Three-dimensional simulation of glaciogenic seeding of clouds over Bethlehem

GW Reuter
Division of Meteorology, Department of Geography, University of Alberta, Edmonton, Alberta

Abstract

A time-dependent three-dimensional cloud model with bulk water parameterisations was applied to simulate heavy silver iodide seeding in an isolated cumulus congestus cloud. The ambient conditions were prescribed using observed sounding data from a case study of the Bethlehem Precipitation Research Project. In the simulations, the total mass of ice crystals formed in the seeded cloud was two orders of magnitude larger than that in natural clouds. Furthermore, precipitation developed slightly faster and more efficiently in the seeded case. However, the cloud updraft was only marginally stronger in the seeded case with almost no lasting effect on the cloud dynamics or cloud size. Seeding effects were also hardly evident in the amount of rainfall at the ground, with the accumulation value increased by only about 1%.

Introduction

The objective of the Bethlehem Precipitation Research Project (BPRP) is to examine summer-time precipitation processes in the interior plateau of Southern Africa and to determine the likelihood of rainfall enhancement through glaciogenic cloud seeding. The Weather Bureau and the Water Research Commission of South Africa have jointly sponsored the project for the last 17 years, from 1975 to the present. In 1990, the project name has been changed to to the National Precipitation Research Project (NPRP). Intensive field observation work is conducted around the town of Bethlehem (28°S, 28°E) in South Africa. Three instrumented aircraft are used for seeding and microphysical measurements, often making simultaneous cloud penetration at different altitudes. A C-band weather radar operating in volume scan, samples the three-dimensional precipitation structure. The field activity and research findings were reviewed by Krauss et al. (1987) and Hudak and List (1988).

In addition to field experimentation, BPRP also contains a modelling component using both simple and complex numerical models to assist in making operational decisions as well as in evaluating seeding cases. Hudak and List (1988) applied Nelson's (1979) one-dimensional model, which computes explicitly the evolution of size spectra of liquid drops and ice particles, to identify case study days that stimulate the rainfall following cloud seeding. One case study, 5 February 1981, was singled out to provide an excellent opportunity for both microphysical and dynamic seeding. Radar observations indicated that one cloud grew rapidly following seeding. However, rapid cloud growth was rather common in the convectively unstable environment existing on 5 February 1981, and therefore it was impossible to provide an unambigious causal relationship between cumulus development and seeding based on observations alone.

A one-dimensional model, in which temperature, updraft and cloud water mixing ratio can vary only in the vertical, has great limitations in simulating the complex cloud circulation. The seedability of the 5 February 1981 sounding conditions should thus be reanalysed using a three-dimensional (3D) model that can more realistically simulate the cloud dynamics. While two-dimensional (slab-symmetric) cloud models have been used extensively in weather modification studies (e.g. Hsie et al., 1980; Orville and Chen, 1982; Orville et al., 1984; 1987; Farley, 1987) fully three-dimensional cloud seeding simulations have been reported only by Cotton et al. (1980) and Levy and Cotton (1984). Three-dimensional cloud models require extensive computing time and core storage and "sacrifices" are thus needed in modelling the cloud microphysics. Usually both warm and cold rain processes have to be parameterised using a bulk water scheme.

The purpose of this study was to use a three-dimensional cloud model with bulk water microphysics to examine the potential for dynamic seeding to stimulate the rainfall of the 5 February case of BPRP. The results would then be compared to those of other studies.

Cloud model

The original numerical code was developed by Steiner (1973) to study moist convection in a three-dimensional sheared environment. Yau (1980) extended the model code to allow for deep convection and warm rain processes. The turbulence closure scheme was amended to include the effect of local buoyancy (Yau and Michaud, 1982) and later an ice-phase parameterisation was added by Yau and MacPherson (1984). The model was applied to tropical rain showers (Turpeinen and Yau 1981), a multi-cell storm (Yau and Michaud 1982) and an Alberta hailstorm (Yau and MacPherson 1984). Reuter (1988) used the model to investigate the water and kinetic energy budget of isolated convection. One of the cases presented, was initialised with the sounding of the 5 February BPRP case study.

