Introduction of prognostic equations for rain in the ECHAM5 GCM

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1. Introduction

Clouds play an important role in the energy budget of the earth. Aerosol particles and their precursors resulting from human activity are thought to change the physical and optical properties of clouds. The first indirect effect refers to decreasing cloud droplet sizes as the concentration of (anthropogenic) aerosols increase. For a constant liquid water content, the higher number of smaller cloud droplets leads to an increase in the cloud albedo and therefore, in the planetary albedo. Furthermore, it is harder for the smaller cloud droplets to grow into precipitation sized drops. This results in a prolonged lifetime of clouds within the atmosphere. This second aerosol indirect effect also causes an increase in the planetary albedo. However, the size of both of these effects is still very uncertain.

The investigation of aerosol effects on large scale precipitation is one of the major goals of this study. As a first step, prognostic equations for rain mass mixing ratio and rain drop number concentration are introduced. In addition to this, an explicit fall speed for the rain drops is derived. Fowler et al. (1996) note that "time stepping" (or iteration with a smaller time step) is necessary for falling rain drops in order to account for the microphysical processes rain is involved.

At this stage, results from a single column simulation with the newly introduced prognostic rain will be presented. The changes in the model results caused by differing the number of iterations will be shown as well as a single time step experiment regarding the influence of aerosol concentration on precipitation formation (Menon et al. 2003). This results will be compared to the standard ECHAM5 (Roeckner et al. 2003).

2. Model description

2a. *The general circulation model ECHAM5*

The general circulation model (GCM) ECHAM5 is based on the ECMWF model and is now further developed at the Max-Planck-Institute for Meteorology in Hamburg. Within ECHAM5, the prognostic equations for temperature, surface pressure, divergence, vorticity are solved on a spectral grid with a triangular truncation (Roeckner et al. 2003). Prognostic equations for cloud water and cloud drop number concentration as well as detailed cloud microphysics were introduced by Lohmann and Roeckner (1996) and Lohmann et al. (1999). Atmospheric aerosol distributions are represented by a superposition of 7 lognormal distributions of different size ranges, solubilities, and constituents within the aerosol module HAM (Stier et al. 2004).

2b. *Prognostic equations for rain*

In the standard version of the ECHAM5, the rain is treated diagnostically and the total rain water is removed from the model after one time step (as surface precipitation flux). This approach is only true for relatively large rain drops. Smaller drops (i.e., drizzle ($25\mu m < r < 100\mu m$)) also sediment but may not reach the surface within one time step. Figure 1 shows the processes that have to be considered for the prognostic treatment of rain. Rain drops are larger than $25\mu m$ in radius in

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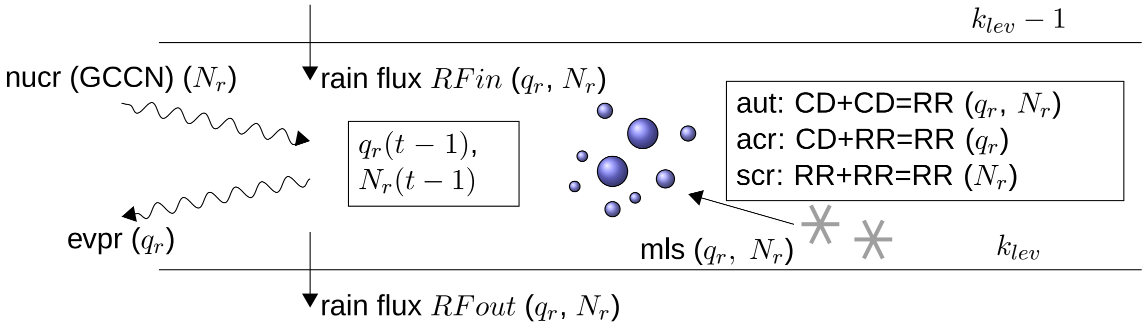

