1.3 A QUASI 2-MOMENT MICROPHYSICAL SCHEME FOR MIXED-PHASE CLOUDS AT MESOSCALE WITH SENSITIVITY TO AEROSOLS (CCN AND IN)

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1. INTRODUCTION

Mixed-phase clouds are the most frequent and active precipitating clouds in the mid-latitudes and in the tropics but the explicit simulation of these clouds is among the most difficult task in mesoscale modeling. Ice phase is intrinsically complex with the coexistence of different types of crystals which have multiple interactions with the warm (liquid and vapor) phase. At the same time there is increasing evidence that many cloud properties depend on characteristics of available aerosols in either warm or glaciated clouds. Thus it is an intringuing idea that the microstructure and hence, the evolution of mixed-phase clouds is probably conditioned by the activation efficiency of cloud condensation nuclei (CCN) at cloud base and by the nucleation modes of a great variety of ice nuclei (IN) above the freezing level. For instance, increasing CCN concentration may suppress the "warm-rain" processes but may favor the supercooling of cloud droplets (if updrafts are intense enough) and then put forward the role of the ice phase to produce rain drops from another pathway, that is from melting graupels or snowflakes (Banta and Hanson, 1987). Therefore to explore the complex nature of thick clouds with warm base, it is fundamental to develop a reliable 3D cloud scheme with a wide applicability to evaluate the relative importance of warm versus cold processes to generate precipitation in convective clouds and to study to what extent this feature critically depends on CCN and IN concentrations.

This paper presents a new bulk microphysical scheme that can simulate an ensemble of microphysical processes that may occur in mixed-phase clouds. The scheme predicts the mixing ratios of six water species and the concentrations of cloud droplets, raindrops and small ice crystals. Concentrations of CCN and IN are also monitored to compel the decrease of the available number of aerosols in case of activation and nucleation. The scheme is tested for a New Mexico summertime cumulus cloud and comparisons are made against results obtained by a detailed bin model (Ovtchinnikov et al., 2000 and hereafter OK2000).

2. A BRIEF REVIEW OF THE SCHEME

2.1 Generalities

The scheme is an extension of the warm 2-moment bulk scheme of Cohard and Pinty (2000). Inclusion of the ice phase is inspired by an earlier work of Pinty and Jabouille (1998) but with substantial modifications.

The bulk scheme predicts the evolution of the mixing ratios of six water species: r_v (vapor), r_c and r_r (cloud droplets and rain drops) and r_i, r_s and r_g (pristine ice, snow/aggregates and frozen drops/graupels ordered with an increasing degree of riming) and the evolution of three concentrations: n_c and n_r (cloud droplets and rain drops) and n_i (pristine ice). The snow and graupel concentrations are diagnosed as simple power laws $N = C\lambda^x$ where λ is the slope parameter of the size distribution and $C - x$ are empirical constants drawn from radar observations and models. The size distribution of each particle is described by a generalized γ-law:

$$n(D) = Ng(D) = N\alpha/\Gamma(\nu)\lambda^{\alpha\nu}D^{\alpha\nu-1}exp\big(-(\lambda D)^{\alpha}\big)$$

where $g(D)$ refers to the normalized form ($n(D)$ is an exponential law for $\alpha = \nu = 1$). The complete characterization of each water and ice category is summarized in the table below with mass-size ($m = aD^b$) and velocity-size ($v = cD^d$) relationships to perform necessary analytical integrations.

Param.	r_c	r_r	r_i	r_s	r_g
α, ν	3,1	1,2	3,3	1,1	1,1
a	524	524	0.82	0.02	196
b	3	3	2.5	1.9	2.8
c	842	$3.2\ 10^7$	800	5.1	124
d	0.80	2.0	1.00	0.27	0.66
C				5	$5\ 10^5$
x				1	-0.5

Table 1: Set of parameters for each water category in MKS

The representation of the warm processes comes from the 2-moment scheme of Cohard and Pinty

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(2000). CCN activation is treated explicitly from adjusted activation spectra or directly from lognormal distributions of aerosols. Coalescence processes are integrated analytically with Long kernels. Raindrop evaporation includes ventilation effect. The cloud droplet autoconversion is parameterized as in the Berry-Reinhardt (BR) scheme and effects due to collisional raindrop breakup are reproduced.

The ice microphysical scheme is described below.