The model was based on the deep anelastic system of equations with a diagnostic equation for the pressure perturbation. The sub-grid scale processes were modelled using a first-order closure scheme with the eddy exchange coefficient depending on deformation shear and local buoyancy. The Coriolis effect was neglected which is reasonable for short-lived convection. The lateral model boundary conditions were assumed to be periodic, i.e., any outflow through a lateral boundary was compensated by the same inflow through the opposite boundary. The bottom and top boundaries were assumed to be rigid, flat and free-slip and there was no outflow of heat and moisture, except for fall-out of precipitation at the ground.

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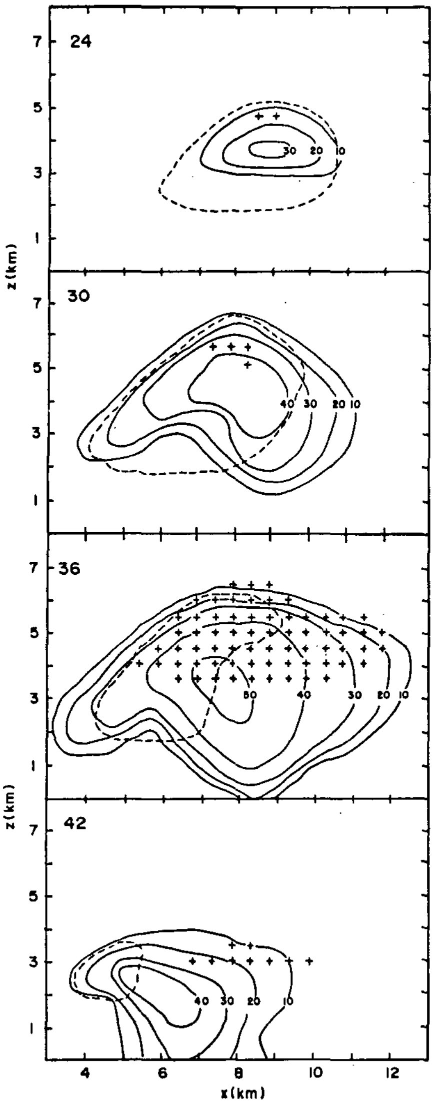

Figure 1
Vertical section depicting the radar reflecticity field (in dBz) at 24, 30, 36 and 42 min. The dashed line is the 0,1 g/kg contour of liquid water mixing ratio and the little crosses indicate grid boxes with mixing ratios of ice exceeding 1 mg/kg.

The bulk water technique was used to treat the microphysics. Prognostic equations were used for four "categories" of water substance: Vapour, cloud water, rain water and one category that contained both individual ice crystals and accumulation of ice crystals (snowflakes). The warm rain process was parameterised using the Kessler scheme (Yau, 1980), while the ice microphysics closely followed that of Koenig and Murray (1976) as documented in Yau and MacPherson (1984).

Cloud seeding was modelled by assuming that silver iodide particles act as **depositional nucleation** (by converting vapor to solid ice at ice supersaturation) and **contact freezing nucleation** (by a crystallisation process upon contact with supercooled droplets). The maximum concentration of ice crystals that can be activated under natural conditions was estimated from Fletcher's (1969) curve given by:

$$N_n = 10^{-5} \exp(0{,}6\,\Delta T) \qquad (1)$$

where N_n is the number of nuclei per liter of air active at the supercooling ΔT. The number of artificial nuclei per liter of air activated by silver iodide particle seeding is estimated from:

$$N_a = \beta \exp(-0{,}22\,\Delta T^2 + 0{,}88\,\Delta T - 3{,}8) \qquad (2)$$

where β is the number of artificial nuclei per liter of air active at -5°C. Equation (2) constitutes the efficiency curve for the combined effect of all nucleation mechanisms derived from measurements for a silver iodide generator in the temperature range between -5°C and -20°C (Orville and Kopp, 1974). In the experiments, seeding was simulated by specifying a seeding time τ. The maximum concentration of ice nuclei activated before τ was given by N_n but was set equal to N_n+N_a after τ. Of course, in the event that there were already ice crystals present only the excess of N_n+N_a was nucleated.

