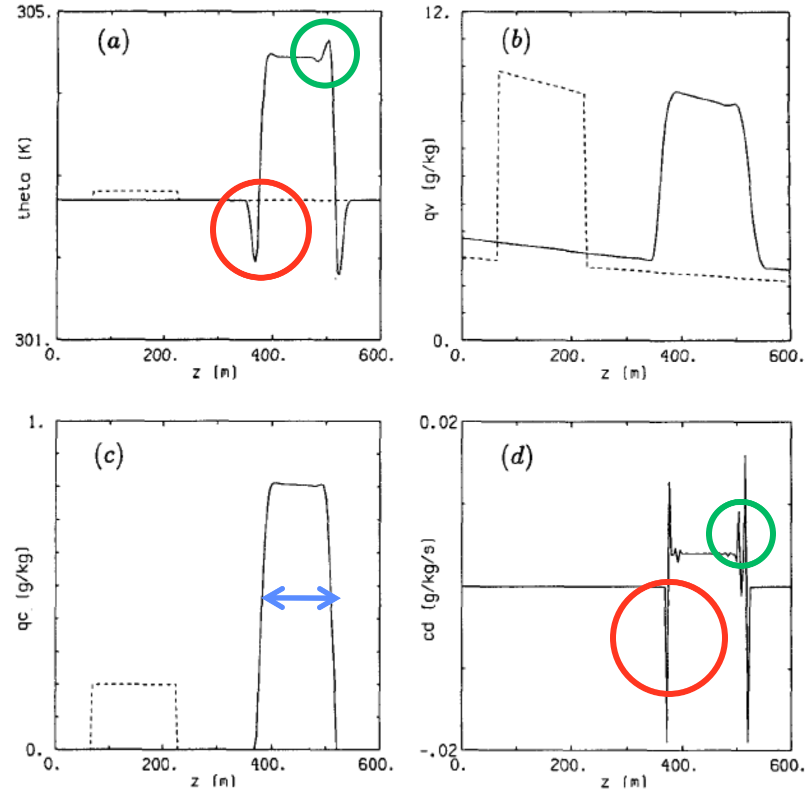


FIG. 4. As in Fig. 3 but with the nonoscillatory MPDATA.

$$\frac{\partial \rho_o \theta}{\partial t} + \nabla \cdot (\rho_o \theta \mathbf{u}) = \rho_o \frac{L\bar{\theta}}{c_p \bar{T}} C_d$$

$$\frac{\partial \rho_o q_v}{\partial t} + \nabla \cdot (\rho_o q_v \mathbf{u}) = -\rho_o C_d$$

$$\frac{\partial \rho_o q_c}{\partial t} + \nabla \cdot (\rho_o q_c \mathbf{u}) = \rho_o C_d,$$

