THE NUMERICAL MODELING OF ICE-PHASE CLOUD SEEDING EFFECTS IN A WARM-BASE CLOUD: PRELIMINARY RESULTS

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Abstract. A numerical simulation of a warm-base cloud in the southeastern United States has resulted in a vigorous cloud development, much in agreement with observations by radar and aircraft on that day (20 July 1986). The case has been rerun with all of the ice processes turned off and vigorous growth still occurs. The natural ice processes enhance the cloud cell development and produce about 12% more precipitation. Simulated cloud seeding of the natural cloud case [testing both silver iodide (AgI) and solid carbon dioxide (CO_2)] produces about 5% less precipitation from this large convective cloud. The same sounding is used but with decreased vapor flux, to produce a smaller warm-base cloud. Simulated cloud seeding of that cloud results in 12% increases in precipitation, illustrating that the dynamics of the cloud are important for determining the seeding results.

1. INTRODUCTION

The use of cloud models to predict and to help understand the effects of cloud seeding has been practiced for many years now, starting with one-dimensional, steady-state cloud models in the early 60's (Simpson and Wiggert, 1969) to the two-dimensional (2D), time-dependent cloud models in more recent times (Hsie et al., 1980; Kopp et al., 1983; Orville et al., 1984; Farley, 1987; Kopp, 1988). The version of the IAS model used in the Hsie et al. paper referenced above did not include the simulation of a snow mixing ratio field, as described in Lin et al. (1983). The preliminary work reported here uses the updated version of the 2D cloud model applied to a warm-base cloud (+18°C) simulated and observed during the Cooperative Huntsville Meteorological Experiment (COHMEX) conducted in Huntsville, Alabama, USA, during the summer of 1986.

2. CLOUD AND MODELING SITUATION

The subject cloud formed about 1400 local time on 20 July 1986. Clouds had formed 30 to 45 min earlier and had grown to between 6 km (MSL) and 8 km producing coalescence rain in the process (Tuttle et al., 1988). At about 1400 a more vigorous growth occurred leading to a cloud topping out at about 14 km and producing copious amounts of rain and small, pea-sized hail. This precipitation led to a strong microburst.

This cloud was well-observed by multiparameter Doppler radars and simulated by the IAS 2D cloud model on the morning before the storm occurred (Tuttle et al., 1988). We have rerun this sounding two years later and on a different computer system and still obtain a realistic simulation of clouds on that day (but not exactly like the original run). We use this later sounding to produce two cloud cases -- one large and one moderate size cloud -- to study the effects of ice on the cloud growth and the effects of ice-phase cloud seeding on precipitation from warm-base clouds. Eventually we hope to run enough cases of both cold- and warm-base clouds to update our earlier cloud seeding study (Hsie et al., 1980).

3. CLOUD MODEL DESCRIPTION

The cloud model used in this study is two-dimensional, time-dependent (Orville and Kopp, 1977; Lin et al., 1983) with bulk water microphysics and 200 m grid intervals over a 20 km by 20 km domain. Cloud seeding simulations employ techniques described in Hsie et al. (1980), Kopp et al. (1983), and Orville et al. (1984). The model is anelastic and uses a vorticity (stream function) approach to obtain the velocity field. Chen and Orville (1980) provide additional information on the dynamic framework of the model.

The bulk water microphysical method is based on concepts suggested by Kessler (1969). Our model divides water and ice hydrometeors into five classes: cloud water, cloud ice, rain, snow and high density precipitating ice (graupel/hail). Rain, snow and graupel/hail, which are assumed to follow inverse exponential size distributions, possess appreciable terminal fall velocities. Cloud water and cloud ice have zero terminal velocities and thus travel with the air parcels. These five classes of hydrometeors interact with each other and water vapor through a variety of crude parameterizations of the physical processes of condensation/evaporation, collision/coalescence and collision/aggregation, accretion, freezing, melting and deposition/sublimation. The microphysical processes and parameterizations employed in the bulk water model are discussed in detail by Wisner et al. (1972), Orville and Kopp (1977), and Lin et al. (1983).

