"REVIEWED"

THE SIMULATION OF CLOUD SEEDING EFFECTS USING NUMERICAL CLOUD MODELS*

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Abstract. One of the technological and scientific developments helping to quantify cloud seeding results is cloud models which, in some instances, require nearly as much computing power as the larger scale climate and general circulation models of the atmosphere. Cloud seeding simulations have been conducted in multi-dimensional, time-dependent cloud models over the past 10 to 15 years, and are increasing in frequency now as computers are more able to handle the task. This presentation will review some of the results obtained. The cloud models are sets of nonlinear partial differential equations, representing the conservation of mass, momentum, and energy. All phases of water are considered. The models treat all types of clouds, from severe convection with hail to gentle upslope motion stratus clouds with snow and light rain, on to non-precipitating clouds. The ice processes are emphasized in both field operations and modeling. Cloud seeding is simulated by changing the initiation and number of ice crystals in the cloud. The most realistic way to make this change is via the simulation of seeding agents, such as silver iodide or solid carbon dioxide, and their interactions with supercooled liquid water and water vapor. The results of the modeling have indicated support for the basic hypotheses of cloud seeding and have shown quantitatively the signals to be expected from the seeding.

1. INTRODUCTION

Numerical cloud models have a long history of application to the weather modification problem, starting as early as the late 1950's, early 1960's. The models were generally one-dimensional and steady-state. They predicted moderately well the response to ice phase seeding and the cloud top to be expected given the cloud or updraft diameter (Simpson et al., 1965, 1967; Simpson and Wiggert, 1969, 1971; Weinstein and Davis, 1968; Hirsch, 1971). However these simple models were, and still are, unable to handle the complexities of precipitation formation, evolution and fallout which require a modeling framework which allows full interactions of atmospheric parcels and particles from one level to another and within the same level.

1.1 Cloud and Precipitation Microphysics

An effective simulation of these interactions requires at least time-dependent models in one, two, and three space dimensions, and the more realistic precipitation simulations require at least two space dimensions, one of them in the vertical. This allows the precipitation to form in an updraft and then fall over the sides of the draft, perhaps forming a downdraft via the drag (load) of the precipitation on the air.

There are at least two precipitation processes that the models must simulate -- one sometimes called the warm rain, the other a cold rain process. The first requires condensation into small droplets and then collision-coalescence of the droplets to produce large enough particles to fall out and survive the inevitable evaporation that the drops suffer from cloud base to ground. The minimum size for such particles is about 200 μm (the initial cloud droplets are only 10 μm average diameter). An average raindrop is 1 mm in diameter so that it takes about one million cloud droplets to form a raindrop. All of the above may occur in clouds completely in the liquid state, at temperatures greater than -10°C. Hence, the name "warm" rain process. (The liquid is called "supercooled" at temperatures below 0°C.)

Significant complexity is added to the precipitation processes when ice is an added component. Ice must be treated as realistically as possible in the models, and is necessary if the models are to be used for most cloud seeding situations. The formation of ice crystals via nucleation on ice nuclei gives a cloud another chance to form precipitation size particles -- particles large enough to fall out of the cloud and survive the subcloud environment. Ice crystals do not normally form at 0°C, but instead may not initiate until temperatures much lower than this, -10°C to -20°C or colder. However, the presence of an ice crystal in a population of supercooled liquid cloud droplets gives the crystal a distinct advantage because it grows at the expense of the droplets. This is caused by the higher supersaturation over the ice crystal than over the droplets which allows the water vapor molecules to diffuse to the crystal preferentially. The crystal grows rapidly, falls faster than the droplets, and grows further by collision and riming (collection and freezing of the cloud droplets). The ice

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particles may then melt to rain at warmer temperatures. This precipitation process was first expounded by European scientists A. Wegener, Tor Bergeron, and Walter Findeisen in the early to mid 1900's and is sometimes called the "cold" rain process because of the role of ice in the process. It is often referred to as the Bergeron process.

The size of the particles is very important, because the terminal velocity of the particles is proportional to their size. Snow particles fall at one to two meters per second, rain and graupel from 1 to 12 m s^{-1}, and hail from 10 to 40 m s^{-1}.

The modeling of these precipitation processes is usually done in one of two ways -- the bulk water method or a more detailed microphysical method.

The first method assumes a distribution function for the precipitation size particles, usually in a form consistent with an exponentially decreasing number concentration as size increases. The basic predictive quantity is the precipitation content, given as a mixing ratio. One conservation equation is required for each precipitation type (rain, snow, graupel/hail), possibly three to five equations.

The second method essentially allows the modeler to predict the evolution of the particle distributions -- from nuclei activation to hailstone evolution. All parameterization is not eliminated in this method because the values of various quantities are required to complete the integrations. The basic quantities predicted are the evolution of the number (or mass) concentrations of the particles classified into a number of size categories. As many as 50 to 100 equations may be required to solve for the evolution of the cloud and precipitation particles, one equation for each size category of liquid or ice particle.