The spatial and temporal distribution of the seeding material is rather complex. Initially the plume of seeding material, when released from aircraft, can be roughly represented by a line source. However, this plume quickly spreads out by diffusion and mixing in the turbulent cloud. We avoided the complexities in describing the exact evolution of the seeding plumes by assuming that the seeding material had an instantaneous spatially uniform distribution. This assumption will likely overestimate the seeding effects, compared to the more realistically case, in which the seeding material was diffused from the flight track.

The horizontal size of the model domain was 16 km x 16 km and its depth was 12 km. The equations were solved by a finite-difference scheme on a staggered grid with uniform mesh size of 500 m. The second-order centered differences were used for spatial derivatives. The leap frog scheme with a constant time step of 8 s was used for the time integrations. The diffusive fluxes were lagged in time. The Asselin time filter was used to avoid splitting of odd and even time steps.

Natural cloud evolution

The atmospheric sounding sampled at 1200 UTC in Bethlehem was presented in Hudak and List (1988) and also in Reuter (1988). The atmosphere was quite unstable to moist adiabatic ascent having a Showalter index of -7,0. Also favourable for convective storm formation was the substantial amount of moisture - the precipitable water content deduced from the sounding amounted to 26 mm. The wind was weak in the lower levels, but intensified strongly in the shear layer observed between 4 to 8 km AGL.

The observed sounding data were used to specify the basic state of the model temperature, vapour and horizontal wind. Since measurements of the meso-scale forcing and surface heating were not available, the simulation runs were initiated with a small humidity disturbance with its base at the convective condensation level. The precise specifications of this moisture bubble are given in Reuter (1988). Small-scale horizontal variation in vapour mixing ratio typically occur in the pre-storm environment, because of the decay of an earlier generation of clouds. The size of such a moisture perturbation can affect the size of the developing cumulus cloud. For studying individual convective clouds, initialisation using moisture perturbations was adequate, but could not be used for an ensemble of clouds.

The precipitation structure is usually observed in terms of the radar reflectivity field Z, which can be related to the mixing ratios of rain and ice based on empirical Z-M relationships. Figure 1 shows the evolution of the vertical structure of the

