Weather Modification by Cloud Seeding–A Status Report 1989-1997

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1 Introduction

The purpose of this chapter is to introduce and explain the status of weather modification by cloud seeding by updating the findings and concepts summarized in *Human Impacts on Weather and Climate* by Cotton and Pielke (1995).

In this chapter I will focus only on three methods of seeding clouds. The first two are related to supercooled clouds and are called the "static mode" of cloud seeding and the "dynamic mode" of cloud seeding. The third method is the modification of warm clouds by hygroscopic seeding.

2 The Static Mode of Cloud Seeding

The main objective of the "static mode" of cloud seeding is to increase the efficiency of precipitation formation by introducing an "optimum" concentration of ice crystals in supercooled clouds by cloud seeding. It was originally thought that clouds were deficient in ice nuclei and therefore additions of modest concentrations of ice nuclei should result in a more efficient precipitation-producing cloud system. All that was needed was to introduce seeding material from the ground or at the base of clouds which would then enhance ice crystal concentrations and thereby increase rainfall. Cotton and Pielke (1995) concluded that physical studies and inferences drawn from statistical seeding experiments over the last 50 years suggests that there exists a much more limited window of opportunity for precipitation enhancement by the static-mode of cloud seeding than was originally thought. The window of opportunity for cloud seeding appears to be limited to:

1) clouds which are relatively cold-based and continental;

2) clouds having top temperatures in the range –10 to –25°C;

3) a time scale limited by the availability of significant supercooled water before depletion by entrainment and natural precipitation processes.

This limited scope of the opportunities for rainfall enhancement by the static-mode of cloud seeding that has emerged in recent years may explain why some cloud seeding experiments have been successful while other seeding experiments have yielded inferred reductions in rainfall from seeded clouds or no effect. A successful experiment in one region does not guarantee that seeding in another region will be successful unless all environmental conditions are replicated as well as the methodology of seeding. This, of course, is highly unlikely.

We argued that the success of a cloud seeding experiment or operation, therefore, requires a cloud forecast skill that is far greater than is currently in use. As a result, such experiments or operations are at the mercy of the *natural variability* of clouds. The impact of *natural variability* may be reduced in some regions where the local climatology favors clouds which are in the appropriate temperature windows and are more continental. A 'time window' may still exist, however, and this will yield uncertainty to the results unless the field personnel are particularly skillful in selecting suitable clouds.

Furthermore, we concluded by stating that "the 'static' mode of cloud seeding has been shown to cause the expected alterations in cloud microstructure including increased concentrations of ice crystals, reductions of supercooled liquid water content, and more rapid production of precipitation elements in both cumuli (Cooper and Lawson, 1984) and orographic clouds (Reynolds, 1988; Super and Boe, 1988; Super et al., 1988; Super and Heimbach, 1988; Reynolds and Dennis, 1986). The documentation of increases in precipitation on the ground due to static seeding of cumuli, however, has been far more elusive with the Israeli experiment (Gagin and Neumann, 1981) providing the strongest evidence that static seeding of cold-based, continental cumuli can cause significant increases of precipitation on the ground. The evidence that orographic clouds can cause significant increases in snowpack, we argued, is far more compelling, particularly in the more continental and cold-based orographic clouds (Mielke et al., 1981; Super and Heimbach, 1988)."

But even these conclusions have been brought into question in the last 10 years. The Climax I and II wintertime orographic cloud seeding experiments (Grant and Mielke, 1967; Mielke et al., 1971; Chappell et al., 1971; Mielke et al., 1981) are generally acknowledged by the scientific community (National Academy of Sciences, 1975; Sax et al., 1975; Tukey et al., 1978) for providing the strongest evidence that seeding those clouds can significantly increase precipitation. Nonetheless, Rangno and Hobbs (1987; 1993) question both the randomization techniques and the quality of data collected during those experiments and conclude that the Climax II experiment failed to confirm that precipitation can be increased by cloud seeding in the Colorado Rockies. Even so, Rangno and Hobbs (1987) did show that precipitation may have been increased by about 10% in the combined Climax I and II experiments. This should be compared, however, to the original analyses by Grant et al. (1969), Mielke et al. (1970) and Mielke et al. (1971) which indicated greater than 100% increase in precipitation on seeded days for Climax I and 24% for Climax II. Subsequently, Mielke (1995) explained a number of the criticisms made by Rangno and Hobbs in regard to the statistical design of the experiments, in particular the randomization procedures, the quality and selection of target and control data and the use of 500 mb temperature as a partitioning criteria. It is clear that the design, implementation, and analysis of this experiment was a learning process not only for meteorologists but statisticians as well.