In summary, the models must include condensation and collision/coalescence as a minimum to simulate the warm rain process. For cold rain they should include condensation, deposition, the Bergeron process and drop freezing as important initiation processes and aggregation, accretion (or riming), and various collection processes (as many as nine in the bulk water simulations), for further growth of the particles. The initiation terms can be much smaller than the growth terms, but are crucial for the formation of a precipitation type. For hail, a few other considerations are needed for the bulk water methods. Also, because knowledge of the distribution of hailstones is sometimes essential for understanding the hail damage that occurs, cloud seeding seeks to change the distributions, to have smaller, less damaging stones. Consequently, the simulation of cloud seeding effects on hail normally will be more realistic and meaningful if done in detailed (or at least "hybrid") microphysical models.

Many auxiliary calculations are needed to make the microphysical calculations correct, or as nearly so as possible. Some of the more important ones are the terminal velocities of the particles and the various collection efficiencies.

In any event, the reader should realize that many interactions can occur in a cloud, that the interactions are oftentimes nonlinear and can be self compensating (i.e., if one process shuts down, another becomes larger and the same precipitation results), and that the initiation processes are crucial for precipitation to occur, but difficult to formulate and simulate. This is perhaps why so many final results of cloud seeding can be hypothesized and yet are so hard to test.

1.2 Cloud Seeding Simulation Methods

This microphysical modeling is combined with various cloud modeling frameworks, typically one, two, or three-dimensional and time-dependent to test cloud seeding concepts, as mentioned above. Each increase in dimensionality takes about two orders of magnitude more computer time, so not much has been done yet in 3D modeling of cloud seeding effects. Recent developments in computer power indicate that this may change in the near future.

The cloud models are composed of a set of equations representing conservation of mass, momentum, and energy. Air motion, temperature, moisture, cloud condensate (liquid and ice), and various precipitation types are predicted as functions of space and time. The most effective cloud models are those that couple the dynamics, thermodynamics, and microphysics so that a change in one quantity affects the other quantities, usually in a nonlinear manner.

The basic tenet of cloud seeding to affect the ice phase in a cloud is that cloud seeding material such as silver iodide particles (AgI) or solid carbon dioxide pellets (CO_2) change the temperature at which the ice phase initiates in a cloud. AgI particles begin ice nucleation at -5°C to -8°C, and CO_2 at 0°C, leading to earlier formation of precipitation lower in the cloud. Unseeded clouds may not begin this process or have significant numbers of ice crystals until -15°C to -20°C, a difference of a few to several minutes and one to two km depth in many convective clouds. In some instances, the ice process may never initiate naturally because of cloud top height remaining at too warm a temperature.

The cloud seeding simulation techniques require some comment. They have progressed from being very simplistic to being relatively close to how the seeding occurs in nature. Early modeling results were based upon changing the temperature threshold at which cloud liquid would change completely to cloud ice; wherever this threshold would occur in the cloud, the change would be made. Subsequent precipitation growth would include the ice-liquid interactions, if any rain were present. This has been called a first generation seeding method.

A step forward was made when this temperature threshold was used to increase the number of ice crystals in the cloudy atmosphere; the entire cloud liquid field was not changed to ice instantaneously, but gradually switched over to the ice fields through various microphysical interactions. This second generation seeding technique has been used by Koenig and Murray (1976) and Levy and Cotton (1984).

A third way, and most realistic simulation, is to actually simulate the release of a seeding agent and follow the agent through the model domain. The seeding agent causes ice initiation as temperatures lower in the cloudy updraft (Hsie et al. 1980), if the agent is silver iodide or some similar material. The agent is depleted by this activation and can be completely consumed. If the agent is dry ice, the subliming dry ice can be followed as it falls through the cloud creating ice crystals in its path (Kopp et al., 1983). The ice crystals then spread through the cloud interacting with the supercooled liquid. Aircraft drops of AgI flares or solid CO_2 pellets into the clouds, broadcast seeding in an updraft under the cloud base or out away from the cloud in the inflow, aircraft release of material directly into clouds, or ground based generator release of AgI can all be simulated using this modeling method. Also, the region affected in the cloud initially is only that where the seeding agent has been, not at all grid points where a threshold temperature is reached as in the other two seeding simulation methods. This latter method we call a third generation seeding method.

The above discussion has concentrated mainly on the microphysical effects of cloud seeding; that is, the accelerated formation of precipitation. However, if ice formation is caused by the ice-phase cloud seeding, then additional latent heat of fusion will be released resulting in increased vigor of the cloud, a dynamic effect of cloud seeding. This effect is often manifest by increased growth of the cloud and higher cloud tops for convective clouds or the formation of embedded convective cells in stratiform clouds. Orville and Hubbard (1973) and Orville et al. (1987) detail the amount of extra heating that can be released in convective and in stratiform clouds.

