Simulation of hail processes with a state-of-the-art 2-moment cloud microphysical scheme

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Motivation

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- **Hail formation on the end of a long process chain:**

  Triggering of convective cells, smaller cloud- and precipitation particles form, under favorable conditions growth of smaller ice paricles to hailstones by collisions with supercooled droplets.

- **Simulation in an NWP-model still a big problem, because relevant processes and time-/space scales only marginally resolved.**

- **Challenge for the microphysics parameterization:**

  Compromise between physical accuracy and efficiency

  → Use of a 2-moment (bulk) cloud microphysical scheme (in this case Seifert and Beheng, 2006) enhanced by an additional hail particle class (Blahak, 2008; Noppel, 2010)

Outline

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- On hail formation
- Parameterzation within the 2-moment-scheme coupled to the COSMO-Model
- Case studies
  - 2 real cases, dx = 1 km
  - Idealized study concerning influence of grid distance

On hail formation

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- **Ingredients:** Updrafts, supercooled droplets, hail embryos (e.g. frozen droplets, graupel, other ice particles)

- Hailstones grow large mainly by collection of supercooled droplets (riming)

  - Large stones by abundance of supercooled droplets and/ or long residence time within such an environment

  - Dry growth / wet growth
    („intermediate“ / „high“ bulk density)

  - **Also decisive: Ratio of available supercooled water to number of embryos / hailstones (Competition situation)**

On hail formation

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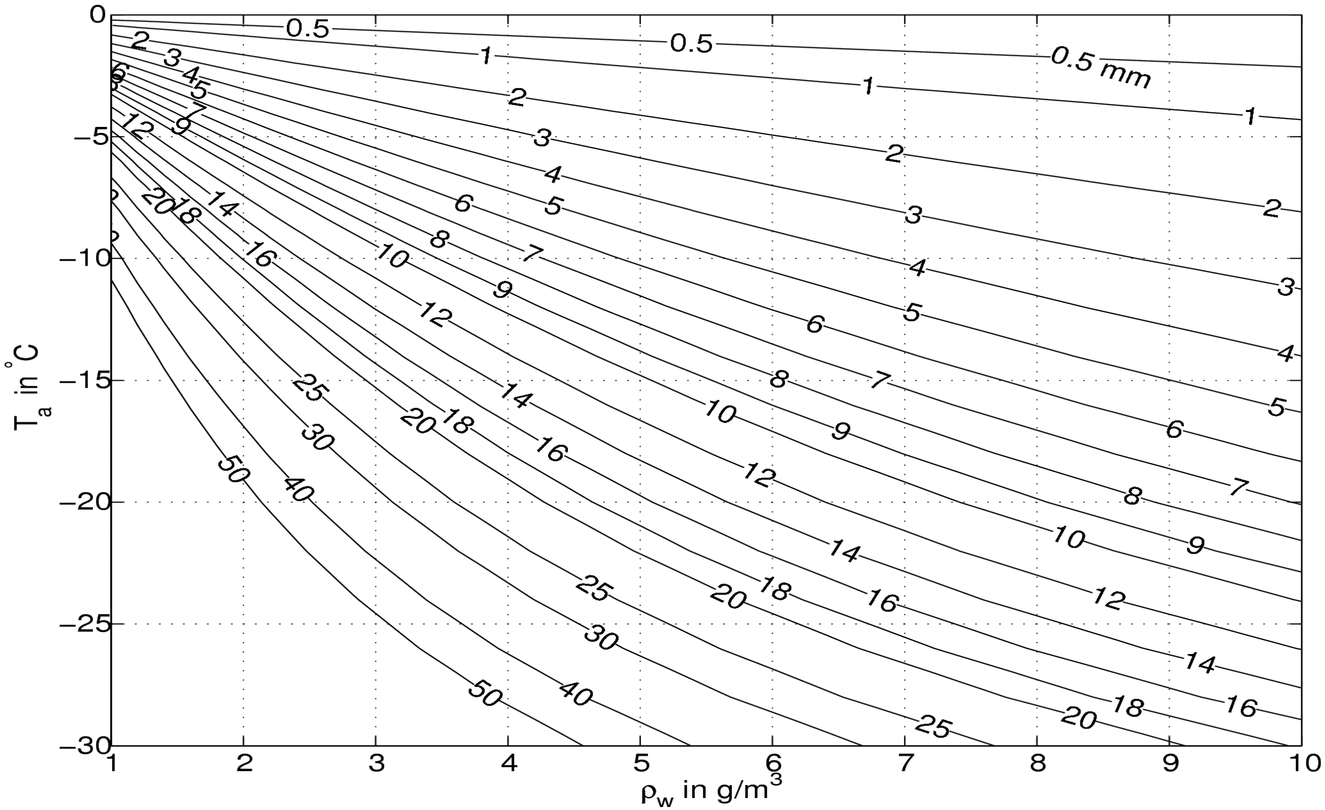
Dry / wet growth:

Regime separation diameter for graupel, p = 600 hPa



On hail formation

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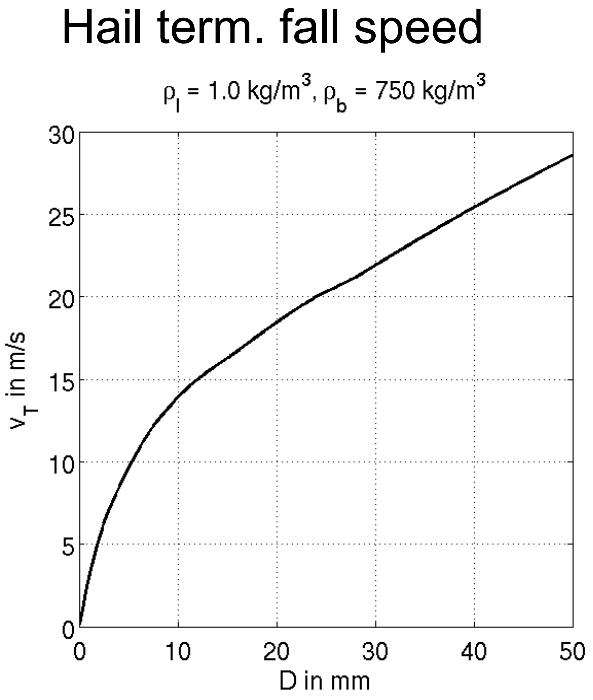
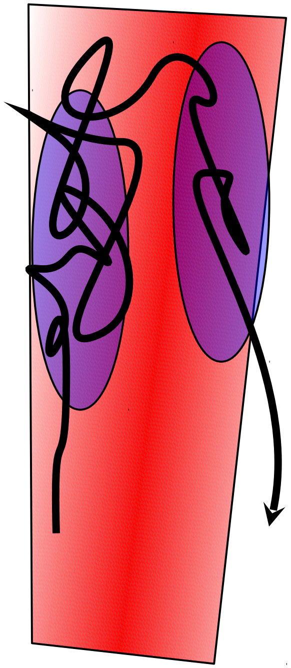
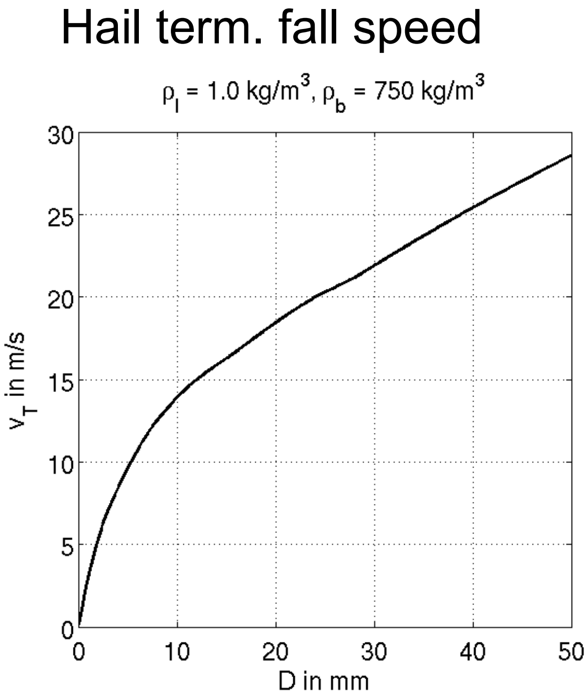
Updraft structures and formation of large hail



On hail formation

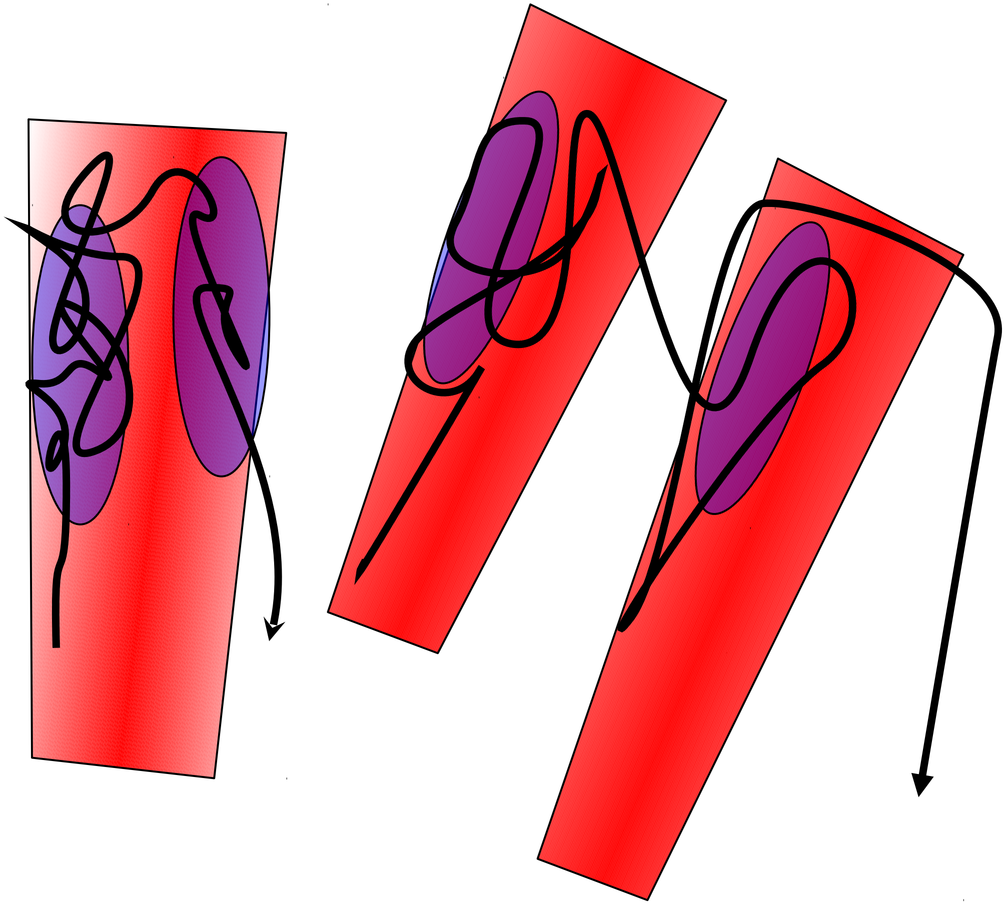
Updraft structures and formation of large hail

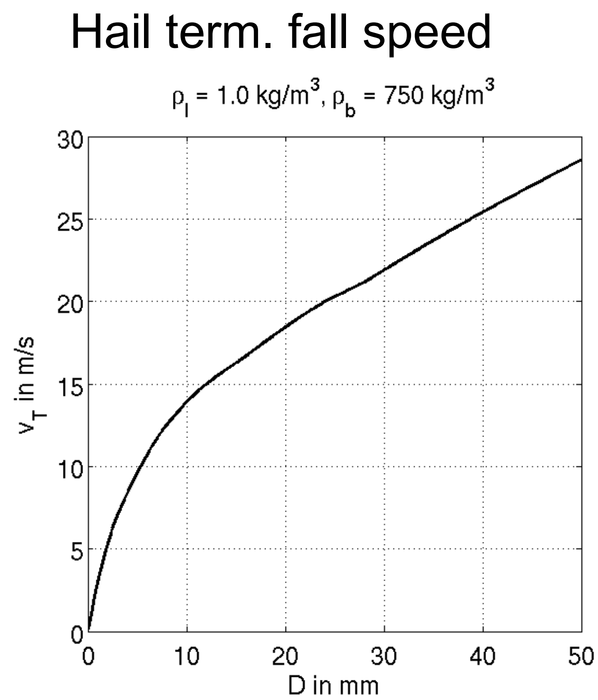




On hail formation

Updraft structures and formation of large hail





2-moment scheme

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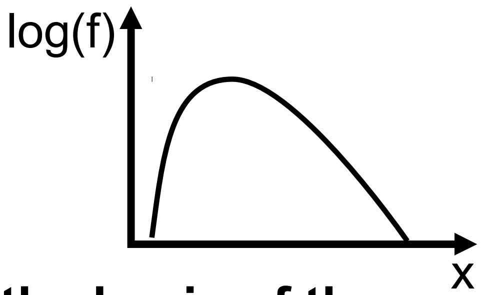
- Hydrometeor classes: cloud droplets, rain, cloud ice, snow, graupel, hail („simple“ extention, Noppel et al., 2006)
- For each class, budget equations for N and Q

$$\mathbf{N} = \int_0^\infty f(x)\,dx \qquad \mathbf{Q} = \int_0^\infty x\,f(x)\,dx$$



- Parameterization of microphysical processes on the basis of the spectral budget equation(s) assuming a generalized gamma-distribution for f(x):

$$f(x) = N_0\, x^\nu \exp\left(-\lambda\, x^\mu\right)$$

$$\nu,\mu = \text{const.}, \qquad \lambda = \left[\frac{\Gamma(\frac{\nu+1}{\mu})}{\Gamma(\frac{\nu+2}{\mu})}\frac{Q}{N}\right]^{-\mu}, \qquad N_0 = \frac{\mu\, N}{\Gamma(\frac{\nu+1}{\mu})}\lambda^{\frac{\nu+1}{\mu}}$$

- Coupling to the COSMO-Model

2-moment scheme

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Considered hail processes (new):

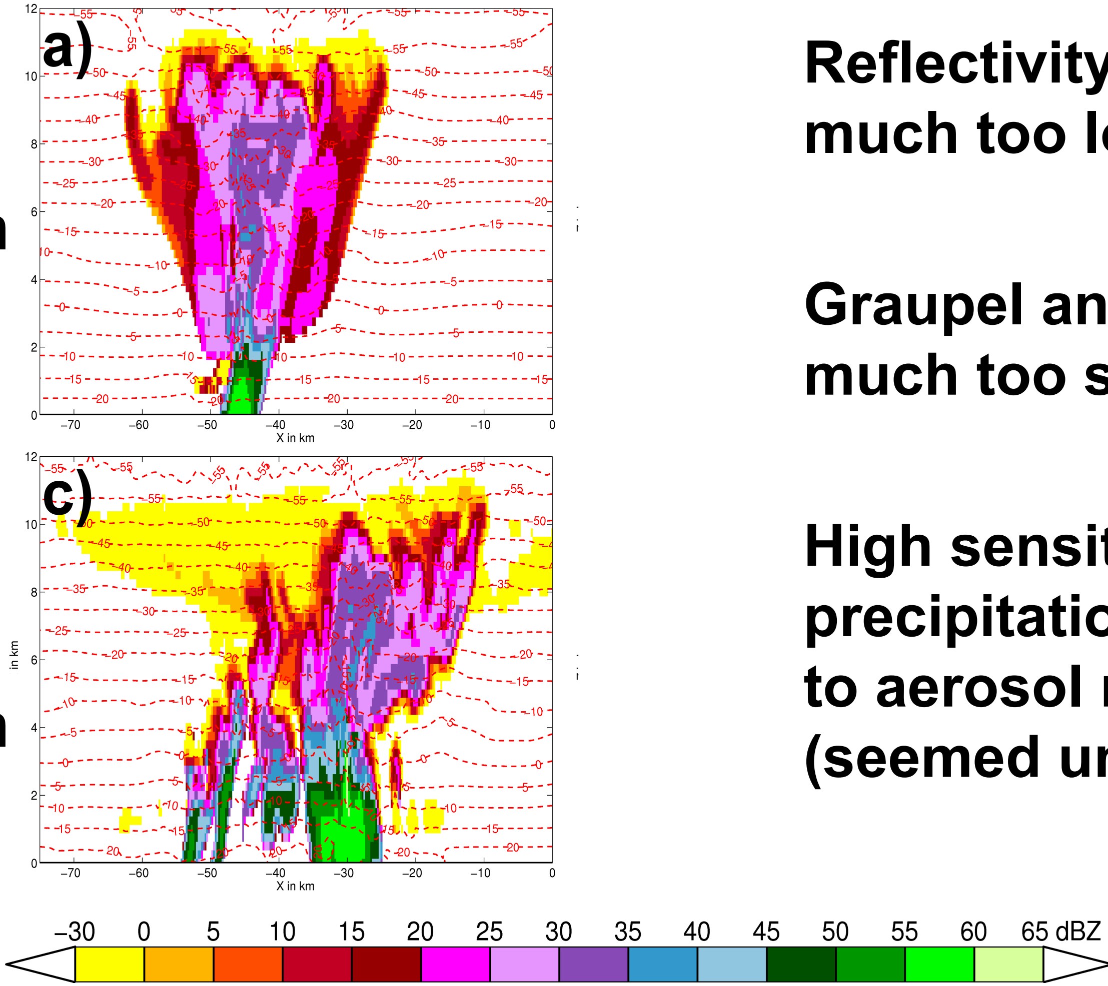
- Dry growth by collection of supercooled droplets
- ~~Wet Growth~~
- ~~Shedding of droplets~~
- Hail embryos: frozen raindrops
- Melting (instantaneous shedding of melt water into rain)
- Dynamic processes (Seeder-Feeder, recirculation, „balancing“ in updrafts) are taken into account, insofar the setup of the COSMO-Model allows that.
- „Competition“ for the available supercooled liquid

