A Three-Category Ice Scheme for LMK

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1 Introduction

The present microphysics scheme operational in LM at 7 km mesh size is dedicated to precipitation formation in stratiform clouds. Ice hydrometeors occuring in deep convective clouds – such as graupel and hail – are neglected. In order to simulate such clouds explicitly – as we intend to do with LM's high-resolution version LMK (Doms and Förstner, 2004) –, ice particles with larger fall velocities than snow must be included to allow for a reasonable physical description of precipitation formation. Therefore the present cloud ice scheme has been extended to include graupel as a third ice category. The scheme considers the mixing ratios of cloud water, cloud ice, rain, snow, and graupel as prognostic condensate categories.

2 Method

For the graupel particles, an exponential size distribution is assumed:

$$f_\mathrm{g}(D_\mathrm{g}) \;=\; N_0^\mathrm{g} \exp(-\lambda_\mathrm{g} D_\mathrm{g})$$

with $N_0^\mathrm{g} = 4 \times 10^6$ m^{-4} (Rutledge and Hobbs, 1984), D_g: diameter of graupel particle. The properties of single graupel particles in the form of power laws are taken from Heymsfield and Kajikawa (1986) for their (low density, $\rho_\mathrm{g} \approx 0.2\,\mathrm{g/cm^3}$) lump graupel: For the mass-size relation, it is assumed: $m_\mathrm{g} \;=\; a_m^\mathrm{g}\, D_\mathrm{g}^{3.1}$ with a_m^g =169.6; and for the terminal fall velocity depending on size: $v_T^\mathrm{gp}(D_\mathrm{g}) \;=\; v_0^\mathrm{g} D_\mathrm{g}^{0.89}$ with $v_0^\mathrm{g} = 442.0$ (all in the corresponding SI units).

Graupel is initiated from freezing of raindrops and from conversion of snow to graupel due to riming. The expression for the conversion rate for snow being converted to graupel due to riming follows from the consideration that a particle is converted from the snow category into the graupel category if the volume of the frozen ice from collected cloud water reaches a certain percentage (here: $\sim 12\%$) of the enveloping sphere associated with the snow particle's maximum diameter, see e.g. Seifert (2002). This process is active if a cloud water threshold of 0.2 g/kg is exceeded. Water vapor deposition, sublimation, melting, and collection of cloud droplets and cloud ice crystals is parameterized for graupel in a way analogous to snow. In contrast to the present scheme, for the (Kessler-type) autoconversion from cloud water to rain water, a cloud water threshold is applied (currently 0.2 g/kg). Figure 1 shows the microphysical processes considered in the parameterization scheme.

3 Results

Idealized 2-d Warm Bubble

Figure 2 compares the simulated hydrometeor distribution of a warm bubble, after 72 min, calculated with standard LM microphysics and graupel microphysics.

The graupel scheme simulates mostly graupel instead of snow, besides the upper part of the cloud. There is also more cloud water and more cloud ice in the simulation with graupel, due

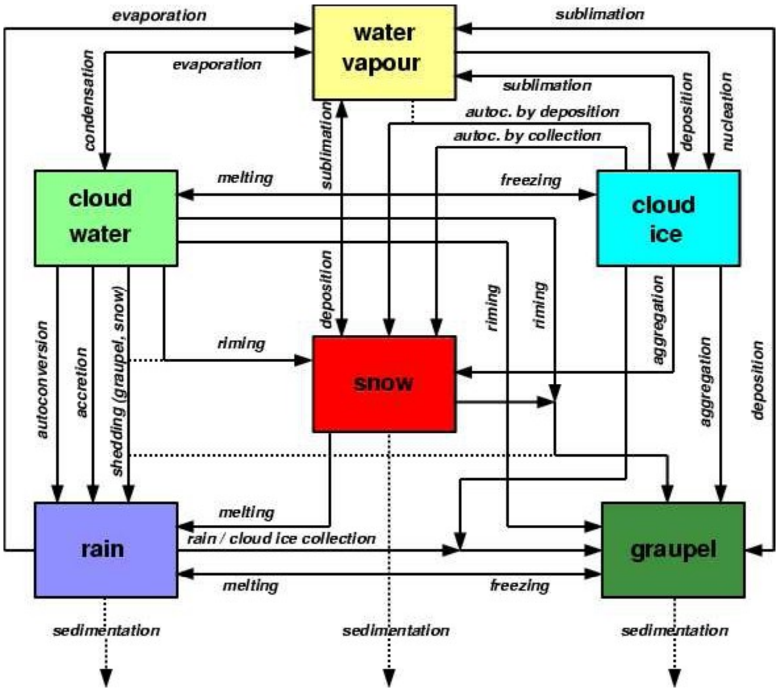

Figure 1: Cloud microphysical processes considered in the graupel scheme.