4. CLOUD MODEL RESULTS

4.1 N2 Case (Large Convective Storm)

4.1.1 Unseeded run

The natural (unseeded) cloud develops much as was described in Tuttle et al. (1988). Early growth of the model clouds is slow and cloud tops cap out at 5 to 8 km. The 0°C level is at about 5 km so very little ice forms in these small clouds. Some small amounts of graupel/hail occur because of the probabilistic freezing of raindrops (Bigg, 1953), formed earlier via coalescence. Cloud ice does not form until temperatures inside the model cloud drop below -20°C. Figure 1 shows the growth curves of various representative clouds appearing in the model domain. Early growth rates of cloud tops are 1 to 3.5 m s^{-1} while the active main cloud top rises at nearly 7 m s^{-1}. Figure 2, left column, shows the general cloud outline and precipitation fields of the unseeded cloud run at various times throughout the cloud's life cycle. A series of cloud developments on the left side of the grid lead to the main cloud formation, evident at 129 min of simulated real time.

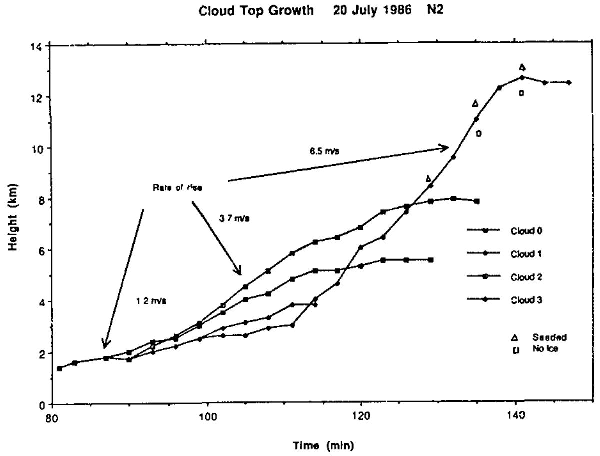

Fig. 1. Plots of various cloud top heights vs. time, which occur in the model results. The Δ and □ symbols give the cloud top height for the seeded and no-ice cases, respectively.

Coalescence growth begins in the model clouds when cloud water mixing ratios exceed 2 g kg^{-1}. This leads to efficient rain production with rain mixing ratios greater than 1 g kg^{-1} initially showing up between 2 and 3 km height in the model.

As seen in Fig. 1, the primary cloud grows rapidly from 123 min to 140 min. The evolution of the cloud over much of this time period is also illustrated in Fig. 2. The ice processes become very active during this time and aid in the production of rain through melting processes. The rain production terms shown in Fig. 3 indicate melting of graupel increasing in magnitude to values greater than 100 kT km^{-1} after 140 min.

Unfortunately for the cloud seeding efforts (as decribed below) the coalescence formation of rain dominates precipitation production in this large cloud situation, as seen in Fig. 3 in the rain accretion term (ACCR) and the autoconversion term (AUTO). As early as 110 min the ACCR term is larger than 10 kT km^{-1} increasing to greater than 100 kT km^{-1} at 125 min. The AUTO term represents rain initiation via coalescence and is in the range of 1 kT km^{-1}, by 110 min indicating an efficient rain formation process. The subsequent rain production is primarily through the accretion of cloud water by the rain.

4.1.2 No-Ice Run

As is evident in Fig. 2 the no-ice run appears to produce clouds similar in shape to the natural cloud but less dynamic. The main cloud is not quite so vigorous and does not grow as high in the atmosphere as its counterpart in either the unseeded or seeded runs. This cloud situation produces about 10% less precipitation than the natural cloud run (see Table 1).

Table 1. Precipitation production from the 20 July 1986 cloud simulations. Units are kT km^{-1}, numbers in parenthesis are percentage change from the unseeded case.

Case	Rain	Hail	Total
N1 (smaller cloud)			
Unseeded	26.7	--	26.7
AgI, cloud base	30.0 (+12.4)	--	30.0 (+12.4)
CO_2, cloud top	29.7 (+11.6)	--	29.7 (+11.6)
AgI, cloud top	29.9 (+12.2)	--	29.9 (+12.2)
N2 (large cloud)			
Unseeded	301.5	3.70	305.2
No-Ice	272.3 (-9.7)	--	272.3 (-10.8)
AgI, cloud base	287.8 (-4.5)	3.36 (-9.2)	291.2 (-4.6)
CO_2, cloud top	286.6 (-4.9)	2.86 (-22.7)	289.5 (-5.2)
AgI, cloud top	285.3 (-5.4)	2.92 (-21.1)	288.2 (-5.6)

4.1.3 Seeded Runs

Cloud-base seeding with silver iodide (AgI) and cloud-top seeding (at about -10°C) with both dry ice (CO_2) and AgI have been simulated, as in Orville et al. (1984) and Kopp (1988). Seeding amounts of about 200 g km^{-1} were simulated at 117 min (cloud base) and 120 min (cloud top) of simulated real time. Figure 2 shows the effects of seeding in a run with AgI seeding at cloud top. More snow and graupel/hail is evident at 129 min in the seeded cloud.

