MICROPHYSICS IN SMALL SCALE CLOUD MODELS

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Precipitation is one of the most sensible parameters of cloud modelling as it integrates the cloud evolution as a whole. Some other parameters, like e.g. cloud base and top, liquid water content and vertical velocity are rather insensitive to changes in cloud microphysics as they are mainly determined by the initial conditions. Consequently, prediction of the amount and time of precipitation can be used as a mean to test model performance. This test has the advantage that it is relatively cheap as it is not coupled to complex and expensive airplane measurements.

1. INTRODUCTION

Small scale cloud models are those in which the clouds are explicitly resolved. Consequently, these models have to have a horizontal and vertical grid resolution on the order of a few hundred meters. The microphysical processes going on in clouds can thus be considered in much more detail than in regional or even larger scale models. Sensitvity studies of this detailed treatment of microphysics can yield information on the impact of different processes on the overall behavior of the cloud. As a further consequence, sensible points of cloud modelling can be identified, which can also help to ameliorate larger scale models.

2. DESCRIPTION OF MODEL

The model used for these sensitvity studies is called DESCAM (DEtailed SCAvenging and Microphysics) model. It was developped to study for convective clouds the dynamics, the microphysics, the scavenging of aerosol particles, the uptake of gases, and subsequent wet phase chemical reactions. The model is described in details, e.g., in Flossmann *et al* (1985), Flossmann (1991, 1994). The model exists in a variety of different versions with different complexities in dynamics, microphysics and scavenging features. The basic concept of the model, however, is that it treats the microphysics of a cloud in a spectral approach.

Consequently, it follows a cloud number density distribution function $f_d(m)$ which changes due to the following processes:

$$\frac{\partial f_d(m)}{\partial t} = -\nabla \bullet [v f_d(m)] + \nabla \bullet [K_m \nabla f_d(m)] + \frac{\partial}{\partial z}[V_\infty(m) f_d(m)]$$

+ *activation (nucleation scavenging)*

+ *condensation/evaporation*

+ *impaction scavenging*

+ *collision/coalescence*

+ *drop breakup*

+ *heterogeneous freezing*

+ *riming of ice crystals and graupels*

+ *melting of ice crystals and graupels*

Furthermore, the model follows an aerosol particle number density distribution function. The reason is that, apart from the pollution of drops through the scavenging of atmospheric particles, aerosol particles serve as CCN (cloud condensation nuclei) depending on their size and their chemical composition.

$$\frac{\partial f_{APa}(m_{AP})}{\partial t} = -\nabla \bullet [v f_{APa}(m_{AP})] + \nabla \bullet [K_m \nabla f_{APa}(m_{AP})]$$

+ *activation (nucleation scavenging)*

+ *condensation/evaporation (equilibrium)*

+ *impaction scavenging*

The treatment of the spectral liquid phase microphysics and aerosol particle scavenging is described in detail in Flossmann *et al* (1985), and the treatment of the spectral ice microphysics can be found in Alheit *et al* (1990) and Respondek *et al* (1994).

Numerous models totally disregard the dependancy of drop nucleation on the existing aerosol particle spectrum, among those all models which treat microphysics via a Kessler-type parameterization. In spectral models it is often only taken into account through a parameterized CCN formulation depending on the supersaturation and two parameters depending on the air mass ($N_{CCN}=cS^k$).

3. EFFECT OF CCN ON DROP SIZE SPECTRUM

In order to test the possible influence of an incorrect representation of the CCN spectrum due to an unknown chemical composition of the atmospheric aerosol particles we made a run with the DESCAM model containing only liquid phase microphysics in the dynamical framework of a simple ascending and entraining air parcel (Flossmann, 1993).

