Secondary Seeding as a Means of Propagating Seeding Effects in Space and Time

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Abstract. Secondary seeding, whereby unseeded clouds ingest ice particles from clouds that earlier had received direct glaciogenic (e.g., silver iodide) treatment, is hypothesized to be a possible additional mechanism for the propagation of seeding effects in space and time. The ingested ice particles, after experiencing some growth in the donor cloud, act to glaciate the receptor cloud during its active growth phase and provide it precipitation embryos. These embryos give the new cloud a head-start on precipitation development as they grow further as graupel to precipitation size in the updraft laden with high quantities of supercooled cloud water. This enhancement of precipitation-forming processes is postulated to be strongest in microphysically continental clouds in which natural and seeding-induced primary glaciation and hydrometeor growth are slow. A case study is presented to illustrate these processes.

1.0 INTRODUCTION

The authors have been involved in the development and testing of the dynamic-mode seeding conceptual model for many years (Rosenfeld and Woodley, 1993, 1997; Woodley and Rosenfeld, 2000). Based on their past observations and the case described here, an additional link involving "secondary seeding" is suggested for the conceptual model. In its present form this model involves the following hypothesized series of meteorological events beginning initially on the scale of individual treated clouds or cells and progressing ultimately to the scale of clusters of clouds: The glaciogenic seeding produces rapid glaciation of the supercooled cloud liquid water content (SLWC) in the updraft by freezing preferentially the largest drops so they can rime the rest of the cloud water into graupel. According to model simulations by Johnson (1987) and by Pinsky et al. (1998), this seeding-induced graupel grows much faster than raindrops of the same mass so that a larger fraction of the cloud water is converted into precipitation before being lost to other processes. Ice multiplication is not viewed as a significant factor in the cloud's glaciation until most of the cloud water has been converted into precipitation. This faster conversion of cloud water into ice precipitation enhances the release of latent heat, increases cloud buoyancy, invigorates the updraft, and acts to spur additional cloud growth and/or support the growing ice hydrometeors produced by the seeding (Rosenfeld and Woodley, 1993). These processes result in increased precipitation and stronger downdrafts from the seeded cloud and increased rainfall in the cloud cluster through downdraft interactions between groups of seeded and non-seeded clouds, which enhance their growth and merger. "Secondary seeding," whereby non-seeded clouds ingest ice embryos produced by earlier seeding of separate clouds, is thought also to play a role in the precipitation enhancements.

Natural seeding, such as the seeding of a supercooled cloud deck by ice streamers from glaciated clouds above, is a recognized natural phenomenon. There has been little discussion, however, of "secondary seeding" in the context of deliberate cloud seeding experiments, although in our experience it is a common occurrence. It is particularly impressive in microphysically continental clouds in which natural primary glaciation and the attendant growth of graupel ice during the cloud's growth phase is slow. Under these circumstances artificial seeding produces graupel ice in the directly-treated clouds and this ice serves as precipitation embryos for non-seeded clouds ingesting it. This can occur regardless of whether the directly-treated cloud showed a growth response to seeding. An example is addressed in this paper.

2.0 MICROPHYSICAL PROCESSES

2.1 Natural Processes

Simplistically, clouds precipitate when their hydrometeors grow large enough to fall against typical (5 to 10 m s^{-1}) updrafts. Because of their wide cloud drop size distribution, microphysically maritime clouds have active coalescence processes and readily precipitate. In microphysically continental clouds having narrow drop-size distributions and high concentrations (> 500 cm^{-3}) of small cloud drops, however, coalescence, leading to the formation of raindrops, is suppressed. Much of the precipitation in such clouds is produced through ice processes, and it is more effective when the natural nucleation of ice takes place earlier during the cloud's active growth phase. In some cases, however, vigorous convective clouds remain supercooled to near the point of homogeneous nucleation (Rosenfeld and Woodley, 2000). The type, size distribution and concentration of ingested CCN (cloud condensation nuclei) aerosols and the vigor of the cloud updraft also play important roles in cloud supercooling.

Adding to this complexity is the observation that the rain production from clouds, especially those in continental regions, often appears to depend on their growth relationship with other clouds in their nearby environment (Rosenfeld and Woodley, 1997). Clouds growing in isolation are much less likely to develop precipitation than those in clusters, especially those in masses in which the new cloud towers are protected and often contiguous with their ancestors. The obvious explanation in such cases is that the younger towers ingest water and ice precipitation embryos from their predecessors, giving them a natural head start in their development of precipitation. As is discussed here, this need not be limited to unseeded clouds.