2.2 Ice nucleation

Ice nucleation modifies n_i according to environmental conditions. Three classes of process are considered. The heterogeneous freezing is based on the IN activation spectrum in the deposition mode (a function of ice supersaturation SS_i) or in the contact mode (function of temperature T) as in Meyers et al. (1992). Newly nucleated IN are time integrated as Lagrangian particles to exclude multiple nucleation. The homogeneous freezing of cloud droplets is parameterized according to DeMott et al. (1994) while the freezing of haze (wet aerosols) is given by Kärcher and Lohmann (2001). The secondary nucleation or Hallett-Mossop process is a by-product of cloud droplet riming on snowflakes and graupels. At $T = -5°$ C, a rate of 5×10^{-3} splinters per droplet with diameter $D_c > 25$ μm is assumed (Mossop, 1976). The fraction of large droplets is obtained by partial integration of n_c (incomplete gamma function). This process does not operate when graupels grow in the "wet" mode.

2.3 Formation/growth of snow and graupel particles

Snow results from vapor-grown pristine ice as in Harrington et al. (1995). The snow source rate is explicitly computed as the deposition growth rate on the large crystal (with $D_i > 125$ μm) fraction of n_i. The process is reversed when snow sublimates.

Snow grows by vapor deposition, collection of small crystals and riming of cloud droplets and rain drops. Collection of large rain drops converts the snowflakes/aggregates into graupel when the density of the ice-raindrop mixture approaches the graupel density. All these microphysical rates are integrated analytically or precomputed in look-up tables as in Ferrier (1994).

Graupels are formed in case of heavy riming of snow and by rain freezing when supercooled raindrops come in contact with pristine ice crystals. Graupels grow in dry or wet mode when they collect other particles. The switch is defined by the heat balance equation giving the total water amount that can freeze at the surface of the graupels.

When $T \geq 0°$ C, the pristine crystals are instantly transformed into cloud droplets while snowflakes are progressively converted into graupels which melt during the fall. The sedimentation of cloud particles and hydrometeores influences the mixing ratios and concentrations

2.4 Diffusional vapor growth and supersaturations

The Bergeron-Findeisen process transfers water mass from cloud droplets to ice crystals in proportion to the saturation conditions over water and over ice. This process is integrated explicitly.

The phase equilibrium between water vapor, cloud droplets and cloud ice is maintained by the reversible processes of condensation/evaporation (C/E) and deposition/sublimation (D/S) but with different relaxation time scales (Khvorostyanov and Sassen, 1998). In the scheme, C/E is implicit and results from a non-iterative saturation adjustment over water (Cohard and Pinty, 2000) while D/S is explicitly computed from pristine ice properties (crystal concentration, capacitance, ventilation factor, etc...). The result is that no supersaturation over water exists when cloud droplets are present but supersaturation over ice can reach several tens percent in pure ice clouds. In mixed-phase regions, a first saturation adjustment, which takes ice into account as in Reisin et al. (1996), is performed over water then the D/S process is explicitly integrated.

3. THE "NEW MEXICO" CUMULUS CLOUD CASE STUDY

The microphysical scheme is tested in the non-hydrostatic host model MésoNH for the New-Mexico cumulus cloud case study of Ovtchinnikov and Kogan (2000). Same environmental conditions and domain definitions are used. Convection is initiated by a warm gaussian bubble of 1 K excess (instead of 3 K in OK2000) superimposed to a 1 K white noise as in the SEI technique. The CCN activation spectrum is fitted from OK2000 data but with a total concentration of 600 cm^{-3} as "observed". The computational domain is $72 \times 72 \times 75$ grid point with a spacing of 100 m in all directions. The timestep is 1 s and the simulation is performed for 1 hour. The simulations are made with open lateral boundary conditions and with an absorbing layer at the model top to damp vertically propagating gravity waves. Turbulence is 3D with a 1.5 level closure based on prediction of the tubulent kinetic energy (TKE).

3.1 Time series

The time evolution of the maxima of some fields is reproduced in Fig. 1. Even with a small buoyant impulse, convection is well developped with a main updraft reaching 9.2 ms^{-1} at 2.8 km after 18 min.

The formation and growth of the cloud droplets follow w with a max value of 4.4 gkg^{-1} at 3.7 km (-3.5° C height level). Downdrafts ($w_{min} \sim -8.5\ \mathrm{ms}^{-1}$ at 2.3 km) occur when a copious amount of rain begins to evaporate during its fall after 37 min. Ice nucleation starts after 15 min and pristine ice is rapidly converted into snow at 5 km. Due to the large quantity of supercooled cloud droplets, snow is efficiently converted into graupels (up to 6 gkg^{-1}). It is worth to notice that rain is produced by melting graupels and not by autoconversion of cloud droplets. The origin of pristine ice concentration is well depicted on the CI/CN plot. Ice is first produced by heterogeneous nucleation ($\sim 2\ \mathrm{l}^{-1}$) but as environmental conditions are very favourable, an explosive increase of n_i ($\leq 180\ \mathrm{l}^{-1}$) is obtained via the Hallett-Mossop process. In contrast with OK2000, this high value of n_i does not persist for more than 10 min due to the strong depletion of the cloud droplets (and ice particles) by wet riming on the graupels. However small ice crystals are still produced by IN nucleation ($n_i < 10\ \mathrm{l}^{-1}$) at cloud top where SS_i attains 20%.