Grabowski and Smolarkiewicz *MWR* 1990

iord=2, monotone MPDATA, invariant variables

$$\frac{d\theta_I}{dt} = 0$$

$$\frac{dQ}{dt} = 0$$

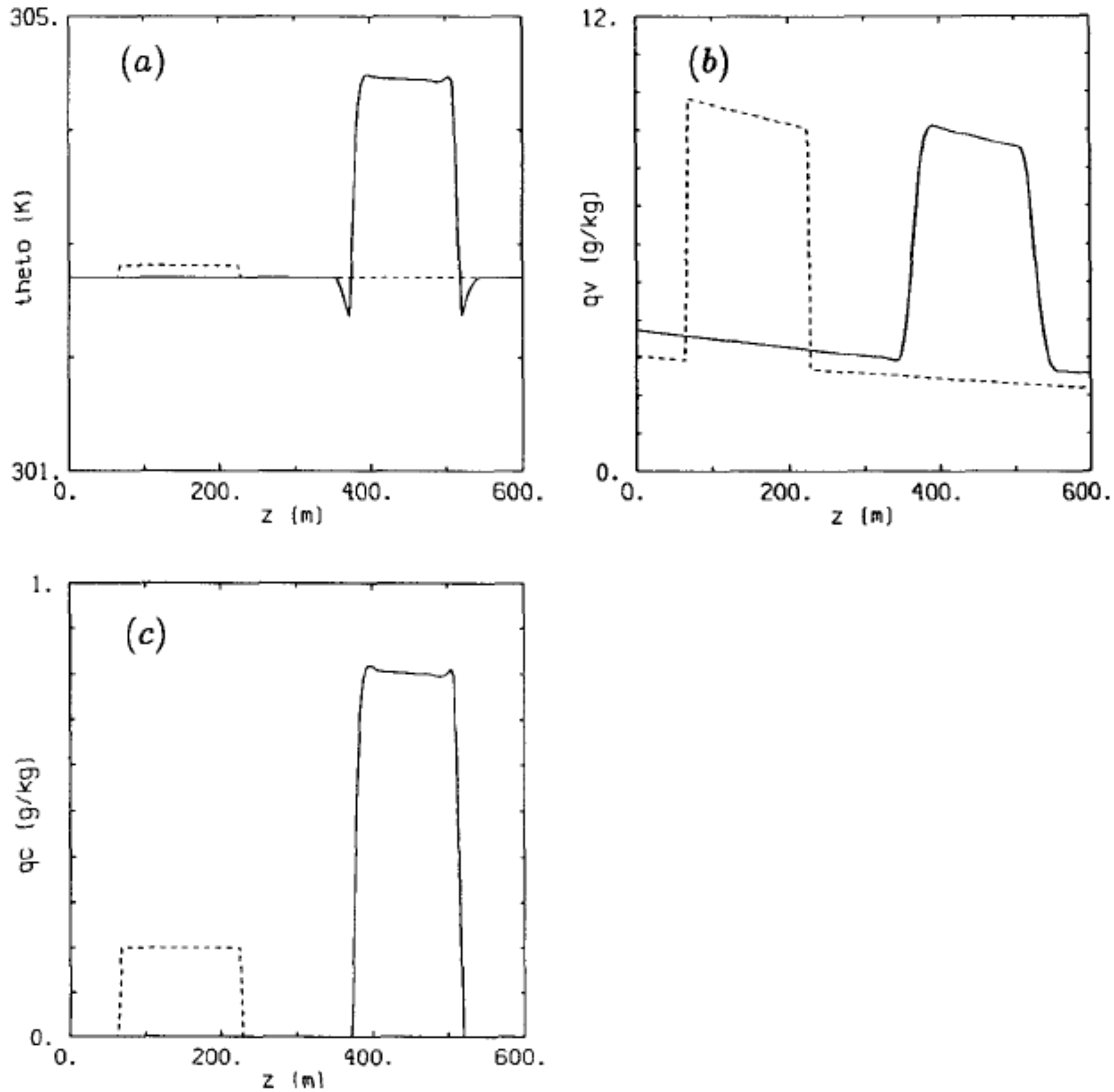
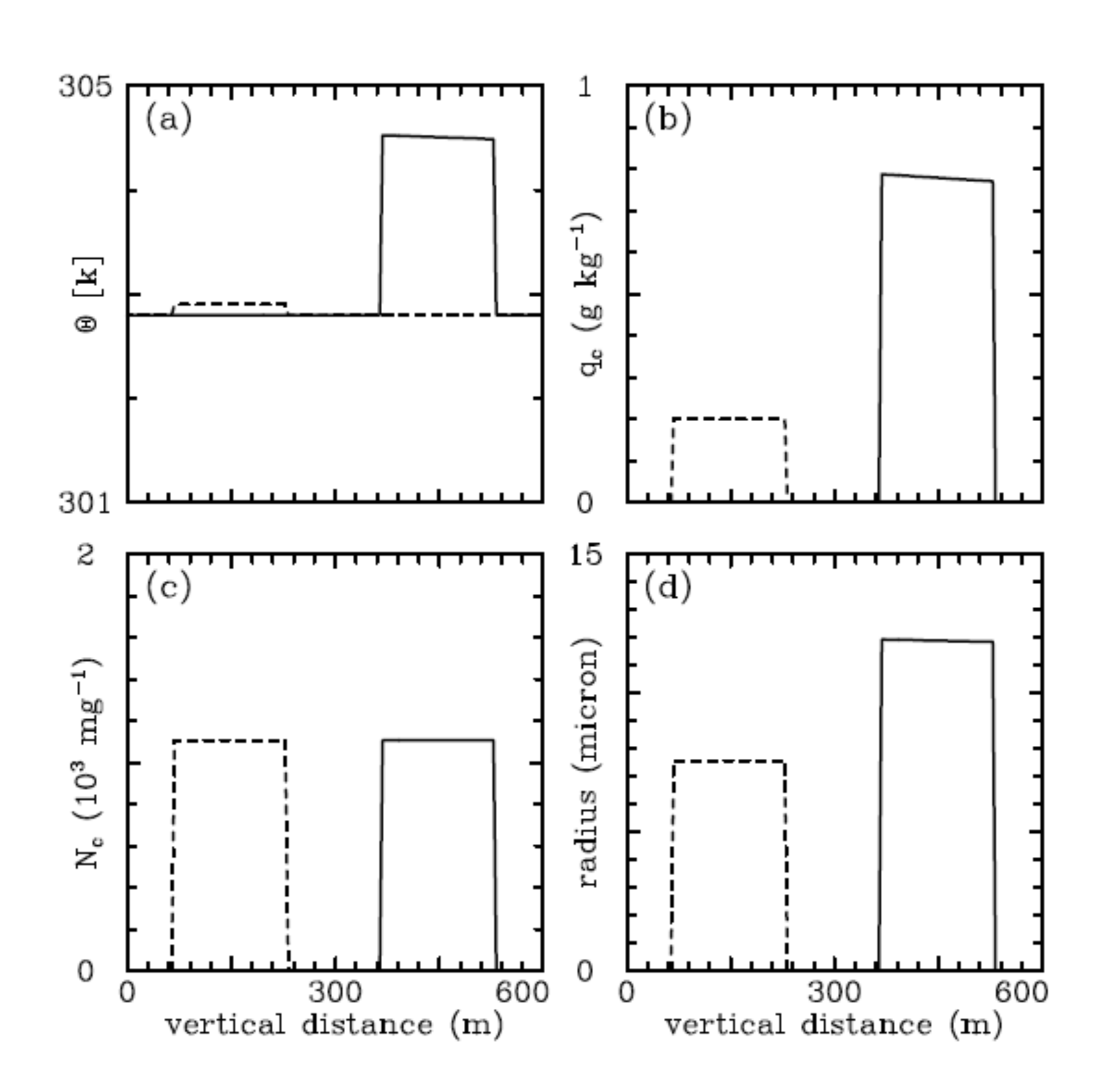