The results of the many re-analyses of the Climax I and II experiments have clearly "watered down" the overall magnitude of the possible increases in precipitation in wintertime orographic clouds. Furthermore, they have revealed that many of the concepts that were the basis of the experiments are far too simplified compared to what we know today. Furthermore, many of the cloud systems seeded were not simple "blanket-type orographic clouds" but were part of major wintertime cyclonic storms that pass through the region. As such, there was a greater opportunity for ice multiplication processes and riming processes to operative in those storms, making them less susceptible to cloud seeding.

As noted above, Cotton and Pielke (1995) concluded that the strongest evidence of significant precipitation increases by static seeding of cumulus clouds came from the Israel I and II experiments. It is clear there are no "sacred cows" in the science of weather modification! Even the Israeli (Gagin and Neumann, 1981) experiments have come under attack by Rangno and Hobbs (1995). From their re-analysis of both the Israel I and II experiments, they argue that the appearance of seeding-caused increases in rainfall in the Israel I experiment was due to "lucky draws" or a Type I statistical error. Furthermore, they argued that during Israel II naturally heavy rainfall over a wide region encompassing the north target area gave the appearance that seeding caused increases in rainfall over the north target area. At the same time, lower natural rainfall in the region encompassing the south target area gave the appearance that seeding decreased rainfall over that target area.

Rosenfeld and Farbstein (1992) suggested that the differences in seeding effects between the north and south target areas during Israel II is the result of the incursion of desert dust into the cloud systems. They argue that the desert dust contains more active natural ice nuclei and that they can also serve as coalescence embryos enhancing collision and coalescence among droplets. Together, the dust can make the clouds more efficient rain-producers and less amenable to cloud seeding.

Cotton and Pielke (1995), among others, argued that the "apparent" success of the Israeli seeding experiments was due to the fact that they are more susceptible to precipitation enhancement by cloud seeding. This is because numerous studies (Gagin, 1971; Gagin, 1975; Gagin, 1986; Gagin and Neumann, 1974) have shown that the clouds over Israel are continental having cloud droplet concentrations of about 1000cm^{-3} and that ice particle concentrations are generally small until cloud top temperatures are colder than -14C. There is little evidence for ice particle multiplication processes operating in those clouds.

Rangno and Hobbs (1995) also reported on observations of clouds over Israel containing large supercooled droplets and quite high ice crystal concentrations at relatively warm temperatures. In addition, Levin (1994) presented evidence of active ice multiplication processes in Israeli clouds. This further erodes the perception that the clouds over Israel were quite susceptible to seeding. Naturally, Rangno and Hobbs (1995) paper generated quite a large reaction in the weather modification community. The March issue of the Journal of Applied Meteorology contained a series of comments and replies related to their paper (Rosenfeld, 1997; Rangno and Hobbs, 1997a; Dennis and Orville, 1997; Rangno and Hobbs, 1997b; Woodley, 1997; Rangno and Hobbs, 1997c; Ben-Zvi, 1997; Rangno and Hobbs, 1997d). These comments and responses clarify many of the issues raised by Rangno and Hobbs (1995). Nonetheless, the image of what was originally thought of as the best example of the potential for precipitation enhancement of cumulus clouds by static seeding has become considerably tarnished.

Recently, Ryan and King (1997) presented a comprehensive overview of over 47 years of cloud seeding experiments in Australia. These studies almost exclusively focused on the static seeding concept. In this water-limited country, cloud seeding has been considered as a potentially important contributor to water management. As a result their review included discussions of the overall benefit/costs to various regions.

In spite of having considerable professional contact with many of the scientists in Australia, I was surprised and overwhelmed by the number of cloud seeding experiments that have been carried out there. Over 14 cloud seeding experiments were conducted covering much of southeastern, western, and central Australia as well as the island of Tasmania. Ryan and King (1997) concluded that static seeding over the plains of Australia is not effective. They argue that for orographic stratiform clouds, there is strong statistical evidence that cloud seeding increased rainfall, perhaps by as much as 30% over Tasmania when cloud top temperatures are between -10 and -12 C in southwesterly airflow. The evidence that cloud seeding had similar effects in orographic clouds over the mainland of southeastern Australia is much weaker. This is somewhat surprising from a physical point of view since the clouds over Tasmania are maritime. As such one would expect the opportunities for warm-cloud collision and coalescence precipitation processes to be fairly large. Furthermore, in those maritime clouds ice multiplication processes should be operative; especially when embedded cumuliform cloud elements are present. Thus natural ice crystal concentrations should be competitive with concentrations expected from static seeding, especially in the -10 to -12C temperature range. If the results of the Tasmanian experiments are real, benefit/cost analyses suggests that seeding has a gain of about 13/1. This is viewed as a real gain to hydrologic energy production. I guess we'll have to wait and see what Rangno and Hobbs have to say about the Tasmanian experiment.