2.2 Response to Seeding

An obvious and continuing uncertainty is whether cloud seeding can be used to enhance the cloud processes that lead to precipitation. How this might be done in the context of the dynamic-mode conceptual seeding model was addressed in the previous section. Not surprisingly, the effects of seeding appear to depend on the cloud microphysical structure at the time of initial seeding (Rosenfeld and Woodley, 1997). In comparing seeded and non-seeded clouds without supercooled raindrops on the initial pass, seeding appeared to result in: 1) graupel growth that was too slow to convert cloud water into precipitable-size particles during the lifetime of the updraft, except for the most vigorous and vertically developed clouds, 2) a glaciation rate that was too slow for enhancement of the updraft, and 3) glaciation during the collapse of the cloud, which accelerated its dissipation, leaving holes in the cloud field. In contrast, in clouds with some supercooled raindrops on the initial pass, seeding appeared to result in: 1) fast freezing of the supercooled raindrops and their continued growth as graupel, 2) enhanced growth of the graupel as compared to supercooled raindrops, in accordance with theoretical considerations (Braham, 1964; Johnson, 1987), and 3) rapid glaciation, which increased cloud buoyancy and invigorated the updraft, providing the mechanism for the support of growing graupel particles.

Woodley and Rosenfeld (2000) studied 21 cloud physics units (14 Seeded and 7 Non-Seeded), which were obtained during cloud microphysical studies in Texas. Composites of supercooled cloud liquid water, 2D-C concentrations and cloud drafts were constructed at the level of seeding (-8°C) for the seeded and non-seeded cases relative to the center of the initial cloud pass for each case. Differences in the composites were then obtained as a function of the treatment decision. The differences at the time of the treatment pass and within 180 s thereafter were small. Subsequently, the seeded clouds near the center of the composite had stronger updrafts with higher 2D-C counts and less cloud water than the non-seeded clouds. These differences persisted for about 11 minutes and then decayed. These findings are in accordance with the conceptual model, which calls for invigorated updrafts during the transition from supercooled water to ice. It appears, therefore, that the main characteristic of seeded clouds is the existence and growth of ice particles in rising air that is being depleted of its cloud water by the growth of the ice.

3. SECONDARY SEEDING

In the context of glaciogenic seeding experiments, we define secondary seeding as the ingestion of ice particles by clouds growing through the cloud debris of previously seeded clouds. Secondary seeding should promote glaciation and the early formation of precipitation in the new cloud, as the ingested particles accrete the cloud water. It is hypothesized that the ingested ice will act to glaciate the cloud, affecting the cloud in much the same way as if it had been seeded directly, but at a faster rate. Regardless of the details, it is easy to see how secondary-seeding processes might propagate the effects of seeding in space and in time. Secondary seeding should be especially important in microphysically-continental clouds in which the natural nucleation and growth of ice particles is much slower than in microphysically-maritime clouds. An example of secondary seeding is provided in the next section.

Secondary seeding is not unique to seeded clouds nor is it a rare event. Further, it need not be limited to ice particles. Rosenfeld and Woodley (1997) discuss a case, showing that "clouds that existed in a clustered environment and had ingested embryos from decayed clouds contained large raindrops on the initial pass through active cloud towers. Subsequently, ice formed faster and the KSLWC (King supercooled liquid water content) decayed more rapidly in these clouds." On the other hand, "clouds that were relatively isolated during their growth phases retained their KSLWC longer than clustered clouds. Rain drops were rare during the initial cloud passes and increased only slightly late." This readily illustrates the importance of the exchange of hydrometeors in the development of precipitation in clouds that could not otherwise develop precipitation on their own.

4. A CASE STUDY

An illustration of secondary seeding comes from Texas during the September 1998 cloud physics program when randomized microphysical case studies were qualified (Woodley and Rosenfeld, 2000). The subject cloud was qualified at 18:33 CDT on 22 September 1998 and treated with nine, 20-gm, BF-1, AgI flares as determined by the randomized treatment decision.