For this large cloud, the icing effects were clear; production terms of rain via ice processes began earlier and radar reflectivity patterns were changed (maximum values higher in the cloud) as well as the reflectivity values increased. Also the seeded cloud grew faster than the unseeded cloud (Fig. 1). However, these changes did not result in greater precipitation fallout, in fact, less. Table 1 shows the precipitation production in the various cases.

One of the effects of cloud seeding is shown in Fig. 3. The dashed curves represent the seeded case. Note that almost immediately after seeding the GMLT (graupel melting) term deviates from the unseeded run GMLT curve. This is caused by the nearly instantaneous transformation of rain to graupel caused by the cloud ice produced by seeding, and the collection of this cloud ice by the rain (Koenig, 1966; Cotton, 1972). The graupel then falls to warmer regions of the cloud and melts to form rain.

Our preliminary analysis of these results indicate that the earlier formation of snow and graupel did not help the precipitation production in this large, vigorous cloud (vertical velocity maxima greater than 25 m s^{-1}). In the seeded runs too much of the snow was transported to the anvil region and never reached the ground.

4.2 Further Tests (N1 Case - Moderate Size Convective Cloud)

One further series of tests has been run at the time of this writing. A smaller, weaker cloud development was produced using this atmospheric sounding by decreasing the water vapor flux at the earth's surface. The main cloud development topped out at about 8 km (-20°C), and produced about an order of magnitude less precipitation than the previous case. The seeded runs produced about 12%