Another exploratory study of static seeding effects on precipitation that has suggested positive yields was reported by Mather et al. (1996a). They analyzed a total of 127 storms over South Africa using an objective radar-based storm tracking technique. They found that the radar-measured rain flux and storm area from seeded clouds was significantly greater than the control population of clouds. These analyses are for radar-defined floating targets. They do not, however, tell one how effective cloud seeding is in increasing rainfall over fixed target areas on the ground.

Overall, since 1989 the scientific basis of static seeding of supercooled clouds has undergone considerable scrutiny and evaluation. While some of the recent work bolsters the early optimism of the potential of static seeding, overall the image of the scientific credibility of the static seeding concept has been tarnished more than it has been enhanced. Skepticism of its overall potential for a significant cost-effective component to water resource management prevails.

3 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 glaciate 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 glaciate 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 it upper portions. Some or all of the increase 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 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 do 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 grauple 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

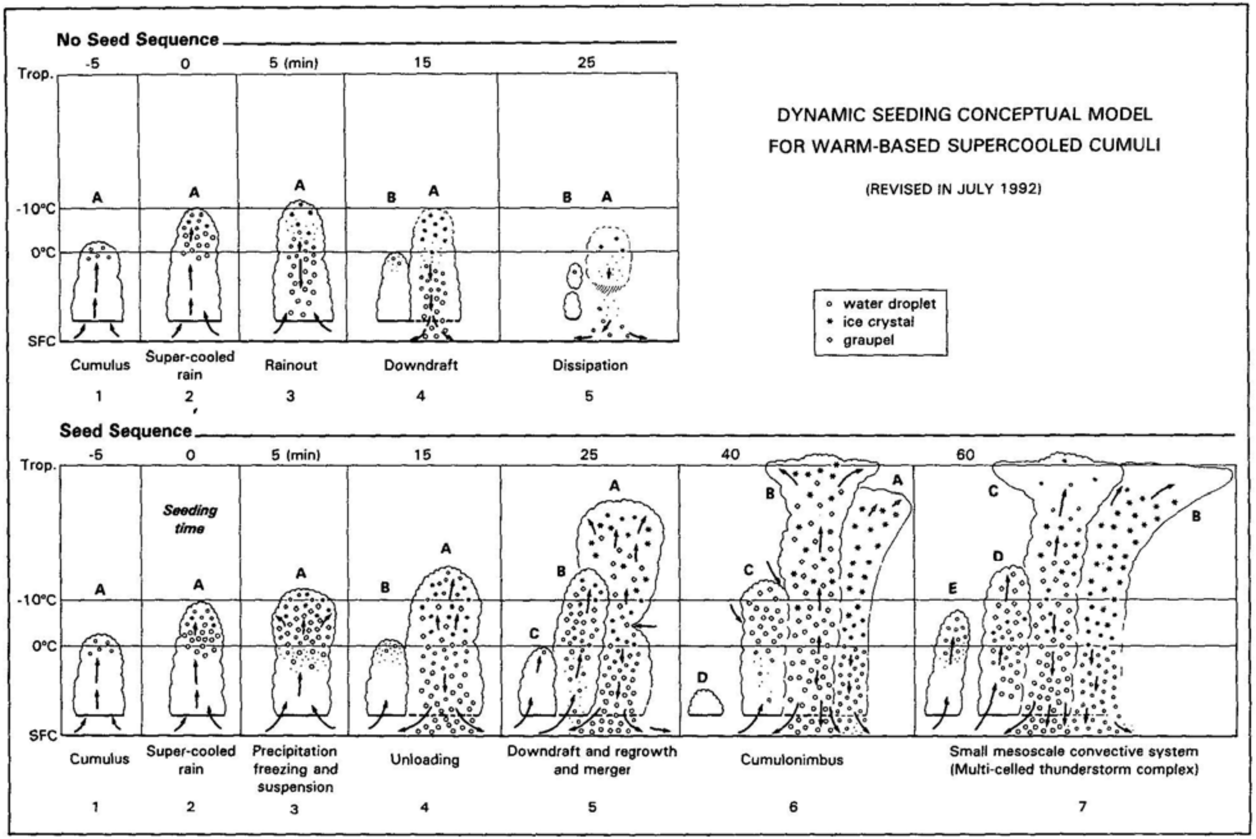
DYNAMIC SEEDING CONCEPTUAL MODEL
FOR WARM-BASED SUPERCOOLED CUMULI
(REVISED IN JULY 1992)
No Seed Sequence
-5
0
5 (min)
15
25
Trop.
-10°C
0°C
SFC
A
B
Cumulus
Super-cooled rain
Rainout
Downdraft
Dissipation
1
2
3
4
5
water droplet
ice crystal
graupel
Seed Sequence
-5
0
5 (min)
15
25
40
60
Seeding time
C
D
E
Cumulus
Super-cooled rain
Precipitation freezing and suspension
Unloading
Downdraft and regrowth and merger
Cumulonimbus
Small mesoscale convective system
(Multi-celled thunderstorm complex)
1
2
3
4
5
6
7

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.]