4.1 The Cloud Physics Aircraft

The cloud physics aircraft used to document this case was equipped with reverse-flow temperature and dew point probes to make atmospheric soundings close in time and space to the intended cloud studies. It had a Ball variometer for the inference of cloud drafts. The variometer does not, however, give an absolute measure of in-cloud vertical motions and is strongly influenced by the actions of the pilot. Care must be taken to maintain constant attitude during cloud penetration. This allows relative comparisons among the clouds. The PMS probes on the Texas cloud physics aircraft were used to measure droplet and particle sizes in the range from 3 to 800 microns. The FSSP probe was used to document the development of the cloud droplet spectrum with height, beginning at and about 100 m above cloud base. The 2D-C probe was used to document the habit, concentrations and sizes of the cloud hydrometeors before and after cloud treatment. The aircraft was equipped also to measure total aerosols and CCN using PCASP and CCN instrumentation, respectively. The aircraft seeding system, consisting of a flare rack and ejectable AgI flares, was used for the seeding component of the investigations. The forward-looking video camera was used for the documentation of each mission immediately after each flight and for subsequent analyses. The GPS navigation system was used to specify where the seeding took place. Finally, a data system that allowed for the recording of the measured parameters and for the transfer of the data to an Exabyte tape for subsequent processing was essential to a successful mission.

4.2 Results

Documentation of the visual history of the subject cloud is provided in Figure 1a-1g. The photographs were taken from frames of the forward-looking video camera. The microphysical history of the cloud is composited in Figure 2, which contains plots of cloud water (in g m^{-3} from the King cloud water instrument), cloud drafts (in ft min^{-1} from the Ball Variometer) and 2D-C shadow/or counts (in # l^{-1} from the PMS 2D-C laser probe) for five cloud passes. The time appearing on each photograph in Figure 1 is GMT on a 12-hr clock. Thus, the time in Figure 1a is 11:32:40 P.M. GMT or 23:32:40 GMT on a 24-hr clock. The corresponding CDT time on a 24-hr clock is therefore 18:32:40. Time in Figure 2 increases from right to left in the plots instead of the conventional left to right. Further, the time between cloud passes has been compressed to facilitate the presentation in a single figure.

The appearance of the isolated cloud 43s before its entry by the aircraft on a SSE heading is shown in Figure 1a. The clouds in the background are debris from dying clouds >10 km away. The subject cloud had maximum cloud water, updraft and 2D-C shadow/or counts of 2.9 g m^{-3}, 2,700 ft min^{-1} and 394 counts l^{-1} during the pass, which began at 18:33:23 and lasted 21 sec. No ice was evident in the images on this pass. The 2D-C counts appeared to be elevated artificially throughout the cloud physics program, so the changes in 2D-C counts for this case relative to what they were on the first pass are more informative than the absolute values. Nine BF1 AgI flares were ejected into the cloud top on this pass.

The visual appearance of the cloud (Figure 1b) and its internal properties (Figure 2) had not changed much prior to and during the second cloud pass, which was made 130 s after the first and again lasted 21 s. The cloud looked fairly hard and the cloud water had dropped to a maximum of 2.5 g m^{-3}, the updraft had decreased to 1,500 ft min^{-1} and the 2D-C counts had risen slightly to 422 counts l^{-1}. There were no obvious signs of glaciation in this view to the NNW. New cloud towers (not seen in the photograph) separate from the subject cloud were growing well below and to its right.