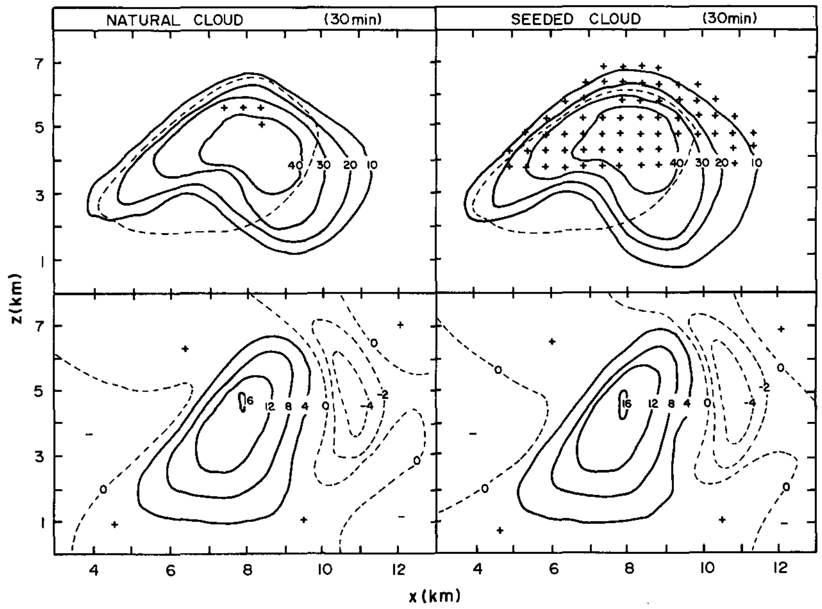

Figure 2

Comparison of natural and seeded cloud as simulated at 30 min. The upper panel shows the contours of radar reflectivity field in dBz, the 0,1 g/kg liquid water mixing ratio contour (dashed line) and ice contents exceeding 1 mg/kg. The lower panel compares the vertical velocity field (in m/s)

simulated radar reflectivity field, through cross-sections of the maximum cloud updraft in the direction of the major vertical wind shear. The cloud base remained flat and at the same altitude throughout the simulation. From 24 to 30 min the cloud expanded rapidly both in width and depth. Cloud water was mainly formed in the upshear side of the storm. The effects of the ambient shear also showed up in the precipitation field, which expanded mainly towards the downshear side. At 36 min, the convection developed into its mature stage with the radar reflectivity reaching its maximum of 52 dBZ (about 90 mm·h^{-1}). All precipitation above the freezing level consisted partially of ice crystals or snow. At this stage, drizzle reached the ground. After 36 min the storm decreased in size and intensity. A comparison of model output with radar observations indicated that the simulation realistically reproduced the size and intensity of the observed radar reflectivity field (Reuter, 1988).

Comparison of seeded and natural cloud simulations

The effect of seeding with silver iodide was investigated by comparing two numerical simulation experiments, termed "natural cloud" (N) and "seeded cloud" (S), respectively. The two experiments differed only in how ice nuclei were activated. Equation (1) was used in experiment N for nucleation under natural conditions; Eq. (2) was used in experiment S after the seeding time τ set to 15 min, at which stage the simulated cloud top was passing through the -10° C level. The concentration of artificial nuclei per liter at -5°C was chosen to be β = 100 per liter, to mimic the scenario of heavy seeding. A simulation run was also made with β = 50 per liter, but the seeding signature for this case of light seeding was less obvious than for heavy seeding.

The changes following seeding were most pronounced at about 15 min after seeding. A comparison of the precipitation structures shown in Fig. 2 indicated that the seeded cloud contained numerous ice crystals that are not present in the "natural"cloud. Also, the radar reflectivity field of the seeded cloud was slightly more developed and the rain had fallen further down. However, the results in the lower portion displaying contours of vertical velocities, suggested that the effects of seeding on the cloud circulation were rather insignificant. The core updraft value was only marginally stronger in the seeded case and downdraft speeds were almost the same. To summarise, the qualitative comparison at 15 min after seeding suggested that the microphysical processes for rain formation were slightly faster (or more efficient) in the seeded cell, but that the cloud dynamics hardly differed.

The effects of seeding were further examined by comparing the instantaneous masses of ice, rain water and cloud water integrated over the model domain (Table 1). In the natural case, the mass of ice was small compared to the mass of rain. The cloud water reached its maximum mass at 25 min, whereafter it decreased gradually as the mass of rain increased. The total accumulated rain that actually reached the ground after 40 min was only 3,23 x 10^4 kg. In comparison, the seeded cloud contained a substantial amount of ice. The ice amount grew mainly by riming and the cloud water was partly depleted through the collection process. At 10 min after seeding, the total mass of ice in the seeded cloud was about two hundred times larger than in the natural cloud. Furthermore, during these 10 min the total rain water increased much faster in the seeded cloud. The simulated accumulation of rain on the ground was almost the same for the natural and seeded cases. The enhancement of seeding towards the surface rainfall was less than 1% at both 35 and 40 min.