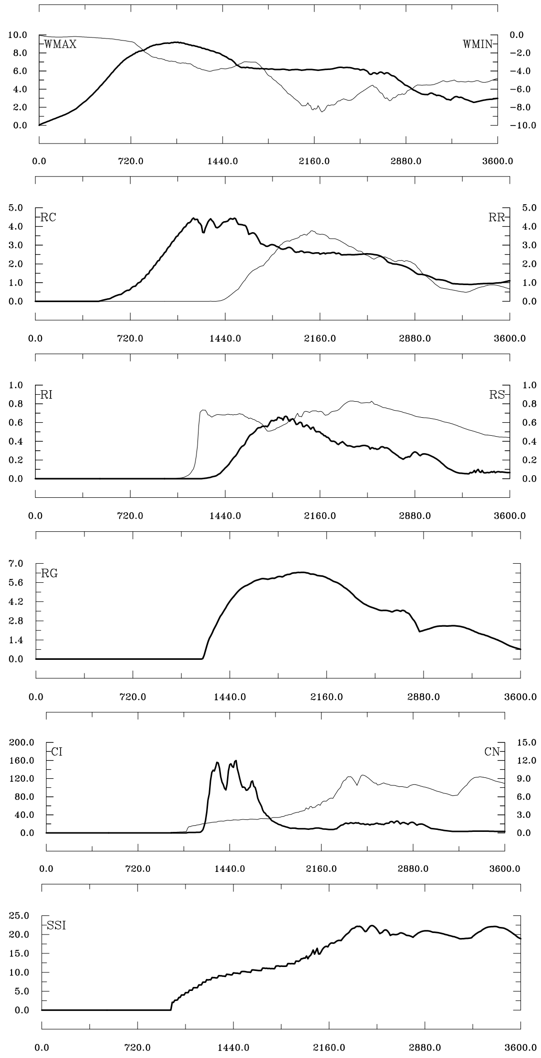


Figure 1: Time series of domain maxima. From top to bottom, the vertical speed (with WMIN minima), the liquid water r_c (bold) and r_r, the un(or lightly)rimed ice r_i (bold) and r_s, the graupel r_g, the ice n_i (bold) and nucleated IN n_n concentrations (l^{-1}) and ice supersaturation SS_i (%).

3.2 Time sequence analysis

Fig. 2 presents the 5 min evolution of the same vertical cross section passing through the center of the domain. The field asymmetry is a consequence of the SEI technique of initialization (OK2000). At

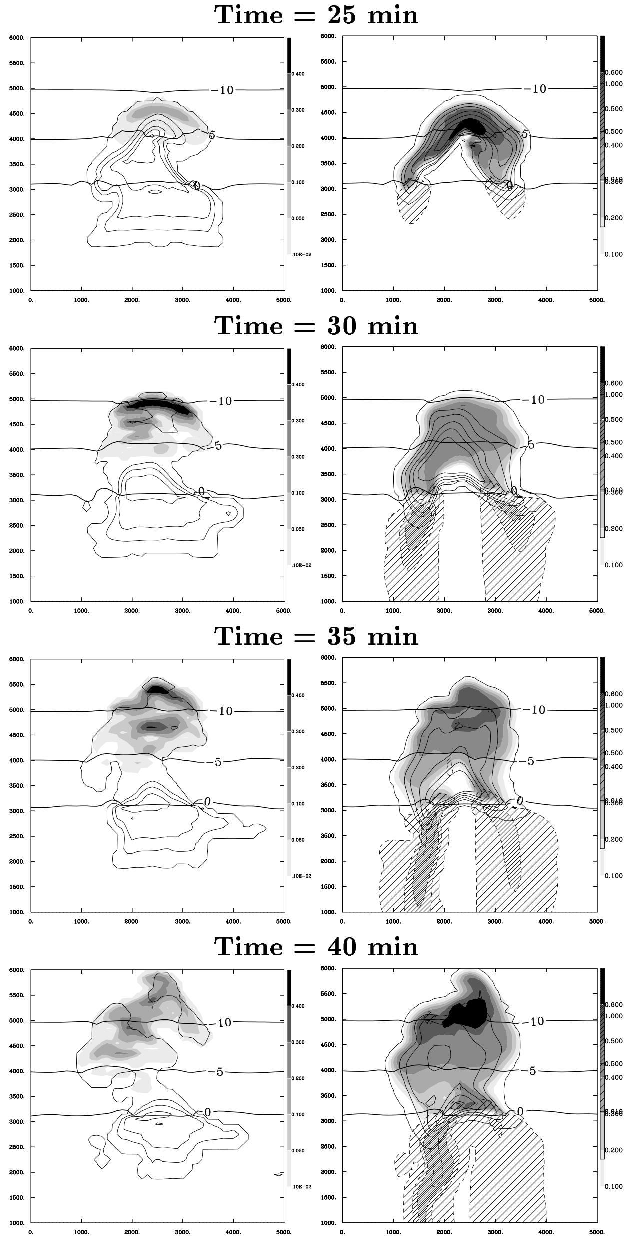
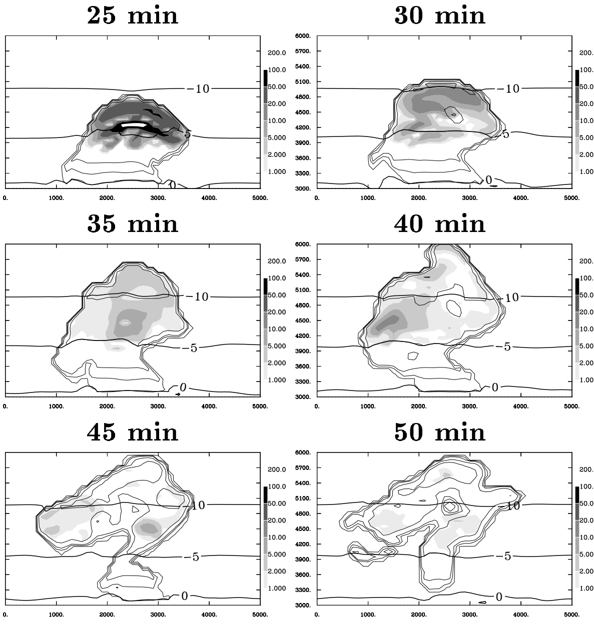


