1.10 THREE-DIMENSIONAL MODELING OF NORTH DAKOTA CLOUDS USING A NEW MICROPHYSICAL SCHEME WITH EXPLICIT TREATMENT OF ATMOSPHERIC AEROSOLS AND HYGROSCOPIC SEEDING EFFECTS

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1. INTRODUCTION

The North Dakota Cloud Modification Project (NDCMP) has conducted warm season cloud seeding operations for hail suppression and rain enhancement on an annual basis for over a quarter of a century. Although the North Dakota seeding operations have traditionally applied glaciogenic seeding materials, staff of the North Dakota Atmospheric Research Board (NDARB, the agency responsible for the conduct of NDCMP) have expressed a keen interest in seeding with hygroscopic flares for both rain enhancement and hail suppression applications. This renewed interest in use of hygroscopic seeding has been spurred by recent successes in South Africa (Mather *et al*., 1997; Cooper *et al*., 1997; Terblanche *et al*., 2000) and Mexico (WMO, 2000; Bruintjes, 1999). These studies have shown that seeding with hygroscopic flares can produce substantial increases in precipitation. The details of the physical mechanisms leading to these increases are poorly understood, especially the longer-term effects typically noted (Bigg, 1997; WMO, 2000). In addition to these successful rain enhancement applications, field work in France has indicated treatment with hygroscopic flares can also suppress hail (Berthoumieu *et al*., 1999).

The purpose of our current research is to apply and evaluate a new microphysical scheme designed for numerical simulations of seeding with hygroscopic flares. This new scheme has been designed to provide for realistic treatment of hydrometeor development as a natural consequence of the nucleation characteristics of the background and seeding aerosol populations. The objective is to provide a framework to study, and hopefully increase understanding of, the physical processes involved in the microphysical and dynamical response of northern Great Plains convective storms to hygroscopic (and glaciogenic) seeding.

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2. DESCRIPTION OF THE NEW PARAMETERIZATION SCHEME

The basic requirement of the new microphysical scheme applied in this study is that it be of sufficient breadth and detail to allow model simulations which reproduce the basic character and evolution of naturally-occurring clouds and cloud systems while treating the nucleation of aerosols in enough detail that the warm rain process and hygroscopic seeding can be realistically simulated. This new scheme is embedded in the three-dimensional cloud model developed by Clark and associates (Clark, 1977; Clark, 1979; Clark and Farley, 1984; Clark and Hall, 1991). The Clark model has recently undergone an extensive recoding effort to allow for efficient calculation on multiple processor environments using the Message Passing Interface (MPI) paradigm.

The new scheme includes the following features:

1.) Nucleation of both natural and artificial aerosols is treated directly, with explicit prediction of supersaturation.
2.) The warm rain process is treated in sufficient detail that development of drizzle and rain is a function of the cloud droplet distributions produced by activated aerosols.
3.) Six hydrometeor classes are used; cloud water and rain define the liquid water spectra, while the ice particle spectra is divided into four classes - ice crystals, snow, graupel, and hail.
4.) Two moments of the size distribution, number concentration and mixing ratio, are predicted for each hydrometeor class, with the particle size distributions generalized as gamma distributions (of which exponential distributions are a special case).

Each hydrometeor class interacts with water vapor and the other hydrometeor classes through a series of idealized representations or parameterizations of the various physical processes which comprise the scheme. These include the physical processes of nucleation of cloud condensation nuclei, condensation/evaporation, collision/coalescence including drop breakup, both homogeneous and heterogeneous nucleation of ice crystals, deposition/sublimation, collision/aggregation, accretion, freezing, melting and shedding, and ice multiplication via the rime splintering mechanism.

The treatment of nucleation of CCN is based on Cohard *et al*. (1998). Warm rain processes are based on the treatment of Cohard and Pinty (2000), who have extended the work of Ziegler (1985) which in turn was based on Berry and Reinhardt (1974) and Long (1974). This improved representation of nucleation and warm rain processes is vitally important for physically-based simulations of seeding with hygroscopic flares.