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.

Ronsenfeld 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.

4 Hygroscopic Seeding

As noted in Cotton and Pielke (1995) the dominant process for precipitation formation in warm clouds is collision and coalescence. We have seen that this process is very effective in clouds which are warm-based and maritime, or have substantial liquid water contents. The collision and coalescence process among liquid drops is also an important contributor to rain formation in many mixed-phase clouds, and the presence of supercooled drizzle-drops and raindrops enhances the rate of formation of precipitation in supercooled portions of clouds as well.

One method of seeding clouds to enhance precipitation is to introduce hygroscopic particles (salts) which readily take on water by vapor deposition in a supersaturated cloudy environment. The conventional approach is to produce ground salt particles in the size-range of 5-100 μm, and release these particles into the base of clouds. These particles grow by vapor deposition and readily reach sizes of 25 to 30 μm in diameter or greater. They are then large enough to serve as "coalescence" embryos and initiate or participate in rain formation by collision and coalescence.

Cotton and Pielke (1995) reviewed the various physical and statistical experiments that have been carried out over the years. The results of the statistical experiments were generally inconclusive though some suggested positive effects. Observational and modeling studies provide further support that at least in some clouds, the addition of hygroscopic seeding material can broaden drop-spectra and at least hasten the onset of precipitation formation. We concluded that " there appears to be a real opportunity to enhance rainfall through hygroscopic seeding in some clouds. It has not been determined how open the 'window of opportunity' actually is. In warm-based, maritime clouds the rate of natural production of rainfall may be so great that there is little opportunity to beat nature at its own game. On the other hand, some cold-based continental clouds may have so many small droplets that seeding-produced big drops cannot collect them owing to very small collection efficiencies. Thus there probably exists a spectrum of clouds between these two extreme types that have enough liquid water to support a warm cloud precipitation process that can be accelerated by hygroscopic seeding. The problem is "to identify those clouds, and deliver the right amount of seeding material to them at the right time."

As optimism for significant precipitation enhancement by static seeding of supercooled clouds has waned, enthusiasm for the potential of hygroscopic seeding has grown. Two ongoing research programs, one in Thailand, the other in South Africa, have contributed to that enthusiasm.

The South African experiment was motivated by a report by Mather (1991) which suggested that large liquid raindrops at -10C found in a cumulonimbus were the result of active coalescence processes caused by the effluent from a Kraft paper mill. Earlier, Hobbs et al. (1970) found that the effluent from paper mills can be rich in cloud condensation nuclei (CCN). Moreover, Hindman et al. (1977a,b) found paper pulp mill effluent to have high concentrations of large and ultra-giant hygroscopic particles, which is consistent with the idea that the paper pulp mill effectively "seeded" the storm.

Another reason for optimism is that Mather et al. (1996b) applied a pyrotechnic method of delivering salt, based on a fog dispersal method developed by Hindman (1978). This reduced a number of technical difficulties associated with preparing, handling, and delivery of very corrosive salt particles. Seeding with this system is no more difficult than silver iodide flare seeding. Compared to conventional methods of salt delivery, the flares produce smaller-sized particles in the size range of 0.5 to 10 μm. Thus, not as much mass must be carried to obtain a substantial yield of seeding material. The question of effectiveness of this size range will be discussed below. Seeding trials with this system suggested that the pyrotechniques produced a cloud droplet spectrum that was broader and with fewer numbers, which would be expected to increase the chance for initiation of collision and coalescence processes.

Mather et al. (1996b) analyzed radar-defined cells over a period of about an hour to identify the seeding signatures for 48 seeded storms compared to 49 unseeded storms. They showed that after 20 to 30 minutes, the seeded storms developed higher rain masses and maintained those higher rain masses for another 25 to 30 minutes. Bigg (1997) performed an independent evaluation of the South African exploratory hygroscopic seeding experiments and also found that the seeded storms clearly lasted longer than the unseeded storms. Bigg also suggested that there was a clear dynamic signature of seeding. He argued that hygroscopic seeding initiated precipitation lower in the clouds, which, in turn, was not dispersed horizontally as much as the unseeded clouds by vertical wind shears. As a result, Bigg speculated that low-level downdrafts became more intense, which yielded stronger storm regeneration by the downdraft outflows, and longer-lived precipitation cells.