Displayed with a solid line in Fig.1a and c is a dry aerosol particle spectrum of a continental total number concentration, i.e. 1000 particles per cm^3. In a first case, illustrated in Fig.1a, we

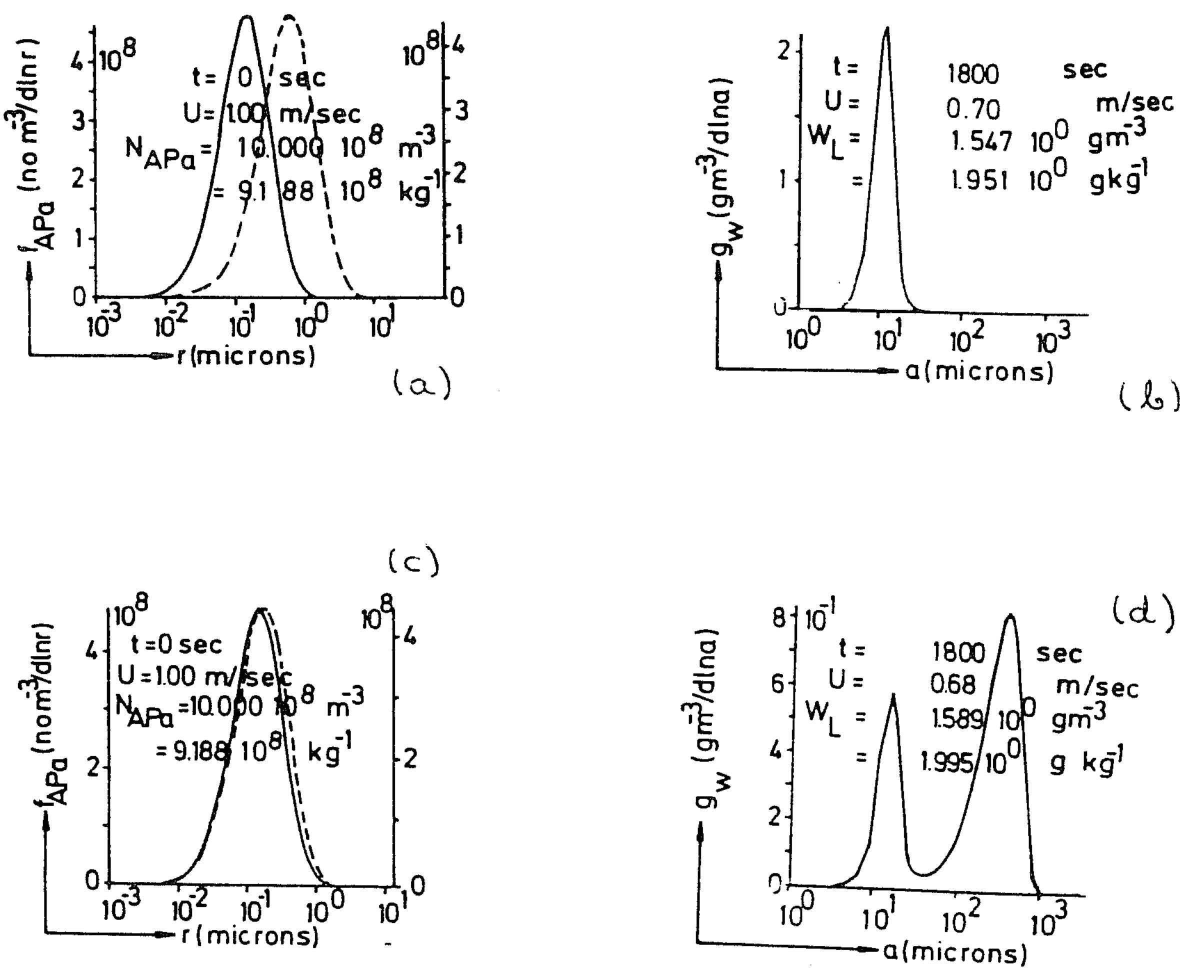

Fig.1: Aerosol number density distribution function at t=0 sec (a and c) and water mass density distribution function after 30min of model time (b and d) in an ascending and entraining air parcel model. For a description of the figure see text below. The figure is a summary of the Figs.3b and d and 4b and d of Flossmann et al (1985)

assumed that the particles entirely consist of $(NH_4)_2SO_4$ and in a second case in Fig.1c it is assumed that only 1% is soluble $(NH_4)_2SO_4$ and the rest is insoluble. The resulting moist aerosol particle spectrum being in equilibrium with an ambient relative humidity of 99% is displayed by the dashed curve which belongs to the right ordinate. The liquid water spectrum that evolved after 30min within an ascending and entraining air parcel (Flossmann *et al*, 1985) is totally different for the two cases considered. In the first case, for which the liquid water spectrum after 30min is displayed in Fig.1b, about 800 drops/cm^3 formed directly at cloud base. These were too numerous to grow by condensation to the extend that collision and coalescence of drops could become effective. Consequently, no precipitation sized drops were formed. Totally different is the case where only 1% of the total material of the particle was soluble. There, only 500 drops/cm^3 were formed and consequently, rain drops of large sizes could be formed as can be seen in the second maximum of the cloud liquid water spectrum in Fig.1d.