FIG. 7. As in Fig. 6 but with the nonoscillatory MPDATA.

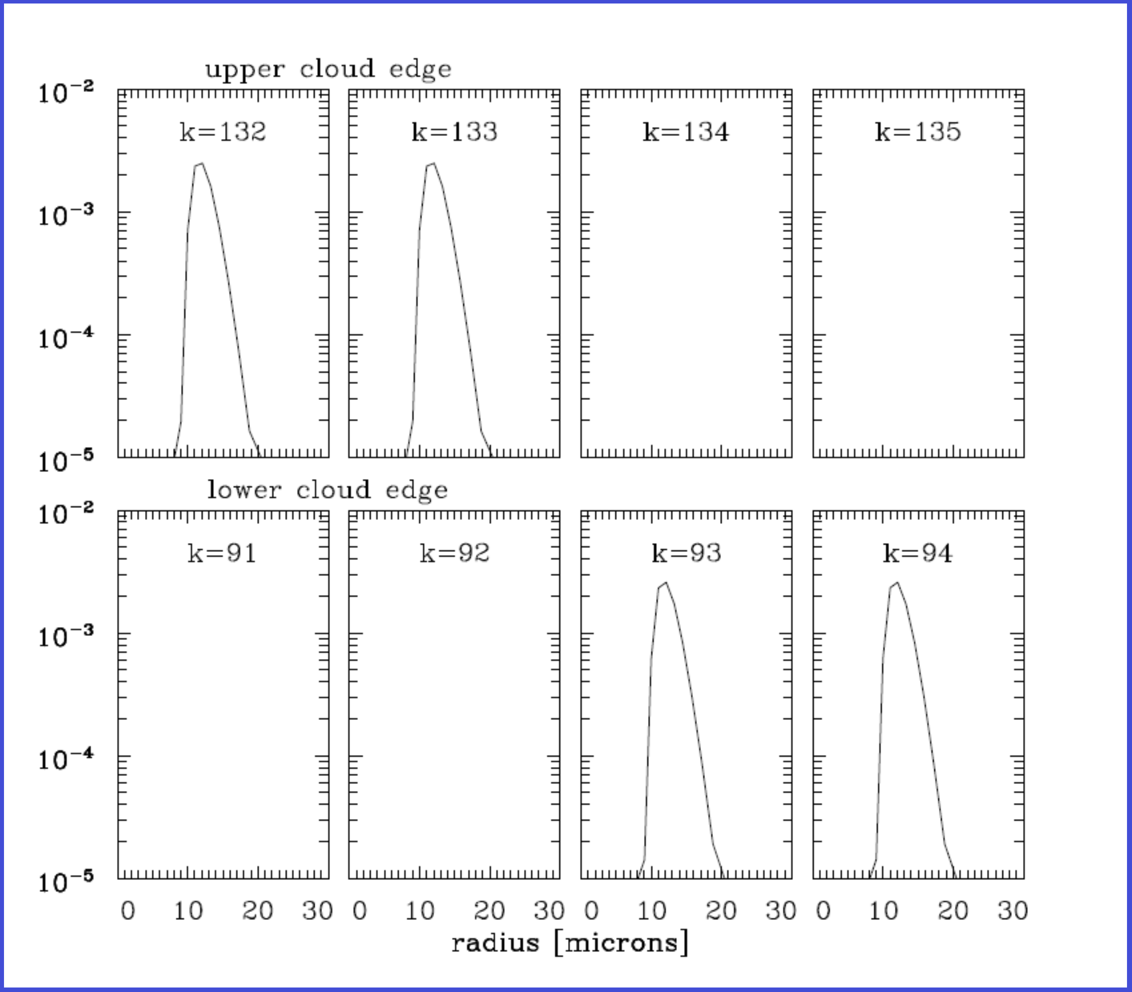
Grabowski and Smolarkiewicz *MWR* 1990

Tests with hybrid bulk-bin scheme

