A comprehensive two-moment warm microphysical bulk scheme. II: 2D experiments with a non-hydrostatic model

By JEAN-MARTIAL COHARD and JEAN-PIERRE PINTY*

Laboratoire d’Aérologie, France

(Received 14 April 1999; revised 14 September 1999)

SUMMARY

A new bulk microphysical scheme containing advanced parametrizations to predict both concentration and mixing ratio of cloud droplets and raindrops (see Part I) is implemented in a three-dimensional non-hydrostatic model. This paper presents results obtained with the complete scheme for two specific experiments of idealized precipitating clouds. In the first case, an orographic cloud is produced at the windward edge of a plateau. The study focuses on the sensitivity of the microphysical fields and precipitation patterns to the upwind cloud condensation nuclei (CCN) activation spectrum. In the second case, a heavily precipitating tropical rainband of the Hawaiian Rainband Project is simulated in a kinematic framework. Analysis of simulated radar-reflectivity time evolution indicates that a realistic development of large raindrops can be obtained as compared to either observations or to results produced by a bin-resolving model. The overall control of raindrop tail distribution by collisional break-up is re-emphasised in the light of earlier results.

The rather simple tests lead to the conclusion that a complete bulk microphysical scheme can simulate warm rain processes with reasonable accuracy. The ability of the model to account for realistic CCN activation spectra with modest programming effort makes the scheme suitable for three-dimensional precipitation simulations that properly take into consideration aerosol dynamics at mesoscale.

KEYWORDS: Cloud physics HaRP experiment Modelling Orographic clouds Two-moment scheme

1. INTRODUCTION

Various microphysical schemes have been developed and are continuously improved for use in mesoscale models because of the importance of resolving explicitly and accurately both warm and cold cloud-scale processes for many purposes: diabatic heating/cooling rates, ground precipitation, radiative transfer, aqueous chemistry, atmospheric electricity, radar and satellite data interpretation, etc. Here our interest is restricted to the representation of warm microphysical processes because these have been studied extensively in the past and so they can now be accurately modelled with minimal uncertainties in setting most coefficients. Unfortunately, this is not true for most of the microphysical interactions involving ice particles because there are still unresolved questions concerning, for example, crystal habits, collection efficiencies and temperature dependences, that render their parametrization difficult despite some recent indisputable progress (Ferrier 1994; Walko et al. 1995; Meyers et al. 1997).

Part I (Cohard and Pinty 2000, hereafter CP00) presented arguments promoting the two-moment approach for warm microphysical schemes. Besides the intuitive fact that modelling both concentration and mixing ratio of the cloud droplets and raindrops is known to improve the handling of liquid water in mesoscale simulations, CP00 showed that transfer rates could be calculated analytically for most processes by using gamma-like functions for drop size distributions. Furthermore as microphysics is known to be highly nonlinear, CP00 made a series of tests in order to verify the behaviour of the two-moment scheme against a bin-resolving model which acts as a reference model. This demanding comparison exercise, undertaken for some individual processes (coalescence and sedimentation), leads to acceptable results for the involved parametrizations of the two-moment scheme.

The purpose of this paper is to illustrate the capabilities of the full scheme to capture the evolution of precipitating clouds with conditions imposed on aerosol characteristics

* Corresponding author: Laboratoire d’Aérologie, UMR CNRS/UPS 5560, Observatoire Midi-Pyrénées, 14 avenue E. Belin, Toulouse, F-31400, France. e-mail: pmjp@aero.obs-mip.fr
and flow dynamics. Two kinds of numerical experiments have been performed with controlled airflow in a non-hydrostatic host model. In the first case, some microphysical aspects of an orographic cloud which results from an upwind homogeneous flow impinging upon a plateau in a moist two-layer atmosphere (Durran and Klemp 1983; Richard and Chaumerliac 1989), are analysed in detail. In the second type of experiment, the scenario proposed by Szumowski et al. (1998b) for the 4th ICML* has been followed to simulate the short lifetime of intense reflectivity cores in a tropical rainband. Additional sensitivity experiments are also presented for this case. Finally a preliminary conclusion is drawn about the accuracy of the explicit modelling of cloud evolution with the present two-moment scheme. Potential improvements to the scheme that follow from the results of two-dimensional (2D) experiments shown here are discussed.