This does not only result in a totally different cloud microphysics and dynamics but also has consequences on the radiative properties of the cloud. And certainly the precipitation intensity of the cloud will be heavily affected. From this, one can speculate, that using a crude CCN parameterization like$N_{CCN}=cS^k$ might lead to even stronger deviations in the resulting drop spectrum, as was also shown by Ahr *et al* (1990).

Another aspect of simplifications in small scale cloud models concerns the overall treatment microphysics, i.e., a bulk microphysics as compared to a spectral microphysics.

4. EFFECT OF CLOUD MICROPHYSICS PARAMETRIZATION

In order to study this aspect, we have applied the DESCAM model containing only liquid phase microphysics coupled to a 2-D dynamics model to cloud observed during the HaRP (Hawaiian rainband project) campaign on 22. Aug. 1990 (Flossmann, 1992). There, the radar pictures showed a narrow rainband almost parallel to the island shore.

The dynamics model is a 2-D slab-symmetric version of the 3-D model which has been described, e.g. by Clark (1977, 1979), Clark and Gall (1982), Clark and Farley (1984), and Hall (1980). As the spectral microphysical and scavenging calculations are very computer time and storage consuming we restricted the domain to two dimensions with 20km in the horizontal and 10km in the vertical. The grid increments were dx=400m and dz=200m and dt=5s.

The same domain and grid increments were used for the bulk microphysical run. There, the spectral microphysics was replaced with a Kessler parameterization as described in Clark (1979).

The model runs were initialized with a wind field. For that, the observed wind fields were projected onto the N-E plane cutting through the rainband. However, the resulting wind vectors were still too large for a 2-D model blowing the cloud rapidly out of the considered domain. Consequently, the wind velocities were reduced to 10% of their original value.

In order to imitate the converging flows from the ocean and the island which are responsible for the development of the quasi-stationary rainbands off the coast of the island the model was driven by a surface sensible and latent heat flux as described in Flossmann (1991).

Furthermore, the spectral microphysical and scavenging model needs the specification of an initial aerosol particle spectrum. For this, we chose the maritime spectrum described in Flossmann (1991) where it is assumed that the small aerosol particles consist of $(NH_4)_2SO_4$ and the large ones of NaCl. The total number concentration of the spectrum yields 173 cm^{-3} and the total particle mass 30 $\mu g\ m^{-3}$. Those values decrease exponentially with height as explained in Flossmann (1991).

Until 34 min of model time the two models produced identical results. Then the cloud formed and the model runs started to deviate. Table 1 summarizes the main results for both cases every ten minutes.

model time (min) cloud life (min)	35 1	45 11	55 21	65 31
cloud top (km)	1.5/1.5	3.8/3.8	3.2/3.2	2.7/2.7
cloud base (km)	0.8/0.8	1.0/1.0	1.0/1.0	1.0/0.8
cloud dim. (km)	1.2/1.2	4.0/3.5	5.5/4.0	5.5/5.5
RH_{max}(%)	100.9/100.	101.7/100.	102.0/100.	101.4/100.
w_{max} (m/s)	6.4/6.4	7.8/8.5	3.7/4.2	2.7/2.4
w_{max} (cld base) (m/s)	6.4/6.4	2./2.	3./3.	1./2.
w_{min} (cld base) (m/s)	–/–	–/–	–2./–2.	–1.6/–2.7
$w_{L,max}$ (g/kg)	0.15/0.18	7.2/4.4+1.8	1.2/1.3+1.1	1.9/2.0+0.1
av. rainrate (mm/h)	0	0	11.2/8.1	0.3/0.2