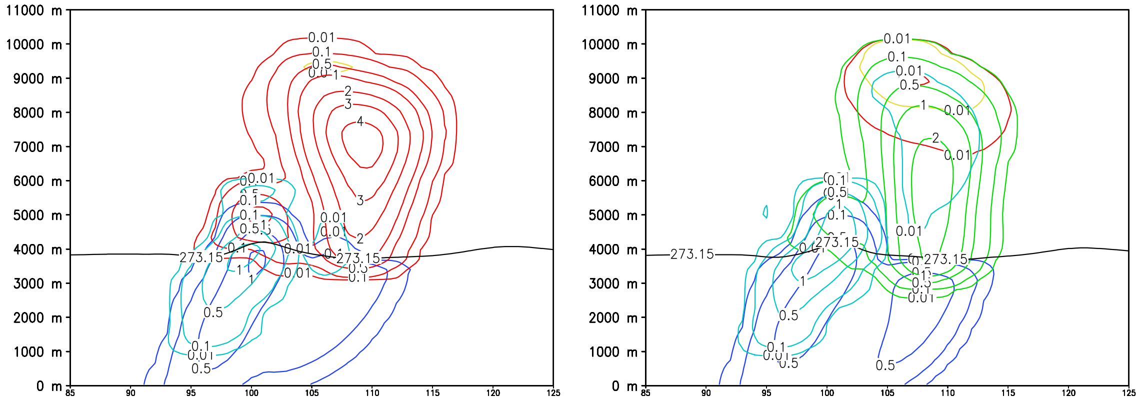

Figure 2: Hydrometeor distribution (mixing ratios in g/kg) of 2-d warm bubble, after 72 min. Mesh size: 2 km. Left: simulation with standard LM microphysics. Right: simulation with graupel scheme. Yellow: cloud ice, red: snow, green: graupel, light blue: cloud water, dark blue: rain.

to less efficient riming and deposition growth of graupel compared to snow, and due to the autoconversion threshold of cloud-water-to-rain autoconversion introduced in the graupel scheme. The zone with precipitating ice (snow, graupel, resp.) reaches further downward in the simulation including graupel, due to higher sedimentation velocity of graupel compared to snow. These features can be assessed as improvements.

Single Cases With LMK

Figure 3 shows west-east cross-sections of hydrometeor distributions for two LMK cases: A stratiform snowfall event from March 2004 and a spring/summer convective event from May 2004.

On the one hand, in the stratiform snowfall event most precipitation ice is simulated as snow, with about only 10 percent graupel. On the other hand, in the convective event, most

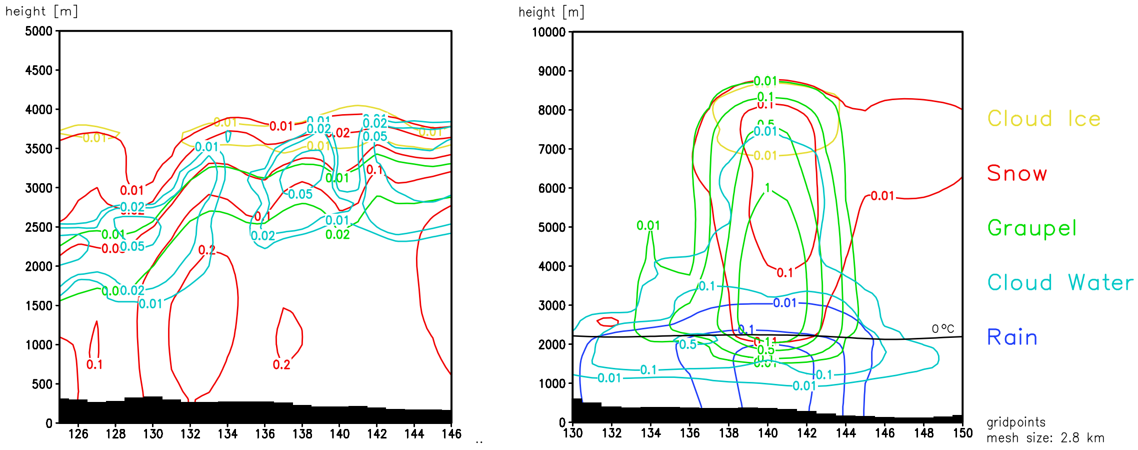

Figure 3: West-east cross-sections of hydrometeor distributions (mixing ratios in g/kg) for two cases simulated with LMK (mesh size: 2.8 km). Left: stratiform snowfall (2004-03-09 00 UTC + 08 h), isolines: 0.01, 0.02, 0.05, 0.1, 0.2. Right: convective cell (2004-05-11 00 UTC + 13 h), isolines: 0.01, 0.1, 0.5, 1. Color code as in Fig. 2.