Fig. 1: Treatment of Rain in level k_{lev}

this case. Firstly, there is the rain flux that comes into the level (RF_{in}) and that leaves the level (RF_{out}). New rain drops (number) form by activation of giant cloud condensation nuclei (GCCN) ($nucr$) and by autoconversion of cloud droplets (aut). Rain drop number decreases by self collection (scr) of rain drops. An increase in rain water is caused by accretion of cloud droplets by rain drops (acr) and the evaporation of rain ($evpr$) leads to a decrease in rain water mixing ratio. A further source of rain drop mass and number is the melting of snow (mls). These processes are summarized in eq. (1). Q and P denote changes in the rain water mixing ratio and in the rain drop number concentration, respectively and the cloud and precipitation fraction are denoted with b_c and b_r, respectively.

$$\begin{aligned}
\frac{\partial q_r}{\partial t} &= b_c\ (-Q_{aut} - Q_{acr}) - (1-b_r)\,Q_{evpr} \\
&\quad + b_r\ (Q_{mls} + Q_{RFin} - Q_{RFout}) \qquad \text{(1a)} \\
\frac{\partial N_r}{\partial t} &= P_{nucr} + b_c\ (-P_{autr}) \qquad \text{(1b)} \\
&\quad + b_r\ (P_{mls} - P_{scr} + P_{RFin} - P_{RFout})
\end{aligned}$$

The parameterization of the microphysical processes (aut, acr and scr) are taken from Khairoutdinov and Kogan (2000), Beheng (1994) or Seifert and Beheng (2001). In case of evaporation, it is assumed that the rain drops get smaller which results in a changed mass mixing ratio but constant rain drop number concentration (Rotstayn 1997). The nucleation of GCCN to rain drops is not yet included in the model. This will be a task for the future to investigate the influence of GCCN on cloud processes and the precipitation formation (Rosenfeld et al. 2002). The determination of the incoming and outgoing rain flux is described in the next section.

2c. *Rain flux and terminal velocity*

To calculate the actual rain flux from one model level to the next, an approach for the fall velocity of rain drops is introduced. In order to account for the larger fall speeds of larger rain drops, different equations for the fall velocity of the rain mixing ratio and the rain drop number concentration are used.

The starting point is the approximation of the fall velocity of a single rain drop by Rogers et al. (1993):

$$v(D) = \begin{cases} a_1\ D\ [1 - \exp(-a_2\ D)] & D \leq 745\ \mu m \\ b_1\ - b_2\ \exp(-b_3\ D) & D > 745\ \mu m \end{cases} \qquad (2)$$

with D denoting the diameter of the rain drop and the constants $a_1 = 4000\ s^{-1}$, $a_2 = 12000\ m^{-1}$, $b_1 = 9.56\,m/s$, $b_2 = 10.43\,m/s$, and $b_3 = 600\,m^{-1}$. First, only drops smaller then $745\ \mu m$ are considered. If at anytime the fall velocity for larger drops is needed the derivation will be quite similar.

In order to obtain the fall velocity for the two bulk parameters mass and number (i.e., q and N) the flux density approach used by Srivastava (1978) (his eqs. (48) and (49)) is applied.

$$\begin{aligned}
\mathfrak{F}_m &= \rho_a\, q_r \cdot v_m = \int_0^\infty m\, f(m)\, v(m)\, dm \qquad \text{(3a)} \\
&\quad \text{(mass flux)} \\
\mathfrak{F}_\mathfrak{n} &= N_r \cdot v_n = \int_0^\infty f(m)\, v(m)\, dm \qquad \text{(3b)} \\
&\quad \text{(number flux)}
\end{aligned}$$

In order to calculate the mass and number flux $\mathfrak{F}_m$ and $\mathfrak{F}_n$, an exponential distribution $f(D)$ is assumed. This kind of distribution was first put forward by Marshall and Palmer (1948).

$$f(D) = N_D\ \exp(-\lambda D) \qquad (4)$$

Grabowski (1999) suggested the following expression for λ and N_D using the model variables cloud water mixing ratio q and cloud droplet number concentration N.

$$\lambda = \frac{1}{D_0} = \left(\pi \rho_w \frac{N_r}{\rho_a\, q_r}\right)^{\frac{1}{3}} \quad \text{and} \quad N_D = \frac{N_r}{D_0} \qquad (5)$$