Figure 2: Vertical cross sections through domain center: r_i ([10^{-3}, 0.05, 0.1, 0.2, 0.3, 0.4 gkg^{-1}] grey scale) and r_c ([10^{-2}, 0.5, 1, 2, 3, 4 gkg^{-1}] (left) and r_s ([0.1, 0.2, 0.3, 0.4, 0.5, 0.6 gkg^{-1}] grey scale), r_g and r_r (hatched areas) with r_c contours (right). Labelled curves are isotherms in ° C.

25 min, the updraft sustains the supercooling of the cloud droplets at -5 ° C. The presence of graupel at this level is optimal for the Hallett-Mossop ice crystal multiplication (see the corresponding n_i plot in Fig. 3). Rain begins to form on the edges of the updraft from the melting graupels and not in the updraft core from the "warm" pathway although r_c is large enough there. The reason is that the BR autoconversion parameterization of the scheme do not produce many raindrops because the cloud droplets are too small (vol. diameter $D_c < 23\ \mu$m). Five min later, the newly nucleated ice crystals have grown (a r_i increase) and are transported upwards to the -10 ° C level. The cloud droplets are clearly depleted to the advantage of the graupels. The narrow rainbands develop and reach the ground (the plots are cut at 1 km high). At 35 min, the cloud continues its ascent by carrying cloud ice and a small amount of cloud droplets. The small ice crystals are progressively converted into snow crystals at 40 min leading to a significant increase of r_s at 5000 m. As the updraft starts to decline, less supercooled water is available for the graupel growth.


25 min

30 min

35 min

40 min

45 min

50 min

Figure 3: Vertical cross sections at same location as in Fig. 2, but for the 3-6 km layer only showing n_i ([1, 2, 5, 10, 20, 50, 100, 200 l^{-1}] grey scale) and SS_i ([0.1,1, 2, 5, 10, 20 %].

The n_i history is plotted in Fig. 3 (log scale and grey shading) with superimposed SS_i isocontours. At 25-30 min, the small ice crystals are (inhomogeneously) present above 4 km height. Then the n_i concentration rapidly decreases at cloud top due to the steady capture by larger snow crystals (35-40 min). This raises locally SS_i well above 10 % because of the limited rate of water vapor deposition when n_i is low (Khvorostyanov and Sassen, 1998). The decaying stage (45-50 min) is characterized by a strong mixing with environmental air. SS_i is reduced and n_i falls below $\sim 1\ \mathrm{l}^{-1}$.

4. CONCLUSION

This study reports first results obtained by a quasi 2-moment microphysical scheme which explicitly incorporates activation and nucleation of aerosols. The New-Mexico cumulus cloud test case shows that the simulated cloud evolution compares reasonnably well with OK2000's bin model results. Next step will explore the complex sensistivity of mixed-phase clouds to aerosols. Preliminary results (not shown here) confirm that the microstructure of these clouds depends on the initial CCN concentration as anticipated.

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