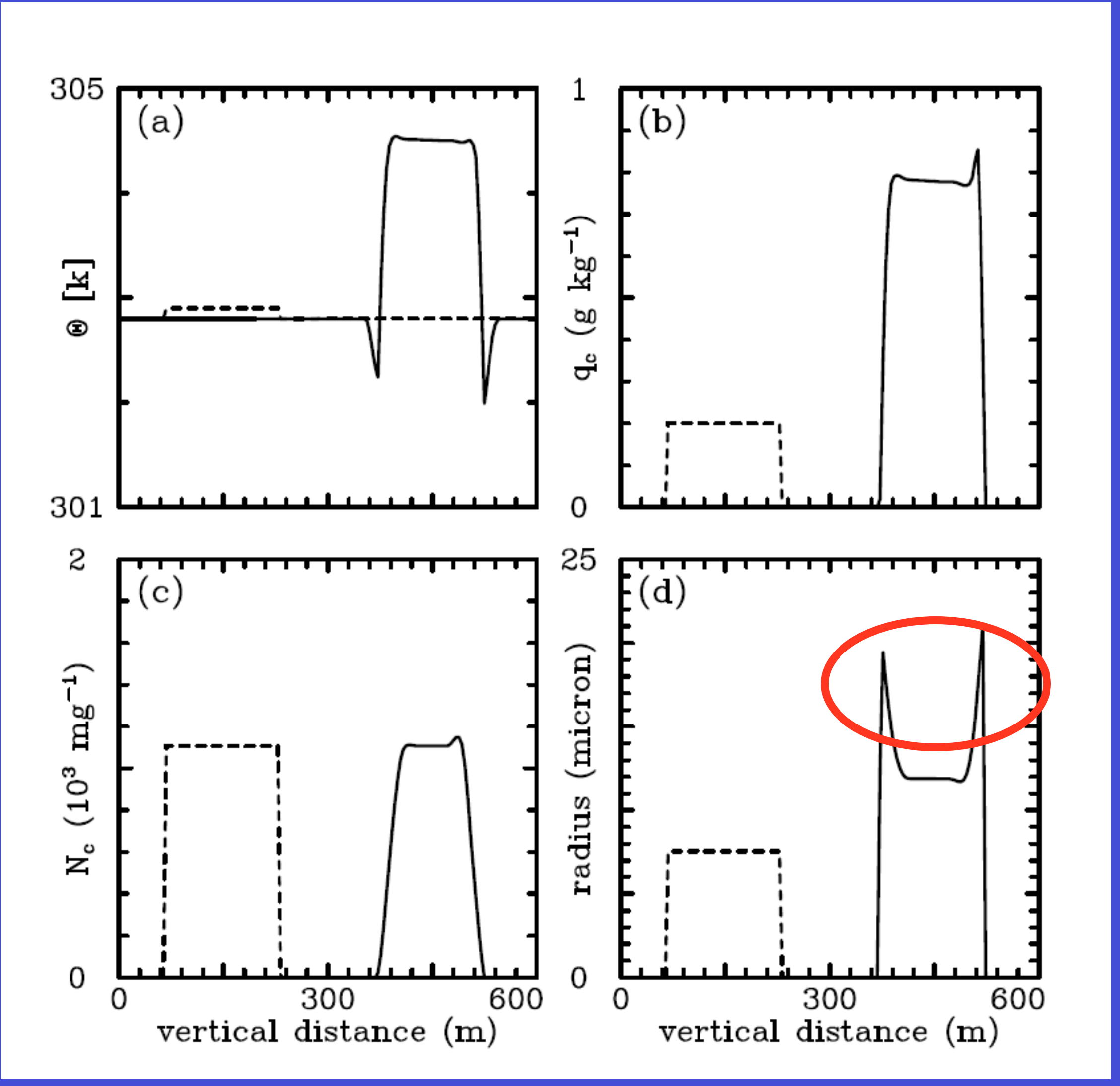
quasi-analytic solution



quasi-analytic solution

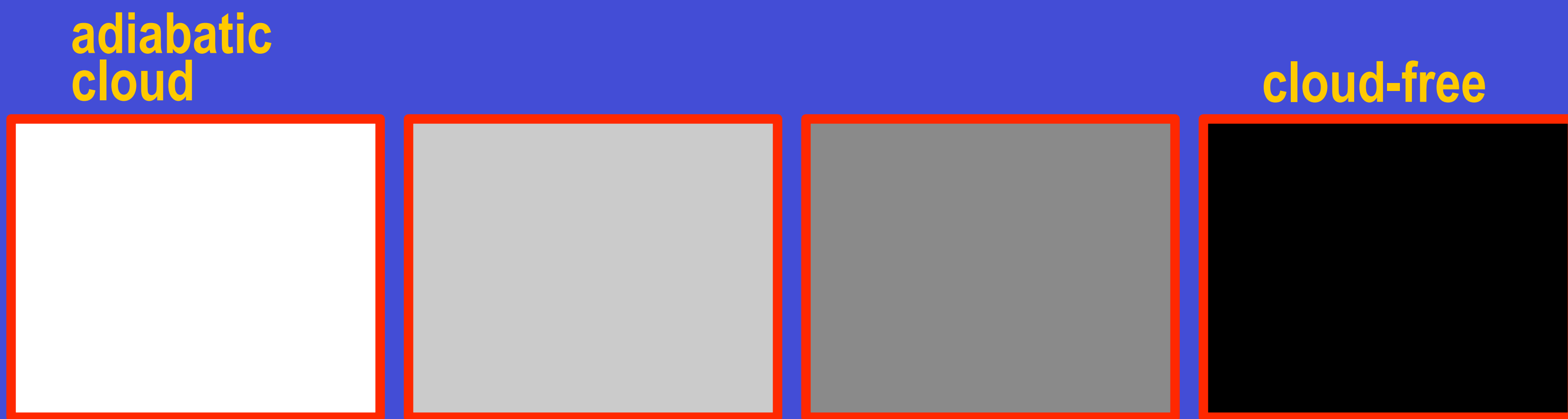


iord=2
monotone
MPDATA