In models it is more convenient to work with the drop mass instead of the droplet diameter. With $m = \frac{1}{6}\, \pi\, \rho_w\, D^3$ and $f(m) = f(D)\, \frac{dm}{dD}$, the rain drop distribution changes from an exponential to a Weibull distribution and has the following form which is used for eqs. (3):

$$f(m) = \frac{N_r}{3} \left(\frac{m}{m_0}\right)^{-\frac{1}{3}} \exp\left[-\left(\frac{m}{m_0}\right)^{-\frac{1}{3}}\right] \frac{1}{m} \qquad (6)$$

D_0 and m_0 are distribution parameters which have the following relationship with the mean mass $\overline{m}$ and mean diameter $\overline{D}$:

$$\overline{m} = \frac{\rho_a\, q_r}{N_r} = 6\, m_0 \quad \text{and} \quad \overline{D} = \sqrt[3]{6}\, D_0 \qquad (7)$$

Inserting equation (6) for the rain drop size distribution into equations (3) leads to the following expressions for the fall velocities v_m and v_n:

$$v_m = \frac{\mathfrak{F}_m}{\rho_a\, q_r} = \begin{cases} 20 \dfrac{a_1\, a_2}{c^2} m_0^{\frac{2}{3}} & \text{for } D_0 \leq 16.67\ \mu m \\ 4 \dfrac{a_1}{c} m_0^{\frac{1}{3}} & \text{for } D_0 > 16.67\ \mu m \end{cases} \qquad (8)$$

$$v_n = \frac{\mathfrak{F}_n}{N_r} = \begin{cases} 2 \dfrac{a_1\, a_2}{c^2} m_0^{\frac{2}{3}} & \text{for } D_0 \leq 41.67\ \mu m \\ \dfrac{a_1}{c} m_0^{\frac{1}{3}} & \text{for } D_0 > 41.67\ \mu m \end{cases} \qquad (9)$$

These asymptotic solutions for the fall velocities of rain mixing ratio (solid lines) and rain drop number concentration (dotted lines) as a function of D_0 for small and large drops are shown in figure 2. It is obvious that v_m is always larger than v_n which mimics the fact that large (heavy) drops fall faster than small (lighter) drops.

The rain flux from one level to the level below will be calculated by estimating the distance the raindrops fall within one time step. By comparing this distance with the model layer thickness, the amount of raindrops reaching the next level can be determined. Thereby, different amounts are valid for drop number and mass as different fall speeds are used.

If using explicit fall speeds for the rain drops, one has to pay attention that the criterion for numerical stability is not violated. This would be the case if relatively large rain drops fall too fast/too far down and, therefore, miss a model level. To prevent this (and the resulting chaotic behavior of the model), a reduction of the time step is necessary. As this would be computational too expensive if applied for the whole model, only the cloud microphysics routine is iterated and, thus, experiences a smaller time step. At the moment, the number of iterations is fixed to a constant value (e.g., 5, 10, 50) that is valid for the whole simulation. In future simulations, it is planned to assign the number of iterations during the simulation dynamically.

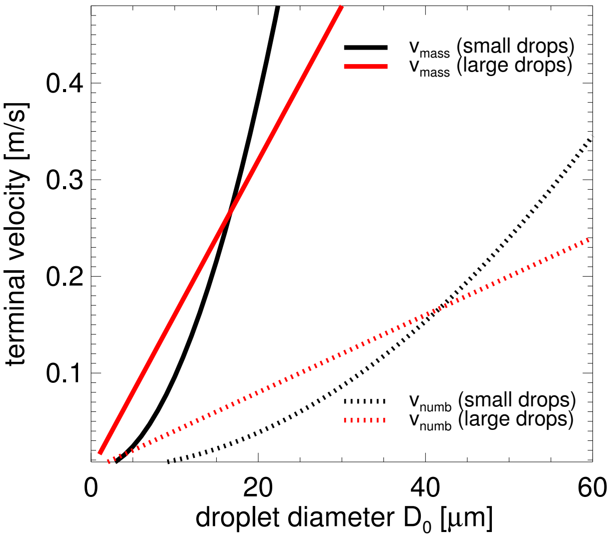

Fig. 2: The fall velocities for bulk mass (solid lines) and bulk number concentration (dotted lines)

