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## The Dynamic Mode of Cloud Seeding

While the fundamental concept of the `static mode' of cloud seeding is that precipitation can be increased in clouds by enhancing their precipitation efficiency, alterations in the dynamics or air motion in clouds due to latent heat release of growing ice particles, redistribution of condensed water, and evaporation of precipitation is also inevitable. Alterations in the dynamics of clouds, however, is not the primary aim of the strategy. By contrast, the focus of the `dynamic mode' of cloud seeding is to enhance the vertical air currents in clouds and thereby vertically process more water through the clouds resulting in increased precipitation. The main difference in implementation of the strategy is that larger amounts of seeding material are introduced into clouds. A goal in the static mode of seeding is to achieve something like 1 to 10 ice crystals per liter at temperatures warmer than -15C. In the dynamic mode of seeding the target ice crystal concentration is more like 100 to 1000 ice crystals per liter, which corresponds to seeding as much as 200 to 1000 g of silver iodide in flares dropped directly into the high supercooled liquid water content updrafts of cumuli. In the 1960's to the 1980's, the hypothesized chain of physical responses to the insertion of such large quantities of seeding materials as summarized by Woodley et al. (1982) included the following: (1) *the nucleated ice crystals glaciates a large volume of the cloud releasing the latent heat of freezing and vapor deposition*, (2) *this warms the cloud yielding additional buoyancy in the seeded updrafts*, (3) *the updrafts with enhanced buoyancy accelerate causing the cloud towers to ascend deeper into the troposphere*, (4) *pressure falls beneath the seeded cloud towers and convergence of unstable air in the cloud will as a result develop*, (5) *downdrafts are enhanced*, (6) *new towers will therefore form*, (7) *the cloud will widen*, (8) *the likelihood that the new cloud will merge with neighboring clouds will therefore increase*, and (9) *increased moist air is processed by the cloud to form rain*.

Few of these hypothesized responses to dynamic seeding have been observationally documented in any systematic way. Observations in clouds seeded for dynamic effects showed that seeding did indeed glaciates the clouds (convert the cloud from liquid to primarily ice) [Sax, 1976; Sax et al., 1979; Sax and Keller, 1980; Hallett, 1981]. Likewise there is evidence that seeding cumulus clouds in the Caribbean and over Florida result in deeper clouds (Simpson et al., 1967; Simpson and Woodley, 1971). The remainder of the elements of the hypothesized chain of events have not been documented, however.

In recent years the dynamic seeding strategy has been applied to Thailand and West Texas. No results are available yet from Thailand but some results from exploratory dynamic seeding experiments over west Texas have been reported by Rosenfeld and Woodley (1989; 1993). Analysis of the seeding of 183 convective cells suggests that seeding increased the maximum height of the clouds by 7%, the areas of the cells by 43%, the durations by 36%, and the rain volumes of the cells by 130%. Overall the results are encouraging but such small increases in vertical development of the clouds is hardly consistent with earlier exploratory seeding experiments.

As a result of their experience in Texas, Rosenfeld and Woodley (1993) proposed an altered conceptual model of dynamic seeding as follows:

``1) NONSEEDED STAGES

(i) *Cumulus growth stage*

The freezing of supercooled raindrops plays a major role in the revised dynamic seeding conceptual model. Therefore, a suitable cloud is one that has a warm base and a vigorous updraft that is strong enough to carry any raindrops that are formed in the updraft above the 0 C isotherm level. Such a cloud has a vast reservoir of latent heat that is available to be tapped by natural processes or by seeding.

(ii) *Supercooled rain stage*

At this stage a significant amount of supercooled cloud and rainwater exists between the 0 and the -10 C levels, which is a potential energy source for future cloud growth.

A cloud with active warm rain processes but a weak updraft will lose most of the water from its upper regions in the form of rain before growing into the supercooled region. Therefore, only a small amount of water remains in the supercooled region for the conversion to ice. Such a cloud has no dynamic seeding potential.

(iii) *The cloud-top rain-out stage*

If the updraft is not strong enough to sustain the rain in the supercooled region until it freezes naturally, most of it will fall back toward the warmer parts of the cloud without freezing. The supercooled water that remains will ultimately glaciate. The falling rain will load the updraft and eventually suppress it, cutting off the supply of moisture and heat to the upper regions of the cloud, thus terminating its vertical growth. This is a common occurrence in warm rain showers from cumulus clouds.

(iv) *The downdraft stage*

At this stage, the rain and its associated downdraft reach the surface, resulting in a short-lived rain shower and gust front.

(iv) *The dissipation stage*

The rain shower, downdraft, and convergence near the gust front weaken during this stage, lending no support for the continued growth of secondary clouds, which may have been triggered by the downdraft and its gust front.

## 2) SEEDED STAGES

(i) *Cumulus growth and supercooled rain*

These stages are the same for the seeded sequence as they are for natural processes.

(ii) *The glaciation stage*

The freezing of the supercooled rain and cloud water near the cloud top at this stage may occur either naturally or be induced artificially by glaciogenic seeding. This conceptual model is equally valid for both cases.

The required artificial glaciation is accomplished at this stage through intensive, on-top seeding of the updraft region of a vigorous supercooled cloud tower using a glaciogenic agent (e.g., AgI). The seeding rapidly converts most of the supercooled water to ice during the cloud's growth phase. The initial effect is the formation of numerous small ice crystals and frozen raindrops.

This rapid conversion of water to ice releases fusion heat--faster and greater for the freezing of raindrops--which acts to increase tower buoyancy and updraft and, potentially, its top height. [The magnitude of the added buoyancy is modified by the depositional heating or cooling that may occur during the adjustment to ice saturation; see Orville and Hubbard (1973).] Entrainment is likely enhanced in conjunction with the invigorated cloud circulation.