Table 1
Selected quantities of "natural" (N) and "seeded" (S) cloud simulations for 5 February 1981 compared at 5-min intervals starting at seeding time 15 min. Shown are the total mass of ice/snow, total mass of rain water, total mass of cloud liquid water, total mass of the condensed water, and the accumulated mass of rain at the ground

Time (min)	Total ice (kg)	Total rain (kg)	Total LWC (kg)	Total condensate (kg)	Rain at ground (kg)
15 N	$2,47x10^{-2}$	$1,01x10^{2}$	$2,52x10^{7}$	$2,52x10^{7}$	0
S	$2,47x10^{-2}$	$1,01x10^{2}$	$2,52x10^{7}$	$2,52x10^{7}$	0
20 N	$2,03x10^{0}$	$9,06x10^{5}$	$4,47x10^{7}$	$4,56x10^{7}$	0
S	$4,50x10^{5}$	$1,47x10^{6}$	$4,65x10^{7}$	$4,84x10^{7}$	0
25 N	$2,41x10^{4}$	$1,91x10^{7}$	$5,88x10^{7}$	$7,79x10^{7}$	0
S	$4,98x10^{6}$	$1,93x10^{7}$	$5,55x10^{7}$	$7,98x10^{7}$	0
30 N	$4,22x10^{5}$	$7,60x10^{7}$	$5,37x10^{7}$	$1,30x10^{8}$	0
S	$2,30x10^{6}$	$7,61x10^{7}$	$4,45x10^{7}$	$1,44x10^{8}$	0
35 N	$8,66x10^{5}$	$1,22x10^{8}$	$2,22x10^{7}$	$1,45x10^{8}$	$3,62x10^{3}$
S	$3,65x10^{7}$	$1,13x10^{8}$	$1,79x10^{7}$	$1,68x10^{8}$	$3,65x10^{3}$
40 N	$8,50x10^{5}$	$9,11x10^{7}$	$5,23x10^{6}$	$9,72x10^{7}$	$3,23x10^{4}$
S	$9,76x10^{6}$	$8,64x10^{7}$	$4,75x10^{6}$	$1,00x10^{8}$	$3,25x10^{4}$

Conclusion

A three-dimensional cumulus model was used to examine the potential for dynamic cloud seeding for atmospheric conditions given by the sounding sampled on 5 February 1981 over Bethlehem. We found that heavy seeding with silver iodide particles changed the microphysical properties of isolated convective clouds: Seeded clouds produced many more ice crystals than natural clouds. The extra ice formed in the seeded cloud only slightly enhanced the formation of rain water. However, the seeding effects were not evident in the dynamics or in the size of the clouds. Also, the amount of rain accumulated at the ground was not changed by seeding. In the simulations, the cloud dynamics controlled the surface rainfall amount while the phase of the precipitation embryos seemed to be rather unimportant.

I want to stress that these findings are based on a single case, and probably do not hold for other atmospheric conditions. Also, the model has some obvious limitations such as a highly simplified parameterisation scheme for warm and cold rain processes. A microphysical scheme that incorporates the formation of graupel and small hail stones, might have produced a faster precipitation rate. Furthermore, the rather coarse resolution of 500 m is clearly not adequate to resolve the details of the motion field within the storm. Despite these shortcomings, our findings should be compared with others.

Our results are consistent with the three-dimensional simulation results by Levy and Cotton (1984) which also indicated that the dynamic effects of sudden glaciation (following seeding) are very small for an isolated cumulus cloud. Our findings are also similar to those of Krauss et al. (1987) derived from statistics of BPRP observations sampled during the summer of 1984 to 1985. They concluded that the injection of silver iodide in semi-isolated cumulus congestus clouds produced high concentrations of ice, but that no clear seeding signature was evident in either the cloud dynamics or radar echoes structure. Our results, however, differ from those of Hudak and List (1988), which were primarily based on the results from a one-dimensional cloud model with detailed microphysics. At least for this particular sounding, the two models disagree about the potential for dynamic seeding. Further research is needed to resolve the issue whether a model with good dynamics but highly simplified microphysics, is superior or inferior to a model with highly simplified dynamics but good microphysics.

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