2. Salient features of the microphysical scheme

The scheme relies on the assumption that the condensed water is bimodal and can be shared out between cloud droplets (with drop diameter $D < 80 \, \mu m$) and raindrops (for which $D > 80 \, \mu m$). In fact each drop category is described by a continuous size distribution, valid for $0 < D < \infty$, that obeys a generalized gamma law:

$$n_i(D) = N_i \frac{\alpha_i}{\Gamma(\nu_i)} \lambda_i^{\nu_i} D^{\alpha_i - 1} \exp(-\lambda_i D)^{\nu_i}. \quad (1)$$

Index $i \in \{c, r\}$ in Eq. (1) stands for cloud or raindrops, respectively, $N_i$ is the total number concentration of the drop category $i$, $\lambda_i$ is the corresponding slope parameter, while $\nu_i$ and $\alpha_i$ are two dispersion parameters, $n_i$ is the drop-size distribution, and $\Gamma$ is the complete gamma function. As usual in two-moment schemes, it is the zeroth- and third-order moments of Eq. (1), i.e. the number concentrations and the mixing ratios ($N_i$ and $r_i = (1/\rho_a) \int_0^\infty (\pi/6) \rho_a \, D^3 n_i(D) \, dD$, where $\rho_a$ and $\rho_w$ are the air and water densities, respectively), which are prognostic variables. The slope parameter $\lambda_i$ is computed from $N_i$ and $r_i$ (Eq. (2) of CP00), so $\nu_i$ and $\alpha_i$ are two degrees of freedom to set for the two drop spectra.

Figure 1 summarizes the warm microphysical processes that are analysed in CP00 and parametrised accordingly. The heterogeneous nucleation process (HEN) feeds the cloud-droplet spectrum from a cloud condensation nuclei (CCN) reservoir of finite number concentration after update of the early activated fraction, $N_a$. Computing the reversible condensation/evaporation rate (CND/EVA) results from a non-iterative implicit adjustment to strict water saturation. The suggestion of Kogan and Martin (1994) to correct the estimated bulk condensational growth by a parametric function of $N_a$, $r_c$, and initial supersaturation has not been considered for the moment. The coalescence terms are split into several parts: autoconversion (AUT), accretion (ACC) and self-collections (SCOC, SCOR) which occur on both droplet and raindrop spectra. The latter process includes effects of raindrop collisional break-up in a crude way. The sedimentation terms (SEDC, SEDR) retain the size-sorting effect on the raindrop spectra as shown in CP00. Finally, the raindrop evaporation (EVA) is integrated from the diffusional-growth equation by taking into account a ventilation effect due to the raindrop fall.

The present two-moment scheme incorporates the most simple description of a water cycle that explicitly generates precipitating drops with respect to CCN spectrum specifications. In this spirit, Cohard et al. (2000) showed that variable CCN spectrum

* International Cloud Modeling Workshop held in Clermont-Ferrand in August 1996.
features can be prescribed directly from microphysical properties of multimodal aerosol populations.

The parametrizations belonging to the scheme in CP00 contain only a few of the most important coefficients that appear, for instance, in the description of autoconversion rates in Berry and Reinhart 1974 and in Long’s kernels (Long 1974). The current values suitable for these coefficients are now widely accepted (Pruppacher and Klett 1997). This is, however, less true for the break-up correcting factor (see Eq. (26) of CP00) where values given by Verlinde and Cotton (1993) for the threshold diameters, \( D_{BK_1} = 600 \mu m \) and \( D_{BK_2} = 2000 \mu m \), need to be tested. Note that it is necessary to explore the range of variation of these parameters once the whole scheme is fully assembled because the break-up process ultimately regulates the raindrop spectrum shape. This question is addressed in the Hawaiian Rainband Project (HaRP) case simulation.