Another dynamic effect occurs when precipitation is formed in a cloud and begins to accumulate in the updraft. This loading effect, alluded to earlier, leads to precipitation fallout and important interactions as the downdraft, caused by the precipitation, impacts the ground. Strong, low-level winds may be formed and the outflow interaction with the environmental airflow may lead to regions of strong convergence and new cloud development or enhancement of the parent updraft. The timing of these events and interactions may be crucial, and unseeded clouds may react more favorably (or less) than the seeded clouds to the precipitation development.

An example of the many possible results of ice-phase cloud seeding is shown in Fig. 1. Ice crystals, as named in the figure, are primary, pristine crystals -- hexagonal, columnar, needles or such -- generally incapable of precipitation. Snow and snowflakes denote larger and multiple crystals capable of precipitation. Graupel is variable density rimed ice particles smaller than 5 mm diameter and larger than a few hundred micrometers. Hail is rimed ice particles equal to or larger than 5 mm diameter.

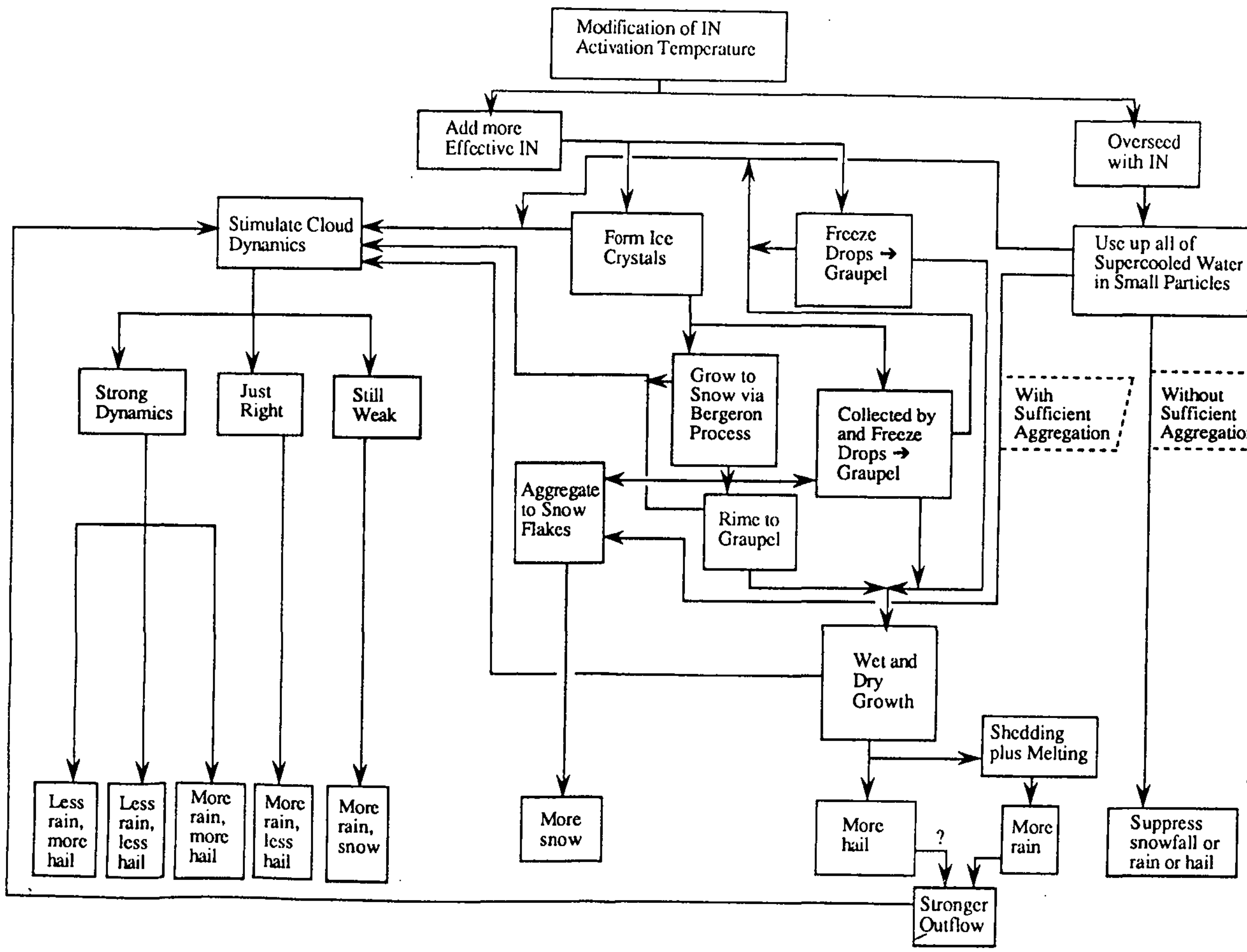

Figure 1: Various outcomes of ice-phase cloud seeding.