The treatment of ice is also improved in the new scheme using a formulation similar to the double-moment four-class ice scheme developed by Ferrier (1994). Unlike Ferrier's formulation, our scheme does not allow mixed-phase particles (ice particles with water coatings). Among the novel attributes of Ferrier's treatment which are retained in our new scheme are the modified collection kernels used to prevent overcounting during drop freezing either by probabilistic or contact freezing and a physically-based rationale for partitioning between various ice classes for three-component accretion processes and conversion during riming.

Ferrier's formulation used a series of look-up tables to evaluate some of the complicated rate expressions, such as one form of precipitation interacting with another. Our scheme avoids the use of such tables, relying instead on the use of correction factors to avoid singularities resulting from simplifying approximations commonly applied to specific terms or factors in derivations of rate expressions (Mizuno, 1990; Murakami, 1990). Ferrier (1994) also suggests that changes in number concentration due to a variety of processes be proportional to changes in mixing ratio. We have found it preferable to use physically-based rate expressions for changes in number concentration whenever possible.

3. IMPLEMENTATION CONSIDERATIONS

During the development of any new scheme there is frequently a period of time devoted to becoming familiar with eccentricities and sensitivities of the new formulation. Performing simulations of a variety of situations ranging from weak to strong convection facilitates the process, both in terms of eliminating coding or conceptual errors and in developing constraints to control anomalous behavior. Unfortunately, constraints to control anomalous behavior are seldom addressed in the literature. An example of such aspects uncovered in initial tests with the new scheme is in its treatment of the autoconversion process.

The autoconversion formulation described by Cohard and Pinty (2000) is based on the earlier work of Berry and Reinhardt (1974). Berry and Reinhardt's parameterization of the autoconversion of cloud water to form rain is based on a characteristic liquid water content acting over a characteristic time scale. These two quantities are functions of the liquid water content, and the mean diameter and standard deviation of the cloud droplet distribution. Initial applications of the new scheme revealed a tendency for autoconversion to occur in the peripheral cloud regions characterized by low water contents and/or number concentrations even though autoconversion was only allowed to occur if the mean diameter and standard deviation were within acceptable ranges. Unrepresentative, but acceptable values of mean diameter and/or standard deviation in these regions are an unpleasant result of the mismatch in transport of mixing ratio and number concentration. These anomalous predictions of autoconversion occurred in spite of constraints applied to derived distribution parameters such as the slope. Subsequent testing revealed that the anomalous autoconversion could be eliminated by allowing the autoconversion process to occur only in cloud regions having a characteristic time scale less than some reasonable value, such as 1000 seconds. It is worth noting that this is the characteristic time scale of small cumulus clouds.

4. RESULTS

In the discussion which follows we compare results of simulations performed with the new scheme and with the widely used Lin *et al*. (1983) IAS scheme. The simulations are applied to the 1 July 1993 severe hailstorm case from the North Dakota Tracer Experiment. We have chosen this case because it was a focus of earlier simulations using the Lin *et al*. scheme (Krcil, 1996), and, due to its severe nature, all physical processes modeled should be active to some degree. We hope to complete additional cases, especially weaker storms from more recent field operations, in time for the conference presentation. Simulations using the new microphysical scheme are compared to results obtained using the older IAS scheme, and to observations, to evaluate the performance of the new scheme. The rationale for comparing results of the new scheme with the results obtained with the older

Lin *et al*. scheme is that this older scheme is well established and has been shown to produce reasonable results compared to observations for a wide variety of cases.