3. Study of a Precipitating Orographic Cloud

Simulations have been performed with a 2D configuration of the non-hydrostatic mesoscale model Meso-NH (Lafore et al. 1998) and after implementation of the present scheme (hereafter the C2R2 scheme). As in many mesoscale models, Meso-NH has an option to run the Kessler parametrization (Kessler 1969), here for comparison purposes.

The model set-up is the following: the domain is 90 km wide and 20 km high. The horizontal resolution is 1 km while vertical resolution varies continuously between 60 m and 1000 m on over 60 levels. The orography is shaped like a mesa, starting at \( x = 30 \) km, ramping with a slope of 0.2 and with a flat top reached at \( x = 1 \) km. The model is initialized for homogeneous atmospheric conditions comprising a constant
wind $U = 20$ m s$^{-1}$ and two layers of dry static stability with $N = 0.01$ s$^{-1}$ for $0 < z < 8000$ m and with $N = 0.02$ s$^{-1}$ above, where $N$ is the Brunt–Väisälä frequency. The air temperature at the first model level is 280 K. The initial relative humidity is 90% from the ground up to $z = 3000$ m and then decreases linearly to 0% at $z = 8000$ m. A top absorbing layer is set above $z = 15$ km to assist the maintenance of a stationary single-node hydrostatic wave which shows up on the vertical velocity field (Fig. 2) after two hours of integration. Open lateral-boundary conditions (Durran and Klemp 1983) are used and a weak fourth-order diffusion scheme with an e-folding time of 50 s for the shortest resolved scale is applied to each prognostic variable. The time-step is 8 s.

A series of three experiments has been performed. In the first one, the Meso-NH code is run with the Kessler scheme while for the two other simulations the C2R2 scheme is used with different initial activation spectra. The nucleating properties of CCN are described as in Cohard et al. (1998) with an activation spectrum of the form:

$$N_{CCN} = C_s v_{c,w} F(\mu, k/2, k/2 + 1; -\beta s_{v,w}^2),$$

where $N_{CCN}$ is the number concentration of the activated CCN at supersaturation $s_{v,w}$, $F(a, b, c; x)$ is the hypergeometric function (Press et al. 1992) and $C$, $k$, $\mu$ and $\beta$ are adjustable parameters. Here the following settings are used corresponding to a maritime case: $C = 2.01 \times 10^{11}$ m$^{-3}$, $k = 3.50$, $\mu = 3.76$ and $\beta = 44.1$. The continental case is simply obtained by increasing $C$ up to $8.04 \times 10^{11}$ m$^{-3}$ to potentially augment the cloud-droplet number concentration $N_c$. Finally, the C2R2 simulations have been performed by taking $\nu_c = 1$, $\alpha_c = 3$, $\nu_r = 2$ and $\alpha_t = 1$.

The microphysical fields that result from the three simulations, are reproduced in Figs. 3 and 4. Comparison between the Kessler and the maritime C2R2 simulations reveals only small differences in the spatial distribution and amplitude of mixing ratios.
The precipitating cloud originates above the slope of the mesa with a plume extending well over the plateau. Precipitation is concentrated at the beginning of the plateau. In contrast, more differences are found between the C2R2 runs depending on the maritime or continental nature of the activation spectrum, as expected. In the maritime case $N_c \sim 110 \times 10^6 \text{ m}^{-3}$, while it is four times larger in the continental run. In this latter case, the smaller cloud droplets produce raindrops less efficiently and so explain...
the dramatic change on the $r_T$ plot. The maximum raindrop number concentration, $N_{r_{max}}$, is $\sim 18 \times 10^3 \text{ m}^{-3}$ for the maritime cloud but reduced by a factor of 100 ($N_{r_{max}} \sim 0.11 \times 10^3 \text{ m}^{-3}$) in the continental case. Such a dramatic change is due to a lack of autoconversion efficiency for droplets of continental origin.

These results lead to a contrasted precipitation efficiency of the clouds as shown in Fig. 5 where the precipitation rate of the continental cloud simulated by the C2R2 scheme is clearly less than in the two other cases.