Bigg's (1997) hypothesis is a plausible scenario that should be examined thoroughly with numerical models and coordinated, high resolution Doppler radars.

Cooper et al. (1997) performed simulations of the low-level evolution of droplet spectra in seeded and unseeded plumes. Following a parcel ascending in the cloud updrafts they calculated the evolution of droplet spectra by vapor deposition and collection. The calculations were designed to emulate the effects of hygroscopic seeding with the South African flares. The calculations showed that introduction of particles in the size-range characteristic of the flares resulted in an acceleration of the collision and coalescence process. If the hygroscopic particles were approximately 10 μm in size, precipitation was initiated faster. But, when more numerous 1 μm hygroscopic particles were inserted, high concentrations of drizzle formed. For a given amount of condensate mass, if the mass is on more numerous drizzle drops than on fewer but larger raindrops, then evaporation rates are greater in the subcloud layer. This could lead to more intense dynamic responses as proposed by Bigg, suggesting that seeding with smaller hygroscopic particles may have some advantages. Keep in mind, however, that this is a very simple model. More comprehensive model calculations should also be performed.

In summary, there are some exciting new results of hygroscopic seeding with flares. This work is still very exploratory and is a long way from proving that such techniques can make significant increases in rainfall on the ground for a variety of weather and climate regimes. It is refreshing for a change to end an overview of the science of weather modification by cloud seeding on a rather upbeat note!

5 Weather Modification Funding

Cotton and Pielke (1995) noted that the funding in weather modification research in the United States peaked in the early 1970's at about \$19 million per year. By the 1990's that funding level had decreased to less than \$5 million a year, with a major part of that funding being a Department of Commerce state/federal cooperative program which we labeled a "pork barrel" program. We discussed a number of factors that could have contributed to such a collapse in weather modification funding which I shall not repeat here. Suffice it to say that there are a number of lessons to be learned from what happened, especially in the global climate program.

In 1997, the Department of Commerce State/Federal program is zero budgeted and the identifiable research funding in the U.S. is about \$0.5 million. Likewise, the government of Israel decided to terminate funding of weather modification research after 36 years of continuous funding. So funding in weather modification research has continued to slide.

Note that this does not mean that weather modification activities have stopped. Operational weather modification programs exist in something like 22 countries worldwide and in the United States alone there may be as many as 40 operational seeding projects going on in any one year. What has happened, is that we have entered the "dark ages" of weather modification where operational cloud seeding projects are if anything proliferating without a sound scientific research program supporting them.

6 Lessons Learned that the Global Climate Change Community Should Pay Attention To

Cotton and Pielke (1995) examined some of the implications of weather modification research to research on global climate change. They considered the following issues:

- The importance of natural variability,
- The dangers of overselling,
- The capricious administration of science, and
- scientific credibility and advocacy.

Let us re-examine each of these common issues more fully, and also discuss the implications of hygroscopic seeding research to the CCN-albedo hypothesis.

6.1 Hygroscopic Seeding and the CCN-Albedo Hypothesis

Twomey (1974) first postulated that increases pollution results in greater CCN concentrations and numbers of cloud droplets, which, in turn, increase the reflectance of clouds. Twomey et al. (1984) argued that enhanced cloud albedo has a magnitude comparable to that of greenhouse warming and acts to cool the atmosphere, in opposition to greenhouse warming.

Subsequently Albrecht (1989) proposed that higher droplet concentrations in polluted air will reduce the rate of drizzle formation, resulting in wetter, more reflective clouds. Furthermore, Ackerman et al. (1993; 1994) proposed that heavily drizzling straticumulus clouds can reduce cloud top cooling to such an extent that a stratus-topped boundary layer can collapse. Pollution-caused increases in CCN can thereby suppress the drizzle process leading to the formation of a stratus-topped boundary layer in some boundary layer regimes that may not otherwise be sustainable. Cotton and Pielke (1995) noted, however, the susceptability of the drizzle process in marine stratocumulus clouds to anthropogenic emissions of CCN may depend on the presence or absence of large and ultra-giant aerosol particles in the subcloud layer. In other words the drizzle formation process is not solely regulated by the concentrations of CCN and cloud liquid water contents but possibly also by the details of the spectrum of the hygroscopic aerosol population. This concept has been reinforced by the hygroscopic seeding simulations by Cooper et al. (1997). Their model calculations suggest that high concentrations of hygroscopic particles in the 0.1 μm to 1.0 μm size range can accelerate the drizzle formation process. An implication is that even though pollution may increase the total concentration of CCN particles, if the concentration of particles greater than 0.1 μm is likewise increased, the drizzle formation process may not be suppressed, but instead could be actually enhanced. This could counter the tendency of clouds in polluted air from being more reflective. Again, we emphasize that knowledge of the total size-distribution of hygroscopic aerosol is needed to assess the potential impacts of polution on global climate!