The two microphysical parameterization schemes used in this study model similar physical processes, but the treatment of the processes differ, sometimes quite markedly. This is especially true for mechanisms for generating the different ice species and conversion from one ice species to another. The new scheme has four ice classes (ice crystals, snow, graupel, and hail) whereas the Lin scheme has three - ice crystals, snow, and a combined field termed graupel/hail. The parameters characterizing the graupel/hail field can be adjusted to represent either graupel or hail depending on which best fits the conditions being simulated. For the simulations reported here, the graupel/hail field is more representative of hail. The Lin scheme is a single moment scheme predicting mixing ratio for each hydrometeor species whereas the new scheme is a two-moment scheme predicting both mixing ratio and number concentration for all hydrometeor classes. The Lin scheme uses the "Fletcher curve" to represent ice nuclei whereas the new scheme uses an expression due to Cooper (1986). The ice classes in the new scheme follow exponential size distributions (gamma distribution shape parameter is zero) whereas the liquid classes follow gamma distributions with shape parameters of 4 and 2.5 for cloud water and rain respectively. Two realizations of the new scheme are presented, with CCN activity spectra representative of maritime (case NM) and continental (case NC) aerosols. Case NM produces maximum cloud droplet concentrations of 170 cm^{-3} while the maximum cloud droplet concentration for case NC is 770 cm^{-3}. The Lin scheme (case LS) assumes a cloud droplet concentration of 600 cm^{-3}.

The general character and evolution of the dynamic and large scale features of the convection are similar in all three cases. As can be seen in Fig. 1, the maximum vertical velocities are in close agreement for the first 40 minutes of the simulations. They drift apart in the later stages such that the old and new scheme runs are out of phase after 60 minutes. This is due to pronounced differences in the partitioning of water mass among the hydrometeor species between the old and new schemes, especially for the ice classes. The Lin scheme indicates much more non-precipitating water mass transported to upper levels and more extensive anvils.