It is clear from this figure that the outcome of ice-phase cloud seeding is not easy to predict and can be either beneficial or not, and may be beneficial to some and harmful to others. As we will see, cloud modeling helps sort out the various effects, but well-designed field projects are necessary to pin down the ultimate cloud seeding results.

The dynamic strength of the cloud (or more basically, the updraft seeded region) is often crucial to the seeded result. If the cloud is composed of 10 m s^{-1} or less updraft speeds, most of the precipitation particles formed can fall out of the cloud, particularly if they are rain, snow, or graupel particles. If the updrafts are in the 15 to 30 m s^{-1} range, then much of the cloud mass is transported to the anvil and not precipitated efficiently.

One other feature that can be critical to the cloud seeding outcome is whether the cloud is considered "cold base" or "warm base." A cold base cloud has a very shallow layer below the 0°C isotherm; the base temperature is typically 5°C to possibly 10°C. Little time is available for the warm rain process to operate in such clouds. Observations inside the clouds by specially instrumented aircraft indicate relatively few to no large drops formed before the ice process initiates precipitation in these clouds.

On the other hand, warm base clouds with base temperatures 15°C or warmer have 3 km or more depth for the coalescence process to produce rain. The ice processes occur later in the updraft history and may aid in the precipitation processes by imparting more energy to the cloud via the freezing processes. As shown in Fig. 1, this can also be a detriment to producing more precipitation.

The review below will consider extratropical cold base clouds first, and then tropical warm base clouds, closing with a section on hail suppression simulations and a short critique of numerical cloud models. An earlier review by Orville (1986) considered one-dimensional models in detail (not considered here) and focused on dynamic seeding concepts.

2. CLOUD SEEDING/CLOUD MODELING REVIEW

2.1 Extratropical Clouds

In this section, we will review very briefly the important results that have been produced in various cloud models which attempt to simulate cloud seeding effects. The emphasis will be on ice-phase cloud seeding simulated realistically in multidimensional cloud models. These models simulate the formation, evolution, and fallout of precipitation from one level in the atmosphere to another. Their use for testing seeding techniques in extratropical clouds (primarily cold base clouds) has been sparse, although the seeding routines in two-dimensional, time-dependent (2DT) models have become relatively sophisticated compared to those techniques used in one- and three-dimensional models. Papers with pertinent results are those by Hsie et al. (1980), Orville and Chen (1982), Kopp et al. (1983), Wu (1985), Kopp (1988), Orville and Kopp (1990), among others.

The paper by Hsie et al. (1980) simulated AgI seeding on three different sounding days, two from Miles City, Montana, and one from St. Louis using an early version of the IAS 2D cloud model. No snow was simulated so that the Bergeron process simulated cloud liquid and cloud ice transforming to graupel. One of the Montana cases and the St. Louis case were situations with relatively large precipitation amounts; the other Montana case was a light raining cloud, but was the one that most of the seeding variations were tested on, such as seeding amount, location, and timing. The results indicated a rather small time window (about 6 min) in which to seed and relatively small sensitivity to seeding amount; this last fact is quite possibly due to the microphysical simulations which solve for the mass of the cloud ice, but not the number concentrations. Rain and graupel/hail amounts were increased in the light rain case and the St. Louis warm base cloud case and decreased slightly in the large rain Montana case.

The study of CO_2 seeding by Kopp et al. (1983) was primarily a microphysical seeding effect simulation and used an improved version of the IAS cloud model with snow included in the microphysics (Lin et al., 1983). The final effect of the seeding was due to a dynamic interaction of two cloud cells, in addition to the microphysical effect of earlier precipitation formation. The seeded cell reacted more vigorously to the cell merger because of the precipitation fallout from the first cell, which enhanced the boundary-layer convergence and the intensity of the merged cell. The seeded cell in this case produced about 20% more precipitation than the unseeded cell (an additional 4 to 5 kT per km width of cloud).

[An important side issue revealed in this paper was the importance of using identical time steps, and sequence of time steps, in both the seeded and unseeded model runs. Otherwise, differences in results may be due more to a difference in time step selection than by the seeding action.]

Earlier work by Orville et al. (1980) had indicated that merged cells produced nearly twice as much precipitation, but that merger was relatively infrequent and depended on cloud cell spacing, intensity (buoyancy), and timing (or life stage) of the cells. Turpeinen (1982) saw no effect from timing or intensity on merger in his three-dimensional simulation of clouds on one day in GATE. No calculation was made by Turpeinen of rain increase from the mergers.