Table 1: Pertinent values for the cloud characteristics (i.e. height of cloud top, height of cloud base, diameter of the cloud, maximum relative humidity, maximum updraft velocity, maximum updraft velocity at cloud base, maximum downdraft velocity at cloud base, maximum liquid water content, and average rainrate) at various model times (corresponding to a certain cloud life time) for the spectral (left number) and the bulk (right number) model results (taken from Flossmann, 1992)

At 35 min of model time the values for the detailed and the bulk case were still nearly identical. However, the values for the liquid water content showed the first difference. It was caused by the different treatment of supersaturation in the microphysical models. In the bulk model saturation is the maximum relative humidity allowed while the detailed model explicitly calculates condensation and evaporation of the drops and thus provides for a supersaturation. Consequently, more condensation occured in the bulk model also resulting in a stronger release of latent heat which in turn resulted in an enhanced condensation and an increase in the liquid water content. This continued for some minutes.

Then, the cloud top reached the very strong inversion around 750mb and even overshot it some hundred meters. Thus, a strong outflow of as large as 5m/s occured at the upper boundary of the cloud transporting cloud water from the updraft region to the downdraft region. There, in the bulk case the water evaporated instantaneously while in the detailed case the drops had much longer residence times in the subsaturated environment. As a result the bulk cloud at 45min of model time was much slimmer than the detailed cloud and the total liquid water of the detailed cloud (7.23 g/kg) was about 1 g/kg larger than that of the bulk cloud (4.38+1.78 g/kg). This was a result of the outflow at the cloud top where the maximum liquid water content was located. In the bulk cloud the outflowing liquid water evaporated completely reducing the maximum liquid water content of the cloud. In the detailed cloud the drops could persist in the subsaturated environment and could be reentrained at a height of about 2km where the strong downdraft region ended. This protected the cloud core from thinning out.

In both runs precipitating drops had formed. In the bulk cloud about 2 g/kg while in the detailed cloud the difference between the maximum total liquid water (7.23 g/kg) and the maximum liquid water content of the drops smaller than 30μm (3.29 g/kg) indicates that about 4 g/kg precipitating drops have been formed. This is just a gross estimate but it is obvious that the larger liquid water content in the detailed cloud had formed more raindrops than in the bulk cloud. These raindrops fell towards the ground and about 5 min later (50 min corresponds to 16 min of cloud life time) the rain reached the surface as can be seen from Fig.2.

Fig.2 displays the rain rate averaged over the cloud as a function of time for both cases and we can see that the detailed model rain started about 1min earlier than the bulk rain and was about twice as large. The maximum was reached around 55 min of model time. Averaged over both space and time the detailed cloud precipitated 1.13mm and the bulk cloud 0.63mm.

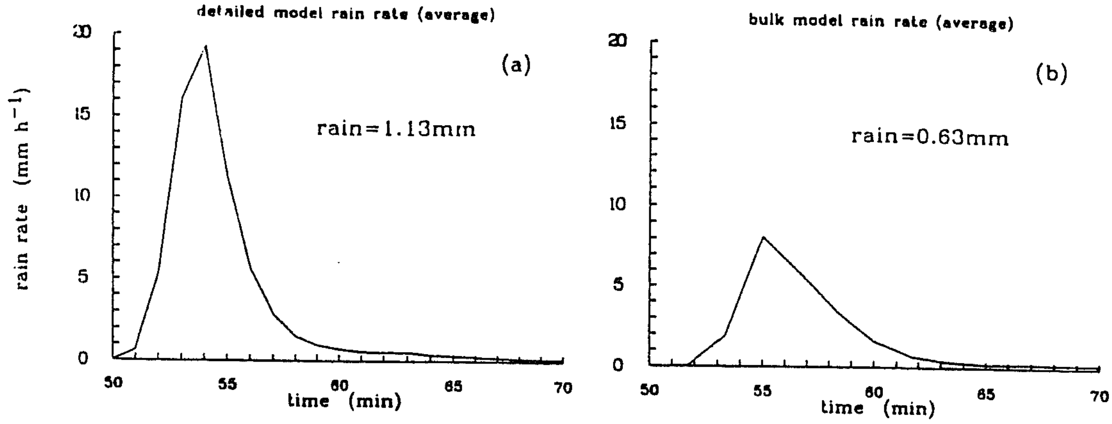

Fig.2: Evolution of the rainfall rate (a) for the detailed model results and (b) for the bulk model results, averaged over the entire rainfall region and 1min (a) and 100s (b) intervals, resp. (taken from Flossmann, 1992)

The cloud characteristics for 55min of model time corresponding to 21 min of cloud life time, as displayed in Table 1 display that the vertical velocity field in the bulk case experienced higher maxima and minima.