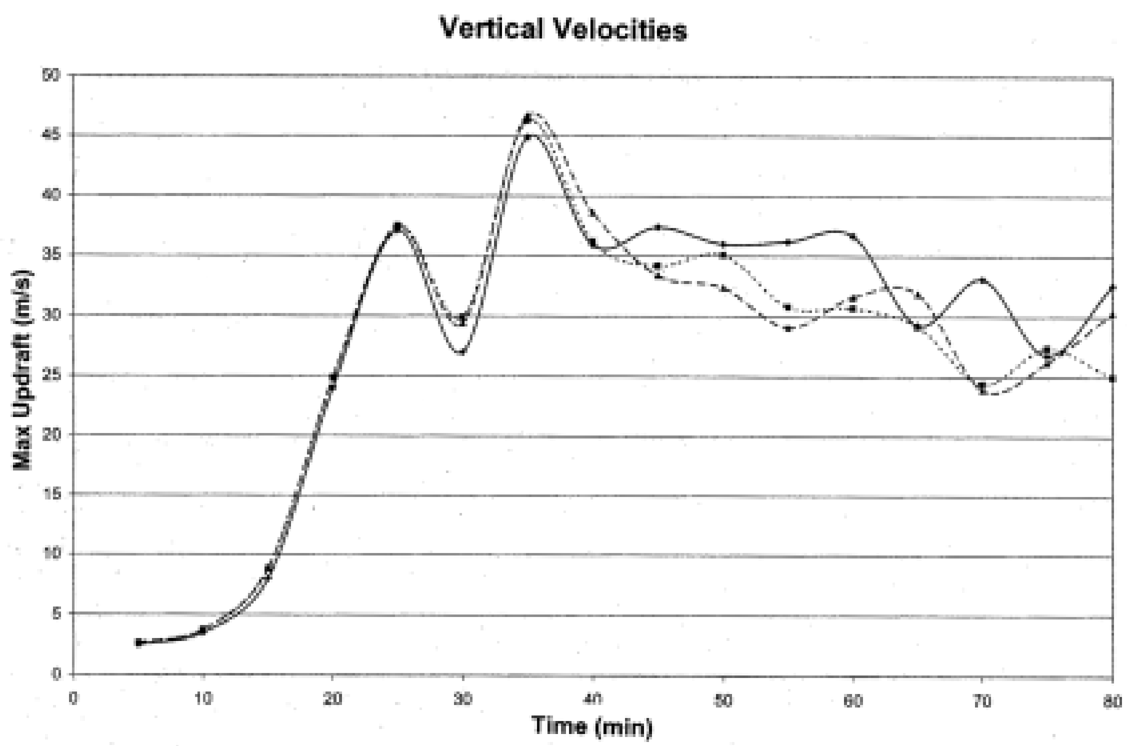

Figure 1: Time evolution of the maximum vertical velocities for the three cases. Results for case LS are given by the solid line, case NC by the short dashed line, and that for case NM by the long dashed line.

Figure 2 displays the time evolution of maximum mixing ratios for the different hydrometeor species. Throughout most of the period shown, case LS indicates intermediate values of cloud water, with case NM indicating lower values and case NC higher values in the early stages prior to 40 minutes. For rain, case NM indicates greater values throughout the period, case NC indicates intermediate values throughout most of the time period, and LS indicates much lower values for much of the time period. It is interesting that LS and NC indicate similar rain values in the earliest stages and again near the end of the simulation. Both cases using the new scheme indicate markedly lower maximum values for cloud ice and snow than LS, with case NM indicating the lowest values. For graupel, both NM and NC indicate comparable values throughout the simulated period, but much less than the combined graupel/hail field of case LS. Cases NM and NC also indicate comparable values for maximum hail mixing ratios which are much greater than for case LS for most of the simulation except the later stages.