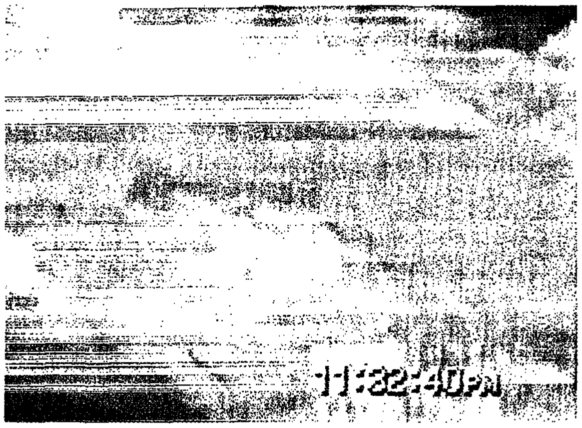

Figure 1a

By the third pass, which came 258s after the first and lasted 18s, the cloud had softened in appearance, suggesting that glaciation was underway (Figure 1c, looking NNW), and the cloud water had dropped drastically to a maximum of 0.6 g m^{-3}, the updraft had decreased further to 400 ft min^{-1} and the 2D-C counts had shot up to 1,264 counts l^{-1}, or 870 counts l^{-1} above the 2D-C maximum on the first pass. Such 2D-C spikes are typical of seeded clouds within 2 to 4 minutes after their seeding. Although the drop in cloud water and the increase in the 2D-C counts is consistent with the conceptual seeding model (Woodley and Rosenfeld, 2000), the cloud had not responded to the seeding with increased growth in the idealized manner described by the conceptual model.

Three photographs, which were taken prior to the fourth pass through the cloud, are shown in Figures 1d-1f. Note that the pictures are just a few seconds apart. By now the subject cloud appeared as glaciated debris framed by the new cloud towers, which were growing through it. This impression is confirmed during the cloud pass at 183937 CDT, which lasted 47 sec and was 374 sec after the initial seeding pass. The same old spike of 2D-C counts (maximum of 940 counts l^{-1}) was penetrated just before the aircraft entered the new cloud tower where a strong updraft (> 2,000 ft min^{-1}) and high cloud water contents (about 4 g m^{-3}) were encountered. Of most interest, the 2D-C counts were elevated to a maximum of 670 counts l^{-1} within the high

Figure 1b

Figure 1c

Figure 1d

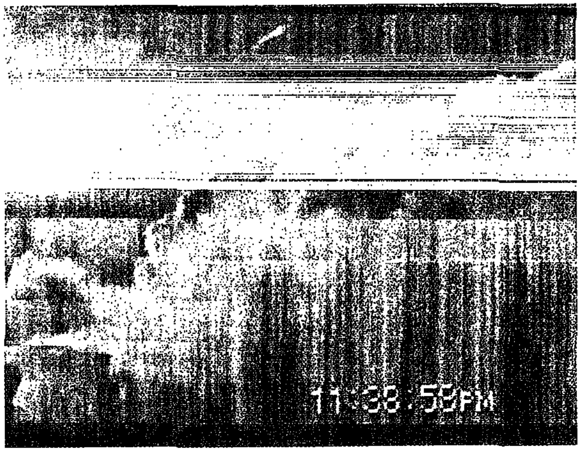

Figure 1e

cloud-water content region. This new cloud appears to have been seeded by the ice particles ingested from the old tower and *this material already appears to have been* distributed over the entire cloud tower. This would be unusual in non-seeded clouds.

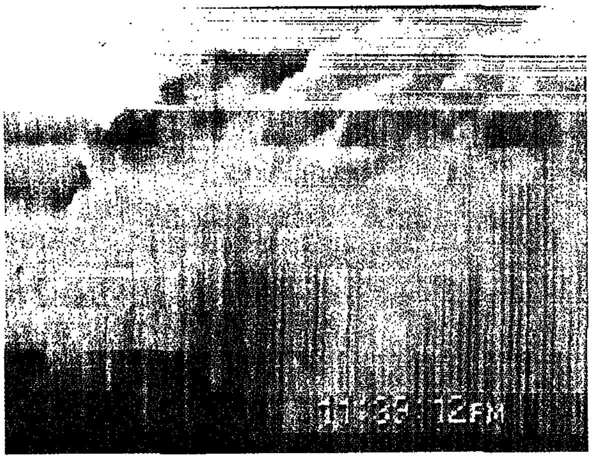

Figure 1f

Only the new cloud tower could be seen at 184119 CDT as the aircraft navigated toward the original treatment position for its fifth pass (Figure 1g, looking SSE). Upon entry at 18:42:06 CDT for the second pass through the new cloud it was determined that the updraft and cloud water contents had decreased (the left-most plot in Figure 2). This pass lasted 48 sec and came 523 sec after the initial seeding pass.

Figure 1g

Figure 1a -1g. Photographs of the seeded cloud from the nose video camera on the cloud physics aircraft flying at 6.1 km. The times on each photo are in GMT on a 12-h clock. Thus, the picture in Figure 1a is at 11:32:40 P.M. GMT or 23:32:40 GMT on a

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24-h clock. To convert the time to local CDT time subtract 5h.