Other evidence of the effects of mergers and cloud interactions is given in Orville and Chen (1982). Their study was designed to quantitatively separate the effects of latent heat of fusion and precipitation loading due to AgI seeding. A series of cloud model runs, with specific effects turned on or off and then the model results subtracted from each other, gave quantitative differences in vertical velocity, cloud liquid water mixing ratios, rain, etc., due to the early formation of ice by the seeding.

The dynamic effects were many: increases and decreases of vertical velocity, enhanced fallout, and new cell development in convergent outflows, among others. The stimulation of the seeded cell via seeding came about through the accretion and associated freezing of the supercooled cloud liquid by precipitating ice, not by the freezing of the individual cloud droplets by the seeding material. These accretional freezing effects had been evident in Koenig (1966), Cotton (1972), and Wisner et al. (1972). Orville and Chen (1982) referred to these effects as indirect freezing, and the freezing of cloud water by the seeding agent as a direct freezing effect. The freezing processes involving graupel in Fig. 1 are examples of indirect freezing.

The net results of the heavy seeding were to stimulate the first cell in a series of cells, but to decrease the overall precipitation from the model storm because of the premature sweepout of the supercooled water in feeder clouds. One link in the dynamic-mode seeding chain of events had been broken, leading to opposite effects than those usually postulated. However, only one cell was seeded; in an operational or research project all cells may have been seeded and different results (of unknown sign at this time) would have occurred.

Regarding the various dynamic effects, these authors showed that in comparison to the unseeded cell, the peak domain-averaged kinetic energy increased by 100% if loading of all condensate was turned off, a 50% increase occurred if only precipitation loading was eliminated, and a 15% decrease occurred if the latent heat of fusion was omitted. Another important result was the illustration that microphysical changes could have significant effects on the total storm precipitation, given the same initial dynamic and thermodynamic conditions.

These authors found that, in the one HIPLEX† model case studied, substantial accretional freezing occurred about 8 min after seeding. The release of latent heat of fusion caused a temperature increase of about 1°C and resulted in a 2.5 m s^{-1} vertical velocity increase compared with the unseeded case (about a 10% change, but this effect is certainly dependent on the sounding). The redistribution of the loading effect by the earlier precipitation formation resulted in significant changes in cloud cell interactions (see also Koenig and Murray, 1983).

A thesis by Wu (1985) used soundings from all the case study days of the HIPLEX field experiment in the IAS cloud model. Hirsch (personal communication) has compiled the precipitation totals for all of the study days (11 unique cases in the model results) and calculated the precipitation amounts for the seeded and unseeded cases. The seeded cases produced 190 kT per km linear length of cloud versus 130 kT of precipitation from the unseeded clouds, a 46% increase. In general, these were isolated cumulus congestus that were simulated; they did not produce much precipitation.

Kopp (1988) simulated the seeding of clouds observed in the Alberta Research Council's cloud seeding experiment of 24 July 1979. Both CO_2 and AgI seeding agents were used. Stratus and cumulus congestus clouds were simulated using the IAS cloud model with improved ice crystal microphysics. This improvement involved an equation for predicting the total number of ice crystals in addition to the total mass -- this last item is the usual output of bulk water microphysical models.

The model simulations formed precipitation earlier in the seeded cases (in the seeded cell); there was no precipitation in the corresponding unseeded cell. The nearby cells produced precipitation in the model simulations, but not until much later in the unseeded case. The neighboring cell in the seeded cases produced precipitation as a result of snow being advected into the cell from the seeded cell. The cells in the model simulation were qualitatively very similar to observations reported in English and Marwitz (1982) at the time of seeding. The stratus deck was reproduced very well, agreeing with the base and top heights. Development of the radar echo patterns in the model was very similar to the observations in the AgI case, with precipitation reaching the ground about 20 min after seeding. The CO_2 case was similar to the AgI case in the simulations, but in the observed clouds produced precipitation much earlier and did not last as long. Certainly, the production of cloud ice in the CO_2 simulation was a short-lived process compared to the AgI simulation, but even so, there was not as dramatic a difference in the two model cases as in nature.

Orville et al. (1984, 1987) simulated the seeding of a stratiform cloud using the IAS cloud model and a sounding from Spain (19 February 1980, Villanubla) as part of the analysis for the Precipitation Enhancement Project (PEP) run by the World Meteorological Organization (WMO). The silver iodide seeding simulations produced strong dynamic responses in the model clouds, even with small amounts of supercooled liquid available and a few natural ice crystals per liter in the cloud. These effects occurred in a nearly moist adiabatic layer as well as in a convectively unstable layer.

The effects appear to be due to the heat released as the liquid freezes and the cloudy environment switches from liquid saturation to ice saturation. Cloud vertical motions of a few to several m s^{-1} are produced in the seeded cloud region. Vertical motions of 10 to 20 cm s^{-1} exist in comparable regions of the unseeded cloud. Precipitation is strongly affected. Consequently, this heat release is much more significant in terms of the overall energetics of the cloud than has been evident in seeding simulation conducted in pure convective situations with much stronger updrafts.