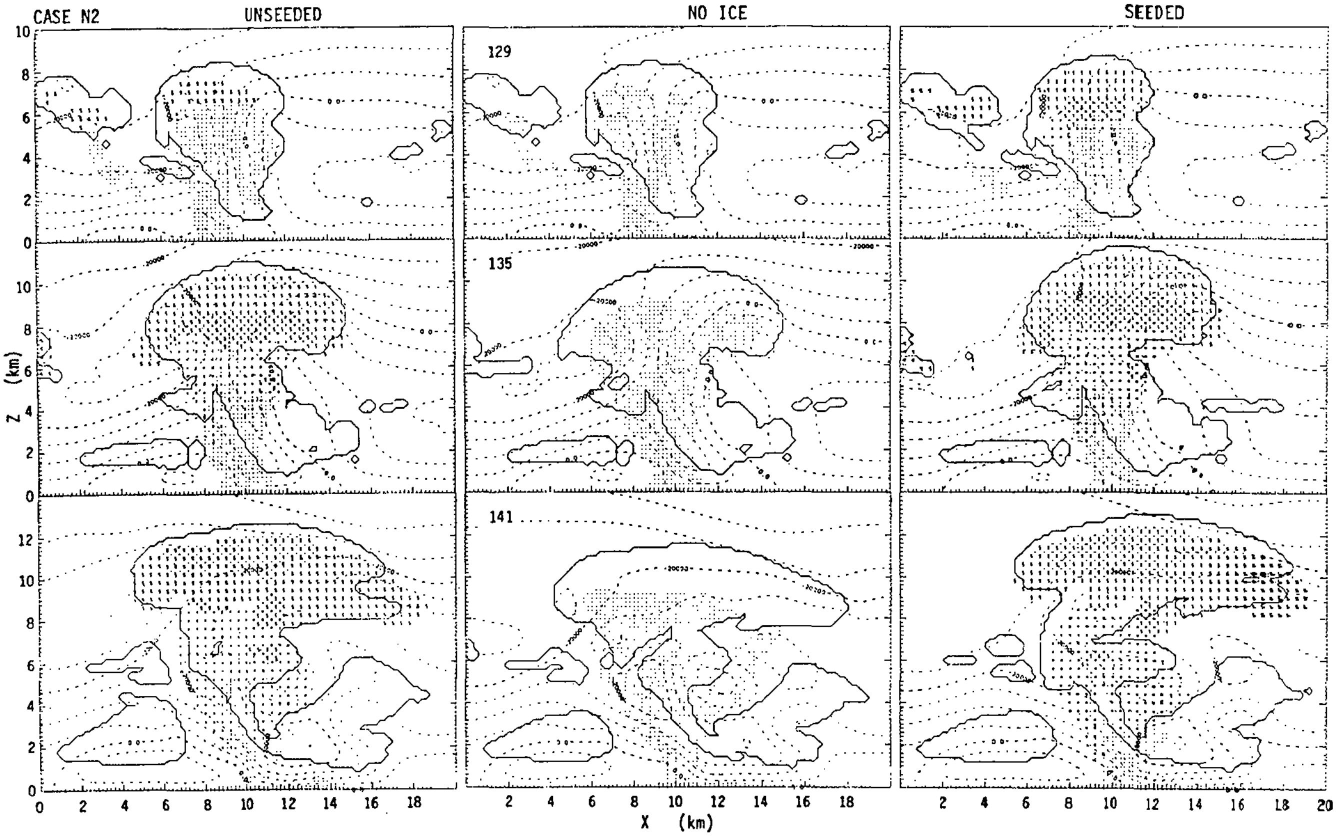

Fig. 2. The general cloud outline and precipitation fields for the unseeded run (left column), no-ice run (central column), and AgI cloud top (-10°C) seeded run (right column) for the large cloud case, N2. The symbols * and • represent graupel/hail and rain mixing ratios greater than 1 g kg^{-1}; the S represents snow mixing ratios greater than 0.5 g kg^{-1}. Time in simulated real time (minutes) is denoted in the upper left corner of the center panels.

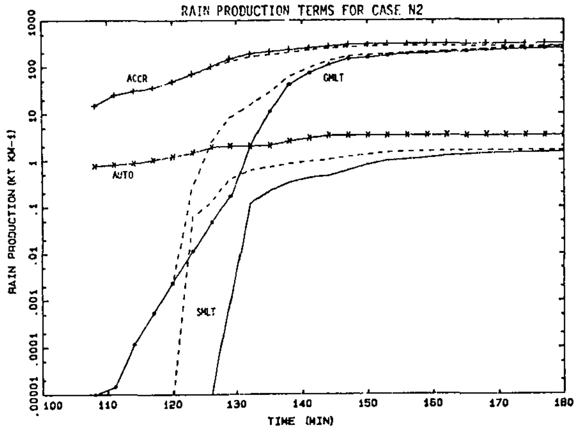

Fig. 3. The rain production terms in the N2 case, unseeded run. ACCR denotes accretion of cloud water by rain, AUTO is the coalescence of cloud water to form rain, GMLT is graupel melt and SMLT is snow melt to form rain. The dashed curves represent the seeded case results.

more precipitation than the unseeded run (Table 1). In this case the earlier formation of snow and graupel helped to process the cloud liquid and cloud ice into precipitation and the weaker dynamics of the cloud allowed more precipitation fallout.

Figure 4 shows the general outline of the unseeded and seeded clouds. The formation of snow and graupel/hail is evident at 186 min in the seeded case, but not until 204 min and at high altitudes in the unseeded case. Actually some graupel/hail formed via the rain freezing process, but remained much less than in the seeded case.

5. DISCUSSION

These modeling tests of the seeding of a large and a moderate size warm-base cloud have produced different effects on precipitation. The modeled clouds have been very efficient producers of warm rain; the ice phase seeding has decreased slightly the total precipitation in the large cloud and increased it moderately in the smaller cloud. However, note that the small percentage change in the large model cloud results in a greater absolute change in precipitation than the moderate percentage change in the smaller model cloud.

These changes due to ice-phase seeding are less dramatic than the changes we have seen in simulations of cold-base convective clouds (Kopp et al., 1983; Kopp, 1988; Orville and Kopp, 1986), where coalescence is not active. In those cases