6.2 The Importance of Natural Variability

We have seen that our ability of determining if cloud seeding *causes* some *observed or hypothesized effect*, such as changes in local rainfall in specified target areas, is strongly dependent upon the *natural variability* of the system. However, the same can be said in assessing if anthropogenic greenhouse gas emissions, or deforestation, or release of CCN have any significant impact on global climate. While the time and space scales are very different, nonetheless the bottom line in examining potential human-caused effects is: *are these effects large enough in magnitude to be extricated from the 'noise' of the natural variability of the system?* There are few, if any, cases in which we can answer this question affirmatively. Ice cores have shown, for example, that a switch from an ice age climate to a non-ice age environment can occur over only a few decades (La Brecque, 1989a,b) without human intervention.

6.3 The Dangers of Overselling

We have seen that funding of the science of weather modification underwent a period of rapid rise, followed by an abrupt crash. One of the leading causes of that crash, we believe, is that the program was oversold. The claims that only a few more years of research and development will lead to a scientifically-proven technology that will contribute substantially to water management and severe weather abatement, were either great exaggerations, or just false. This is largely because we greatly underestimated the complexity of the scientific and technological problems we were (and still are) faced with.

The same can be said about human impacts on global climate. There are many scientists who are claiming that the short-term (periods of year-to-year, or decades) variations in weather and climate are clear evidence that we are experiencing the effects of anthropogenic greenhouse emissions. Moreover, many claim that the 'forecasts' being made by global climate models, represent realistic expectations of global-averaged changes in temperature and rainfall in the next decade or century. In my opinion, both of these claims represent overselling of the climate program. These claims appear and are discussed in the professional literature (e.g., Schneider, 1990; Titus, 1990a,b; IPCC, 1991; Kellogg, 1991) and in the lay press (e.g., Brooks, 1989; Schneider, 1989; Thatcher, 1990; Bello, 1991; Luoma, 1991; UCAR/NOAA, 1991). Titus (1990a), for example, proposes the rerouting of the Mississippi River to save coastal Louisiana! As an example of such extreme claims to mitigate anthropogenically caused global warming, a 1991 National Academy Press report (National Academy of Sciences, 1991) has considered the insertion of 50,000 100 km^2 mirrors in space to reflect incoming sunlight. Such gross global climate engineering represents a close analog to the exaggerated claims in weather modification which were made in the 1960s and 1970s. Short-term variations of weather and climate are clearly within the *natural variability* of climate to the extent that we can realistically assess it. Moreover, the models are not really 'forecast' models. They are simply research models designed to simulate the responses of hypothesized anthropogenic changes to weather and climate, *other things being the same.* Besides having many limitations in their physical/chemical parameterizations, they are not designed to simulate (or predict) the consequences of many other natural factors affecting climatic change. That is because we simply do not know enough about all the processes of importance to climatic change to include them in any quantitative forecast system. What it amounts to is that many scientists are grossly underestimating the complexity of interactions among the earth's atmosphere, ocean, geosphere, and biosphere. These problems are so complex that it may take many decades, or even centuries, before we have matured enough as a scientific community to make *credible predictions* of long-term climate trends and their corresponding regional impacts. Even then, we may find that the uncertainty level of those predictions due to outside (the earth) influences may be so large that those predictions are not useful for social planning.

6.4 The Capricious Administration of Science and Technology

In the United States, as well as many developed countries, science and technology, is often poorly administered. As we have seen in weather modification, administration of many programs is fragmented among a number of basic and mission-oriented agencies, all of which compete for funding at national and state levels. This competition amongst the agencies often leads to the greatly exaggerated claims that many of the scientific and technological issues will be solved in the next five to ten years.

In addition, because many of these agencies are mission-oriented, their job is to examine the impacts of human-induced changes on weather and climate on energy, air quality, water resources, or agriculture. Their job is not to advance the fundamental scientific issues regarding the behavior of the earth system, but to get on with the business of evaluating the impacts of anthropogenic activity on their programs. As a result, they are often looking for shortcuts to bottom line answers that can probably only be obtained through meticulous, often time consuming scientific research.