More insight into the functioning of the C2R2 scheme for the maritime cloud simulation can be obtained by looking at conversion rates (see Eqs. (4a)–(4d) and Table 1 in Part I for the nomenclature which is not repeated here). The condensation rate, RVCONC, plotted in Fig. 6, is strongly correlated to the vertical velocity (Fig. 2); but the atmosphere being drier above $z = 3000$ m causes a reduced vertical extent of the cloud above the mesa slope. Over the plateau, the partial evaporation of cloud droplets (negative values for RVCONC) in the mesoscale downdraught is balanced by a horizontal transport of $r_c$ from the growing region to the plume (see Fig. 4). The $r_t$ and $N_t$ microphysical budget terms are displayed in the left and right columns of Fig. 7, respectively. The raindrop evaporation term, RREAV, has been omitted because of its lesser importance in this case. Combining the RVCONC plot of Fig. 6 to the $r_T$ tendency terms in Fig. 7 shows that the microphysical processes do not reach their full amplitude at the same location in the cloud due to horizontal advection. As drops are formed and transported in the flow, they successively experience autoconversion (RCAUTR) to produce the first raindrops which further grow by accretion (RCACCR) until they fall to the ground by gravitational settling (RSEDR) well downwind from the area where
they have been created. This effect is less visible when looking at the \(N_r\) tendency plots of Fig. 7. However, it is interesting to analyse simultaneously the \(r_t\) and \(N_r\) tendencies corresponding to the same process such as autoconversion and sedimentation because of their different patterns in Fig. 7. The cloud-droplet autoconversion is parametrized by means of two growth regimes in the present scheme (CP00). In the leftmost part of the cloud, an autoconversion `initiation' stage can be activated if cloud droplets are large enough \((D_c > 19 \mu m)\) to allow for positive values of \(L\) and \(\tau\) in Eqs. (15) of CP00). As CCAUTR is proportional to RCAUTR in such a case, the formation of a copious number of raindrops leads to a relatively large increase of \(N_r\) as compared to the impact on the \(r_t\) field. Then following the flow across the edge of the plateau, the cloud droplets will experience the `feeding' stage for which the CCAUTR rate is reduced (see Eq. (19) in CP00). These two different regimes of drop growth by autoconversion fully explain the dissimilar aspect of the RCAUTR and CCAUTR plots. For the sedimentation case, one observes in Fig. 7 a downwind location of the RSEDR maximum rate as compared to that of CSEDR. This is clearly not due to a size-sorting effect because the plots do not suggest that it is the largest drops that precipitate first. In fact the RSEDR and CSEDR patterns are the result of a mean-size increase of the raindrops along-wind as
will be shown later. A final point worth mentioning in Fig. 7 is the importance of the self-collection term CRSCOR, a process by which raindrop spectra are shifted towards larger diameters and whose amplitude is comparable to that of the CCAUTR and CSEDR terms.

To summarize the two-moment scheme contribution to the simulation of precipitating orographic clouds, it is instructive to look at the mean-volume drop diameters, $D_c$ and $D_r$, reproduced in Fig. 8. These quantities with definition given in CP00, appear to be helpful in analysing the drop-size evolution because they outline the continuous growth of the cloud droplets and of the raindrops. The mean droplet size shows a sharp horizontal gradient near the ground along the slope of the mesa where the condensation growth is the largest. Over the plateau, the vertical stratification of $D_c$ is an indication of a standing horizontal advection of the cloud. Slightly different behaviour can be observed in Fig. 8 for the mean-volume raindrop size, $D_r$. The fact that more processes, including those acting specifically on the number concentration, influence the raindrop growth is indicative of a more steady growth of the raindrops at the leading edge of the mesa. The slow decrease of the $D_r$ isocontours downwind is, however, attributable to significant size sorting by drop sedimentation.

4. Simulation of the Highly Precipitating Rainband in the HARP Campaign

The tropical environment and the convergence associated with the flow deformation offshore of the Island of Hawaii are the essential ingredients for the formation of shallow, but very vigorous rainbands on short time-scales (Smolarkiewicz et al. 1988). Here we choose to simulate the selected HaRP rainband case studied by Szumowski et al. (1997 and 1998a). This case has been idealized in the 2D kinematic framework proposed by Szumowski et al. (1998b). The flow is in anelastic balance for a $z$-varying reference state of air density. Only advection and microphysical tendencies are considered in the following numerical experiments. The recommended MPDATA advection scheme of Smolarkiewicz (1984) has been implemented in MesoNH (Lafore et al. 1998) to run simultaneously with the Kessler and C2R2 schemes.