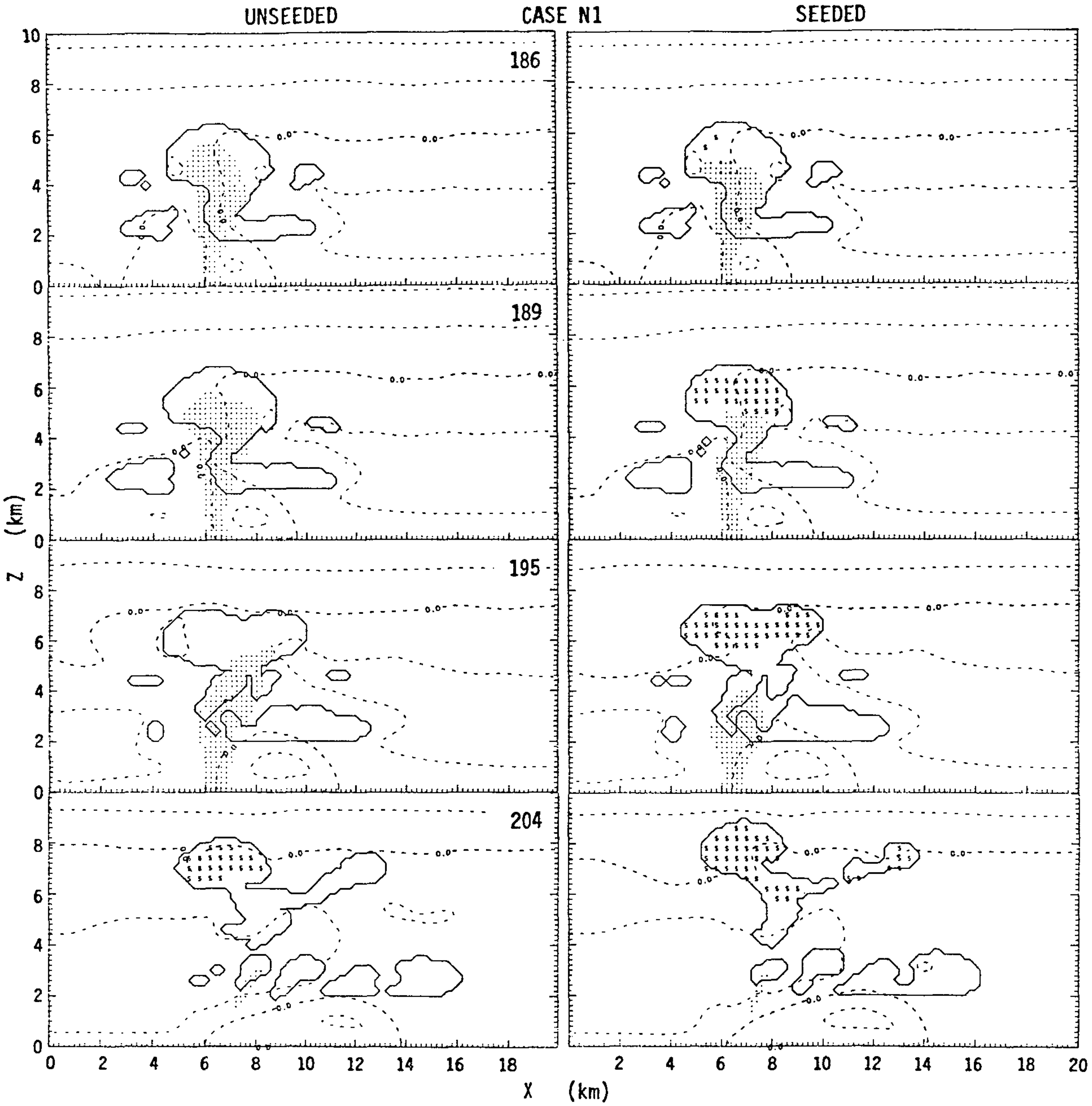

Fig. 4. Similar to Fig. 2, but for the smaller cloud case, N1. The unseeded run is on the left, seeded on the right.

increases ranging from 20 to 100% or more resulted, primarily by the process of creating precipitation via the cloud seeding at an early stage of the cloud's limited life history.

The results shown here regarding a large warm-base cloud do not appear consistent with the results of Hsie et al. (1980) concerning the warm-base cloud produced in the model using an atmospheric sounding from St. Louis. In that case a healthy increase in precipitation was noted.

We ascribe the differences to changes in ice microphysical simulations since that 1980 study. The inclusion of a snow mixing ratio field in the model has made the precipitation simulations more realistic. The ice-phase seeding simulations now form snow initially (via cloud ice) instead of graupel/hail immediately as in the Hsie et al. study. If the storm dynamics are great enough, the snow is carried aloft and may not result in precipitation on the ground.

The vigor of the large cloud is increased by the ice-phase seeding, but an inhibiting inversion is not present. That type of inversion situation has been hypothesized in the past to be favorable for positive cloud seeding effects, but we have not simulated such a case yet. Also, the ice-phase cloud seeding would be expected to be more effective in warm-base clouds that have a less efficient warm-rain process than that which was modeled. So far only a relatively few cases have been run. These results appear to be consistent with the discussion of the seeding of isolated convective clouds presented in Dennis (1980), in which he suggests that moderate size convective clouds are the prime targets for rain enhancement via ice-phase cloud seeding.

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