2-moment scheme

First experiences in 2006:

00:50 h

02:00 h



Reflectivity in Ice region much too low

Graupel and „hail“ much too small

High sensitivity of precipitation efficiency to aerosol regime (seemed unrealistic)

(2D idealized, warm bubble)

2-moment scheme

Changes:

1) **Assumptions about size-mass- and fallspeed-mass-relations altered (ice, snow, graupel, hail)**

2-moment scheme

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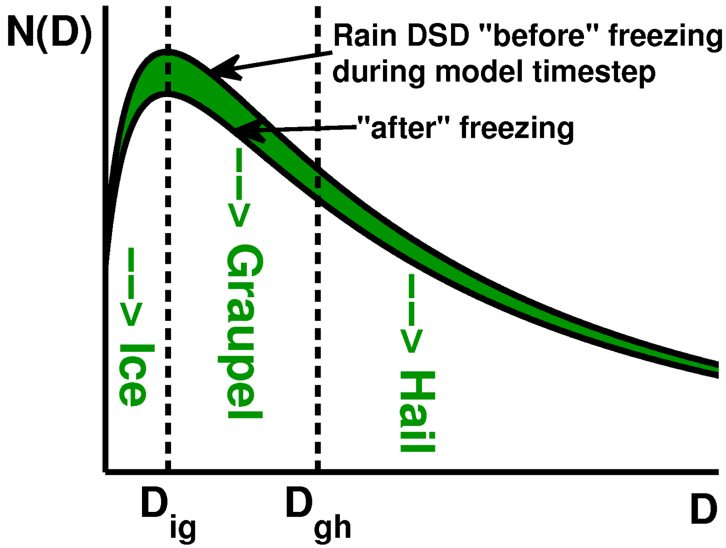
2) **raindrop freezing changed:**



2-Momenten-Schema

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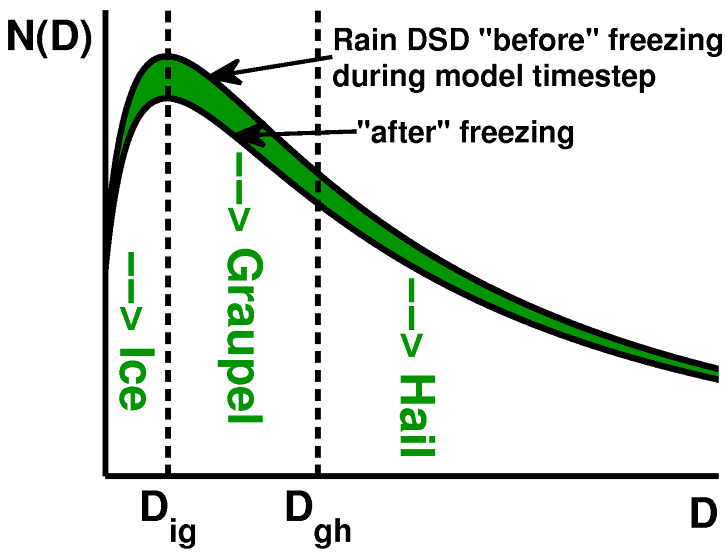
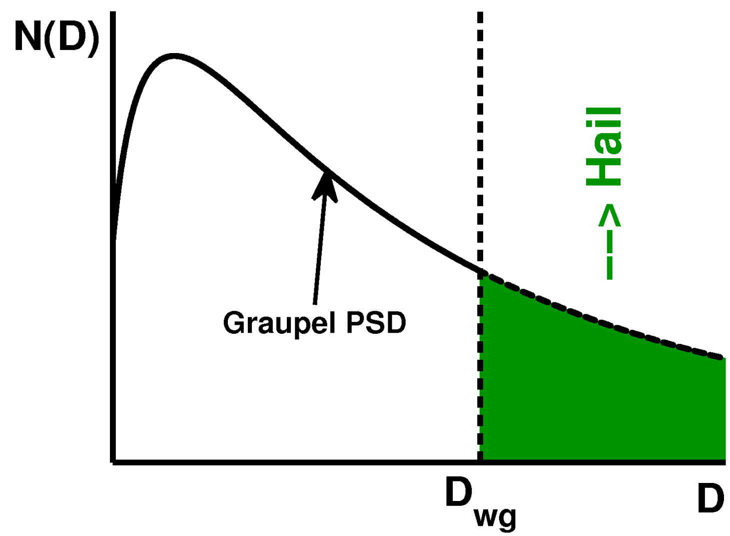
Changes:

1) Assumptions about size-mass- and fallspeed-mass-relations altered (ice, snow, graupel, hail)

2) raindrop freezing changed:

3) New: conv. graupel → hail by wet growth of graupel





2-moment scheme

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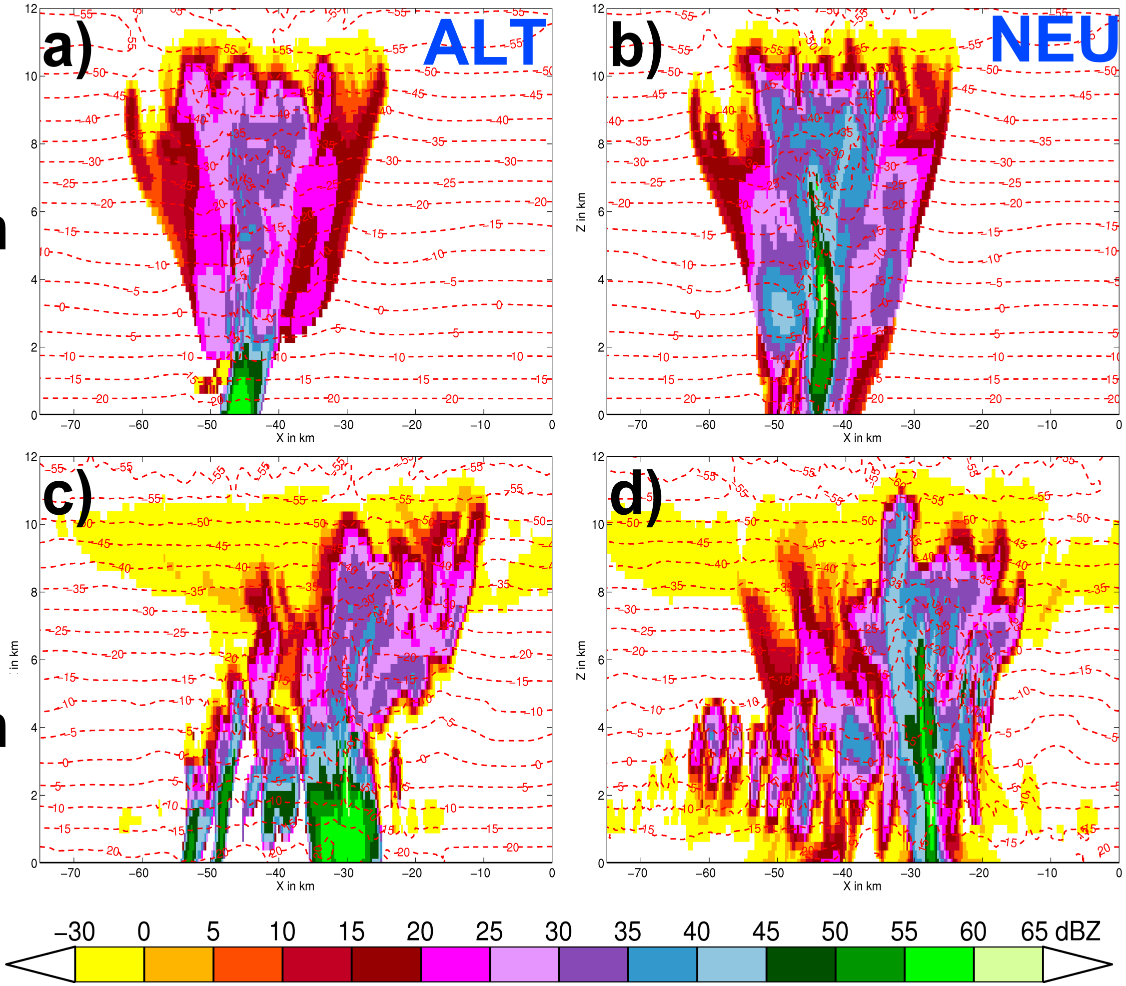
Effect of changes:

00:50 h

02:00 h



(2D idealized, warm bubble)

2-moment-scheme

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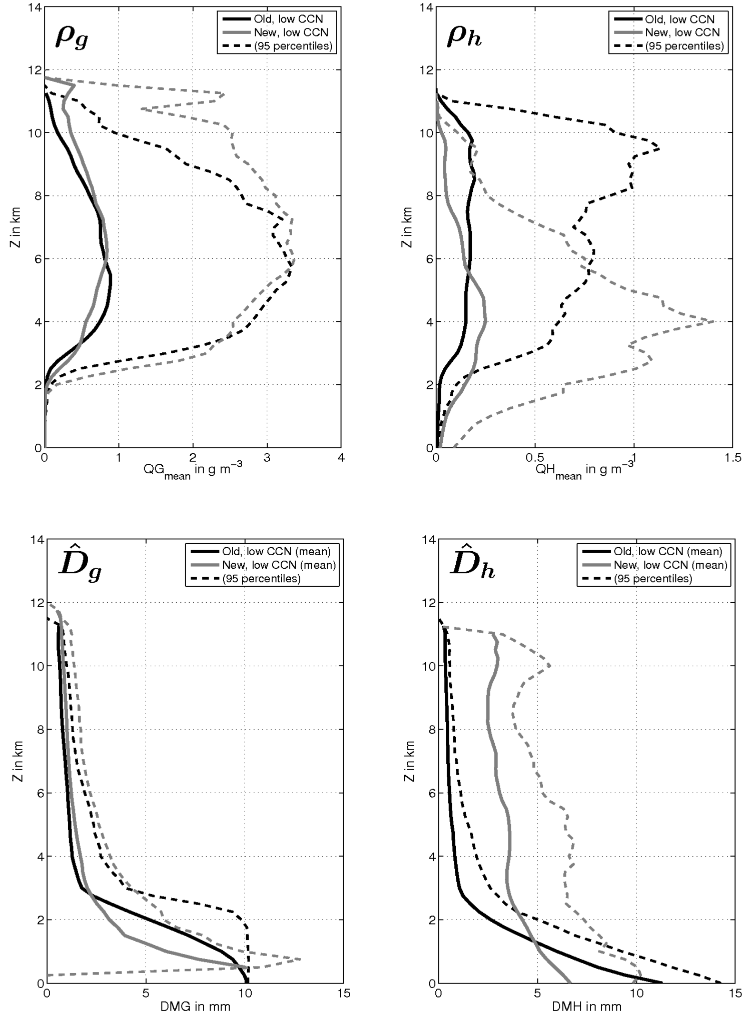
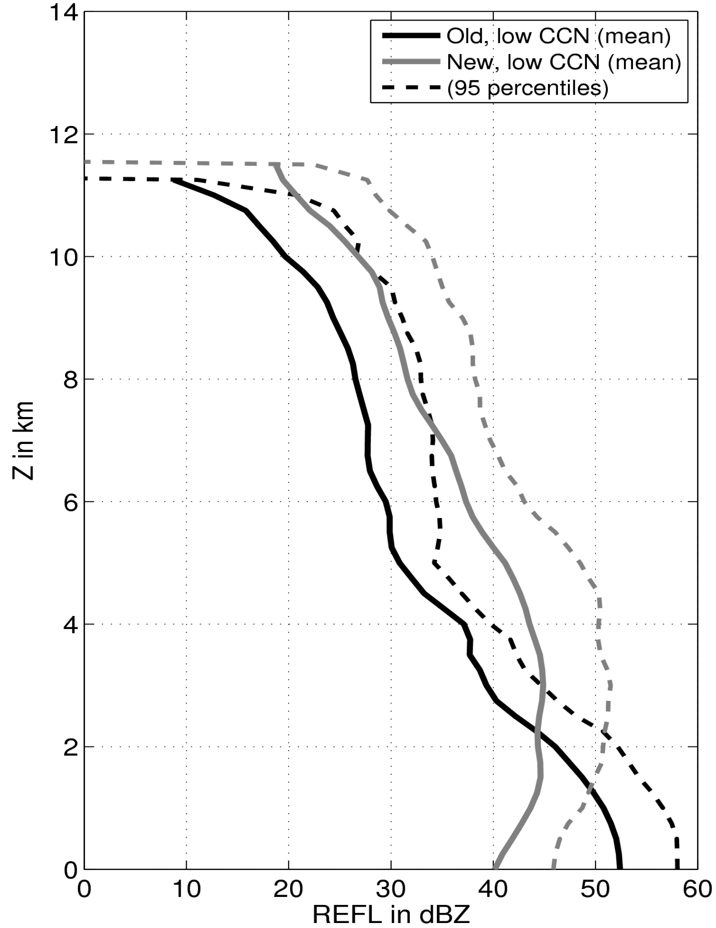
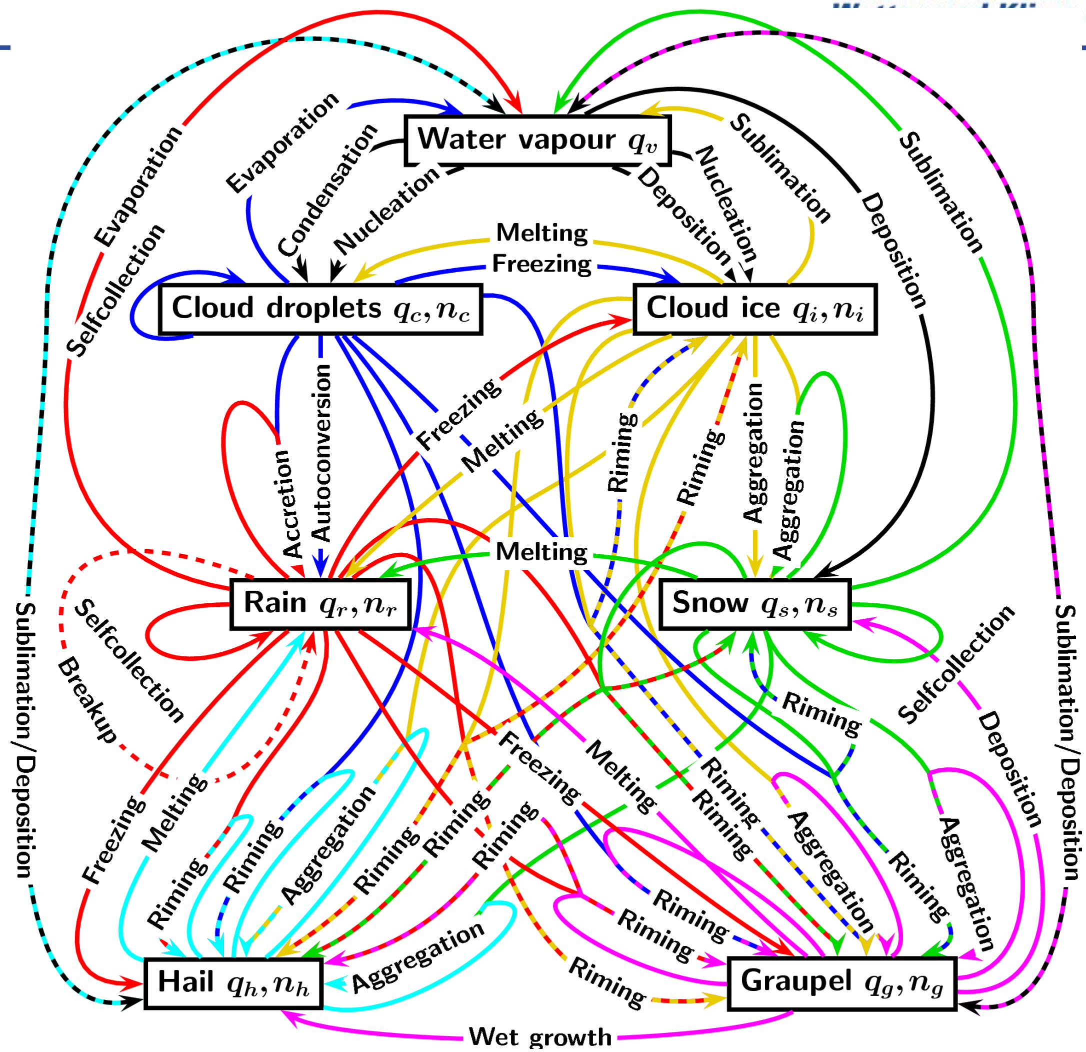
Effect of changes:





2-moment scheme

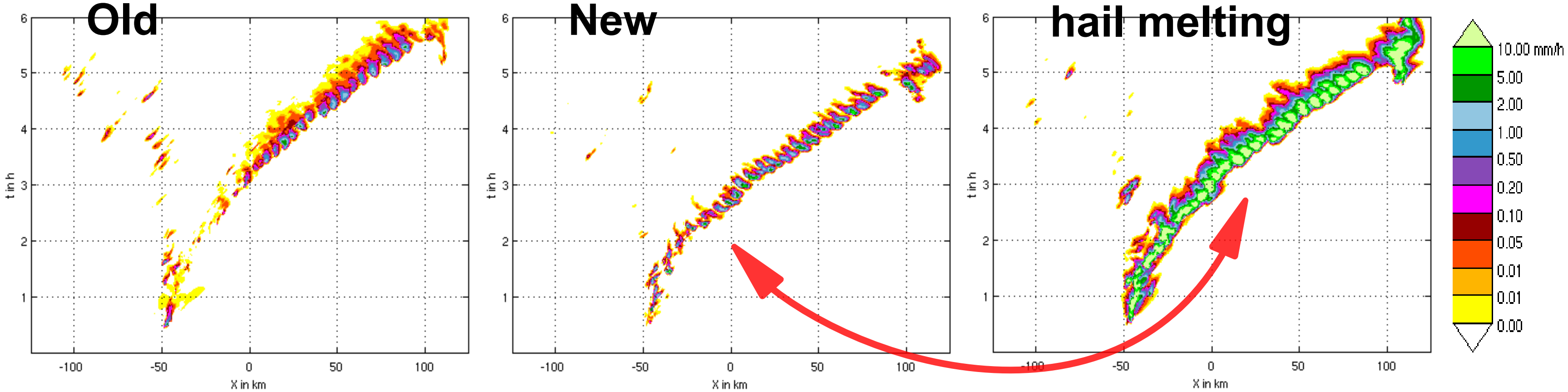
Deutscher Wetterdienst



Seifert and Beheng (2006a,b), Seifert et al. (2006), Noppel et al. (2006), Blahak (2008), Seifert (2008)

BUT: problem with too fast melting!

Hovmöller-Plots of the hail rate:



Huge effect; hints on overestimation of melting

2-moment scheme

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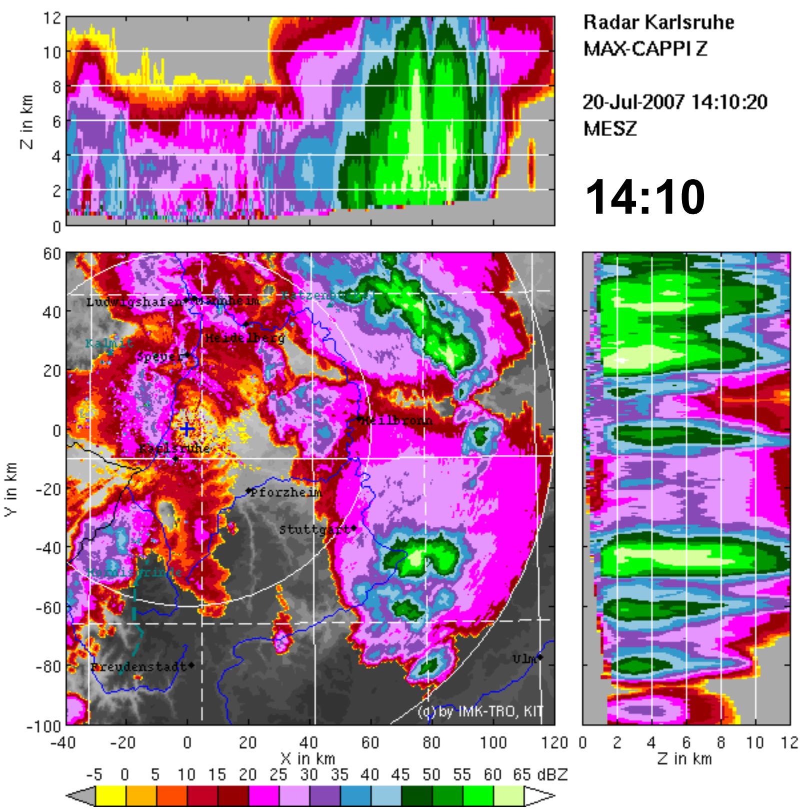
Considered hail processes (new):

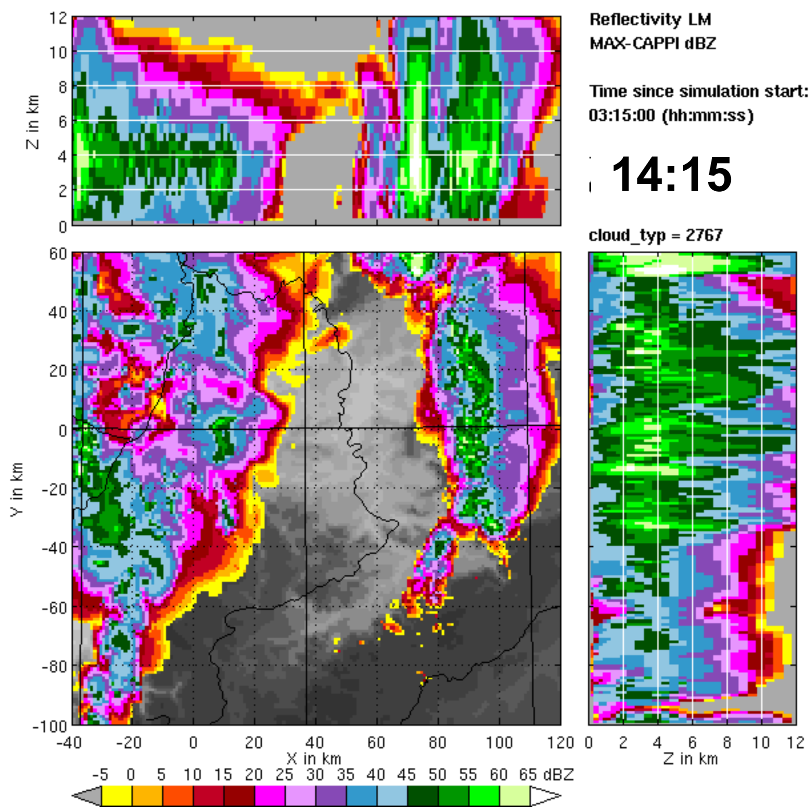
- (Re-tuning of size-mass- and fallspeed-mass-relation parameters)
- Dry growth by collection of supercooled droplets
- ~~Wet Growth~~
- ~~Shedding of droplets~~
- Hail embryos: „large“ frozen raindrops + wet growing graupel
- Melting (but is at the moment systematically overestimated)
- Dynamic processes (Seeder-Feeder, recirculation, „balancing“ in updrafts) are taken into account, insofar the setup of the COSMO-Model allows that.
- „Competition“ for the available supercooled liquid

Case study: 20.7.2007

Radar Karlsruhe



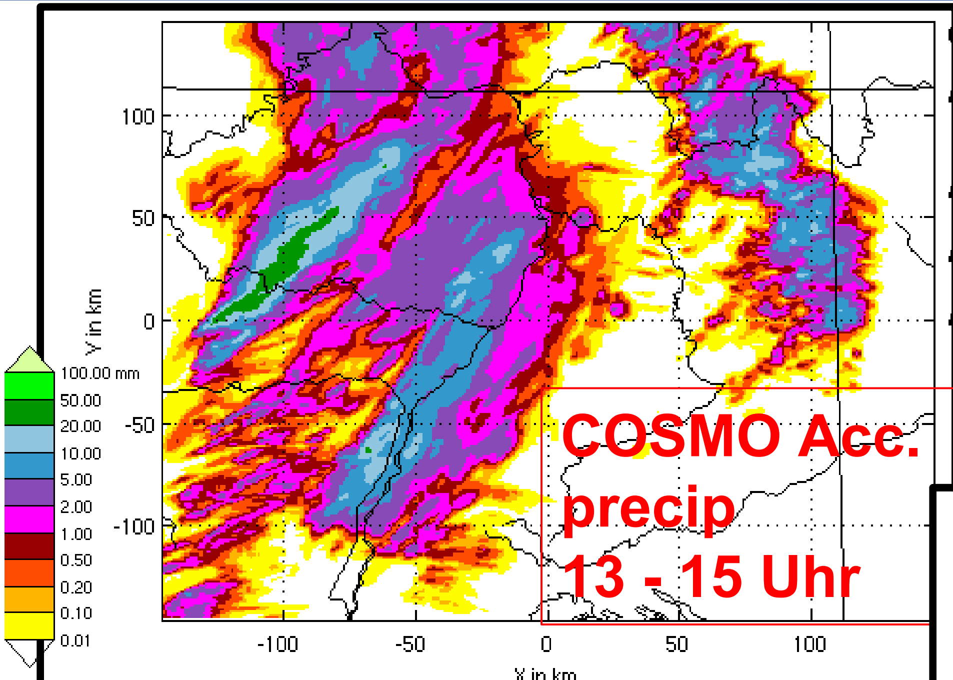
COSMO - 2MOM



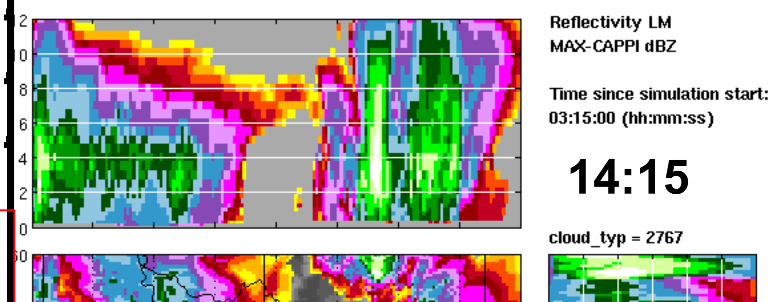
(dx = 1 km, nested into COSMO-DE, LES turbulence scheme, **„low CCN“**)

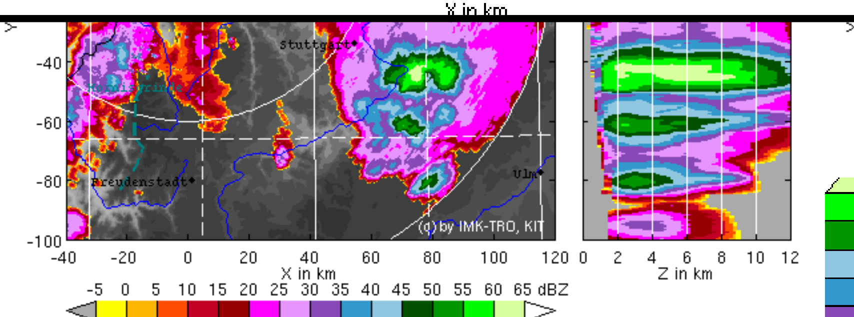
Case study: 20.7.2007

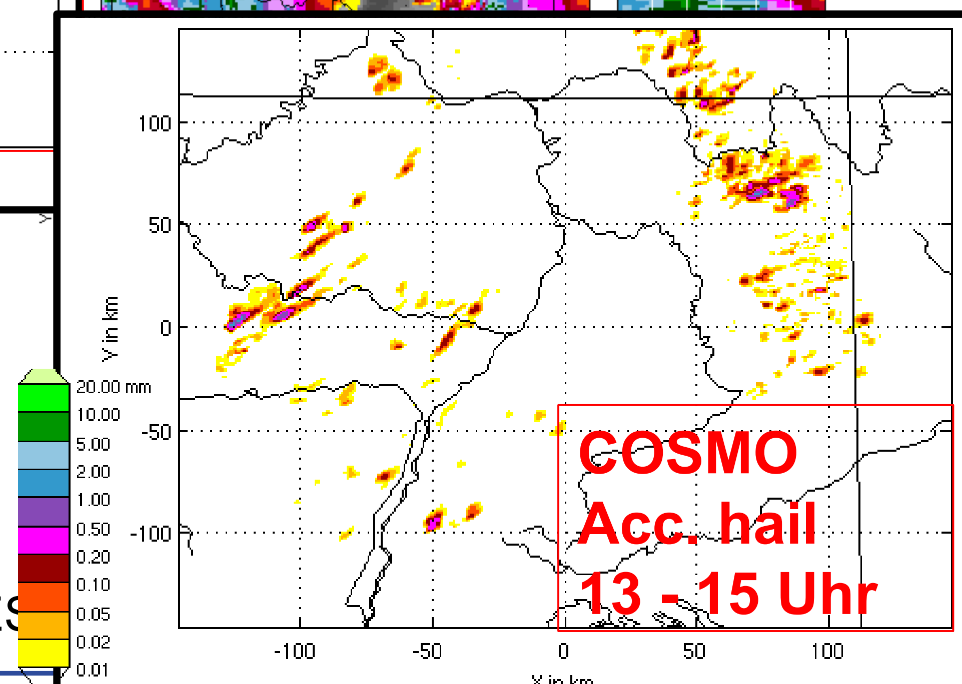
Deutscher Wetterdienst
Wetter und Klima aus einer Hand