precipitation ice is simulated as graupel, with snow occuring mostly in the upper part (and also in an anvil-like part) of the cloud. These seem to be reasonable results. Therefore, it can be concluded that the scheme simulates graupel principally in a plausible way.

Testsuite July to September 2004

A three-month comparison (two 18-h forecasts daily, starting 00 UTC and 12 UTC, for July to September 2004) of LMK results computed with the new scheme shows a small (5 %) decrease in total precipitation compared to the present microphysics scheme. Generally, standard verification scores (against synoptic observations) were not affected significantly. The positive frequency bias for small (0.1–2 mm/h) precipitation events was slightly reduced which might be caused by the introduction of the threshold for cloud water autoconversion. It can be concluded that the scheme behaves well also for a large series of forecasts, but improvements in forecast skill could not be found yet from the verification carried out up to now. The graupel scheme is now default for ongoing LMK testsuites.

4 Sensitivity to Graupel Particle Properties

Gilmore et al. (2004) carried out sensitivity tests with respect to the assumed properties of the graupel/hail category within a bulk (one-moment) microphysics parameterization. They used an idealized convective environment for their model setup (1 km mesh size, 30 m/s and 50 m/s wind speed with veering wind shear, supercell development, similar to Weisman and Klemp, 1984) and varied the intercept parameter N_0^{g} of the graupel particle size distribution and the graupel particle density ρ_{g}. Decreasing N_0^{g} as well as increasing ρ_{g} each changes the bulk properties of the particle ensemble towards more hail-like properties, e.g. faster sedimentation and less rapid melting. In general, more precipitation accumulated at ground was found in the cases with the graupel/hail category weighted towards large hail. These sensitivities could be found also with LMK simulations in a similar idealized 3-d convective setup (2.8 km mesh size, unidirectional wind shear only, wind speed 25 m/s, symmetric storm splitting, similar to Weisman and Klemp, 1982). Surface precipitation (both mean and maximum) tends to be higher with the graupel category weighted towards hail-like properties, i.e. smaller intercept parameter and larger particle density, see Table 1. A large sensitivity

N_0^{g}	ρ_{g}	TotP	TotG	MaxP	MaxG
4×10^4	≈ 0.2	36.17	0.1069	23.03	0.0001
4×10^5	≈ 0.2	27.55	0.0000	16.91	0.0000
4×10^6	≈ 0.2	14.80	0.0000	10.91	0.0000
4×10^4	0.4	35.51	0.1883	22.79	0.5017
4×10^5	0.4	32.02	0.0000	19.07	0.0000
4×10^6	0.4	25.79	0.0000	16.05	0.0000
4×10^4	0.9	32.82	3.4673	25.56	5.8234
4×10^5	0.9	35.01	0.0000	21.27	0.0000
no graupel	–	4.13	–	4.26	–

Table 1: Comparison of surface precipitation for simulations with different assumed intercept parameter N_0^{g} (in m^{-4}) and graupel particle density ρ_{g} (in $\mathrm{g/cm}^3$). Accumulated mass on ground (total precipitation (TotP) and graupel (TotG) in Tg and maximum total precipitation (MaxP) and maximum graupel precipitation (MaxG) in mm. All after 2 hours. For $\rho_{\mathrm{g}} = 0.4\,\mathrm{g/cm}^3$ and $\rho_{\mathrm{g}} = 0.9\,\mathrm{g/cm}^3$, the velocity-size relationship is taken from Lin et al. (1983).

to N_0^{g} is found in the $\rho_{\mathrm{g}} \approx 0.2\,\mathrm{g/cm}^3$ and $\rho_{\mathrm{g}} = 0.4\,\mathrm{g/cm}^3$ cases: With N_0^{g} decreasing from $4 \times 10^6\,\mathrm{m}^{-4}$ to $4 \times 10^4\,\mathrm{m}^{-4}$ total surface precipitation increases by 144 % and 73 %, resp. Higher mass-weighted sedimentation velocity of the graupel particle ensemble (i.e. smaller N_0^{g}) makes the particles less susceptible to horizontal advection (and subsequent evaporation outside the storm) and can therefore lead to more surface precipitation. As to be expected, with decreasing N_0^{g} and increasing ρ_{g} more unmelted graupel/hail can reach the ground. Much less surface precipitation (compared to all simulations including graupel) is found in the no-graupel (= standard LM microphysics) case confirming the need of a faster-than-snow falling ice species when simulating severe convection.