However, liquid water field now displays a higher liquid water content for the bulk case than for the detailed case. This is caused by the fact that the detailed cloud had already lost the main water mass due to precipitation (compare Fig.3) while the bulk model was just at the maximum of its rain intensity.

10 minutes later the clouds had weakened substantially as can be seen from Table 1. And after 5 more minutes the rain stopped and we terminated the calculations.

We can conclude that differences between the two results occur which mainly were caused by the different treatment of the supersaturation. The largest differences occur in the amount of rain fallen from the clouds as these values integrate the life history of a cloud.

The third example foccuses on another aspect of simplifications in cloud models. This aspect concerns the ice phase. Ice in clouds occurs in a variety of different forms: pristine ice crystals have different crystal shapes depending on the vapor supply and the temperature (see e.g. Pruppacher and Klett), crystals and graupels form aggregates among themselves and through riming of cloud droplets. All these different ice particles experience a different dynamical, microphysical and scavenging behavior in clouds and consequently are difficult to treat in cloud models. Consequently, numerous models try to approximate the behavior of cold clouds by just considering the liquid phase. The errors committed by this approach are the subject of the third example.

5. THE EFFECT OF THE ICE PHASE

In order to study this effect we have applied the DESCAM model with warm and cold microphysics, coupled to the 2-D model of Clark and coworkers to the CCOPE experiment on July, 19 1981. The cloud observed was extremely well documented by Dye *et al* (1986), but unfortunately, no specific date detailed size distribution of aerosol particles and their chemical composition were available for model initialzation. However, measurements of Hobbs *et al* (1985) for this geographical site could be used to close this gap. The results of this simulation will appear soon in Respondek *et al* (1994).

Our calculations were started at 15:05 MDT (mountain daylight time). The surface sensible and latent heat flux caused the air to rise rapidly so that at 16:00 MDT (cloud life time t_w=0min) a cloud had formed with a base near 3.5km ASL in fair agreement with the observed base height of 3.9 km (ASL) (note that ASL=z+0.8km, where z is the height in the model and 0.8km is the elevation of Miles City, Montana). In Table 2 we have listed the pertinent cloud characteristics computed with our model and compared them with the observations of Dye *et al* (1986) for some particular local times (MDT).

During the first 20min of its life time the model cloud experienced a moderate growth rate with maximum vertical velocities varying between 7 and 10m/s at 5.3 km ASL while the cloud top rose to 7.3km ASL. At an altitude of 6km ASL the vertical velocity was about 4m/s which agrees well with observations which found with the KING AIR airplane a vertical velocity of 3 to 5 m/s (Table 2). Within the first 20min the model cloud consisted mainly of liquid hydrometeors in agreement with observations which found negligible ice until 16:18 MDT. At 16:21 MDT the drop concentration in the model cloud had reached in the upper part of the cloud 553cm^{-3} at a level of 6.3km ASL which agrees well with the observations which observed with the KING AIR airplane 600cm^{-3} at 6 km ASL. No millimeter sized ice particles were observed at that time in agreement with our results from the model cloud. At 16:21 MDT the liquid water content of the model cloud had reached at 6km ASL a liquid water content of about 2.7g/kg (~ 1.78 g/m^3) slightly larger than the values of 1 to 1.75 g/m^3 measured by the KING AIR at that level between 16:21 to 16:23 MDT at the level of 6km ASL (Table 2).