COSMO - 2MOM





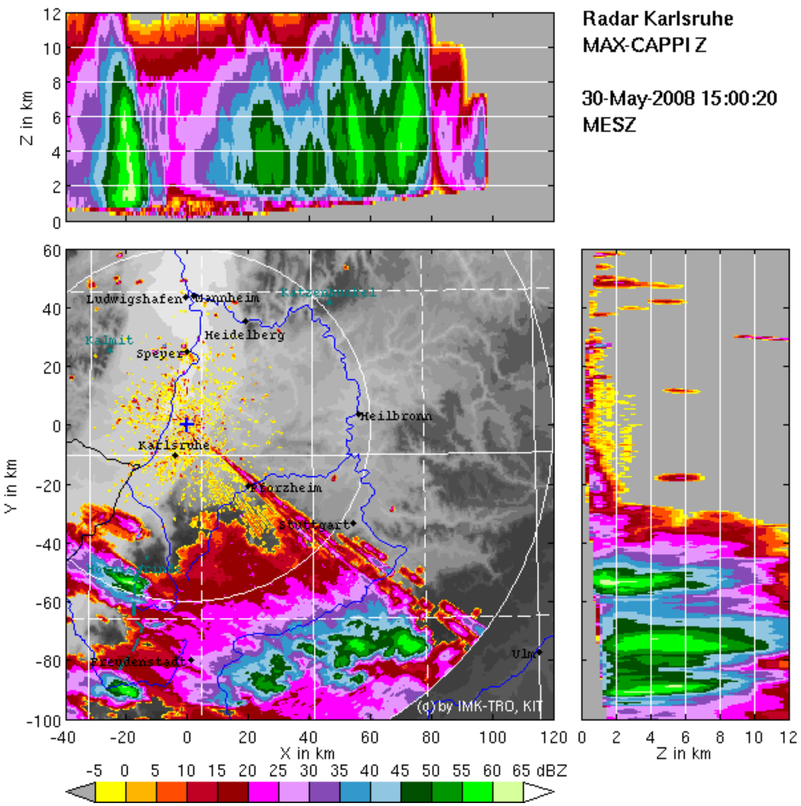


(dx = 1 km, nested into COSMO-DE, LES

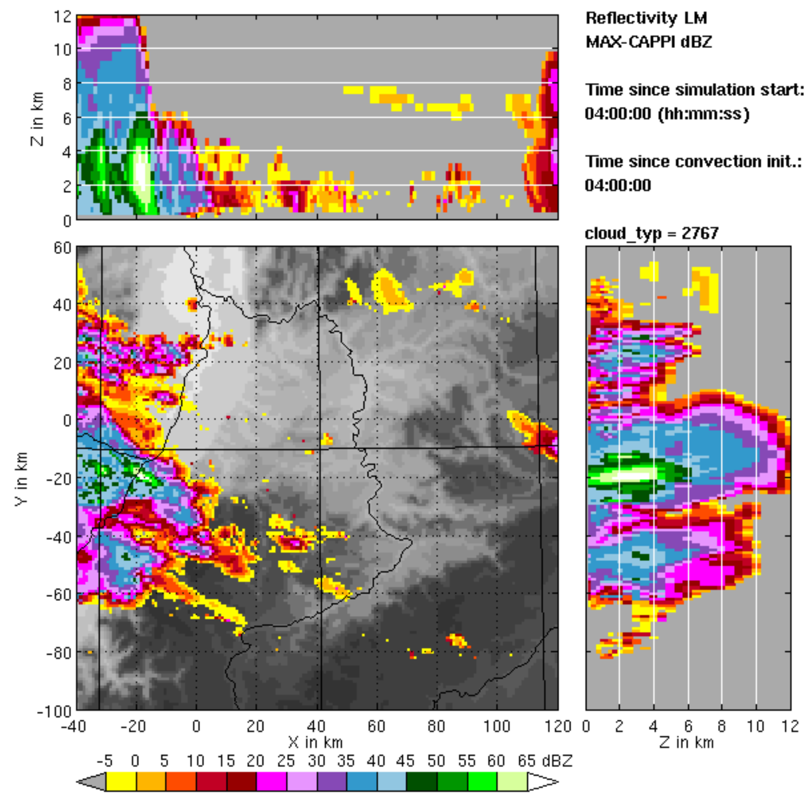
Case study: 30.5.2008

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Radar Karlsruhe



COSMO - 2MOM



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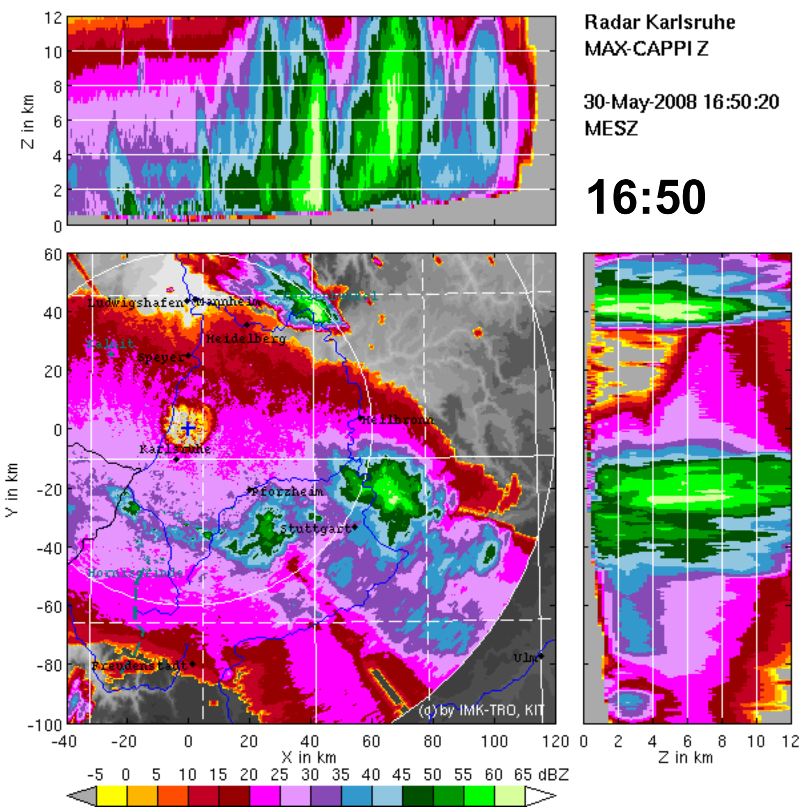
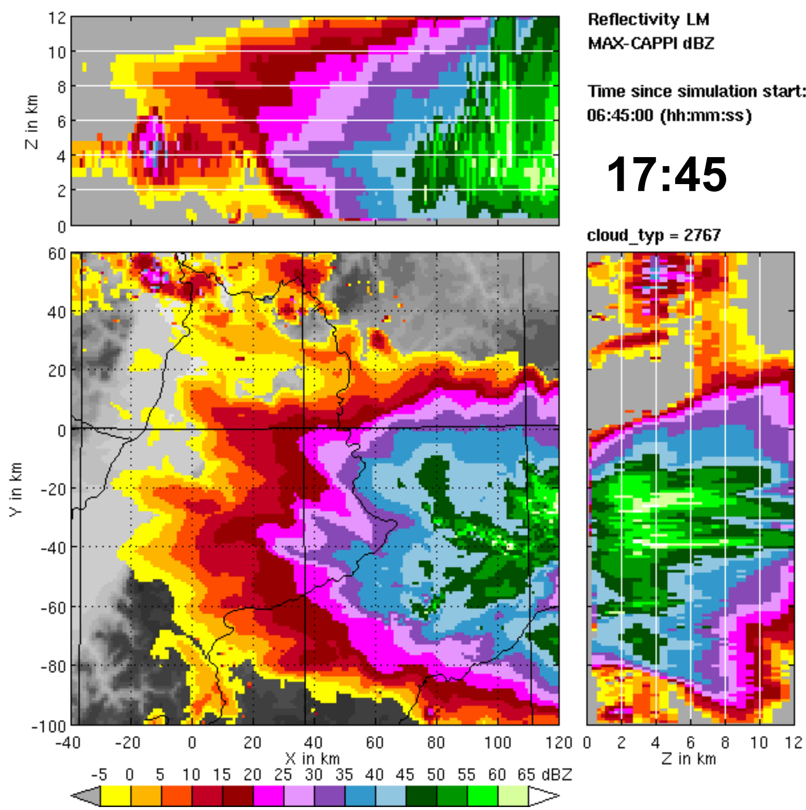
Case study: 30.5.2008

Radar Karlsruhe



COSMO - 2MOM



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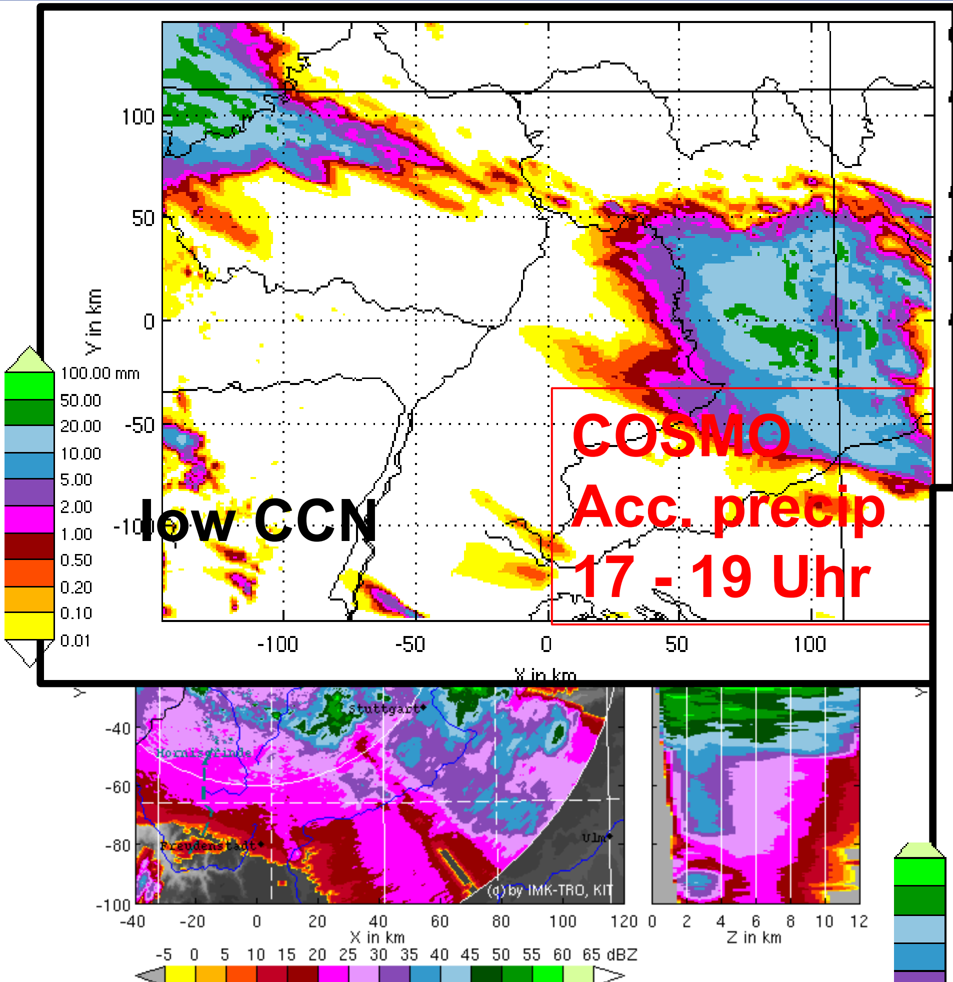

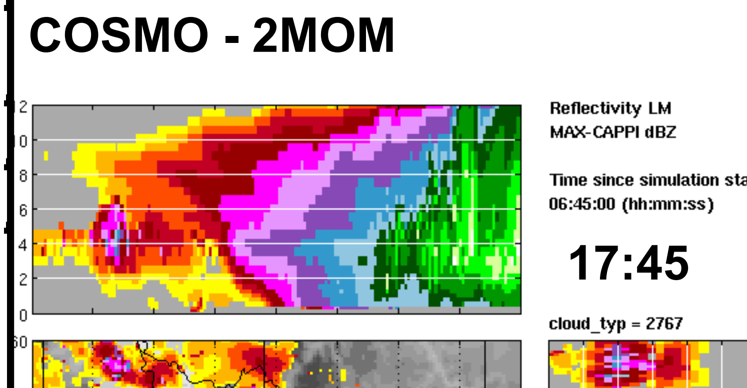

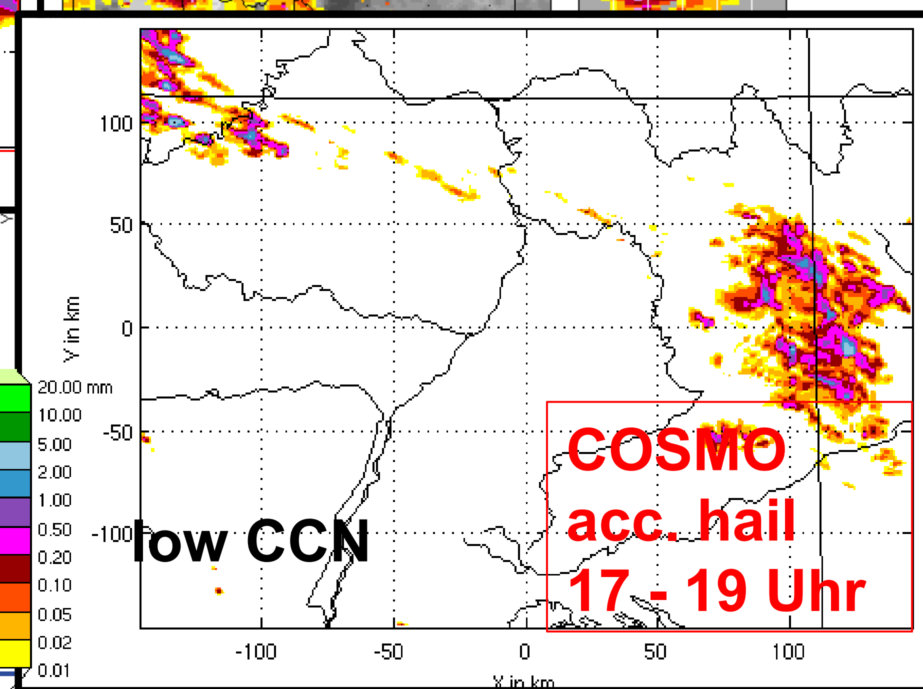

(dx = 1 km, nested into COSMO-DE, LES

Case study: 30.5.2008

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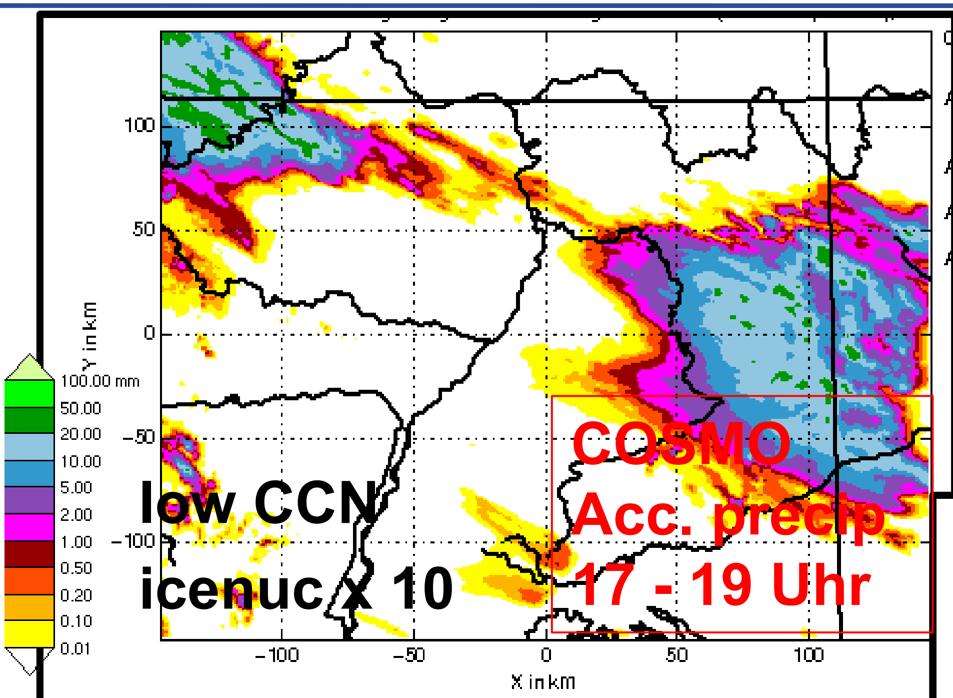
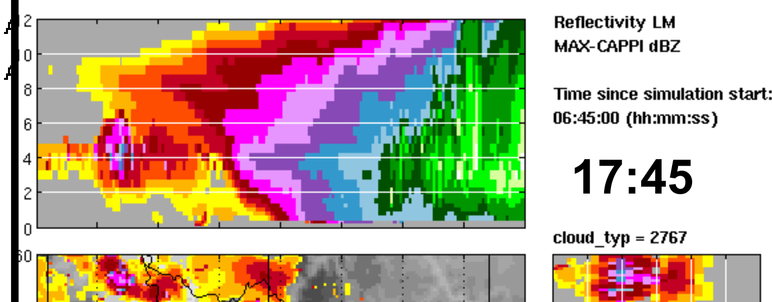
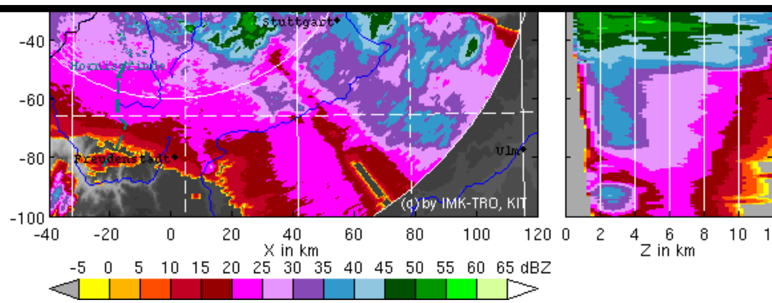
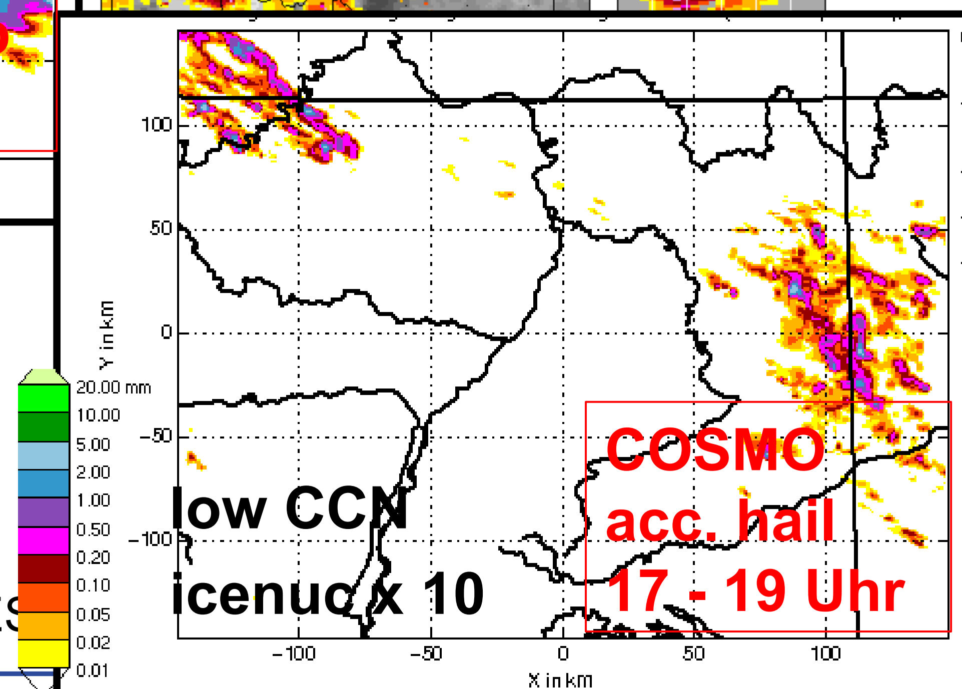
Wetter und Klima aus einer Hand