3. Results

3a. *Iteration test case*

After including the iteration loop and the fall velocities for rain drops a test case was designed to evaluate the effects of these changes in the Single Column Model of the ECHAM5. Therefore, a rain water content of $0.15\ 10^{-3} kg/kg$ and a rain drop number concentration of $10^6 m^{-3}$ were initialized in model level 21 (of a 31 level model) and all microphysical processes (autoconversion, accretion, selfcollection, evaporation of rain, etc) were switched off. The artificially included rain drops move down in the model column according to the calculated fall velocities and the reduced time step. Fig. 3 and table 1 show the results of this test. The more iterations that were performed, the more rain stays in the atmosphere

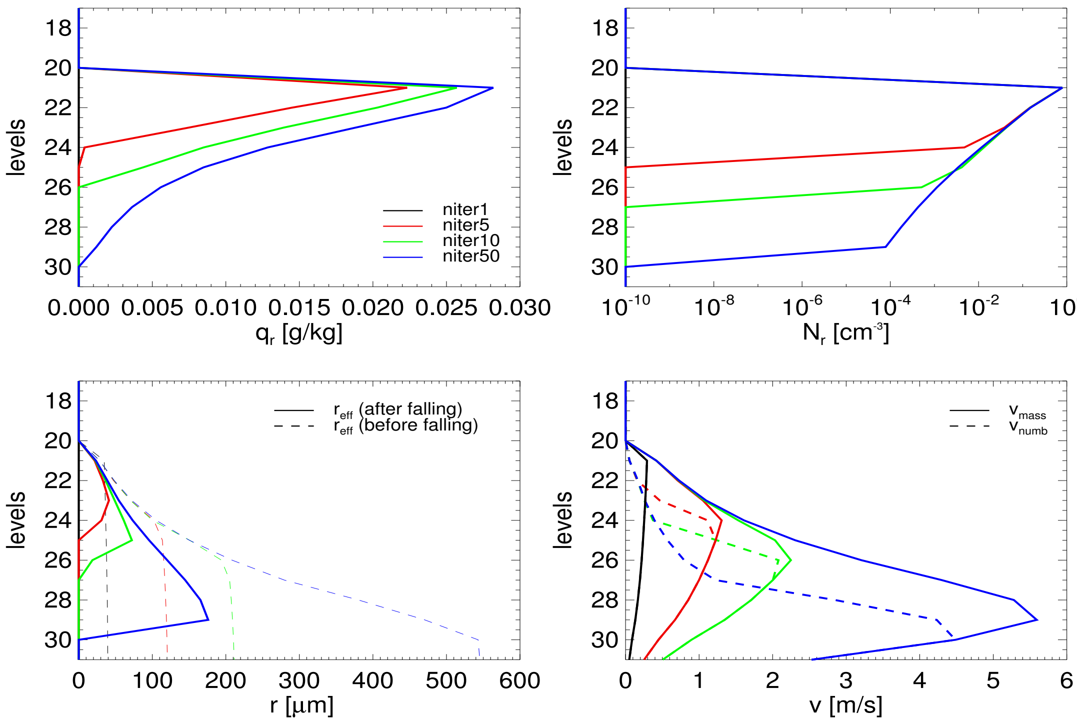

Fig. 3: Iteration test case for the rain water content (upper left), rain drop number concentration (upper right), effective radius before and after falling (lower left) and the fall velocities for rain mass and rain drop number (lower right) (shown is only the effect of the fall velocity, no cloud microphysics is included)

(see Fig. 3 upper left and right panel) and does not reach the surface. Therefore, the rain rate decreases with an increasing number of iterations (see table1). The smaller time steps also lead to larger rain drops that remain within the atmosphere. The maximum rain drop size (see Fig. 3 lower left - dashed line: drop size before falling) changes depending on the number of iterations . Once this maximum size is reached all drops will fall to the next level. This results from the fall velocities of mass and number being the same. (see 3 lower right). The fall velocities start to decrease in the lower levels as the drops are not allowed to fall further than one level within one time step. As the level thickness decreases towards the surface the fall velocities also have to decrease.