In agreement with the observation of the KING AIR and the sailplane a vigorous growth phase of the model cloud began about 16:22 MDT. This growth phase lasted till about 16:33 MDT. At 16:25 MDT the vertical velocity of the model cloud reached a maximum of 16.5m/s

		model	observation
height of cloud top (km)	16:15 MDT 16:25 MDT	6.0 - 6.5 10.2 - 10.6	6 10.5
cloud base (km)		3.2 - 3.5	3.8
liquid water content at 6 km (g/m^3)	16:21 MDT 16:25 MDT 16:29 MDT	1.78 2.2 0.73	1–1.75 2.5 1.8–2.5
liquid dry out begin end		 16:30 MDT 16:45–16:50 MDT	 16:32 MDT 16:45 MDT
vertical velocity (m/s)	16:20 MDT 16:25 MDT	4 (at 6 km) 16.5 (at 6.8 km)	3 - 5 (at 6 km) 15 (at 6.5 - 7 km)
begin of vigorous growth phase		16:22 MDT	16:22 MDT
drop number concentration (cm^{-3})	16:21 MDT 16:33 MDT	553 (6.3 km) 662 (4.2 km)	600 (6 km) 600 (4 - 4.5 km)
maximum rainfall rate		16:55-17:00 MDT	16:55-17:00 MDT
max. ice particle concentration (per liter)	6 km 7.7 km 7.3 km	10 (16:41 MDT) 80 (16:41 MDT) 20 (16:49 MDT)	64 (16:48 MDT) — -
first graupel	at 5.8 km	16:23 MDT	16:26 MDT
graupel concentration at 6 km (per liter)	16:25 MDT 16:30 MDT 16:41 MDT	1–70 0.1 1.8	2–5 0.24 1.5
at 4.6 km	16:40 MDT	1	4

Table 2: Comparison of model results with observations of Dye *et al* (1986); altitudes are given in ASL (taken from Respondek *et al*, 1994).

at 6.8 km ASL in agreement with the maximum vertical velocity of ~15 m/s observed with the sailplane which at 16:27 to 16:29 MDT had reached an altitude of 6.5 to 7 km ASL (Table 2). By that time the top of the model cloud had reached its highest level of 10 to 11km ASL in agreement with the observations. At 16:29 MDT the liquid water content of the model cloud had already significantly decreased to about 1.1g/kg (~0.73g/m^3) at 6.8km ASL. At that time the sailplane observed still 2.5g/m^3 at 6 to 7 km ASL and the KING AIR 1.8g/m^3 at 6 km ASL decreasing rapidly to 0.7g/m^3 already ao 16:32 MDT. The maximum drop number concentration in the model cloud had reached 600 to 900 cm^{-3} in agreement with the sailplane observations of about $600 cm^{-3}$ at that time and level.

The ice particle concentrations observed at 16:25 to 16:30 MDT had sharply increased and was observed by the KING AIR and the sailplane to range between 2 and 5 per liter at a level of 6 to 7 km ASL. At the same level the number concentration of ice particles in the model cloud was between 1 and 70 per liter. Ice particles of millimeter size (graupel) were observed for the first time by the KING AIR at 5.8km ASL and 16:26 MDT reaching by 16:30 MDT a concentration of 0.24 per liter, in agreement with the model predicition of 0.1 per liter at 6km ASL (Table 2).

The model prediced a rapid weakening of the updraft and a liquid dry out of the modl cloud to set in at 16:30 MDT. The significant decrease in the liquid water content was due to the rapid growth of the graupel. Maximum graupel sizes of 4 to 7 mm diameter were observed by both the KING AIR and the sailplane around 5 to 6km ASL between 16:30 and 16:51 MDT in good agreement with the graupel sizes of 2 to 4 mm in radius produced by the model cloud by 16:41 MDT at 5 km ASL. Liquid dry out was completed in the model cloud 16:45 - 16:50 as was observed. After 16:41 MDT the observed concentration of the ice particles increased at 6km ASL from a few per liter to 64 per liter at 16:48 MDT. The model cloud produced during that time at 6km ASL up to 10 ice particels per liter at 16:41 MDT and about 80 per liter at 7.7 km ASL, and at 16:49 MDT about 20 per liter at 7.3 km ASL were observed. The concentration of ice particles > 1mm in diameter (graupel) predicted by the model for 6km ASL at 16:41 MDT of ~1.8 per liter is also supported by the observations.