COSMO - 2MOM







(dx = 1 km, nested into COSMO-DE, LES

Case study: 30.5.2008

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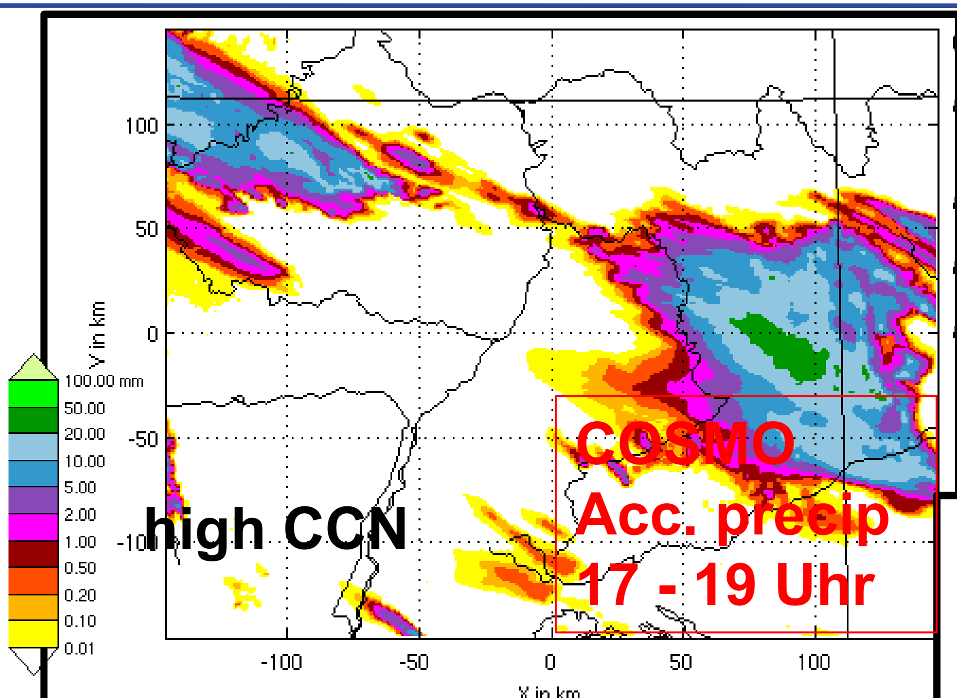

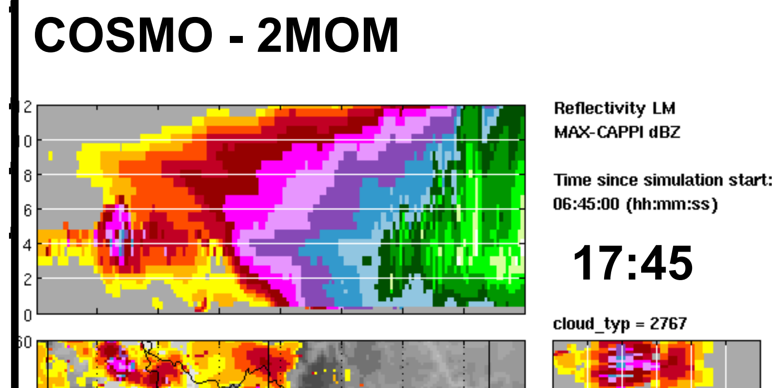

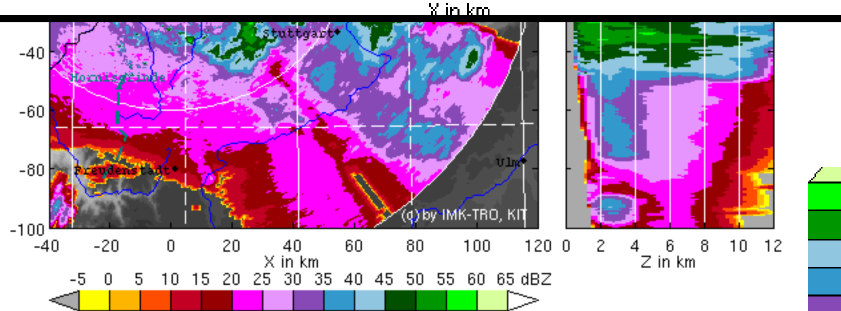

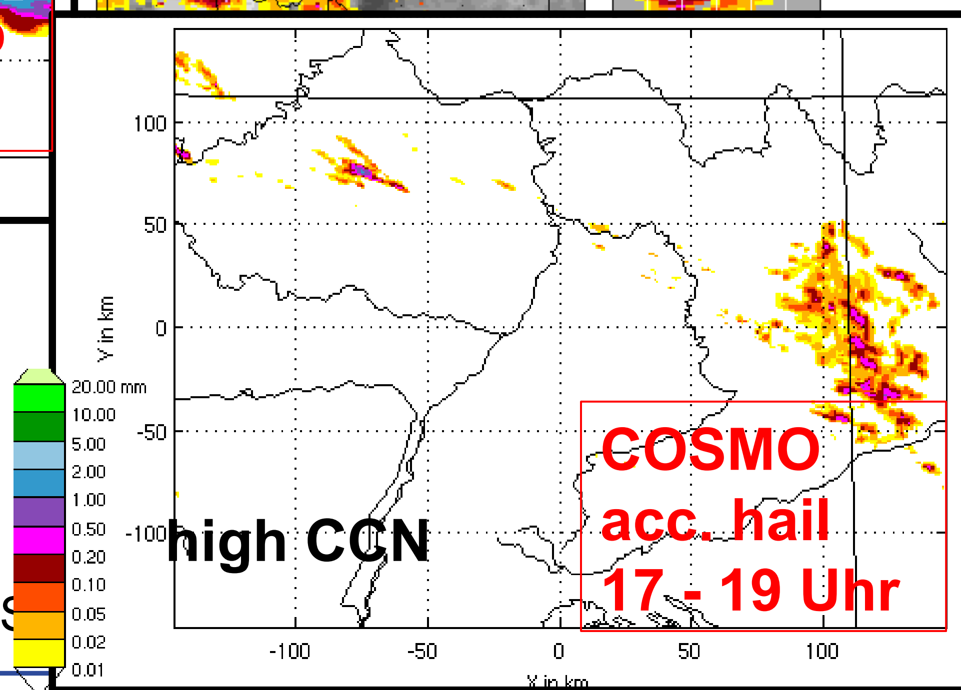

(dx = 1 km, nested into COSMO-DE, LES

Case study: 30.5.2008

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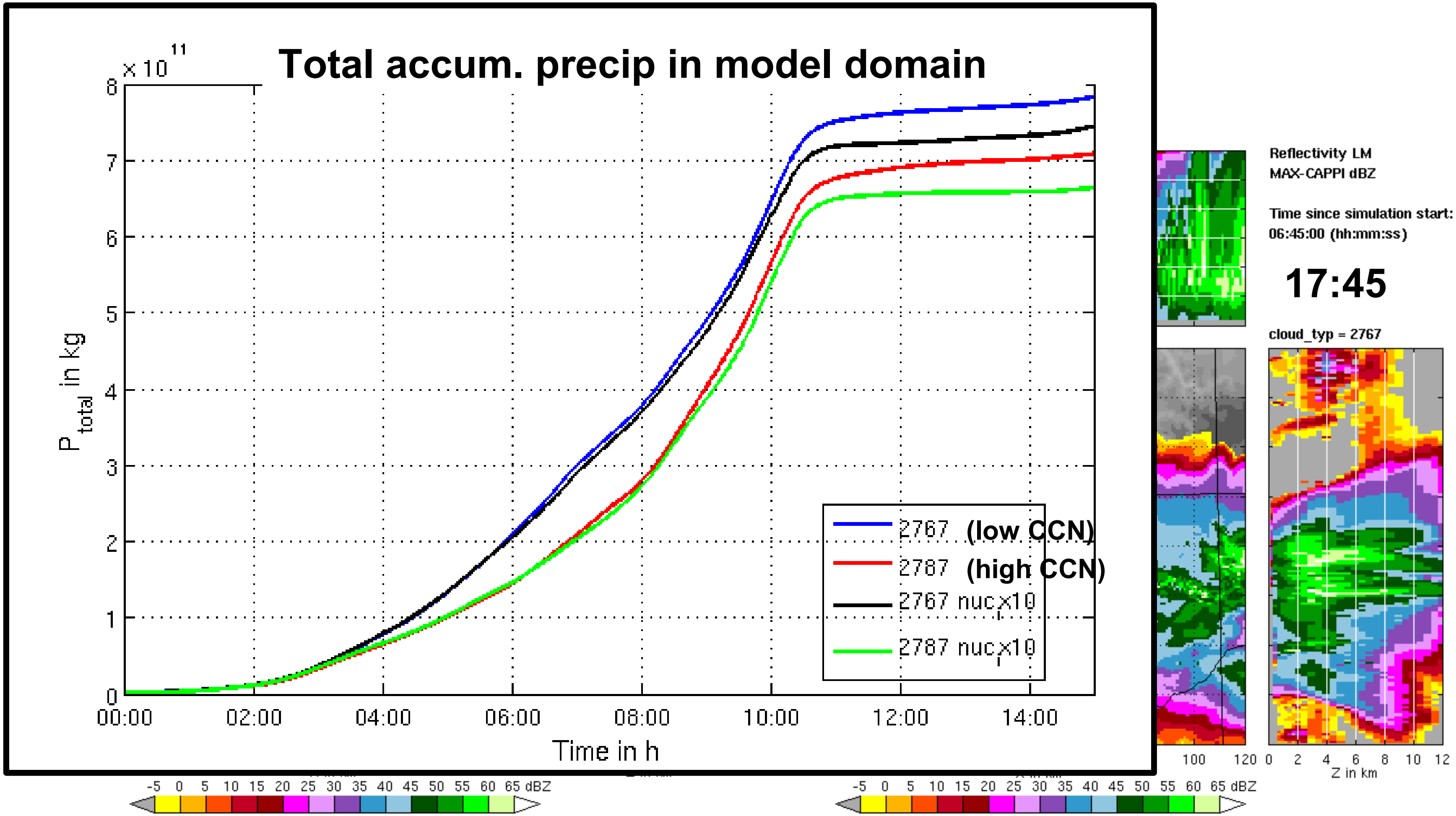
Wetter und Klima aus einer Hand



(dx = 1 km, nested into COSMO-DE, LES turbulence scheme, **„low CCN“**)

Case study: 30.5.2008

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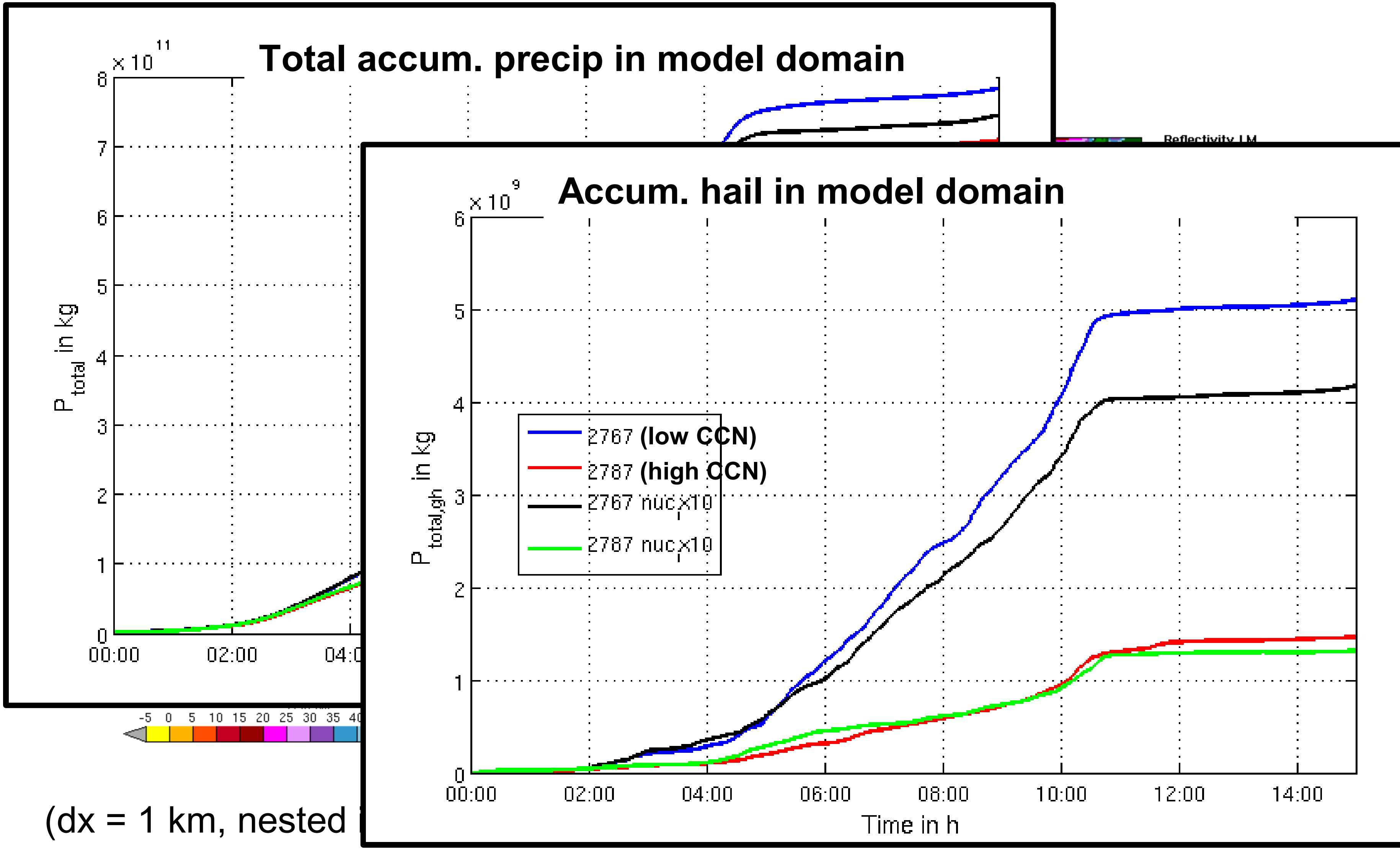
Wetter und Klima aus einer Hand



(dx = 1 km, nested

Case study: 28.6.2006 „Villingen-Schwenningen-Zelle"

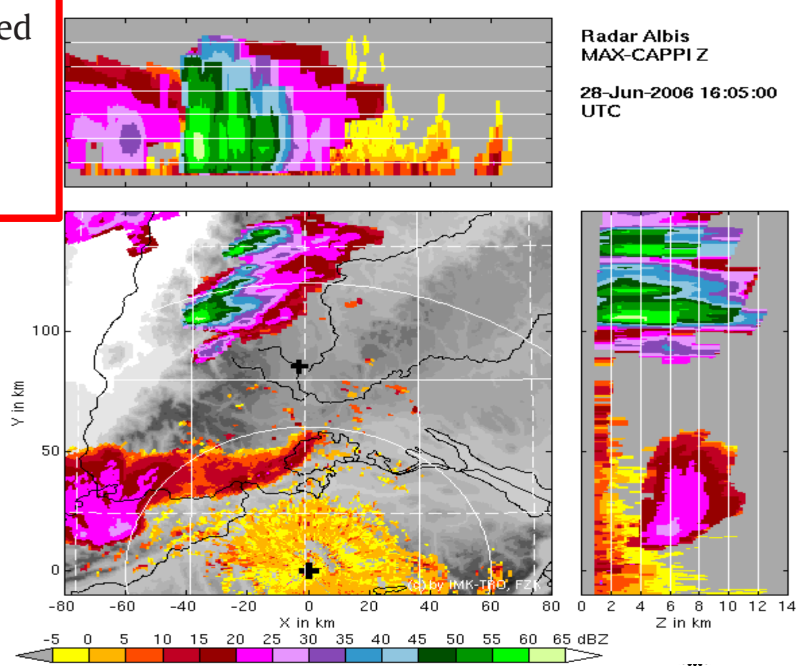
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- **ANTISTORM-project (Antropogenic Aerosols Invigorating Convective Storms)**
- **Golden case: Hail event in Villingen-Schwenningen on 28.6.2006**
- **Supercell developing over Black Forest, splitting; right-mover is longlived and brings a lot of big hail over the City**
- **Simulations with HUCM in 2D (Khain et al.) and COSMO in 2D and 3D**
- **COSMO 3D results published in Atmospheric Research:**