The simulation conditions are described extensively in Szumowski et al. (1998b) and so will not be repeated here. Open boundary conditions are still used. Explicit numerical diffusion is turned off for MPDATA. A time step of $2 \text{s}$ is chosen for a mesh size of $50 \text{m}$ in the $x$ and $z$ directions. The model is integrated for $3000 \text{s}$ corresponding to the mean life cycle of HaRP precipitating cells which is produced by a narrow (1 km) wave with a slightly tilting updraught peaking at $8 \text{ m s}^{-1}$ after $1500 \text{ s}$. 
Figure 9. Activation spectra use for the HaRP experiment with the C2R2 scheme with data (crosses), fit of Eq. (2) (solid line) and simple $N_{CCN} = C s^k$ law (dashed line) (see text).

(a) Reference simulation

The reference simulation is made with the C2R2 scheme using the activation spectrum suggested by Szumowski et al. (1998b). Because the given $N_{CCN}$ function is defined by parts, the activation spectrum defined by Eq. (2) has been fitted to use the nucleation parametrization of Cohard et al. (1998). The result of the crude adjustment shown in Fig. 9 is in acceptable agreement with the discretized original spectrum. The four coefficients shaping Eq. (2) are those corresponding to the maritime case of the preceding orographic precipitations experiment.

The evolution of the highly reflective cell of the HaRP campaign, as simulated by the Kessler and C2R2 schemes, is shown in Fig. 10 at selected times. Computation of the radar reflectivity $Z$ is straightforward from the sixth-order moment of the raindrop size distribution. After 1200 s a significant radar echo is obtained but with different patterns for the Kessler and C2R2 runs. The reflectivity intensifies dramatically at 1500 s with heavy precipitation at sea level for the run based upon the C2R2 scheme. Conversely, the simulation with the Kessler scheme produces only a very sharp precipitating band because the raindrops are smaller in this case and so are concentrated aloft (at $z \sim 1800$ m). After 1800 s, the cell begins to decay with the C2R2 scheme while it achieves a maximum development according to the Kessler scheme. High $Z$ is found with both schemes at the end of the simulation.

It is interesting to analyse these two simulations by looking at the maximum values reached by some microphysical fields during the course of the model integration. This is done in Fig. 11 for $Z$, $r_T$ and $RR$ (accumulated precipitation). Also illustrated in Fig. 11 is the imposed vertical velocity $w$ with marks for the time location of the plots in Fig. 10. The $Z$ maximum ($Z_{max} = 66.1$ dBZ) is achieved simultaneously with the $w$ maximum for the C2R2 scheme. This value is, however, about 4–5 dBZ larger than observations and numerical results obtained with a detailed bin model (Reisin et al. 1998). The corresponding maximum is reached later with the Kessler scheme but for a better value of $Z_{max}$ (60 dBZ). A more striking feature to examine now is the time evolution of the $r_T$ maximum. This quantity ends as an unrealistic value of 9.76 g kg$^{-1}$ for the Kessler scheme while it reaches 2.5 g kg$^{-1}$ with the C2R2 scheme. This fact illustrates
Figure 10. Simulated radar reflectivity (dBZ) for the HaRP experiment at (a)-(b) 1200 s, (c)-(d) 1500 s, (e)-(f) 1800 s and (g)-(h) 3000 s with the Kessler scheme (left column) and with the C2R2 scheme (right column).

convincingly the superiority of a two-moment approach, because such a scheme with a prognostic equation of the raindrop number concentration is able to produce large drops (high $Z$) in a reasonable concentration (moderate $r_T$).

