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Hail Suppression

The only basic field research in the United States that is directly related to hail suppression occurred under the direction of the North Dakota Atmospheric Resource Board as part of the NOAA-AMP, and in conjunction with the long-running, state-sponsored, operational seeding program of the North Dakota Cloud Modification Project (NDCMP). *Boe et al.* [1992] and *Smith et al.* [1992a] have summarized the North Dakota NOAA-AMP field programs conducted during the summers of 1987, 1989, and 1993. Basic research has emphasized physical studies of clouds and cloud processes, opportunity recognition, transport and dispersion, and cloud modeling for a better understanding of hail and precipitation production. Some progress was made with an innovative statistical analysis [*Smith et al.*, 1987] using historical and target-control crop hail insurance data, that suggested a decrease of crop loss, on the order of 40%, in the operational NDCMP [*Smith et al.*, 1992b], but changes in farming technology and practices are still factors that reduce confidence in the observed effects as a whole.

North Dakota NOAA-AMP research has accentuated the use of tracers in convective cloud modification to address questions about the transport and dispersion of seeding material and to study basic cloud physics processes such as mixing and entrainment [*Stith and Politovich*, 1989], and ice initiation [*Detwiler et al.*, 1994]. The North Dakota tracer studies have indicated that seeding material may indeed be reaching targeted regions but perhaps by circuitous routes. For example, sulfur hexafluoride gas (SF_6) released in upper cloud volumes has in one case indicated transport by updraft to cloud top where the gas subsided along the cloud edge until it was laterally reintroduced into the cloud [*Stith and Benner*, 1987], rather than being exclusively confined to affect interior cloud regions [*Stith*, 1992; *Stith et al.*, 1990]. Spatial correlation between observed concentrations of SF_6 and ice crystals in seeded clouds has provided evidence that directly links observed ice crystals to seeding [*Stith et al.*, 1990]. This work is an important first step in monitoring the evolution of in-cloud conditions and making comparisons between seed and no seed clouds. The use of dual-polarization radar to track chaff [*Moninger and Kropfli*, 1987] released at cloud base has revealed 3-dimensional evolution, with ascent rates matching vertical growth and nearly constant horizontal expansion [*Martner et al.*, 1992; *Martner and Marwitz*, 1990].

North Dakota NOAA-AMP research has also focused on a number of other areas significant for hail suppression. Progress has been made in opportunity recognition (i.e., identifying when and where clouds suitable for seeding will occur). For example, *Boe and Jung* [1990] successfully used near real-time satellite observations to guide field operations. *Kopp and Orville* [1994] demonstrated that a complex, two-dimensional cloud model initialized with 1200 UT data could provide realistic forecasts by noon local time of specific convective cloud characteristics (updraft velocity, liquid water content, etc.), that could be used as specific convective cloud characteristics (updraft velocity, liquid water content, etc.), that could be used as input for making operational decisions. During the North Dakota Thunderstorm Project the model correctly forecast convective development 80% of the time, and precipitation or no precipitation greater than 70% of the time. Microwave radiometry to assess for regions of supercooled liquid [*Anantharaj*, 1990] and acoustic sounding to measure boundary-layer wind profiles [*Boe and Johnson*, 1990] have shown promise for estimating moisture fluxes into the project area. Cloud model simulations combined with observations have indicated that cloud based releases of AgI in the operational NDCMP may indeed be reaching desired regions of supercooled liquid [*Houston et al.*, 1991].

Ice nucleation and initiation have been an emphasized area of research in the North Dakota program. *DeMott* [1992] conducted a laboratory study that characterized ice nucleation rates as a function of particle size and nucleation mode that was applied in a parcel model and combined with observation indicating that it may be possible, at least for North Dakota clouds, to account for the onset of natural ice by primary ice nuclei that later produce graupel [*Detwiler et al.*, 1994].

A randomized hail experiment, Grossversuch IV, was conducted in central Switzerland during 1977-1981. Research groups from France, Italy, and Switzerland participated in the experiment to test the Soviet hail suppression method. The experiment was designed on the theory that hail grows from embryos of large supercooled raindrops in water accumulation zones supported by updrafts. Massive AgI seeding was attained by launching high altitude ground-to-air rockets into the water accumulation zone where the seeding material was released. The purpose was to produce many small hailstones, rather than a few large natural ones, by competition of the artificial ice embryos for the available water.

Major efforts were made to exactly duplicate Soviet seeding methods by using the same radar wavelength to detect hail cells, by following the same type of seeding criteria, and by using Soviet rockets and rocket launchers. Grossversuch IV's radar and rocket launching crew were trained by Soviet hail prevention specialists and received certification that they were capable of carrying out the Soviet hail suppression technique.

Experimentation was conducted over a five-year period to obtain an acceptable statistical sample to draw out potential effects on hail kinetic energy, the primary response variable determined from radar and hail pad data. A total of 76 days of operations occurred during the experiment: 33 seed and 43 no seed. Findings from Grossversuch IV first began to emerge in the mid-1980s and continue into the present review period. The principal result of the Grossversuch IV experiment was that seeding according to the Soviet method, did not result in a statistically significant effect on hail kinetic energy [*Federer et al.*, 1986]. However, additional exploratory evaluations of the data grouped by certain meteorological predictor variables indicated that a statistically significant reduction of hail kinetic energy and a reduction in mean hailstone number per square meter may have occurred [*Federer et al.*, 1986].

In an effort to obtain physical evidence with respect to the seeding hypothesis, a major effort was undertaken using data from a T-28 armored airplane and radar. These data showed only a few cases confirming the existence of accumulation zones for supercooled liquid water [*Waldvogel et al.*, 1987]; not supporting the basic assumption required in the Soviet conceptual model for hail suppression. *Mezeix* [1990] conducted further exploratory analyses of seeding effects on storm types and spatial patterns. This work indicated a tendency for seeding to reduce hailfall intensity for storms classified as either single or complex cells along with an increased intensity for storms classified as repetitive cells. *Schiesser* [1985] examined rainfall data for seeding effects both in and outside the Grossversuch IV target area. The analysis indicated a short term statistically significant, increase in rainfall upwind of the target area when none should have been expected. *Schiesser* [1985] concluded that other effects in the target must be chance occurrences.

Dessens [1988] suggested that the lack of a strong statistical signal may have occurred if the effect of seeding was negatively dependent on the hail severity of a particular day. *Bader et al.* [1992] found evidence that only the first rocket launch in a potential hail cell decreases hail kinetic energy. *Lacaux et al.* [1985] reported on case studies of seeded cells from four storms observed during Grossversuch IV. The study of two cells showed that seeding coverages were small and that estimated residence times for AgI in cloud temperatures colder than -5 C were too short to allow for significant ice phase modification. Two other cells had seeding coverages of 100% and AgI residence times in a cold cloud which were greater, thus resulting in adequate modification of the water-to-ice balance. A positive correlation was found between precipitation intensity and seeding concentration when the seeding material had a long residence time in cloud at temperatures colder than -5 C. This was not the case when the AgI was scavenged very shortly after seeding.

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U.S. National Report to IUGG, 1991-1994