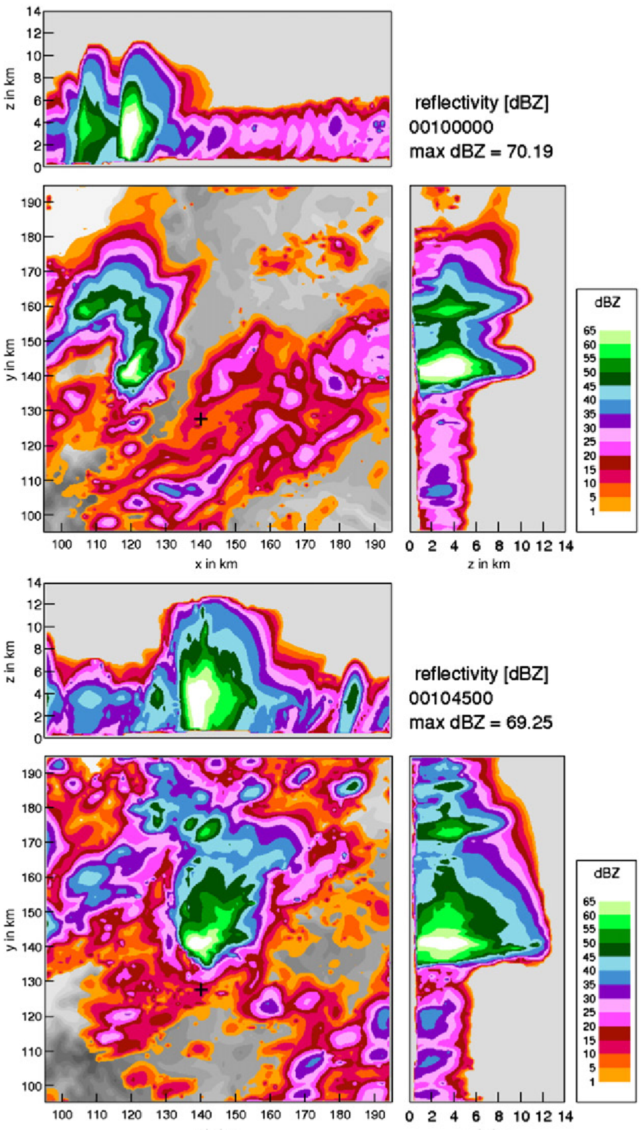
Simulations of a hailstorm and the impact of CCN using an advanced two-moment cloud microphysical scheme

Heike Noppel [a,*], Ulrich Blahak [a], Axel Seifert [b], Klaus D. Beheng [a]

[a] Institut für Meteorologie und Klimaforschung, Universität/Forschungszentrum Karlsruhe, P.O. Box 3640, D-76021 Karlsruhe, Germany
[b] German Weather Service, Frankfurter Str. 135, D-63067 Offenbach, Germany



Case study: 28.6.2006 „Villingen-Schwenningen-Zelle“



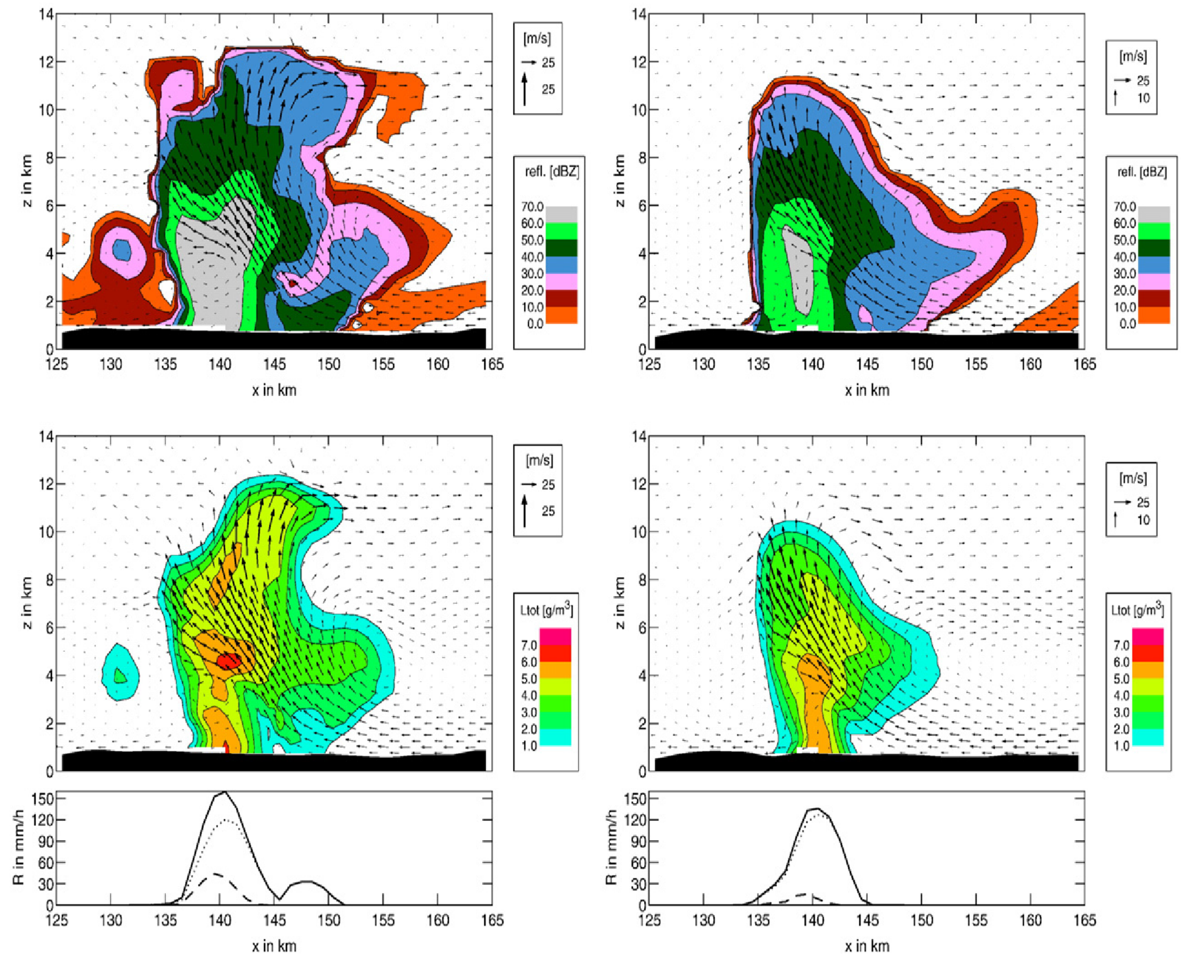


Fig. 10. Same as Fig. 9 but for different parameters. Top: radar reflectivity; center: total hydrometeor mass content; bottom: precipitation rate at the ground by rain (dotted line), by hail (dashed) and in total (solid).

Case study: 28.6.2006 „Villingen-Schwenningen-Zelle"

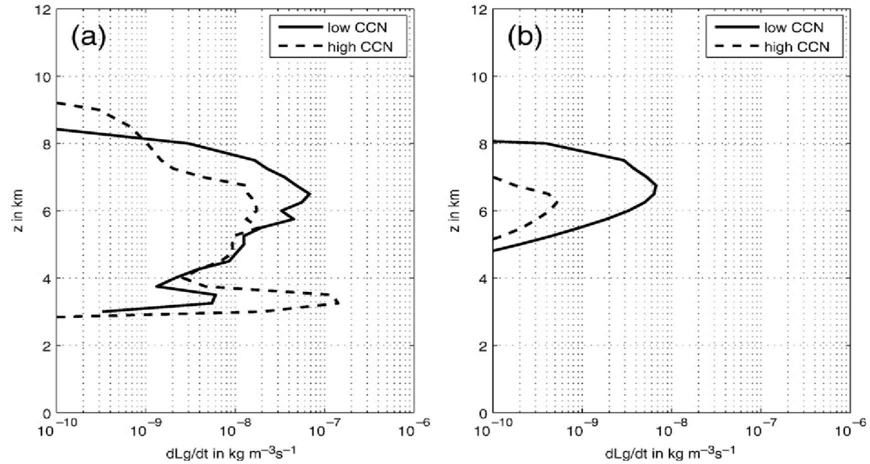


Fig. 16. Profiles of graupel production (a) by riming of ice and snow and (b) by freezing of drops at $t = 10{:}45$ horizontally averaged over the region where total cloud mass exceeds $10^{-2}\,\mathrm{g\,m^{-3}}$.

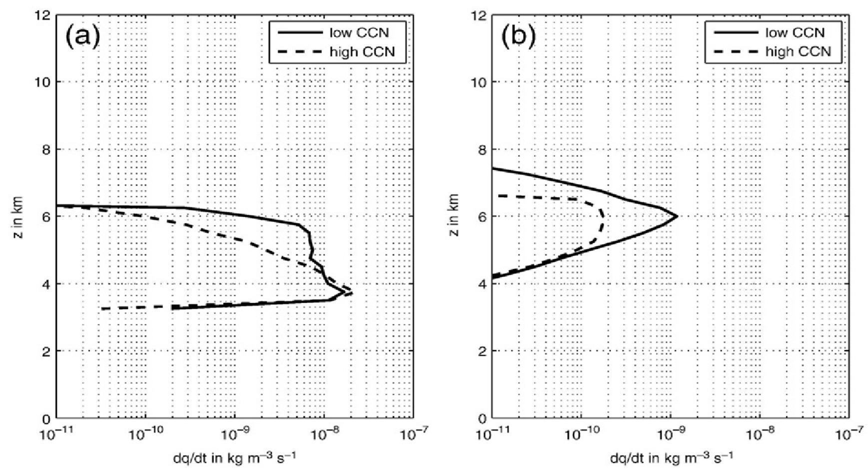


Fig. 17. Same as Fig. 16, but for the production of hail (a) by riming of graupel (wet growth) and (b) by freezing of drops.

Case study: 28.6.2006 „Villingen-Schwenningen-Zelle“

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- **Main results (COSMO):**
  After some trying, good simulation of super cell (a little late, but in the right place). Simulated hail at the ground decreased with increasing CCN concentration. Cell life time and total precip was rather in-sensitive to CCNs.
- **COSMO 2D and HUCM 2D were in qualitative agreement, but did not produce the same sensitivities of hail at the ground to changes in CCN and 0-degree-level ...**
- **Topic still open ...**

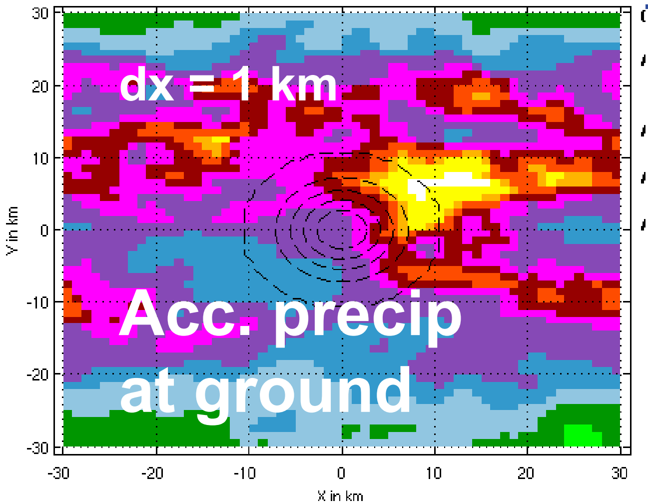
Table 2
Maximum accumulated total precipitation in mm, after 12 h simulation time for different model runs, taking into account only the right-moving cell.

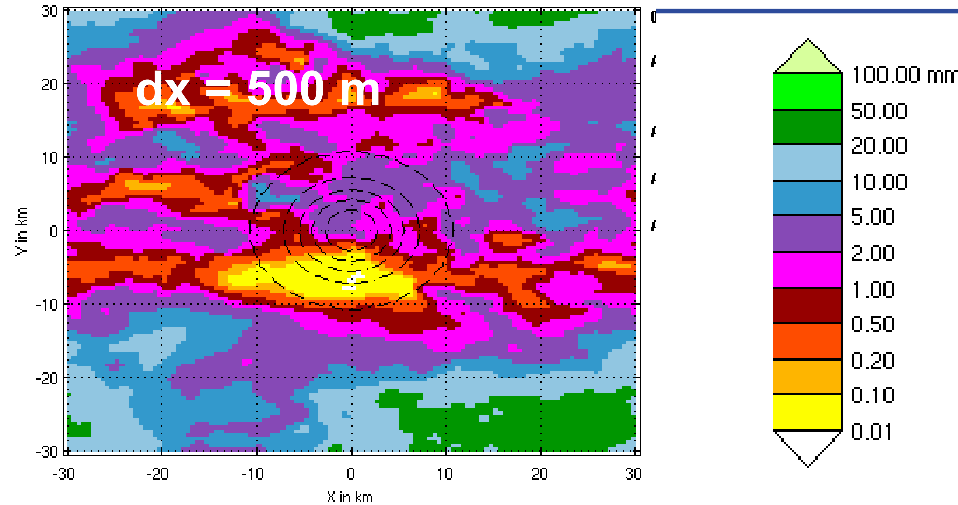
	Cloud droplet size distribution		
CCN concentr.	(a) Broad	(b) n-small	(c) n-large
1 Low	51	50	35
2 Intermediate	44	40	41
3 High	39	43	38
4 Very high	37	37	45

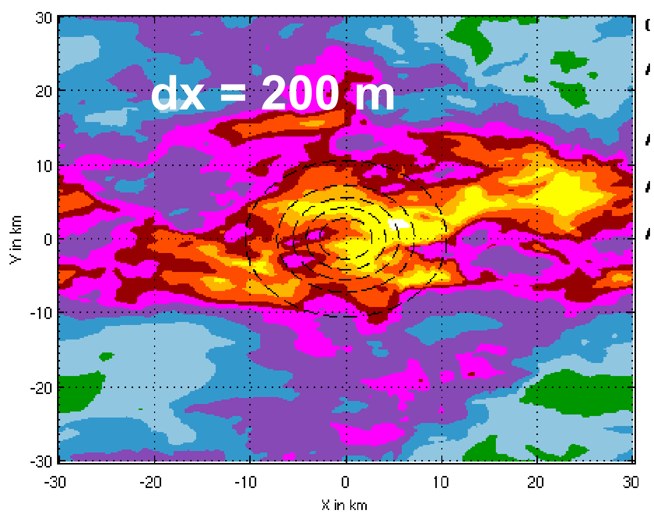
Table 3
Same as Table 2 but for precipitation by hail only.

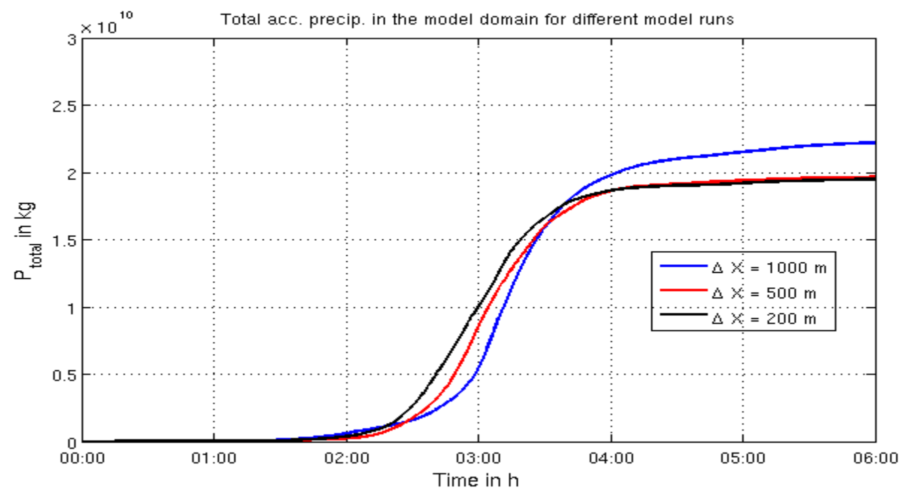
	Cloud droplet size distribution		
CCN concentr.	(a) Broad	(b) n-small	(c) n-large
1 Low	14.9	12.1	9.1
2 Intermediate	9.9	8.5	11.5
3 High	5.6	6.5	2.0
4 Very high	1.5	3.5	2.1

Is dx = 1 km „enough“?