The preliminary conclusion that can be drawn from the run with the C2R2 scheme is that an excess of reflectivity is probably due to a bad estimate of $N_r$ in the highly precipitating core because maximum values of $r_T$ remain in a very acceptable range. Note that the proper simulation of this HaRP event constitutes a stringent test for any microphysical model. For instance, the maximum $Z$ value of 61.4 dBZ obtained by
Reisin et al. (1998), is likely an underestimate because there is a clear spectrum cut-off of the drops due to the finite number of bins (2 × 34) in their simulation (see Fig. 6 of their paper). We note in passing that the growth of large raindrops in models of increasing bin size raises serious questions about the accuracy of radar reflectivity estimates due to the sixth-order moment dependence of $Z$. The next section will present sensitivity experiments related to the effect of collisional break-up, aiming at improving the present results through a better control of the large raindrop concentration.

(b) Effect of the CCN spectrum shape

A short sensitivity experiment has been performed by replacing Eq. (2) with a more traditional activation spectrum: $N_{CCN} = 120 s_{v,w}^{0.4}$ (units are in cm$^{-3}$). This relation is adapted to the HaRP experiment for the $0.1 < s_{v,w} < 0.63$ range of supersaturation according to Szumowski et al. (1998b). The power-law dependence of the new $N_{CCN}$ is reproduced in Fig. 9. The main difference between the two $N_{CCN}$ curves is the absence of saturation effect on the last simplified formula.

Simulation results are plotted in Fig. 12 along with the reference simulation. The time evolution of $Z_{max}$ is similar in both cases but a short time-lag of about 120 s is observed. Changes are more dramatic on the $r_r$ maximum with a clear underestimation ($r_r < 0.94$ g kg$^{-1}$) in the new simulation. This effect is confirmed by plots of precipitation rate $PR$ and accumulated precipitations $RR$ below. The main reason for this discrepancy between the two simulations is the number concentration of cloud droplets which is four times larger ($\sim 400 \times 10^6$ m$^{-3}$) using the modified $N_{CCN}$ formula. Consequently, the raindrop formation is delayed and is less efficient. So, because fewer raindrops exist, their growth by accretion is enhanced to the stage of giant drops as detected by the fairly high level of $Z_{max}$. 
This simple experiment, whose purpose is to examine the consequence of varying the CCN nucleation properties, confirms the acute sensitivity of the present scheme on this point. Without proper handling of CCN activation spectra such as that proposed by Cohard et al. (1998), it seems quite impossible to get accurate results with bulk microphysical schemes.

(c) **Effect of varying the raindrop break-up parameters**

Once formed by autoconversion, raindrops continue to grow by accretion at the expense of cloud droplets. The only way to limit the growth of the largest drops is the rapid sedimentation of the biggest ones and the efficiency of collisional break-up—an alternative process to raindrop self-collection. The numerical framework of the HaRP experiment with heavy precipitation, offers a good opportunity to test the break-up parametrization employed in the C2R2 scheme and more specifically, the sensitivity of the $D_{BK1}$ and $D_{BK2}$ diameters (see section 2) to $Z_{\text{max}}$.

A new simulation with the C2R2 scheme has been performed but starting with the following settings: $D_{BK1} = 2400 \, \mu m$ and $D_{BK2} = 3000 \, \mu m$. This significant increase of $D_{BK1}$ and $D_{BK2}$ tries to investigate the impact of the collisional break-up parametrization by attenuating its effects in the reference scheme. The results are shown in Fig. 13. The near removal of break-up limitation reinforces unrealistically the production of very large drops by self-collection throughout the simulation. The persistent high values of $Z_{\text{max}}$ and the time-narrowing of the precipitating event on the $PR$ plot, are indicative of an excess of giant drops. It is instructive also to notice the rain mixing-ratio sensitivity in Fig. 13 because the $r_\tau$ maximum is distinctly reduced whereas $Z_{\text{max}}$ is increased. In fact, as $Z \propto r_\tau^2/N_\tau$, the decrease of $N_\tau$ is so high that it compensates for the decrease of $r_\tau$, thus proving that care must be exercised in the interpretation of intense radar reflectivities.
Figure 13. As in Fig. 12, but dashed lines refer to the simulation with modified break-up characteristics.