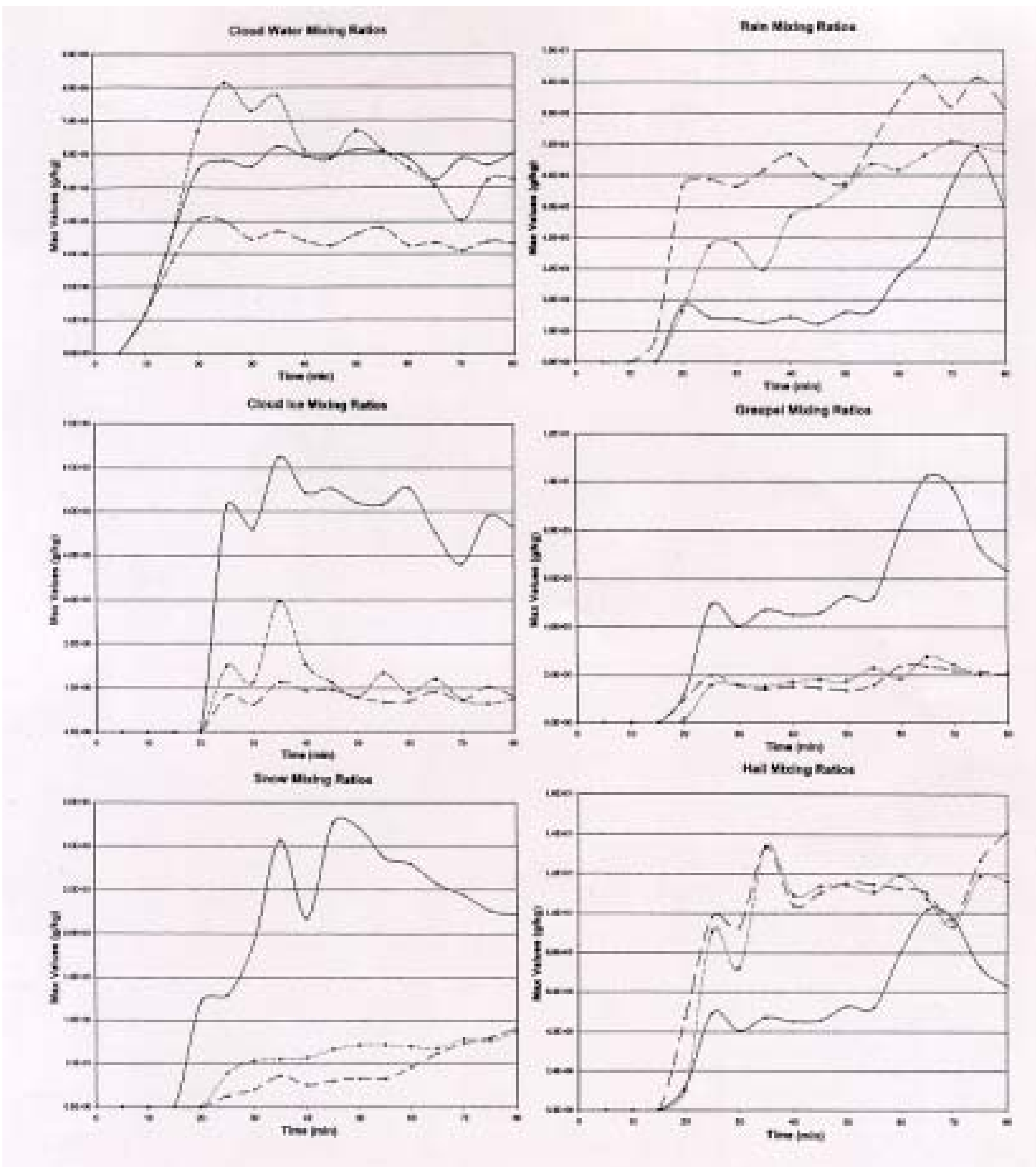

Figure 2: Time evolution of the maximum mixing ratio values for the various hydrometeor classes for the three cases. Line patterns have the same designations as in Fig. 1.

Figures 3 and 4 compare the vertical profiles of the horizontal means of the various hydrometeor classes for the three cases. The results shown are taken at 50 minutes, but are representative of the vertical distribution of water forms throughout much of the storm evolution. The maximum cloud water is near 6 km for case LS, between 4 and 6 km for case NC and near 4 km for case NM. Although the shape of the vertical profiles of cloud water are similar in the cases, the LS and NC have about 60% of the values shown for LS. Case NM indicates much lower cloud water values above 4 km than either of the other cases. The vertical distribution of the cloud ice field has the same general shape in all three cases, with maximum values between 10 and 11 km. Case LS indicates much higher values. Note the different scales for the three cases which could result in misleading impressions on casual inspection. The two cases with the new scheme indicate higher cloud ice contents below 7 km; this is a reflection of the differences in the Cooper and Fletcher IN spectra. The vertical distribution of the total cloud field (cloud water plus cloud ice) indicates most of the non-precipitating water mass is in the anvil for case LS with much lower values at upper levels for both cases with the new scheme. Careful inspection of profiles reveals that case LS indicates higher values for much of the liquid portion of the clouds as was noted earlier.