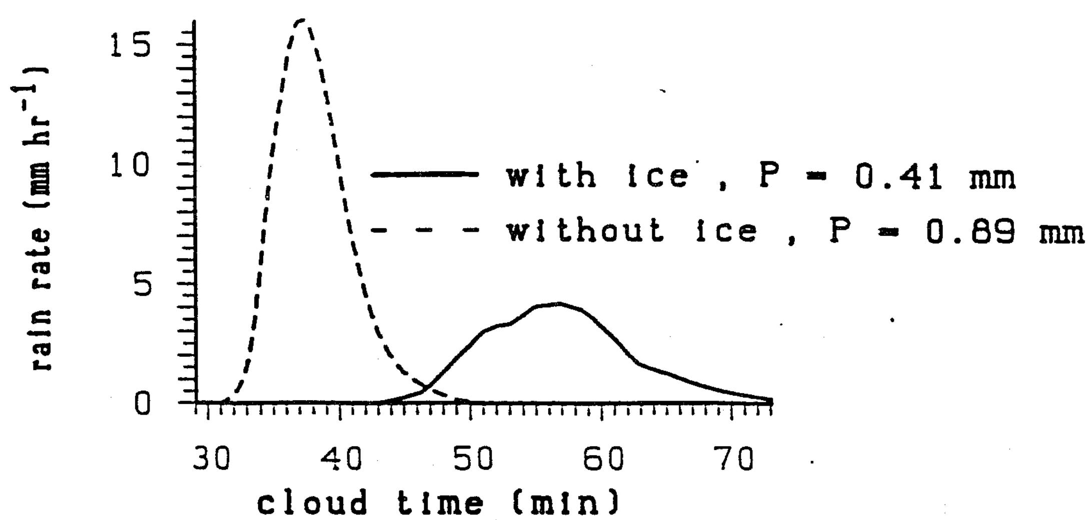

Fig.3: rain rate in mm/hr averaged over the cloud domain for model run with ice (solid line) and without ice (dashed line): P: cumulative precipitation in mm (taken from Respondek *et al*, 1994).

Rain falling from the model cloud began reaching the ground around 16:45 and lasted till about 17:10MDT. This is illustrated in Fig. 3 in terms of the precipitation rate averaged over the cloud precipitation area. We note that the rainfall rate reaches a maximum at 16:55 and that the precipitation was a result of melting graupel, as was confirmed by the observations. This excellent agreement between the predicted and the observed microphysics motivated us to investigate the importance of the ice phase for these results. So by purposely inhibiting the appearance of an ice phase we determined for otherwise identical initial conditions, the effect on the resulting cloud. Although overall the main dynamic features of the cloud evolution without ice was not very different from that with evolved ice significant differences showed up with regard to the onset of precipitation and the duration of precipitation (see Fig.3). We note that precipitation is much earlier in the cloud without the presence of an ice phase than in the mixed ic-water cloud. This is a result of collisional growth process which in the all water cloud is the only precipitation forming process. Growth by riming, on the other hand, has to await the presence of frozen drops respectively ice crystals which by vapor diffusion must first grow to a critical size before riming may commence (see Pruppacher and Klett, 1978). Furthermore, Fig.3 shows that the precipitation event lasts longer and produces lower rates for the mixed ice-water cloud with melted graupel as precipitating hydrometeors than the event involving the all-water cloud. This, again is a result of the less efficient conversion of cloudwater to rain water via riming than via coalescence of drops and the prominent evaporation process in the large regions of liquid dry out.

6. CONCLUSION

In three examples we have tested the influence of different treatments of microphysics in small scale cloud models on the evolution of the cloud. The first example concerned the treatment of the nucleation of drops from cloud condensation nuclei. The second one compared the results of a spectral microphysics with the ones obtained via a bulk parameterization from a Kessler type, and the third example dealt with the influence of the ice phase on the cloud evolution.

All tests had in common, that the influence on the overall parameters of the cloud, like cloud base and top, liquid water content and vertical velocity were noticeable but not servere. However, the consequences for the rain process were extremely prominent.

In the first example, the chemistry of the aerosol particles determined the initiation of the collision and coalescence process and consequently the rain formation.

In the second example, the bulk parameterization resulted in a rainfall rate which only was about half the value of the one of the spectral microphysics model.