Moreover, national governing bodies (legislatures, presidents, etc.) all work on time scales of two, four, or six years, and want to be able to identify impacts of their programs on time scales of their tenure. If significant progress is not made on those time scales, then often funding in those programs is reduced, if not curtailed, and new, competing programs are brought to the forefront. This results in shortsighted funding in science and technology in which programs are begun and before they reach maturity they are curtailed, then the rush is on to get on the bandwagon with the latest fad. The scientific and technological problems associated with furthering our understanding of human impacts and natural variability and feedbacks of weather and climate are so complicated and multifaceted that many of the issues will not be resolved on time scales of decades or possibly centuries. *Thus, programs associated with the investigation of human impacts on weather and climate require sustained, stable national funding at a high level.* A view supporting this idea has been recommended in the Policy Statement of the American Meteorological Society on Global Climate Change (1991) and in the report, Global Climate Change: A New Vision for the 1990s (Michaels, 1990), which was produced by a group of climate scientists in the fall of 1990 who questioned the overselling and shortsighted perspective of current climate change government policy.

7 Scientific Credibility and Advocacy

We have seen that with few exceptions, the scientific evidence is not conclusive cloud seeding is causing the desired responses. More over, the evidence that human activity is "causing" observed changes in weather and climate is also quite tenuous. With that in mind we ask, *should scientists be actively involved in advocating that we apply cloud seeding techniques to enhancing rainfall, or reducing emissions of greenhouse gases to alleviate greenhouse warming?* Certainly the scientists are the best informed with regard to the consequences of human activity and, one could say, that if the informed scientist does not take an advocacy role in recommending that action be taken, then no one else will.

Such a position is not without its dangers, however. If, for example, scientists participate in an operational cloud seeding program or play an obvious role as advocates of applying cloud seeding, they can jeopardize their credibility as truly objective scientists and therefore adversely affect both the program and the individual scientists. The same can be said with regard to advocates of major disruptive societal changes with regard to greenhouse emissions.

Some might argue that the risk of losing one's scientific credibility is purely a personal one and must be weighed against the potential societal gains by taking immediate action to relieve drought or reduce greenhouse warming. In fact, the adverse impacts extend far beyond those affecting the individual scientist. Loss of scientific credibility is infectious and can, therefore, propagate through an entire scientific discipline and even to the scientific community as a whole. The fall of the science of weather modification by cloud seeding was almost certainly due, in part, to a loss of scientific credibility. The global climate change community must likewise be careful that a loss of scientific credibility does not propagate through their discipline, or the discipline of atmospheric science as well. Thus premature advocacy that action be taken now, could, in the long run, destroy the prospects for obtaining solid scientific evidence that human activity is affecting weather and climate.

7.1 Should Society Wait for Hard Scientific Evidence?

Overall there is little hard scientific evidence that anthropogenic activity, either advertently or inadvertently, is causing significant changes in weather and climate, particularly on the global scale. This is certainly true with respect to cloud seeding where there are only a few limited examples of where cloud seeding has been scientifically shown to be effective in enhancing rainfall. Nonetheless, there are many nations which are currently running operational cloud seeding projects. Apparently, the decision has been made in those nations and states that the benefits outweigh the risks of applying the scientifically unproven technology of weather modification by cloud seeding. The major risks, however, are limited to the possibility of creating severe weather or floods, and to increasing rainfall in one local region at the expense of rainfall in a neighboring local region. Often the decision to apply cloud seeding technology in a particular country or state is a prescription of a *political placebo* or a decision that it is better to do something than to sit idly by and do nothing as reservoirs dry up and crops wither and die due to the absence of water.

Again, the situation is not much different with respect to human impacts on global climate. We lack hard scientific evidence that anthropogenic activity is causing, or will cause, changes in global climate. Nonetheless, there is convincing evidence that CO_2 concentrations are increasing at an alarming rate . Clearly, reductions in CO_2 emissions in many of the industrialized countries will have a significant impact on global CO_2 emissions and reduce the chance that human activity will have a significant impact on weather and climate. Certainly there is evidence that the more developed nations are at least causing a leveling off of CO_2 emissions.

But what are the costs? Some of the costs are in terms of reduced industrial productivity which impacts employment and the general standard of living. Another cost is associated with the impacts of using alternate energy resources. One could decide to convert to "cleaner" nuclear power rather than fossil fuels as has been done in France. In this case one is trading off the potential impacts of CO_2 emissions on global warming against the long-term problem of disposing of nuclear waste as well as the dangers of inadvertent releases of nuclear materials. Is this a wise tradeoff? Without solid scientific evidence that CO_2 emissions are causing significant changes in climate, one cannot make an objective evaluation of the relative cost of each alternative.

