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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 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.


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