The frozen water drops continue to grow as graupel as they accrete any remaining supercooled liquid water in the seeded volume and/or when they fall into regions of high supercooled liquid water content. These graupel particles will grow faster and stay aloft longer because their growth rate per unit mass is larger and their terminal fall velocity is smaller than water drops of comparable mass. This will cause the tower to retain more precipitation mass in its upper portions. Some or all of the increased cloud buoyancy from seeding will be needed to overcome the increased precipitation load.

If the buoyancy cannot compensate for the increased loading, however, the cloud will be destroyed by the downdraft that contains the ice mass. The downdraft will be augmented further by cooling from the melting of the ice hydrometeors just below the freezing level.

The retention of the precipitation mass in the cloud's upper portions delays the formation of the precipitation-induced downdraft and the resultant disruption of the updraft circulation beneath the precipitation mass. This delay allows more time for the updraft to feed additional moisture into the growing cloud.

(iii) *The unloading stage*

The greater precipitation mass in the upper portion of the tower eventually moves downward along with the evaporatively cooled air that was entrained from the drier environment during the tower's growth phase. When the precipitation descends through the updraft, it suppresses the updraft. If the invigorated pulse of convection has had increased residence time in regions of light to moderate wind shear, however, the precipitation-induced downdraft may form adjacent to the updraft, forming an enhanced updraft-downdraft couplet. This unloading of the updraft may allow the cloud a second surge of growth to cumulonimbus stature.

When the ice mass reaches the melting level, some of the heat released in the updraft during the glaciation process is reclaimed as cooling in the downdraft. This downrush of precipitation and cooled air enhances the downdraft and the resulting outflow beneath the tower.

(iv) *The downdraft and merger stage*

The precipitation beneath the cloud tower is enhanced when the increased water mass reaches the surface. In addition, the enhancement of the downdraft increases the

convergence at its gust front.

(v) *The mature cumulonimbus stage*

The enhanced convergence acts to stimulate more neighboring cloud growth, some of which will also produce precipitation, leading to an expansion of the cloud system and its conversion to a fully developed cumulonimbus system.

When this process is applied to one or more suitable towers residing within a convective cell as viewed by radar, greater cell area, duration, and rainfall are the result. Increased echo-top height is a likely but not a necessary outcome of the seeding, depending on how much of the seeding-induced buoyancy is needed to overcome the increased precipitation loading.

(vi) *The convective complex stage*

When seeding is applied to towers within several neighboring cells, increased cell merging and growth will result, producing a small mesoscale convective system and greater overall rainfall.

This is an idealized sequence of events. Dissipation may follow the glaciation stage or at any subsequent stage if the required conditions are not present."



**Figure 1:** Diagrammatic illustration of the dynamic seeding conceptual model for warm-based supercooled cumuli. Revised as of July 1992. [From Rosenfeld and Woodley, 1993.]

Figure 1 illustrates their revised conceptual model of dynamic seeding. This conceptual model differs from the earlier one in that it emphasizes the conversion of liquid water into graupel particles which fall slower and grow faster than water drops of comparable mass. The seeding-induced graupel particles will reside in the cloud updraft longer and achieve greater size than a population of water drops in a similar unseeded cloud. They explain the lack of enhanced vertical development of the seeded clouds to increased precipitation mass loading. The enhanced thermal buoyancy of the cloud due to seeding-induced ice phase conversion, they argue is offset by the increased mass loading which results in only modest increases in updraft strength and cloud top height.

This new concept emphasizes that rapid conversion of supercooled liquid water into graupel must take place in the seeded plume. As such, it is limited to rather warm-based, maritime clouds having a broad cloud droplet distribution and supercooled raindrops. Numerous modeling studies have shown that the speed of conversion of supercooled liquid water to ice is facilitated by the presence of supercooled raindrops (Cotton, 1972a,b; Koenig and Murray, 1976; Scott and Hobbs, 1977; Lamb et al., 1981). The supercooled raindrops readily collect the ice crystals nucleated by the seeding agent and freeze. The frozen raindrops then collect cloud droplets becoming low-density graupel particles if the liquid water content of the cloud is low or modest, or become high-density hailstones if the liquid water contents are rather large.

Rosenfeld and Woodley (1993) argue that the retention of the increased ice mass in the form of graupel

is an important new aspect of their dynamic seeding conceptual model. This may delay the formation of a downdraft and allows more time for further growth of the cloud. The eventual unloading of the enhanced water mass, they argue, is favorable for subsequent regeneration of the cloud by the downdraft-induced gust fronts leading to larger, longer-lived cells.

In summary, the concept of dynamic seeding is a physically plausible hypothesis that offers the opportunity to increase rainfall by much larger amounts than simply enhancing the precipitation efficiency of a cloud. It is a much more complex hypothesis, however, requiring greater quantitative understanding of the behavior of cumulus clouds and their interaction with each other, with larger-scale weather systems, and depends on the details of precipitation evolution. Being a complex, multi-link chain of steps, the hypothesis is very vulnerable to one link of the chain being wrong, or that the full chain works together in rather limited circumstances. Measurements and modeling studies are needed to support this hypothesis since the seeding experiments while suggestive of being successful, are still vulnerable to type-I statistical errors. This is always a concern with convective storms since the *natural variability* of these storms is so large.

Overall, the dynamic seeding experiments have demonstrated rainfall increases for radar-defined ``floating" targets or clusters of convective cells. They have not demonstrated, however, that rainfall can be increased over fixed ground target areas consistently. Thus the dynamic seeding concept remains as yet an unproven candidate for application to water resource management.