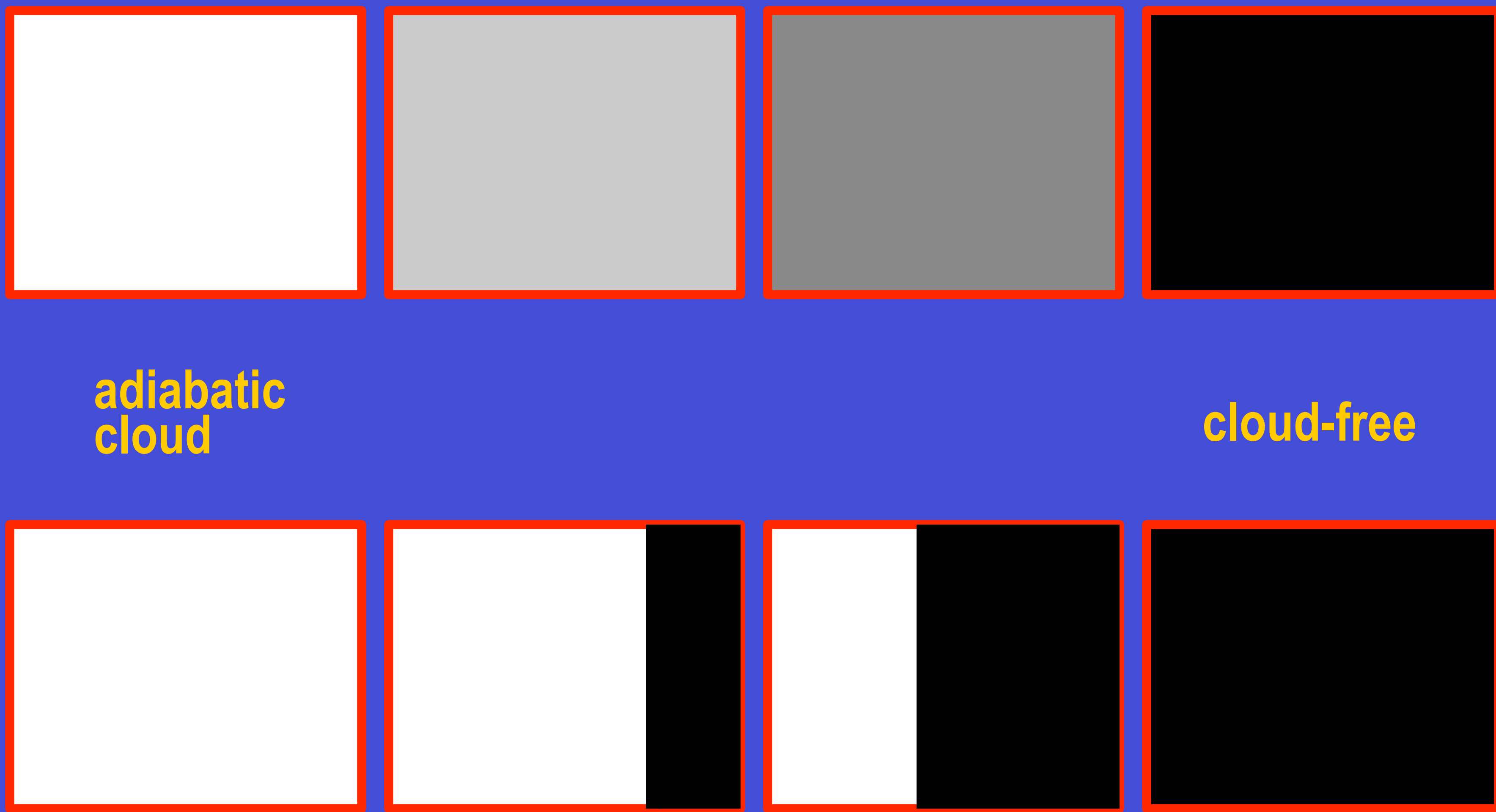
The results are consistent with the view that gridboxes are homogeneous – this results to the “super-adiabatic” growth or cloud droplets.