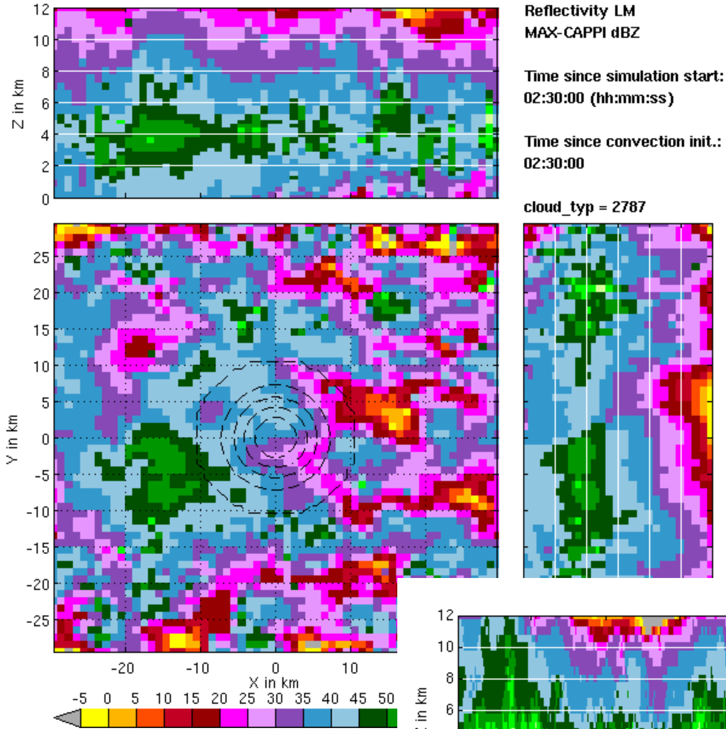


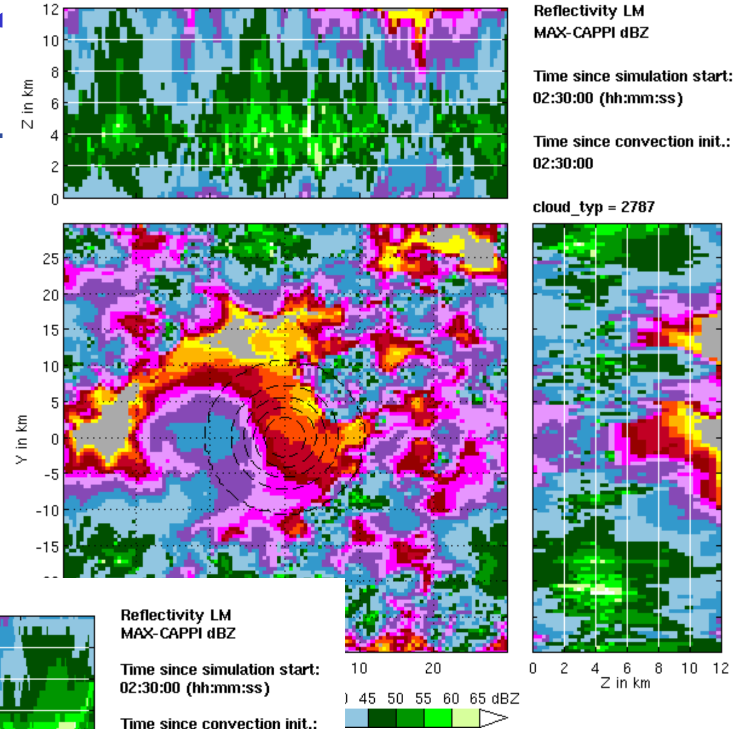


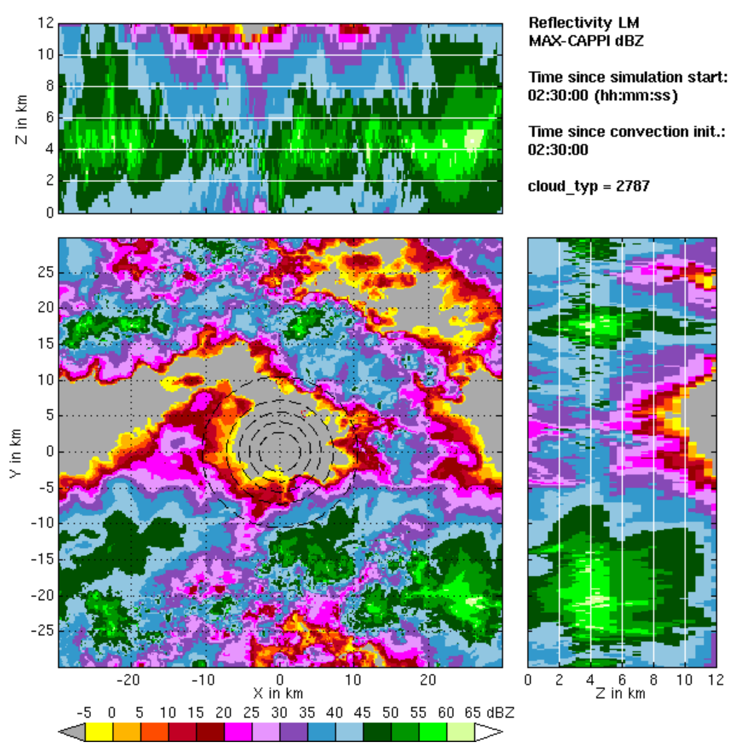


(Idealized, periodic BCs, pre-specified H0 und E0, LES-turbulence closure, initial profiles after Weisman and Klemp (1982) with CAPE = 2800 J/kg, U0=10 m/s)

Is … "

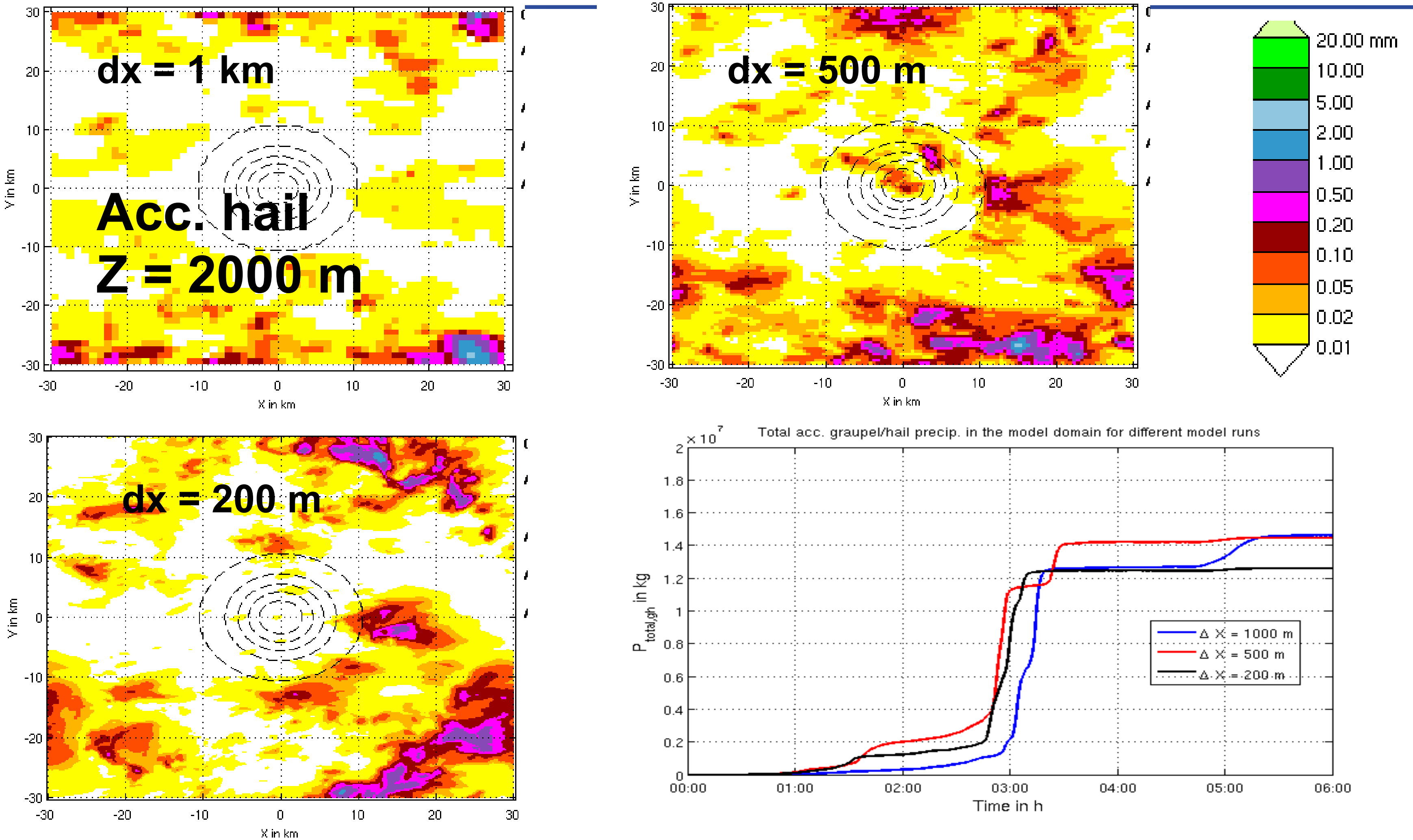






(Idealized, periodic BCs, pre- … osure, initial profiles after Weisman and Klemp (1982) …

Is dx = 1 km „enough“?



(Idealized, periodic BCs, pre-specified H0 und E0, LES-turbulence closure, initial profiles after Weisman and Klemp (1982) with CAPE = 2800 J/kg, U0=10 m/s)

Summary

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- 2-moment-scheme extended by a „hail“ class and „tuned“.
- Most of the relevant processes are covered, but melting is probably overestimated.
- Compared to 3D radar data, obtain realistic simulation of convective cells and „reflectivity cores“ (although anvils sometimes too small).
- Allows for formation of large hail, but interpretation has to be done with care, in light of the parameterization assumptions!
- Mesh sizes of 1 km may sometimes be „enough“ for the simulation of hail processes, at least for the COSMO-Model with two-moment scheme in some cases and regarding spacial hail statistics. But certainly more experience needed here!

Summary

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- **Outlook:**
  Introduction of additional variables, which describe the internal water content of partially melted ice particles.
  With this, the parameterization of melting will be enhanced and shedding and wet growth of hail may be taken into account explicitly.

- **Oulook 2:**
  Splitting of the outcome of collision terms for solid-to-rain collisions according to size ranges, based on partitioning of the integral and use of incomplete gamma functions.
  Development has been done, now case studies are necessary.

Microphysics „physics“

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- **Gleichung für die spektrale Anzahldichteverteilungsfunktion:**

$$\frac{\partial f_j(\vec{r},t,x)}{\partial t} + \nabla \cdot \left(\vec{v}(\vec{r},t) f_j(\vec{r},t,x) \right) + \frac{\partial}{\partial z}\left(v_{sj}(x) f_j(\vec{r},t,x) \right) + \frac{\partial}{\partial x}\left(\dot{x} f_j(\vec{r},t,x) \right) = \sum_{k=1}^{N} \sigma_{jk} \qquad j = 1 \ldots N$$

$$\sigma_{jk} \neq \sigma_{kj}$$

- **Kollisionsterme (σ_{jk}): Beispiel Regen (j=2) – Graupel (k=5)**

$$\sigma_{25} = \left. \frac{\partial f_r(x_r)}{\partial t} \right|_{coll,gr} = - \int_0^\infty f_r(x_r)\, f_g(x_g)\, K_{gr}(x_r, x_g)\, dx_g$$

$$\sigma_{52} = \left. \frac{\partial f_g(x_g)}{\partial t} \right|_{coll,gr} = + \int_0^{x_g} f_g(x_g - x_r)\, f_r(x_r)\, K_{gr}(x_g - x_r, x_r)\, dx_r - \int_0^\infty f_g(x_g)\, f_r(x_r)\, K_{gr}(x_g, x_r)\, dx_r$$

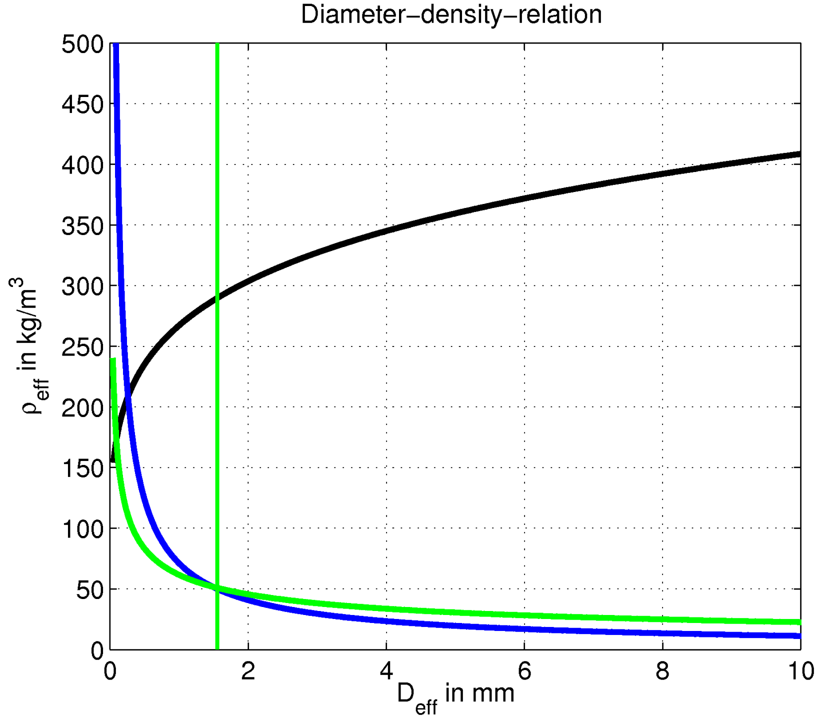
„Geometrische“ Koagulationsfunktion:

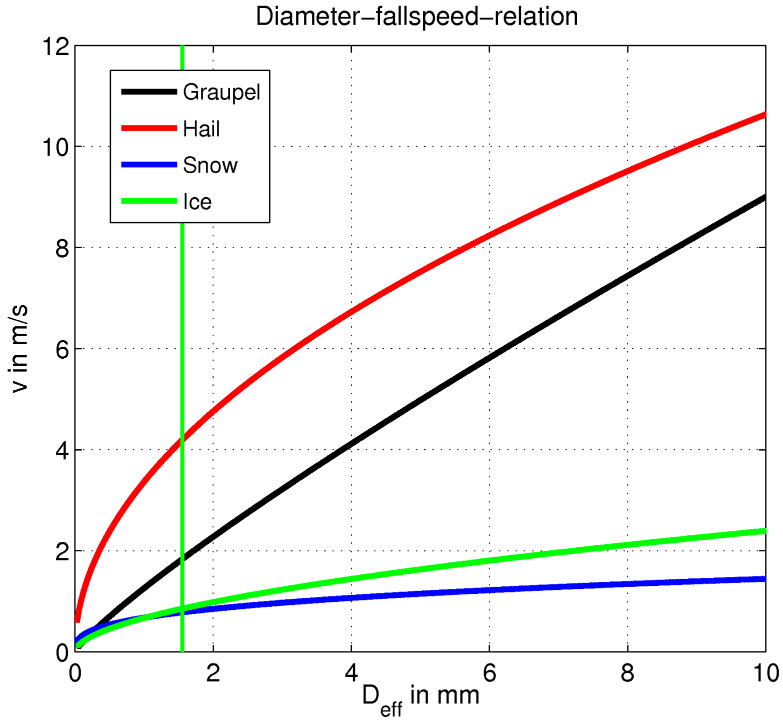
$$K_{gr}(x_g, x_r) = \frac{\pi}{4} \left(D_g^2(x_g) + D_r^2(x_r) \right) \left| v_g(x_g) - v_r(x_r) \right| E_{gr}(x_g, x_r)$$

Microphysics parameterization

1) Aufteilung in Hydrometeorarten **(Wahl)**

2) Festlegung von Durchmesser-Masse- und Durchmesser-Fallgeschwindigkeits-Beziehungen **(Wahl)**





3) ...

Microphysics parameterization

- **3a) Bin-Schema:**

Gleichung für die spektrale Anzahldichteverteilungs-funktion wird durch numerische Diskretisierung in „bins" gelöst. Je gewählter Hydrometeorart gibt es eine solche diskretisierte Gleichung pro „bin"!

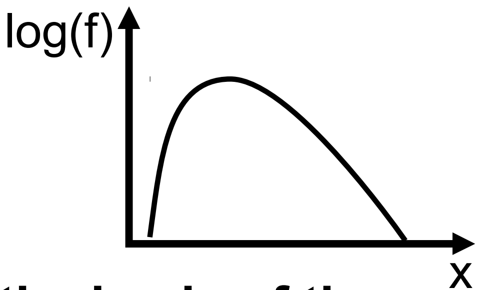
(z.B. Khain, 1996; Geresdi, 1998)

Sehr aufwendig, deswegen bisher fast nur in 2D eingesetzt.