The tests of dry ice seeding indicated small effects, but this was largely due to the rapid fall of the dry ice pellets through the cloud and to the short time period available for the seeding to take effect. More rain fell from the seeded cloud, with some redistribution evident. A few tenths of a millimeter of rain accumulated on the ground.

This work compared with other results on warm base tropical clouds indicates that when seeding clouds for dynamic effects, less heating than expected is produced in high liquid water content

†High Plains Experiment -- a Bureau of Reclamation field experiment in the late 1970's and early 1980's.

(LWC) clouds (cumuliform) and more heating than expected is produced in low LWC clouds (stratiform). Consequently, the dynamic effects of cloud seeding are more ubiquitous than previously thought. For a thorough understanding of the seeding effects, nearly all cloud seeding experiments need to take into account the heating (and loading) effects caused by the "early" formation of precipitating ice. Numerical cloud models with coupled microphysics and dynamics help in this understanding.

A paper by Orville and Kopp (1990) reports on a cloud simulation from the HIPLEX field experiment, a cloud case which was also one of the case studies focused upon in the First International Cloud Modeling Workshop held in Irsee, FRG, in 1985 (WMO, 1986). The IAS 2D cloud model with improved ice crystal modeling was used on this case. Detailed analysis of the cloud simulation showed that the early formation of cloud ice and its interaction with the cloud circulation and rain formed from melted snow caused the early formation of graupel. The observationalists had thought that aggregation was most likely the cause of the rapid graupel formation, and it may have been, but not in the model results. Aggregation occurs in the simulation, but later than the other process noted above. The simulation shows a 36% increase in seeded rainfall compared with the unseeded model cloud.

2.2 Tropical Clouds

A few multidimensional cloud models have been applied to the problems of seeding of tropical clouds, primarily for dynamic effects. Murray and Koenig (1972) and Koenig and Murray (1976) studied the effects of ice and liquid microphysics on cumulus towers. Important effects due to evaporation at the cloud edges were noted by these authors. The cloud turret's decay was particularly dependent on the evaporation of the cloud liquid at the cool cloud cap.

Koenig and Murray (1976) used their two-dimensional, axisymmetrical cloud model to simulate massive infusions of ice in a cloud, a second generation seeding method. The model cloud grew taller and broader than clouds with less ice, but the simulations did not result in more rainfall, perhaps due to the continual supply of ice to simulate seeding instead of an instantaneous pulsed increase.

Levy and Cotton (1984) used a three-dimensional cloud model with a second generation seeding method to analyze the effects of cloud seeding on Florida clouds. Their interest was in trying to see how large releases of latent heat in middle cloud levels would affect the cloud system and pressure patterns in the cloud and subcloud layer. Seeding was simulated by increasing the ice crystal concentration to 100 L^{-1} at the -10°C level and above for 10 min after the tower reached that temperature. The results were examined with respect to dynamic responses and the communication of the effects to the subcloud layer. The authors found that the glaciation caused vertical motion changes by as much as 2.5 m s^{-1}, but only weak responses in the subcloud layer and no additional precipitation. Horizontal responses at the level of seeding were much stronger than the vertical responses lower in the cloud.

A thesis by W. T. Chen (1982) also considered the heavy seeding of a Florida-type cloud using the two-dimensional, time-dependent cloud model of Orville and associates referenced earlier. This model was modified to account for the warmer cloud bases and more efficient coalescence processes of tropical clouds, compared with the extratropical clouds normally simulated in the model. The sounding used was the same as that used in the study of Levy and Cotton (1984) above. Observations of clouds on this day were reported on by Cunning and DeMaria (1981). Comparisons of the model results with the Cunning and DeMaria (1981) cloud outlines were favorable. Results of seeding these model clouds showed about a 3 m s^{-1} increase in vertical velocity and enhanced precipitation processes early in the life cycle of the cloud, but decreases in the later stages.

The paper by Orville et al. (1989) reports on seeding simulations of warm base clouds similar to those observed in the Cooperative Huntsville Experiment (COHMEX) conducted in the summer of 1986 in the southeastern U.S. The bulk water IAS model was used. The seeding simulations were tested on a model cloud that grew past 12 km height and one that grew to 8 km height. Warm rain coalescence was very important in the simulations, but ice processes still played an important role in the total amount of precipitation produced by the clouds.

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

The changes due to ice-phase seeding of these warm-base convective clouds were less dramatic than the changes seen in simulations of cold-base convective clouds (Kopp et al., 1983; Kopp, 1988; Orville and Kopp, 1990) reported above where coalescence is not active. In those cases, 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 of this study 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.