Less sensitivity is found in two simulations of real (convective) weather situations: A prefrontal squall-line case (July 18, 2004) and a case with less organized, more isolated convection in a situation with weak large-scale gradients (August 7, 2004), see Tab. 2 and 3 and Fig. 4. In contrast to the idealized warm-bubble setup, in the August 07 case area-mean precipitation tends to decrease when moving from light-graupel to hail-like particle properties in the graupel/hail category, while in the July 18 case one might see the same but very much damped tendency as in the idealized setup. As in the idealized setup, in both real cases maximum precipitation is lower in the no-graupel simulation than in any of the simulations including graupel. From the precipitation patterns shown in Fig. 4 it can be inferred that in the August 07 case simulated precipitation becomes less widespread (i.e. areas receiving precipitation becoming smaller without maxima being reduced) when moving from the no-graupel over the low-density-graupel to the high-density-graupel/hail case which might be due to the effect of ice precipitation becoming less subject to horizontal advection when sedimenting faster. In the July 18 case (no figure shown), this feature is not seen.

That the sensitivity to the assumed properties of the graupel category is smaller in simulations of real convective cases compared to the idealized setup may be attributed (i) to more (negative) feedbacks being active in longer integration time and on a larger domain and (ii) to graupel being overall less important in simulations of real weather events (since there are always also more stratiform and snow-dominated areas) compared to the idealized simulations where much more graupel than snow is simulated. Tab. 2 and 3 show also that in simulations weighted towards large hail (all N_0^{g}=$4 \times 10^4\,\mathrm{m}^{-4}$ simulations; the more the higher ρ_{g}) explicit simulation of hail occurence at the ground is possible.

N_0^{g}	ρ_{g}	MeanP	MeanG	MaxP	MaxG
4×10^4	≈ 0.2	0.3627	0.0004	64.05	0.46
4×10^5	≈ 0.2	0.4461	0.0000	57.64	0.00
4×10^6	≈ 0.2	0.4548	0.0000	47.71	0.00
4×10^4	0.4	0.3136	0.0002	49.55	1.07
4×10^5	0.4	0.4023	0.0000	58.61	0.00
4×10^6	0.4	0.4846	0.0000	57.92	0.00
4×10^4	0.9	0.3109	0.0061	73.71	10.15
4×10^5	0.9	0.3129	0.0000	56.61	0.05
no graupel	–	0.4190	–	41.96	–

Table 2: As Tab. 1, but for simulated 23-hour precipitation sum of LMK forecasts started at August 07, 2004 00 UTC. Numbers are valid for the area shown in Fig. 4 (total domain larger than domain shown). MeanP and MeanG stand for mean total precipitation and mean graupel precipitation (in mm), resp.

N_0^{g}	ρ_{g}	MeanP	MeanG ($\times 10^3$)	MaxP	MaxG
4×10^4	≈ 0.2	4.384	0.222	91.37	1.65
4×10^5	≈ 0.2	4.318	0.0	94.46	0.0
4×10^6	≈ 0.2	4.183	0.0	81.20	0.0
4×10^4	0.4	4.369	2.098	98.34	3.15
4×10^5	0.4	4.341	0.0	83.31	0.0
4×10^6	0.4	4.341	0.0	83.71	0.0
4×10^4	0.9	4.276	20.906	98.39	9.60
4×10^5	0.9	4.334	0.047	86.73	0.0
no graupel	–	4.154	–	79.41	–

Table 3: As Tab. 2, but for simulated 23-hour precipitation sum of LMK forecasts started 2004-07-24 00 UTC.

5 Outlook

It is under consideration to change the bulk properties of the graupel category in such way that more hail-like particles instead of low-density graupel particles are represented. This would allow for an explicit simulation of surface hail occurence. Then it would be more consistent to take into account also wet growth of the hailstones which is neglected currently. On the other hand, medium- and low-density graupel would then be represented less accurately. A compromise might be to make N_0^{g} dependent on the graupel/hail mixing ratio, i.e. let N_0^{g} decrease when q_{g} increases.