Tab. 1: Rain rate $[mm/h]$ at the surface

	niter1	niter5	niter10	niter50
rain rate	0.031	0.020	0.013	0.0057

3b. *Single Time Step Experiment (1TS-EXP) for ACE2-cloudycolumn*

To verify the changes in the cloud microphysics due to the prognostic rain equations and the iteration loop, the single time step experiment described in Menon et al. (2003) was redone. It uses data from the ACE2-cloudycolumn campaign to investigate the ability and limitation of a SCM to describe aerosol-cloud-radiation interaction for a clean (June 26) and polluted (July 09) case. For the 1TS-EXP, the values for the total liquid water (TWC = cloud water + rain water), total aerosol number N_a, and cloud cover b at cloud height were prescribed (see table 2). The aerosol particles were activated (Lin and Leaitch 1997) to 77 cm^{-3} and 163 cm^{-3} cloud droplets

Tab. 2: Cloud properties used for the 1TS-EXP

	June 26	July 09
TWC [mg/m^3]	$125 + 23.2$	$110 + 2.1$
N$_a$ [cm^{-3}]	256	575
b	0.87	0.5

for June and July, respectively.

The results for the rain flux just below the cloud are shown in table 3 and Fig. 4 together with the rain properties q_r and N_r. Values measured during ACE2 are indicated as numbers at the top of the plots.

Tab. 3: Rain flux $[mg/(m^2\ s)]$ at cloud base

	June 26	July 09
obs	5.4	0.8
standard	$4.45 \cdot 10^{-2}$	$7.00 \cdot 10^{-4}$
niter1	$4.46 \cdot 10^{-2}$	$9.46 \cdot 10^{-4}$
niter5	$6.55 \cdot 10^{-3}$	$5.90 \cdot 10^{-4}$
niter10	$3.04 \cdot 10^{-3}$	$2.72 \cdot 10^{-4}$
niter50	$5.73 \cdot 10^{-4}$	$5.08 \cdot 10^{-5}$

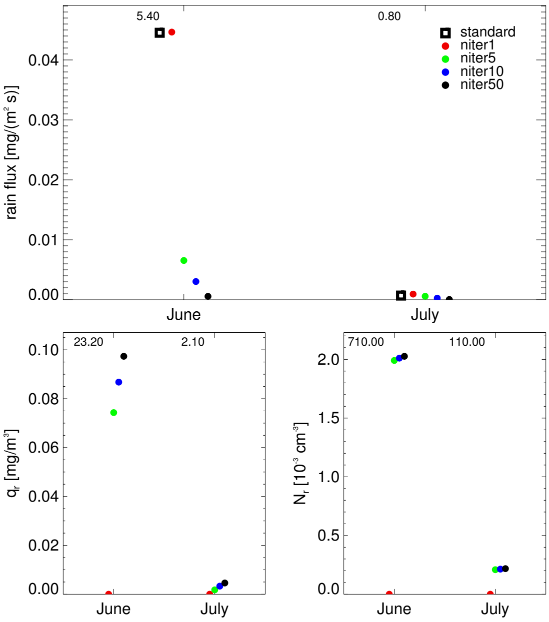

Fig. 4: Rain flux, rain mixing ratio q_r and rain drop number concentration N_r for different number of iterations for the Single timestep experiment

Again, the increase in the number of iterations leads to a decrease in the rain flux below the cloud, whereas, rain mass and number concentration are increasing. Nevertheless, the amount of rain flux (as well as rain mass and number concentration) is well below the measured values, most propably due to too low conversion rates of cloud water to rain water (i.e., accretion and autoconversion). The standard ECHAM5 and the simulation with one iteration time step (i.e., no iteration) shows quite similar results because the fall velocities are the same in both cases: the level thickness/time step.

4. Conclusions and Outlook

Prognostic equations for the treatment of rain were included into the ECHAM5 GCM. First tests revealed a decreasing amount of rain flux with an increasing number of iterations used as more and more of the rain water stayed within the atmosphere. Iterations became necessary to prevent the rain drops from falling to the surface within one model time step as it was done in the original diagnostic rain scheme. Comparisions of Single Column Simulations with measurements from the ACE2 campaign also show that the rain mass and the rain number are too low to create a sufficient amount of precipitation.

Further studies will include global simulations with the prognostic rain equations, first with a constant number of iterations, later with dynamically assigned iterations (i.e., depending on cloud cover, height of cloud base, etc). A future goal will be to include the effect of Giant CCN on precipitation formation (Rosenfeld et al. 2002).

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