3b) 2-moment scheme

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- Hydrometeor classes: cloud droplets, rain, cloud ice, snow, graupel, hail („simple“ extention, Noppel et al., 2006)
- For each class, budget equations for N and Q



$$\mathbf{N} = \int_0^\infty f(x)\,dx \qquad \mathbf{Q} = \int_0^\infty x\,f(x)\,dx$$

- Parameterization of microphysical processes on the basis of the spectral budget equation(s) assuming a generalized gamma-distribution for f(x):

$$f(x) = N_0\,x^\nu \exp(-\lambda\,x^\mu)$$

$$\nu,\mu = \text{const.}, \qquad \lambda = \left[\frac{\Gamma(\frac{\nu+1}{\mu})}{\Gamma(\frac{\nu+2}{\mu})}\frac{Q}{N}\right]^{-\mu}, \qquad N_0 = \frac{\mu\,N}{\Gamma(\frac{\nu+1}{\mu})}\lambda^{\frac{\nu+1}{\mu}}$$

- Coupling to the COSMO-Model

3b) 2-moment scheme

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- **Parametrisierung von Kollisionen (Seifert und Beheng, 2006)**

  Beispiel: Graupel + Regen = Graupel

$$\left.\frac{\partial N_g}{\partial t}\right|_{coll,gr} = 0$$

$$\left.\frac{\partial N_r}{\partial t}\right|_{coll,gr} = -\frac{\pi}{4}\,\overline{E}_{gr}\,\overline{\Delta v_{gr}^{(00)}}\,N_g\,N_r\left(\delta_{gg}^{(00)}\,D_g^2(\overline{x}_g) + \delta_{gr}^{(00)}\,D_g(\overline{x}_g)\,D_r(\overline{x}_r) + \delta_{rr}^{(00)}\,D_r^2(\overline{x}_r)\right)$$

$$\left.\frac{\partial L_g}{\partial t}\right|_{coll,gr} = \frac{\pi}{4}\,\overline{E}_{gr}\,\overline{\Delta v_{gr}^{(01)}}\,N_g\,L_r\left(\delta_{gg}^{(01)}\,D_g^2(\overline{x}_g) + \delta_{gr}^{(01)}\,D_g(\overline{x}_g)\,D_r(\overline{x}_r) + \delta_{rr}^{(01)}\,D_r^2(\overline{x}_r)\right)$$

$$\left.\frac{\partial L_r}{\partial t}\right|_{coll,gr} = -\left.\frac{\partial L_g}{\partial t}\right|_{coll,gr}$$

Insgesamt 18 derartige Kollisionsprozesse im 2-Momenten-Schema

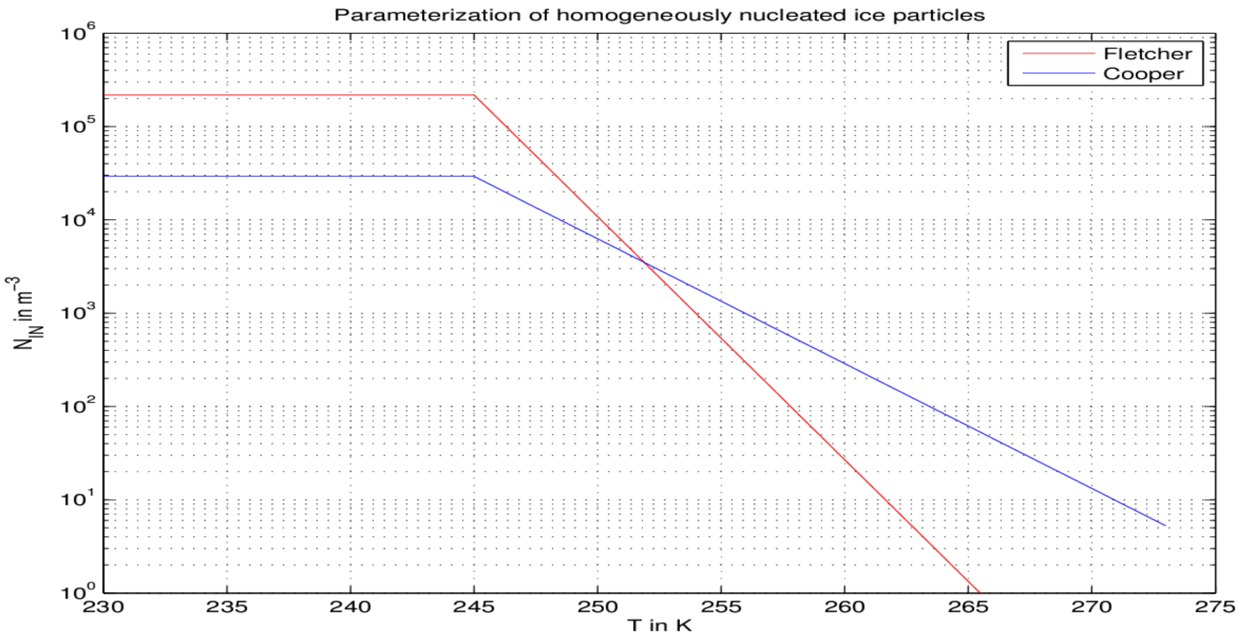
3b) 2-moment scheme

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- **Eisnukleation „traditionell“ (Fletcher, Cooper):**

$$N_{ice,diag} = a \exp(b\,(T - T_0))$$

$$\frac{\partial N_i}{\partial t} = \begin{cases} \dfrac{N_{ice,diag} - N_i}{\Delta t} & \text{for } N_{ice,diag} > N_i \\ 0 & \text{otherwise} \end{cases}$$



3b) 2-moment scheme

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- **Eisnukleation „traditionell“ Fletcher (T), Cooper (T), Meyers (S_i)**

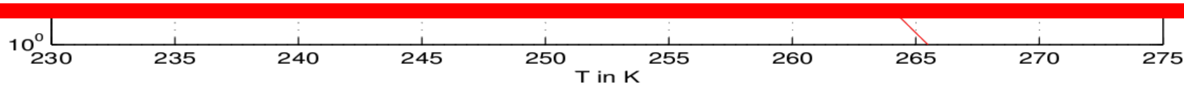
$$N_{ice,diag} = a \exp(b(T - T_0))$$

$$\frac{\partial N_i}{\partial t} = \begin{cases} \frac{N_{ice,diag} - N_i}{\Delta t} & \text{for } N_{ice,diag} > N_i \\ 0 & \text{otherwise} \end{cases}$$

Inzwischen auch andere Möglichkeiten implementiert:

1) **Für Cirren / stratiforme Eiswolken:**
basierend auf Kärcher und Lohmann (2002), Kärcher et al. (2006)

2) **Für Kopplung mit explizitem Aerosol-Modul (COSMO-ART):**
Phillips et al. (2008)



3b) 2-moment scheme

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Homog./heterog. freezing:

$$\frac{1}{f_w(x,t)} \frac{\partial f_w(x,t)}{\partial t} = x\, J(T)$$

Heterog. Freezing:

$$J(T) = a \exp\left(b(T - T_0) - 1\right)$$

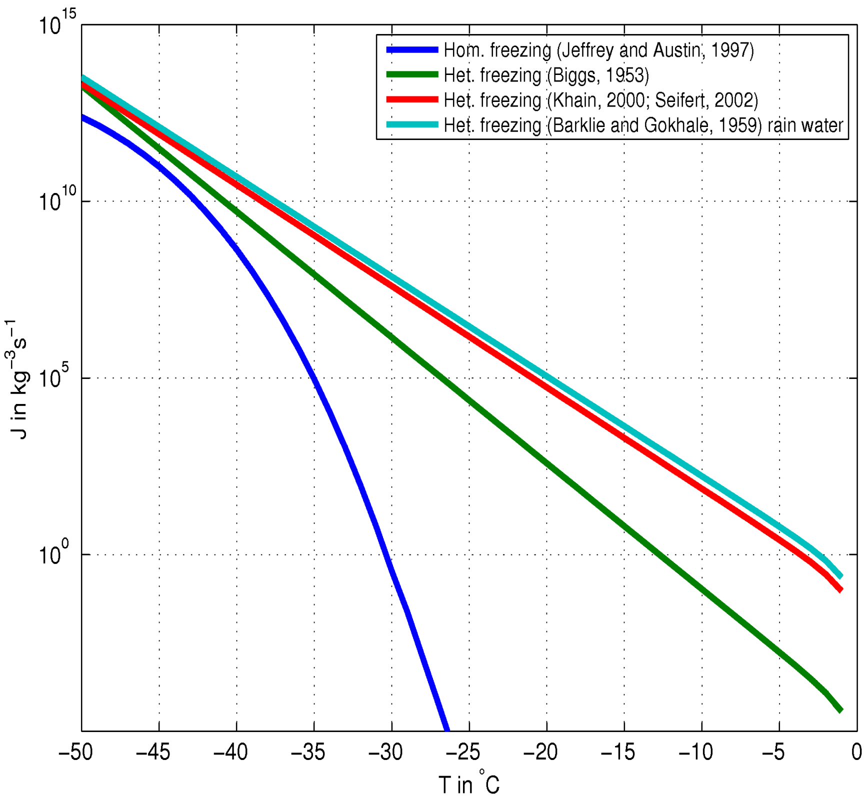
Homog. Freezing:

$J(T)$ after Cotton und Field (2001)

Integration of $\partial_t f_w$ and $x\,\partial_t f_w$ over x:

$$\Rightarrow \left.\frac{\partial N_w}{\partial t}\right|_{\text{freeze}} = -Q_w\, J(T)$$

$$\Rightarrow \left.\frac{\partial Q_w}{\partial t}\right|_{\text{freeze}} = -M_w^{(2)}\, J(T)$$



3b) 2-moment scheme

Deutscher Wetterdienst
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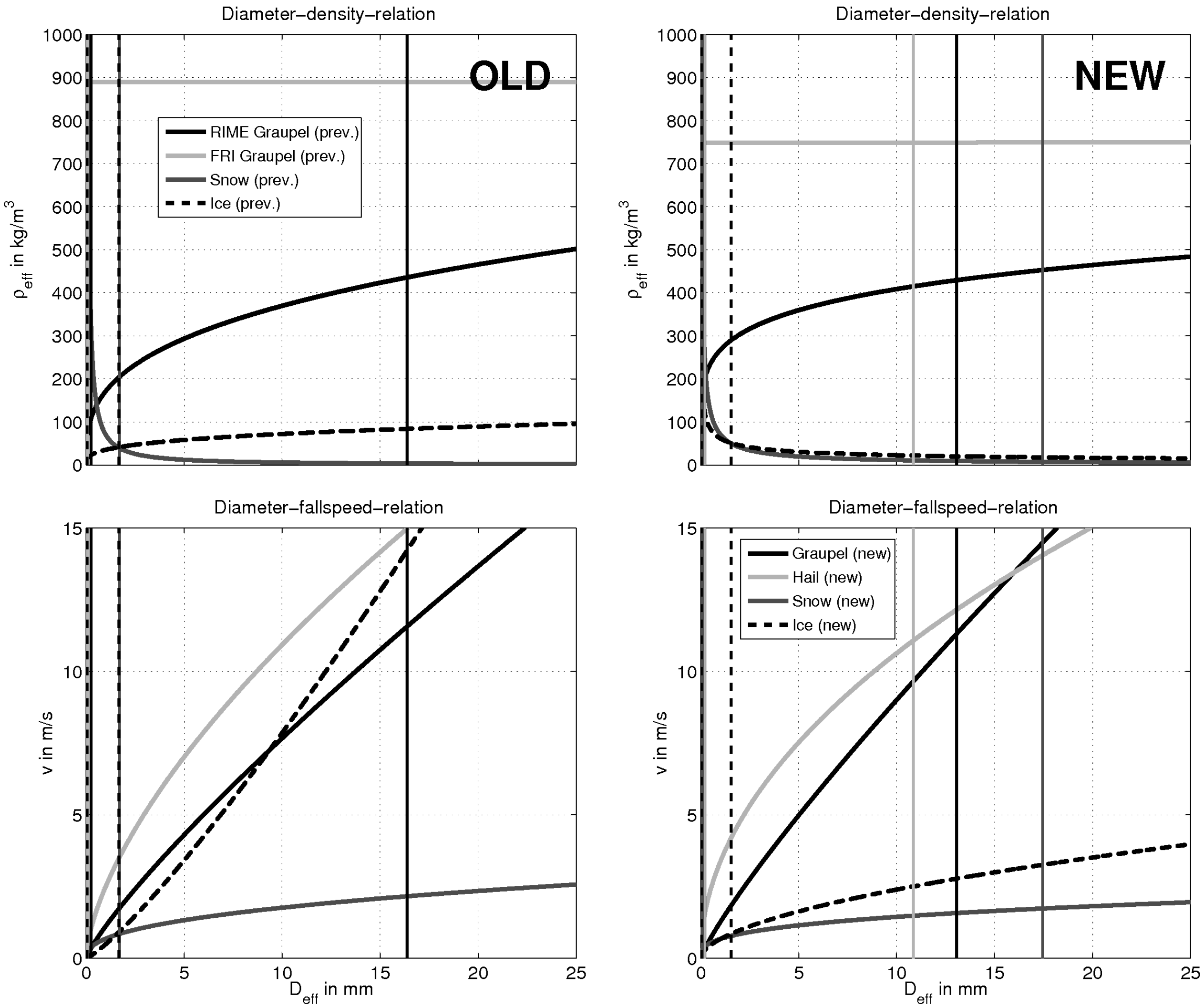
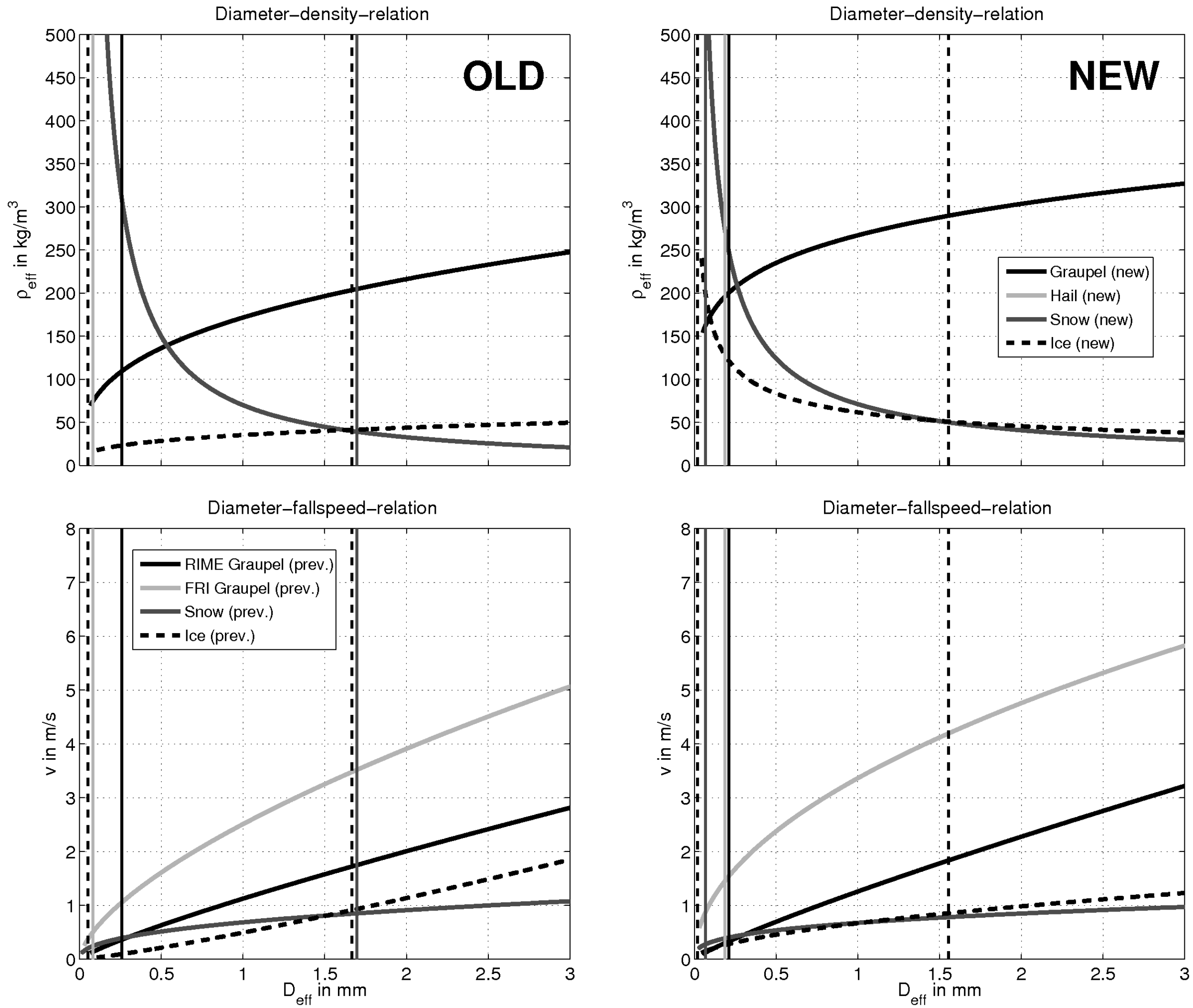


3b) 2-moment scheme

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



3b) 2-moment scheme