But this is inconsistent with the analytic solution!



Is there any solution to this problem?

Homogeneous gridboxes



Heterogeneous gridboxes

homogeneous spectral change

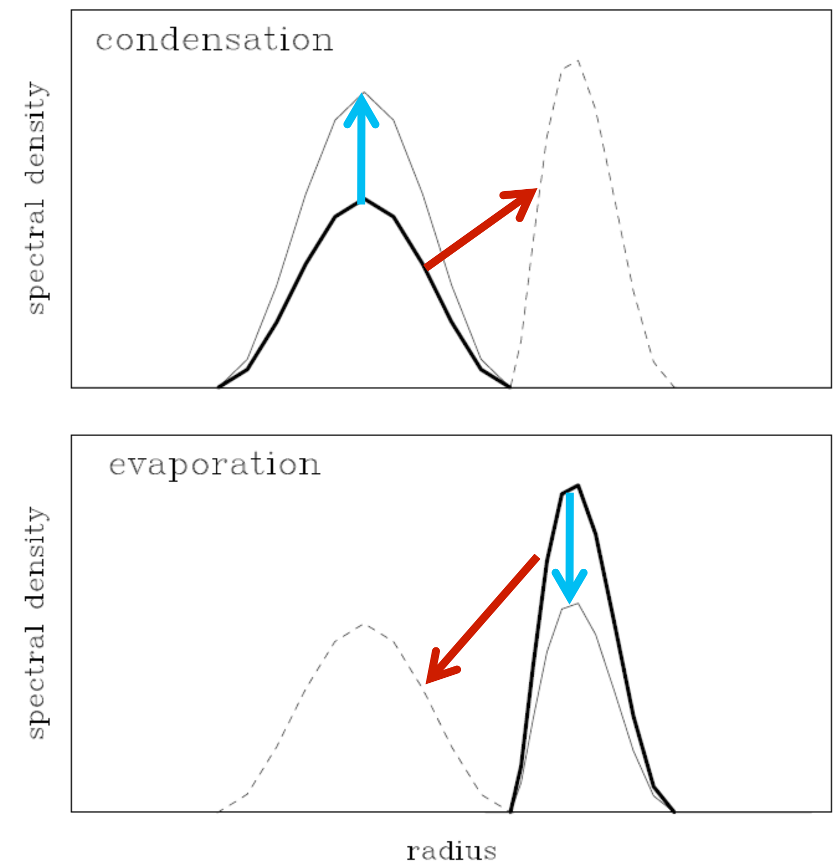


Figure 6: Schematic illustration of the condensation (upper panel) and evaporation (lower panel) associated with homogeneous and heterogeneous processes. In each panel, the thick solid line shows the initial droplet spectral density function. The homogeneous condensation/evaporation results in the spectral density showed using the dashed line. The heterogeneous process results in the spectral density showed by the thin solid line.

heterogeneous spectral change (e.g., increasing cloud fraction)

A caveat: heterogeneous spectral change should not increase droplet concentration beyond what is allowed by activation.

How to decide between homogeneous and heterogeneous spectral change?

Using the adiabatic condensation rate!