The differences can be ascribed to changes in ice microphysical simulations since that 1980 study. The inclusion of a snow mixing ratio field in the model (Lin et al., 1983) 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 strong enough, the snow is carried aloft and may not result in precipitation on the ground.

The 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.

Before leaving these cloud modeling discussions concerning rain or snow bulk water modeling, it should be mentioned that important microphysical modeling of the rate of glaciation and the amount of ice needed to form efficient precipitation processes in various situations had been carried out by Jiusto (1973) and Lamb et al. (1981). Lamb et al. present new observational data from Florida cloud samples "that the primary microphysical role of seeding is the creation of many small ice particles that substitute for the secondary ice splinters of naturally induced glaciation. The aerodynamic capture of the splinters by the supercooled rain leads to the formation of new graupel particles and the rapid release of fusional heat." A relatively narrow time window was calculated for the heat effects from seeding-induced glaciation. More about these processes is given in a paper by Hallett (1981).

2.3 Seeding Effects on Hail

A study by Farley (1987) is the most advanced work on this topic. He used a version of the 2D IAS model with a more complete treatment of the ice processes. He used 20 categories to follow the evolution of the precipitating ice particles, ranging in size from 100 μm in diameter to approximately 5.0 cm. Rain, cloud liquid, and cloud ice are treated via the bulk water microphysical method, making this a "hybrid" model. A summary of his results derived from the application of the model to an Alberta hailstorm case follows, along with a short discussion of the hail process.

It is generally assumed that the production of hail requires a two-stage process, an embryo stage and a hail stage, and that these stages occur in different regions of the storm (Young, 1977). The Alberta operations assume that feeder clouds adjacent to the main storm are the embryo source region. English (1986) discusses a number of hypotheses whereby artificial seeding may lead to a hail suppression effect. These may be termed, respectively, the beneficial competition hypothesis, the embryo competition hypothesis, and the premature rainout hypothesis, and may be briefly stated as follows:

> Beneficial competition. Seeding with an ice material in the embryo source region in such a manner as to produce many more embryos that are just like the natural embryos will promote beneficial competition in the main updraft and limit the growth of all hailstones.
>
> Embryo competition. Seeding with an ice nucleating material in the embryo source region in such a manner as to produce competition for the available liquid water in that region will limit the growth of embryos and will make the hail process in the main storm less efficient.
>
> Premature rainout. Seeding with an ice nucleating material in the embryo source region before any significant numbers of [natural] ice crystals develop there will accelerate the precipitation process. In this case, some of the precipitation particles will fall out of the embryo source region before they can be delivered to the main updraft, thereby reducing the supply of embryos to the storm.

In addition to these three main hypotheses of hail suppression, a number of sub-hypotheses were offered as a means of testing the overall hypotheses. These will not be enumerated here, but the interested reader is encouraged to refer to English (1986).

In general, the model results lend support to the premature rainout hypothesis, although not strictly in the manner stated above. Several of the sub-hypotheses are common to all of the main hypotheses and can be considered verified, both in terms of observations following seeding experiments in the field and for the model seeding experiments. These involve the direct effect of seeding relative to the production of high concentrations of ice crystals and the subsequent production of snow and graupel particles. Furthermore, the model results show that precipitation particles can be made to develop earlier in the life of the feeder cell, with some precipitation fallout also occurring sooner than in the unseeded cases. The model results fail to show any significant suppression effect on hail from the main storm, however. It should be borne in mind that these model simulations have only been applied to one hailstorm case, and that this case is not particularly representative of the Alberta conceptual model.

One important item suggested by the model results, but not included in the premature rainout hypothesis as stated above, is the possibility that earlier precipitation development and fallout may alter the interaction dynamics between the feeder cell and the main storm. This is more evident for the expanded number of cases discussed in Farley and Orville (1986). The dynamics of these interactions are highly complex and of a variable nature, and can result in either a suppression or enhancement of the main storm. It is unclear at this time to what extent these features revealed by the simulations are model artifacts induced by the two-dimensionality of the model and the proximity of the main storm to the right boundary.

Another feature of the model results, which may also be occurring in nature, is the fact that certain aspects of the different hypotheses are active to some extent somewhere in the storm. In particular, Farley noted the temporary attainment of enhanced competition evidenced by depleted cloud water amounts in the upper portions and right flank of the feeder cell for the seeded cases. This depletion was caused by increased concentrations in the snow and graupel size ranges. Although these features were produced by the earlier precipitation formation component of the premature rain out hypothesis, they also lend some support to both the beneficial competition and embryo competition hypotheses.

2.4 Critique

All models suffer from inadequate simulation of the microphysical processes, to a greater or lesser extent. The extreme complexities of the ice processes make it impractical to include all facets in coupled microphysical-dynamical, multidimensional, time-dependent models, so simplifications have to be made. The importance of crystal habit, particle density and terminal velocity, aggregation, accretion, ice nucleation, coalescence, and many other processes is still under active investigation, some of which was started because of cloud seeding experiments. The early field experiments could not adequately account for these processes in the theories and operational methods. A modicum of hope was relied upon then, and even now, that the various effects were occurring as postulated.