In the third one, the ice phase resulted not only in a cutting in half of the precipitation rate but also in an offset of the beginning of rainfall by more than 10min.

This shows, that precipitation is one of the most sensible parameters in cloud modelling as it integrates the cloud evolution as a whole. Consequently, it will be one of the most difficult features to predict. On the other hand, it also is the most challenging one, as a good prediction gives confidence in the model used. Thus, prediction of the amount and time of precipitation can be used as a mean to test model performance. This test has the advantage that it is relatively cheap as it is not coupled to complex and expensive airplane measurements.

7 ACKNOWLEDGEMENTS

This research was funded with the financial support of the Deutsche Forschungsgemeinschaft under project Fl 186/1-1. The author also acknowledges with gratitude the financial support of the Ministry for Research and Technology of the Federal Republic of Germany under project 325-4007-07EU7148 and the CEC under contract no. STEP-CT90-0047.

8 REFERENCES

Ahr, M., A.I. Flossmann, and H.R. Pruppacher, 1990: A comparison between two formulations for nucleation scavenging. *Beitr. Phys. Atmos.*, **62**, 321-326.

Alheit, R.R., A.I. Flossmann, H.R. Pruppacher, 1990: A theoretical study of the wet removal of atmospheric pollutants. Part IV. *J. Atmos. Sci.*, **47**, 870-887.

Clark, T.L., 1977; A small scale dynamic model using a terrain-following coordinate transformation. *J. Comput. Phys.*, **24**, 186-215.

Clark, T.L., 1979; Numerical simulations with a three dimensional cloud model. *J. Atmos. Sci.*, **36**, 2191-2215.

Clark, T.L., and Gall, R., 1982; Three dimensional numerical model simulations of air flow over mountainous terrain: A comparison with observation. *Mon. Wea. Rev.*, **110**, 766-791.

Clark, T.L. and Farley, R.D., 1984; Severe downslope windstorm calculations in two and three spatial dimensions using anelastic interactive grid nesting. *J. Atmos. Sci.*, **41**, 329-350.

Dye, J.E., J.J. Jones, W.P. Winn, T.A. Cerni, B. Gardiner, D. Lamb, R.L. Pitter, J. Hallett and C.P.R. Saunders, 1986: Early electrification and precipitation development in a small, isolated Montana cumulonimbus. *J. Geophys. Res.*, **91**, 1231-147.

Flossmann, A.I., W.D. Hall, and H.R. Pruppacher, 1985; A theoretical study of the wet removal of atmospheric pollutants. Part I. *J. Atmos. Sci.*, **42**, 582-606.

Flossmann, A.I., 1991: The scavenging of two different types of marine aerosol particles calculated using a two-dimensional detailed cloud model. *Tellus*, **43B**, 301-321.

Flossmann, A.I., 1992: Simulation of the 22 Aug. 1990 HaRP case; a comparison between detailed and bulk microphysics in a 2-D framework. *WMO Report* No. 20 of the International Cloud Modeling Workshop/Conference; Toronto 1992, 39-46.

Flossmann, A.I., 1993: Small and Medium scale cloud modelling. In: Physico-chemical behaviour of atmospheric pollutants. Proceedings of the 6th european symposium in Varese 18-22 Oct. 1993, 872-881.

Flossmann, A.I., 1994: A 2-D spectral model simulation of the scavenging of gaseous and particulate sulfate by a warm marine cloud. *J. Atmos. Res.* **32**, 233-248.

Hall, W.D., 1980: A detailed microphysical model within a two-dimensional dynamic framework: Model description and preliminary results. *J. Atmos. Sci.*, **37**, 2486-2507.

Hobbs, P.V., D.A. Bowdle, L.F. Radke, 1985: Particles in the lower troposphere over the high planes of the United States. Part I., *American Meteorological Society*, **24**, 1344-1356.

Pruppacher H.R., and J.D. Klett, 1978: Microphysics of clouds and precipitation. D. Reidel.

Repondek, P.S., A.I. Flossmann, R.R. Alheit, and H.R. Pruppacher, 1994: A theoretical Study of the wet removal of atmospheric pollutants. Part V. J. Atmos. Sci., accepted for publication.