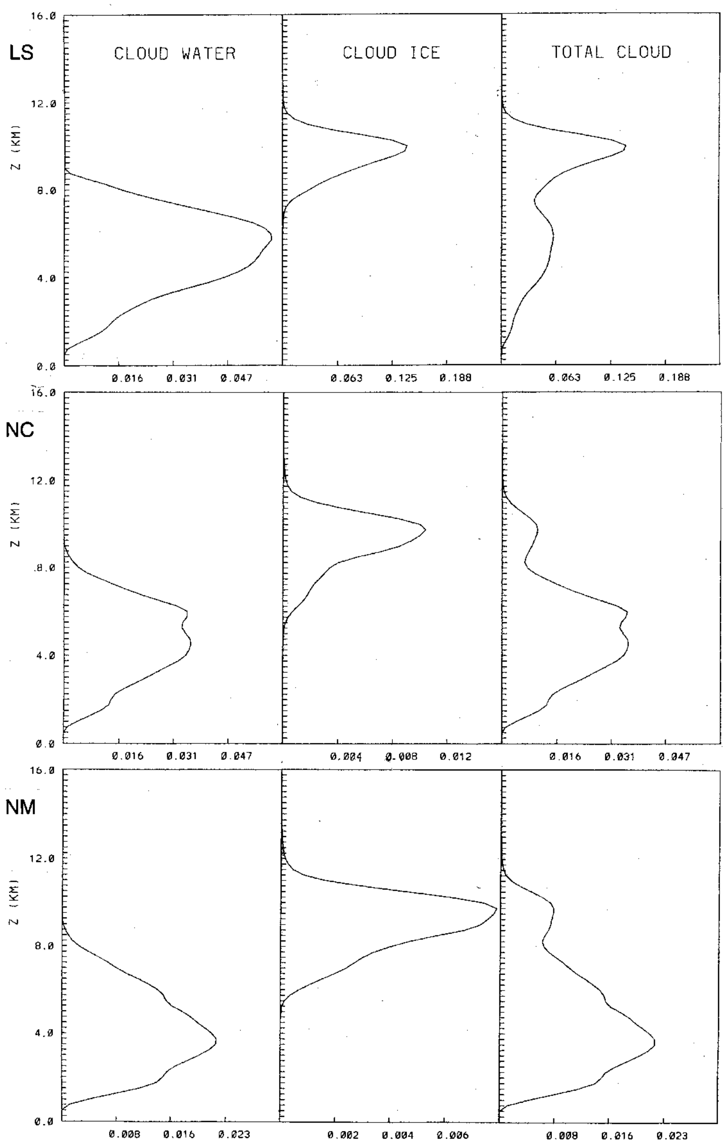

Figure 3: Vertical profiles of the horizontal mean values of mixing ratio (g/kg) for the non-precipitating hydrometeor classifications at 50 minutes. The top row of panels gives the results for case LS, the middle row gives the results for case NC, and the lower row of panels gives the results for case NM. Comparison of the results for the three cases is complicated by the fact that the horizontal scale can vary from one case to another for a given hydrometeor class.

The vertical profiles of the precipitating hydrometeor species (Fig. 4) also show pronounced differences between the Lin scheme and the two cases with the new scheme. For rain, all three cases indicate a region of significant rain between 4 and 5 km, although cases NM and NC both indicate maximum values near the surface. Case LS indicates less rain than either of the cases for the new scheme, with case NM indicating more rain than case NC as expected. Cases NM and NC both indicate the maximum snow is near 10 km, while case LS has its maximum snow near 7 km. The maximum mean snow for case LS is about six times that of case NC which in turn is about a factor of two greater than case NM. The vertical distribution of the graupel and hail fields are similar for cases NM and NC. Case LS indicates a similar height for the maximum graupel/hail contents but greater values