Related to these weaknesses in microphysical modeling is the simplistic modeling of the seeding process in many models. The change of liquid to ice at predetermined temperature criteria is oversimplified, but is commonly done in the one-dimensional models. The icing of the cloud depends on many other items as well, such as updraft (condensation rate), ice nuclei amount and type, nuclei and crystal dispersion, liquid sweepout rate by the larger ice particles, etc. Improvement in seeding routines is made when the number of ice crystals is increased in time-dependent models. Better yet is the inclusion of equations to treat the seeding agents in the models. Only then can the time dependency of the seeding processes be examined and the importance, or even possibility, of freezing be determined. Of great importance in such models is when the freezing is initiated and what influence this has on the model cloud development.

Most field experiments have lacked numerical modeling support over the entire scale of the experiment. Individual cloud elements are seeded and several scales of interactions are expected. Cloud models with 100 m or so grid intervals are needed to track the seeding agent and simulate the cloud-scale responses. Mid-level inversions require small grid intervals so that enough grid points are available to faithfully represent the atmospheric sounding. These inversions are important for inhibiting early convection and for allowing the atmosphere to store up energy for the later deep convection to occur. The dynamic-mode seeding concept depends, at times, on the ability of seeded clouds to break through the inversion, while unseeded clouds cannot. The computer resources required to simulate these conditions are formidable.

Coarser grids may be adequate for the downdraft interactions in the boundary layer, but much larger domains are then needed to include the cloud-scale effects on the mesoscale. Nested grids will help in future studies (Clark and Farley, 1984).

The cloud and precipitation interactions with the boundary layer require that active lower boundary surfaces be modeled. Heating and evaporation rates at the earth's surface should be included in the models that attempt to understand the dynamic effects of seeding and cloud interactions. In addition, mesoscale convergence-divergence values are important in some instances and need to be simulated in the cloud-scale models. Past experiments have lacked such modeling support, but future experiments would have available such models.

3. SUMMARY

3.1 Cold Base Extratropical Clouds

3.1.1 Convective clouds

The numerical modeling work indicates that substantial percentage increases in rain from moderate size clouds may occur (20 to 100%). The increase comes about through earlier formation (by 6 to 8 minutes) of precipitation at lower elevations in the cloud. The snow and rain formed by the seeding may then interact to form graupel, allowing more efficient sweepout of the cloud liquid than occurs in the unseeded model clouds.

In some instances, with larger storm systems, the timing of precipitation formation and the precipitation interaction with cloud cell circulations and liquid water content can lead to less rain in the seeded storm system.

3.1.2 Stratiform clouds

The modeling results of relatively heavy seeding of supercooled stratiform clouds predict the formation of embedded convective cells in the stratiform cloud. Enhanced rain or snow, as well as redistribution of precipitation can result. The dynamic results depend on the heat release due to a switch from saturation with respect to liquid to saturation with respect to ice in the cloud.

3.2 Warm Base Tropical Clouds

Studies of ice phase cloud seeding effects on these clouds have focused on the dynamic effects of such seeding. The models have not validated the increase of circulation within the entire storm to bring added moisture into the clouds from the moist boundary layer. Ten to 15% increases in vertical motions due to the seeding have been detected. If the clouds were already quite vigorous and large, the seeding effect was to create more snow that was then transported to higher levels and not precipitated efficiently; less rain occurred in the seeded cloud in some cases.

Moderate size clouds, when seeded, produced more rain. Presumably the seeding initiated the ice precipitation processes sooner than in the unseeded clouds and made the seeded cloud more efficient.

3.3 Hail Results

The one study reviewed showed the possibility of simulating the seeding of a hailstorm and the effects on the evolution of the hailstone size distribution. More rain and less hail were produced from the seeded feeder cell, but interactions of the outflow from the cell with the main storm negated any strong hail suppression effect.

3.4 Further Remarks

It is now possible to apply more appropriate 3D cloud models and mesoscale models with realistic precipitation processes to the cloud seeding problem. Hopefully, field experimentation will be supported to test the modeling results and new hypotheses developed. Indeed, no cloud seeding research program is complete now without:
1) first rate equipment such as conventional and multiparameter radars, microwave radiometers, cloud physics instrumented aircraft, surface precipitation and wind flow measurement networks, upper air measuring systems, and satellite

receiving equipment; 2) state-of-the-art statistical design for evaluation of the field project; and 3) cloud scale and mesoscale numerical models to aid in the design, conduct, and evaluation of the project. Much has been accomplished in the past, but much more can be accomplished in the future to establish the effects of cloud seeding on precipitation and hailfall.

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