Having shown that collisional break-up must be accounted for in two-moment schemes, a complementary experiment as been designed to investigate whether an earlier break-up on the raindrop spectrum could improve the simulation of the HaRP case. This has been performed with $D_{BK1} = 150 \ \mu m$ while $D_{BK2}$ is kept to its original value (2000 $\mu m$). The results are not presented here since they do not differ very much from those of the reference simulation. This lack of sensitivity is explained by the fact that, for cases where break-up must occur, $D_r$ values are well beyond 600 $\mu m$, so break-up effects that cancel raindrop self-collection are already maximized. The original tuning for the $D_{BK1}$ and $D_{BK2}$ diameters appears to be acceptable.

(d) Inclusion of a mean-volume drop-size limiter

The above results show that although the present treatment of collisional break-up is felt useful to simulate the HaRP case, it fails to remove some giant drops that presumably contribute to an excess of radar reflectivity in the preceding simulations. This deficiency in the C2R2 scheme can be alleviated by application of a drop-size limiter with cut-offs based upon the mean-volume diameter $D_r$ of the raindrop size distributions.

Several arguments can justify the need for such a limiter which can be seen as a crude bulk parametrization of the spontaneous break-up. For instance, the $r_r$ and $N_r$ prognostic equations are coupled in a very complex nonlinear manner. However, $r_r$ and $N_r$ are not fully independent variables because their ratio, $r_r/N_r \propto D_r^3$, must remain in an acceptable range of variation. Violation of this assumption can occur in cases where residual drops, brought for instance by $r_r - N_r$ differential sedimentation, can be interpreted erroneously as very large hydrometeors. Furthermore, it is important to recall that one issue of raindrop break-up is to counteract raindrop self-collection, or in other words to reduce the sink of $N_r$. In case of external forcing, such as the intense
raindrop growth by accretion in the HaRP case, the slowing down of the evolution of $N_r$ due to drop break-up effects has no means of hindering any exaggerated increase of $D_r$.

The mean-drop-size limiter acts on the $N_r^*$ field obtained after integrating all the microphysical processes that lead to a first estimate of $N_r$. The limiter is applied with the following rules: if $D_r < 3000$ $\mu$m, $N_r$ is unchanged (or $N_r = N_r^*$) and whenever $D_r > 5000$ $\mu$m, $N_r$ becomes $N_r = N_r^* (D_r/4000)^3$. The transition, $3000 < D_r < 5000$ $\mu$m is covered by taking $N_r$ with a parabolic dependence on $D_r$. It is worth mentioning that the range of application of the limiter ($D_r > 3000$ $\mu$m) is well beyond the region where collisional break-up is active ($D_r > 600$ $\mu$m) and that cases where $D_r > 5000$ $\mu$m are no longer possible.

The benefit of the limiter is clearly illustrated in Fig. 14 which shows the $Z_{max}$ field with (without) the limiter after 1500 and 1800 s. Obviously the limiter tends to shrink the high-reflectivity core characterized by $Z > 60$ dBZ. Note that after 1500 s, the core does not reach sea level, in agreement with the reflectivity pattern obtained by Reisin et al. (1998). After 1800 s, the effects produced by the limiter on the $Z$ field are less pronounced, probably because of the absence of very large drops. Figure 15 summarizes the improvement made by the limiter in the reference simulation. The most successful impact of the limiter is that $Z_{max}$ is lowered to 62.6 dBZ and the period of time where $Z_{max} > 55$ dBZ (~ 900 s) is recovered. This result is very encouraging if one refers to Fig. 4 of Szumowski et al. (1998b). However, $Z_{max}$ is still much too high at the end of the simulation compared with Reisin et al. (1998). In fact the decay of $Z_{max}$ at the end of the precipitating event is partially controlled by the imposed $w$. For instance, lowering $w$ progressively past 1500 s (see in Fig. 11(a) again) in order to get $w = 1$ m s$^{-1}$ at the end of the simulation (as against 2 m s$^{-1}$ in the reference case), causes a significant decrease of $Z_{max}$ (44 dBZ as compared to ~ 50 dBZ in Fig. 15) after 3000 s.
Figure 15. As in Fig. 12, but dashed lines refer to the simulation with inclusion of the limiter.