Of course, doing nothing could have costs as well. If indeed anthropogenic CO_2 emissions are causing global warming, then by doing nothing at this time, our climate could be shifting toward irreversible states or the cost of reversing such climatic shifts becomes ever more costly. The point is: the scientific evidence that anthropogenic emissions of CO_2 is causing or will cause global warming is not much more compelling than that cloud seeding can increase rainfall. The decision to do or not do something about it is therefore a political decision and not a scientific/technical decision.

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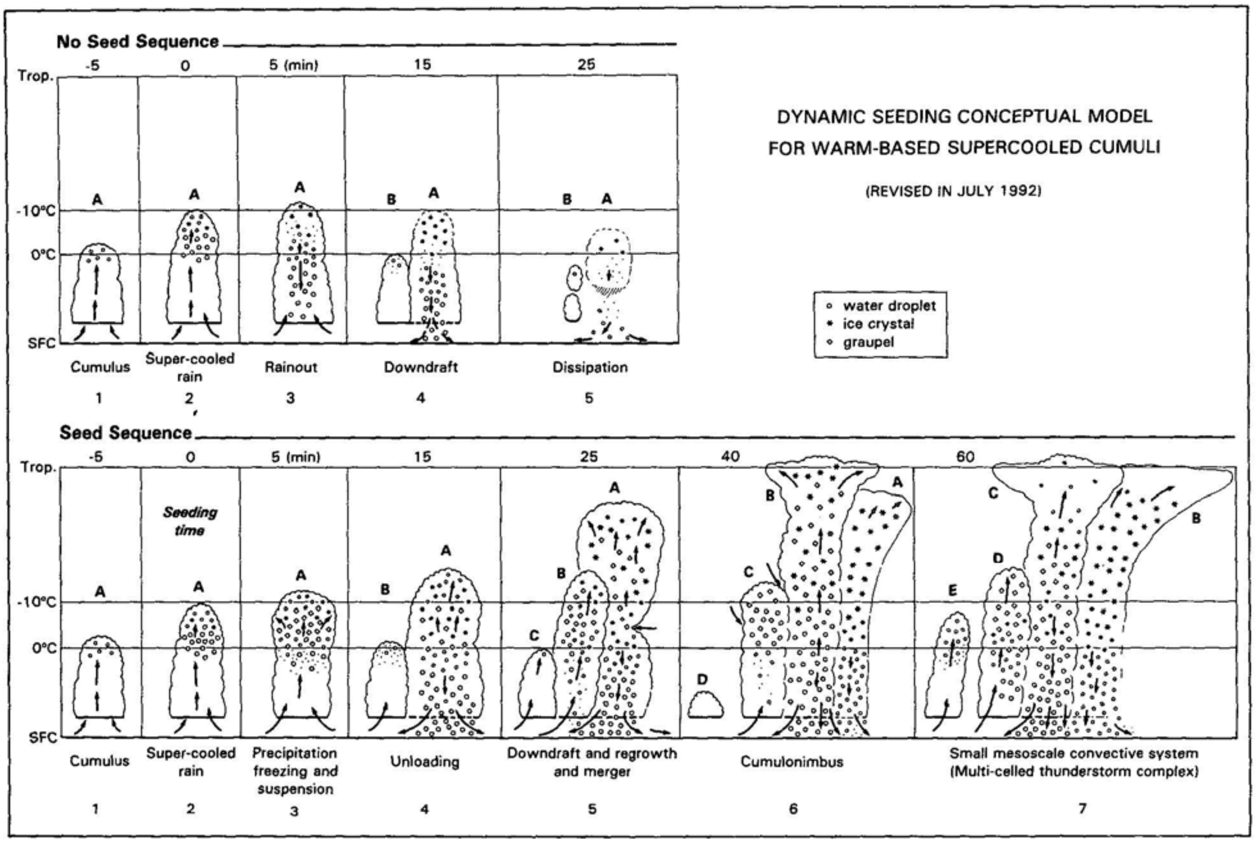
DYNAMIC SEEDING CONCEPTUAL MODEL
FOR WARM-BASED SUPERCOOLED CUMULI
(REVISED IN JULY 1992)
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water droplet
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Cumulus
Super-cooled rain
Rainout
Downdraft
Dissipation
1
2
3
4
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Seed Sequence
-5
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5 (min)
15
25
40
60
Seeding time
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E
Cumulus
Super-cooled rain
Precipitation freezing and suspension
Unloading
Downdraft and regrowth and merger
Cumulonimbus
Small mesoscale convective system (Multi-celled thunderstorm complex)
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