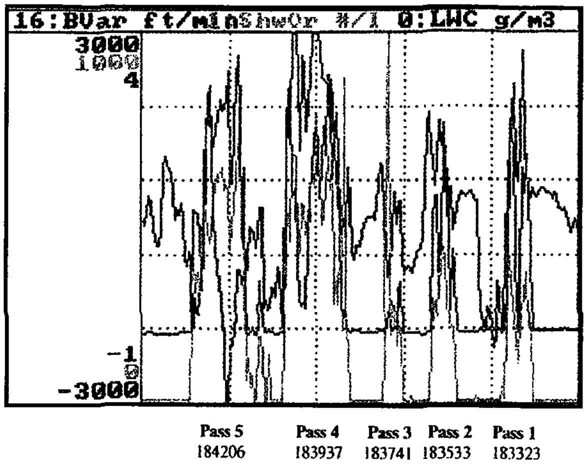

Figure 2. Plots of cloud drafts (ft min^{-1}) from the Ball variometer, cloud liquid water (gm m^{-3}) from the DMT hot wire and shadow/or counts (# l^{-1}) from the PMS 2D-C laser probe. The cloud passes and their entry times are as shown. Time increases from right to left in the plot and has been compressed between the cloud passes.

Three more passes were made into this cloud mass but are not presented here because they add nothing to the material already presented. The sixth pass showed a further decrease in cloud water, updraft and 2D-C counts. The seventh and eighth passes came too far from the original position of the seeded cloud to permit any conclusions regarding the effects of seeding. It is not known whether this cloud produced rain to the ground, because it was beyond the range of the project radar.

This case readily illustrates secondary seeding in the context of cold-cloud seeding experiments. It can be seen that an initial direct seeding action can be propagated in time by ingestion of ice that originated with the first seeding. Glaciation and the development of precipitation-sized particles is accelerated in the receptor clouds. It is important to note that secondary seeding need not depend on the growth response of the initially seeded cloud. Seeding-induced glaciation in clouds with slow natural glaciation is the prime requirement. If this is one of the mechanisms (downdrafts being another) for the propagation of seeding effects, it is obvious that it will be most effective on days when there is enough forcing to produce groups of clustered clouds. Without such forcing the clouds will be seeded in isolation and secondary seeding will not be a factor because there are no clouds in the vicinity to ingest the cloud debris.

Secondary effects of cloud seeding are probably of lesser consequence on days with strong mesoscale forcing that results in massive, clustered, long-lived, convective systems. On such days natural processes are able to operate long enough in the clouds for the natural development of precipitation without the boost that might be provided by primary and/or secondary seeding.

5. CONCLUSIONS

The recirculation of hydrometeors among clouds has been recognized for many years as a means for clouds to influence one another. In microphysically-continental clouds it appears to be a major factor in the development of precipitation in cloud elements with limited lifetimes.

Although secondary seeding, as defined here, can occur in both seeded and non-seeded clouds, it is predominant in seeded clouds when natural glaciation and the development of precipitation-sized particles are slow. Secondary seeding will be most effective when the directly-seeded cloud responds with increased growth, leading to large areas of icy debris as it decays. As shown here, however, secondary seeding can occur even when the directly-seeded cloud shows only a glaciation signature without much growth.

Although it was not possible in the example to document precipitation development in the receptor cloud, its early history showed the probable importance of secondary seeding for precipitation development in clouds not so disposed. The observation in the receptor cloud of high concentrations of ice particles coexisting with a strong updraft (> 10 m s^{-1}) and maximum water contents approaching 4 g m^{-3}) is quite rare in our experience. The potential for the accelerated development of precipitation in such clouds is readily obvious.

Although it seems now an obvious thought, recognition of the potential importance of the ingestion of hydrometeors from seeded clouds as a means of propagating the effects of seeding in space and time may be original to this study. Although it is theoretically possible to simulate these processes, no one has yet made it the focus of their research. Thus, the hypothesized role of secondary seeding in cloud seeding experiments requires additional observations and relevant model simulations.

6.0 ACKNOWLEDGEMENTS

The research described herein was supported by the Texas Natural Resource Conservation Commission (TNRCC). We are indebted especially to Mr. George Bomar, Senior Meteorologist formerly at the TNRCC for his support and encouragement. We appreciate also the input from the two reviewers that resulted in an improved paper.

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