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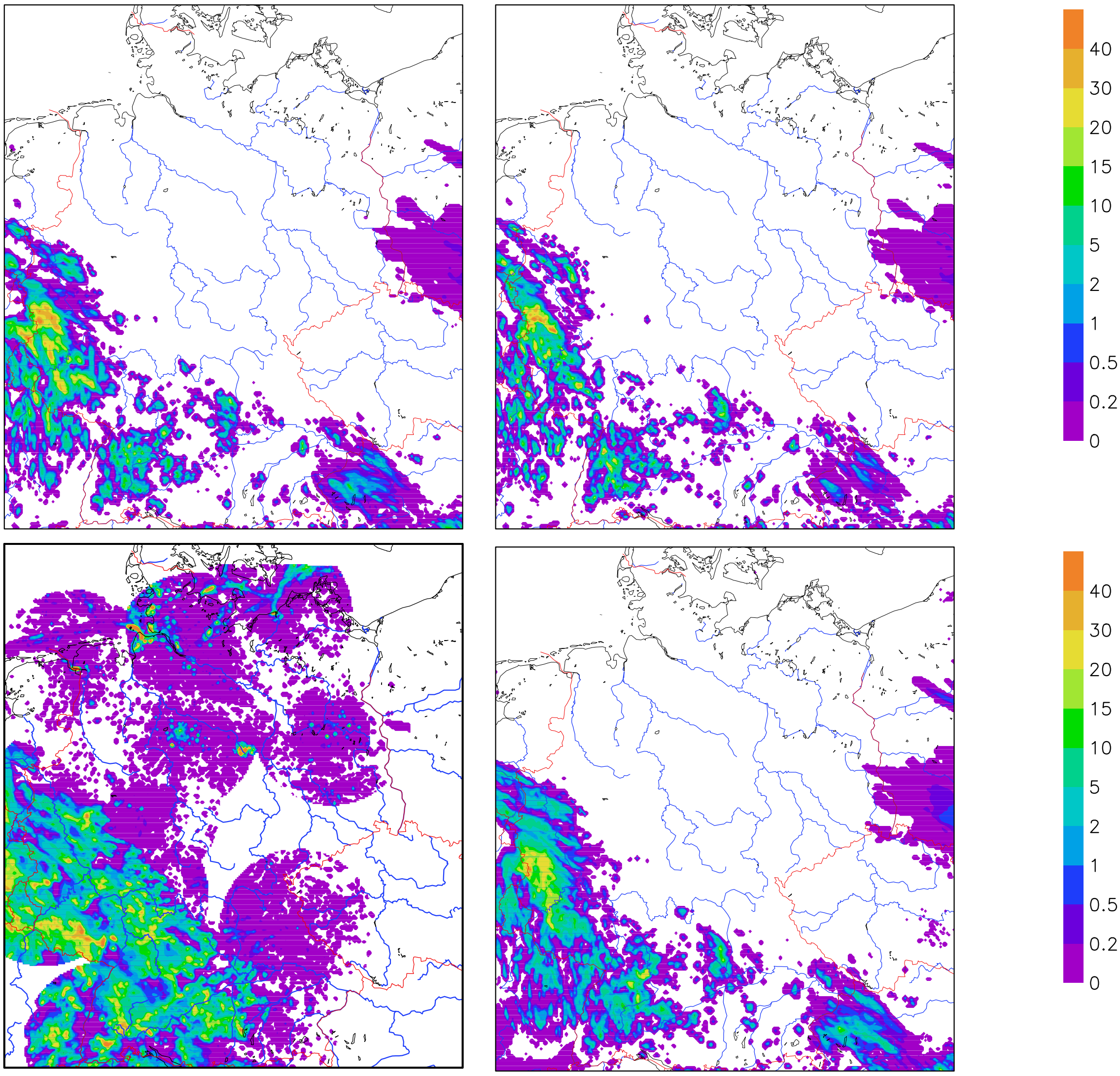

Figure 4: Simulated 23-hour precipitation sums (in mm) of LMK forecasts started 2004-08-07 00 UTC. Upper left: $N_0^{\rm g}$=4 × $10^6\,{\rm m}^{-4}$, $\rho_{\rm g} \approx 0.2\,{\rm g/cm}^3$; upper right: $N_0^{\rm g}$=4 × $10^4\,{\rm m}^{-4}$, $\rho_{\rm g} = 0.9\,{\rm g/cm}^3$; lower right: no graupel (standard LM microphysics). Lower left: corresponding radar-derived precipitation observation.

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