Inclusion of the limiter in the C2R2 scheme also has a noticeable effect on the $r_T$ maximum which is increased to 3 g kg$^{-1}$. This shows that the two-moment warm scheme is fairly sensitive to the number of large drops at the trailing edge of the raindrop spectrum because, once eliminated, more rainwater can be sustained in the updraught core for further growth. The last feature to comment on in Fig. 15 is the significant increase of rainfall rate despite a reduction of $Z$ due to a better control of $N_T$.

5. CONCLUSION

The two-moment warm microphysical scheme described in Part I has been implemented in a non-hydrostatic mesoscale model. Two test cases have been simulated to study a sequential regime of drop growth (orographic precipitation case) and the ability of the scheme to generate very large drops (HaRP case). For this second type of numerical experiment, the accuracy of the model results is evaluated by comparison with data and with detailed numerical simulations. Tests conducted with the two-moment scheme show that this scheme is reliable and attractive because it reacts properly to the many features of known warm cloud processes.

The strength of the present microphysical scheme is its ability to simulate warm processes at a modest cost (C2R2 code has a 40% extra computing burden than Kessler code) in a non-hydrostatic mesoscale model. This makes the scheme suitable for realistic 3D numerical experiments like Large Eddy Simulation of precipitating stratus or detailed studies of warm precipitating systems at the mesoscale. Part of the success of the scheme relies on its capacity to cope with realistic activation spectra and their impact on the formation and evolution of raindrop spectra. Moreover simulations of the HaRP case suggest that proper handling of giant drops in tropical rainbands is possible in the scheme but better accuracy is achieved by including a permanent mean-volume-drop limiter in the present scheme.
There are still some aspects of the present scheme version that can be improved, particularly to unravel the collisional break-up effects and to revise its parametrization as there exist possibilities of integrating analytically break-up efficiencies directly in Long’s kernels (see CP00). Also, the autoconversion contribution to the raindrop number concentration needs to be explored in more detail as well as the importance of accurate sedimentation schemes. These elements of the present scheme that can be potentially improved need, however, specific benchmarks patterned after the HaRP experiment, so it is expected that true evaluation of bulk microphysical models can be made through intercomparison programs involving detailed bin models.

Besides the preceding remarks, the C2R2 scheme is intended to be used in real-case experiments of precipitating systems over orography. The sensitivity to the upstream activation spectra, with perhaps some new interesting aspects of cloud microphysics resulting from vertically stratified properties of the CCN as found in the real world, could be explored at this time.

ACKNOWLEDGEMENTS

We would like to thank W. W. Grabowski for producing all the necessary data to run the HaRP case and E. Richard for discussions about the orographic precipitations. We gratefully acknowledge our colleague R. Laprise (on sabbatical leave from Université du Québec A Montréal, Canada) for his careful review of an earlier draft. Computational resources were provided by Institut du Développement et des Ressources en Informatique Scientifique (Palaiseau, France), and J. Duron (Laboratoire d’Aérologie, Toulouse, France) is acknowledged for assistance with the graphics. We also thank our colleagues at Laboratoire d’Aérologie and Météo-France (Toulouse, France) for their programming efforts during the development phase of Méso-NH, which greatly facilitated this study.

REFERENCES


Pruppacher, H. R. and Klett, J. D.

Reisin, T. G., Yin, Y., Levin, Z. and Tzivion, S.

Richard, E. and Chaumerliac, N.

Smolarkiewicz, P. K.

Smolarkiewicz, P. K., Rasmussen, R. M. and Clark, T. L.

Szumowski, M. J., Rauber, R. M., Ochs, H. T. and Miller, L. J.

Szumowski, M. J., Rauber, R. M., Ochs, H. T. and Beard, K. V.

Szumowski, M. J., Grabowski, W. W. and Ochs, H. T.

Verlinde, J. and Cotton, W. R.

Walko, R. L., Cotton, W. R., Meyers, M. P. and Harrington, J. Y.


1993 Fitting microphysical observations of non-steady convective clouds to a numerical model: An application of the adjoint technique of data assimilation to a kinematic model. Mon. Weather Rev., 121, 2776–2793