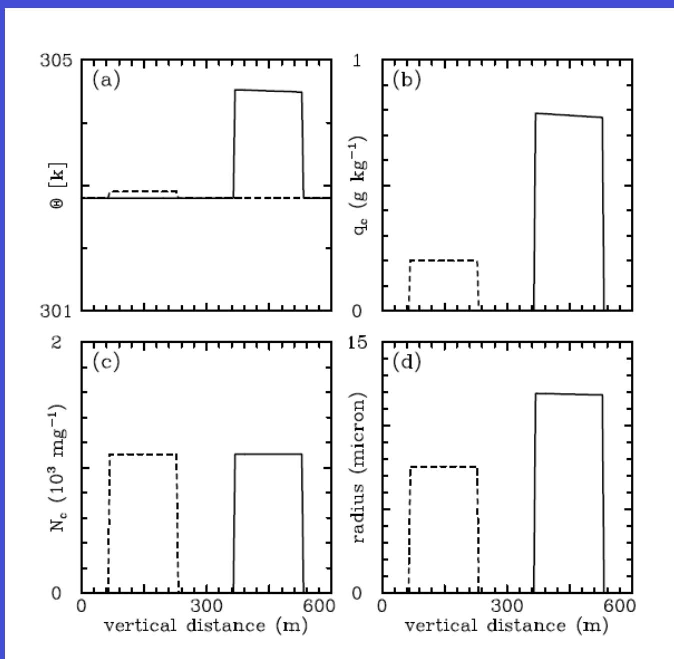
$$C^a = -\frac{dq_{vs}}{dt}$$

$$C^a = gw\frac{\rho_e q_{vs}}{p_e - e_s}\left(\frac{R_d L_v T_e}{R_v c_p T^2} - 1\right) \times \left(1 + \frac{\rho_e q_{vs}}{p_e - e_s}\frac{R_d L_v^2 T_e}{R_v c_p T^2}\right)^{-1}.$$

Grabowski *JAS* 2007

If finite-difference model predicts $C \approx C^a$, assume homogeneous gridbox. If not, assume that the gridbox is heterogeneous.