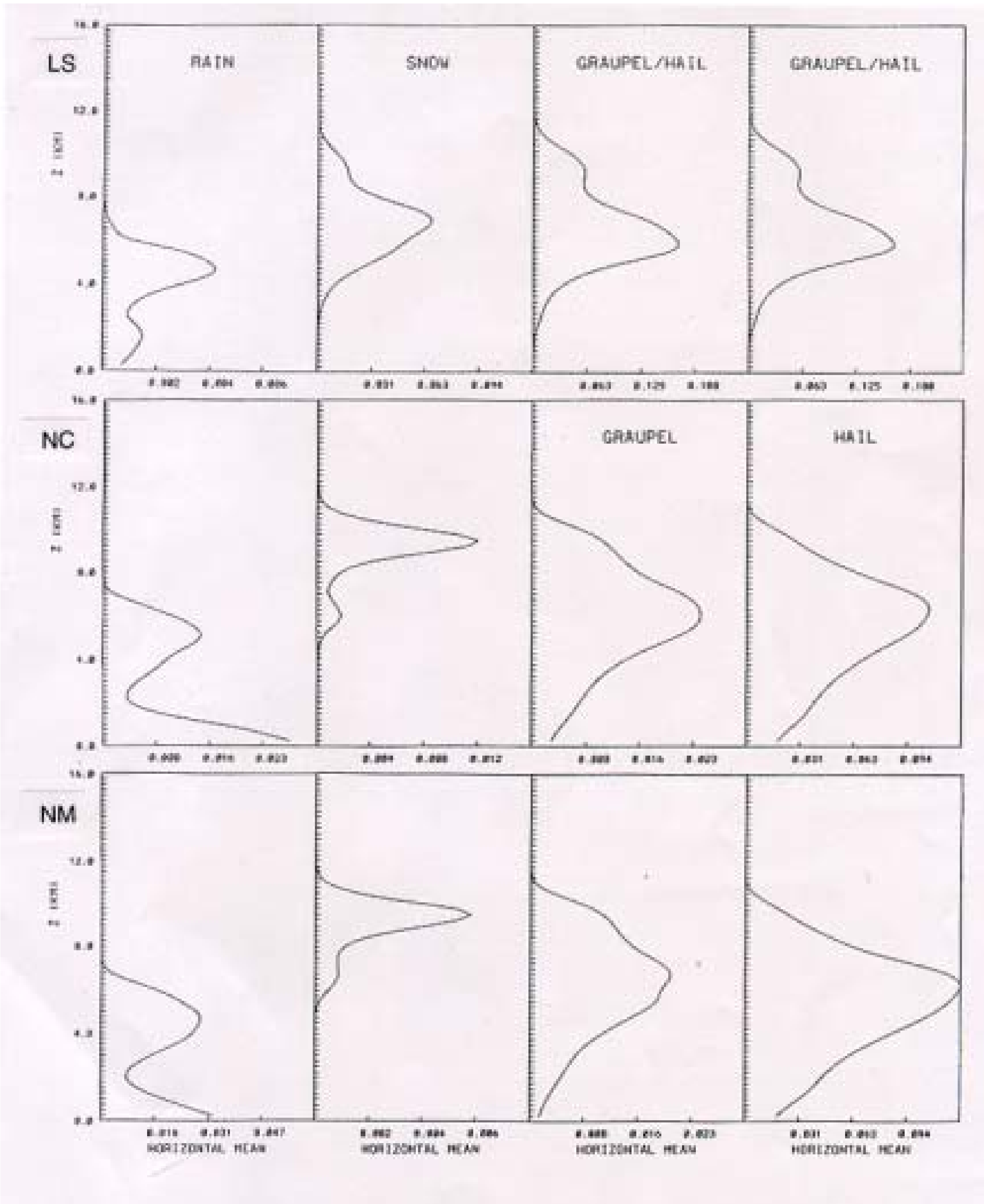

Figure 4: As in Fig. 3, but for the precipitating hydrometeor classes.

at upper levels. Graupel contents for cases NM and NC are much lower than the graupel/hail field in case LS. Although the Lin scheme indicates greater hail contents at mid and upper levels, cases NM and NC indicate more hail at lower levels.

At earlier times the cloud water and rain for case NC and case LS display similar vertical structures. In the extreme later stages of the simulations the vertical structure of the rain and hail fields are similar in all three cases. In general, both cases with the new scheme are more efficient in converting cloud water into precipitating hydrometeor forms than the Lin scheme, hence less water is transported to the anvil.

The results presented here indicate that the liquid components of the new scheme display the proper response to differences in CCN activity. Unfortunately, the ice components of the new scheme require further refinements to produce more realistic partitioning of water mass among the various ice classes. This conclusion is based on the structure and evolution of the simulated radar reflectivity fields (not shown), which compare much more favorably with observations for the Lin scheme than for either case with the new scheme.

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