iord=2
monotone
MPDATA
with homo/
hetero logic



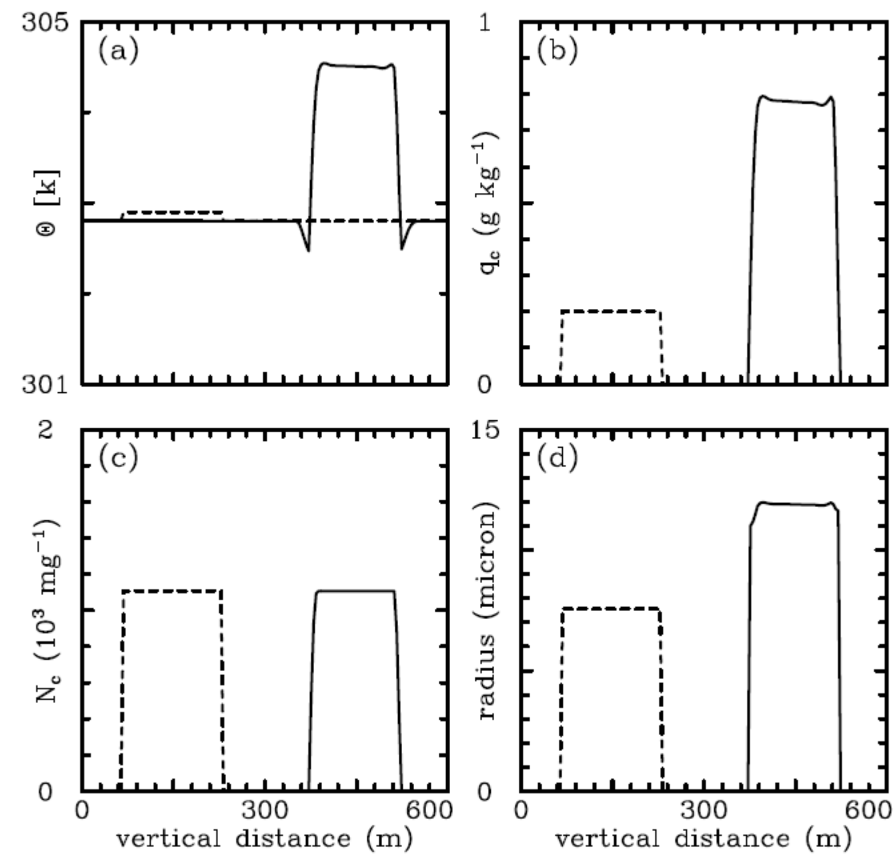
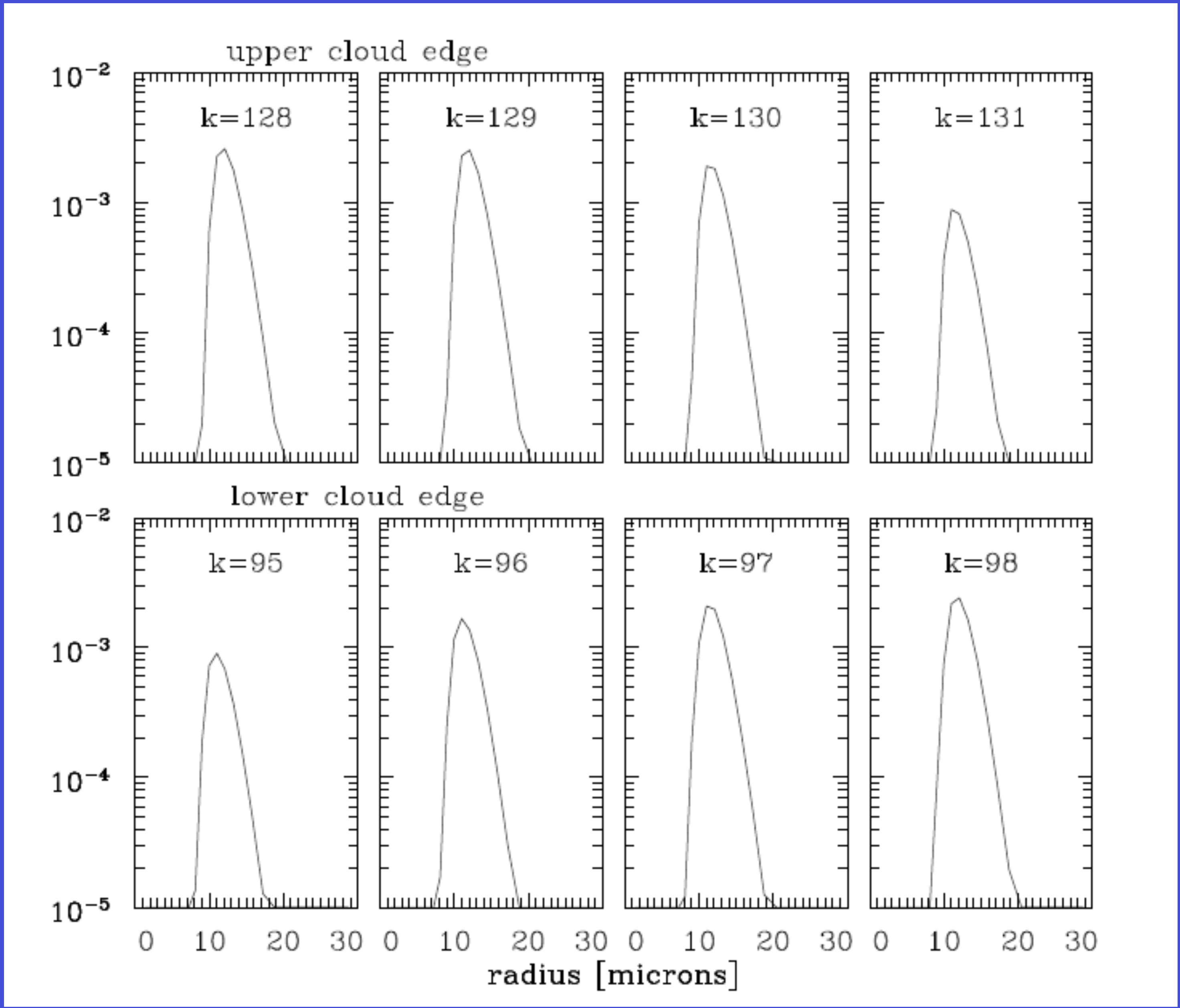


Figure 7: Results of the 1D advection-condensation test of GS90 using invariant variables approach and the hybrid bulk-bin scheme. The panels show (a) the potential temperature, (b) cloud water mixing ratio, (c) cloud droplet concentration, and (d) mean volume radius.

iord=2
monotone
MPDATA
with homo/
hetero logic



A hybrid bulk-bin scheme has been developed based on the observation that supersaturations inside clouds are small and bulk condensation rate provides sufficiently accurate prediction of spectral changes. When condensation first occurs (e.g., near the cloud base), activation parameterization inserts activated droplets near the low end of the spectral representation. Subsequent growth by diffusion is represented by shifting the spectrum towards larger sizes so that the spectral changes match the bulk condensation rate. Growth by collision/coalescence leads to formation of drizzle and eventually rain as in the bin scheme.

The hybrid bulk-bin approach eliminates the need for supersaturation prediction, which is numerically cumbersome, especially near cloud edges, and typically requires high spatial and temporal resolution (e.g., near the cloud base where droplet activation takes place).

A simple approach is proposed to deal with numerical artifacts near cloud boundaries. The key point is to recognize the need for both homogeneous and heterogeneous advection-condensation processes. The analytic bulk condensation rate guides the selection of either homogeneous or heterogeneous numerical representation.

Tests in a multidimensional cloud model that applies invariant variables approach to model condensation (French Meso NH model) will follow.