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Precipitation Enhancement---Winter Clouds

Cloud seeding experiments have been conducted in Israel since 1960 and are among the few that have consistently indicated positive statistical evidence of precipitation enhancements. These experiments have been designed according to the static seeding hypothesis, which postulates that the conversion of cloud water into precipitation is inhibited due to a lack of sufficient concentrations of ice crystals in some clouds. The work in Israel has resulted in three randomized experiments: Israeli-I (1961-67), Israeli-II (1970-75), and Israeli-III (1976-94). The experiments were designed with a northern and southern target area. Seeding has been conducted during the wet season (November--April) using aircraft to release AgI at cloud base along a line upwind of the targets. Since 1975, seeding has been used operationally in the northern target area to enhance rainfall in the catchment area of Lake Kinnert.

Gabriel and Rosenfeld [1990] reanalyzed results from the Israeli-II experiment and found a positive enhancement of 13% in the northern target area (significant at the 2.8% level) and a non-significant decrease of 2.5% for the total target. This decrease contrasts with the increase for the total target area that was originally reported. *Rosenfeld and Farbstein* [1992] continued analysis of the Israeli-II and Israeli-III experiments and reported that no enhancement was evident in the southern target area. The data were also grouped according to ``dust'' and ``no-dust'' days. This grouping revealed a 26% increase of rainfall on ``no-dust'' days and no effect on ``dust'' days. They concluded that dust, blown from the Sahara and Arabian deserts bordering the southern target area plays a significant role in the natural precipitation process such that seeding is beneficial only when the dust is absent. Measurements of aerosol properties on no-dust and dust days have indicated high ice nuclei and aerosol content on dust days, implying a more active natural ice process and a higher probability of giant CCN to initiate the warm rain process, making the aerosol properties of the dust days compatible with a lack of seeding effect [*Levi et al.,* 1994].

Precipitation enhancement of winter orographic clouds continued to receive a great deal of attention in the United States. Research related to the modification of these cloud systems was conducted as part of the NOAA-AMP in Arizona, Nevada and Utah, and in northern California by the California Department of Water Resources with technical assistance from the U.S. Bureau of Reclamation. Most attempts to modify winter orographic clouds to augment snowfall involved conventional ground-based release of AgI, or aircraft releases of AgI or dry ice. However, a complex compound of silver iodide ($AgI.NH_4I.NH_4.CIO_4$ burned in an acetone solution) was found to be effective at very warm temperatures (-6 C), and the use of propane, also effective at warm temperatures, was investigated as a alternative to conventional agents. In the last review [*Dirks,* 1982], it was noted that the modification potential of winter orographic cloud systems could not be specified by any single parameter (such as cloud-top temperature), and that the physical rationale and evaluation of the experiments needed improvement. Some of these needs began to be addressed in the late 1980s by work documenting natural storm structure, and targeting of the seeding agent (for example, *Heggli and Rauber,* 1988; *Rauber and Grant,* 1986; *Rauber and Grant,* 1987; *Rauber et al.,* 1986; *Reynolds and Kuciauskas,* 1988; *Reynolds,* 1988; *Super and Boe,* 1988a; *Super and Boe,* 1988b; *Super and Heimbach,* 1988], and by papers on new evaluation techniques [*Warburton et al.,* 1985; *Warburton and DeFelice,* 1986; *Warburton et al.,* 1989; *Warburton and Stone,* 1990].

Super [1990] examined five steps in the physical chain of events that are important for winter cloud seeding to enhance snowfall in mountainous terrain: 1) the seeding material must be reliably generated; 2) it must be transported to regions of supercooled liquid or regions of ice supersaturation in excess of that which can be converted naturally; 3) it must disperse to affect a significant cloud volume; 4) it must be effective so that the cloud must be suitably supercooled; and 5) once formed the artificial ice crystals must reside in a growth region and reach a target. Much of the research has focused on one or more aspects of these steps.

Long et al. [1990] conducted a detailed synoptic and mesoscale analysis, and computed water release rates for a single winter storm that was monitored in the Tushar Mountains. Horizontal mesoscale kinematic variables were computed from volume velocity processing of a single C-band (5.45 cm wavelength) Doppler radar. Water release rates for the updrafts were derived from the radar data and saturation mixing ratio of the sounding, and found to vary with storm structure, implying that certain stages of a storm may be potentially more suitable for seeding than others.

From dual-channel microwave radiometer, polarized lidar, and K_a-band (0.866 cm wavelength) Doppler radar measurements, *Sassen et al.* [1990] distinguished between storm properties dominated by forced orographic lifting and those dominated by propagation of mesoscale disturbances. Orographic clouds were found to be composed of weakly supercooled liquid water (warmer than -10 C) with precipitation that evolved through riming in lower cloud layers. More precipitation was produced when the orographic clouds coupled with a propagating mesoscale system. They concluded that, when decoupled from the mesoscale system, low-level orographic supercooled liquid water clouds were generally inefficient precipitation producers.

Wintertime, ground-based cloud seeding conducted in the Tushar Mountains of southern Utah were reported on by *Huggins and Sassen* [1990]. Radiometric measurements indicated that supercooled liquid water was abundant and sufficiently supercooled. This work illustrated the difficulty of discerning effects of seeding on physical processes, in that during two estimated periods when effects should have been apparent, no enhanced silver content in the snowfall and no clear microphysical or radar seeding signatures were found. They concluded that this likely occurred because the natural characteristics of the storm resembled those expected from seeding.

Sassen and Zhao [1993] studied embedded supercooled liquid water clouds based on data from polarized lidar and a dual-wavelength microwave radiometer for 17 winter storms that occurred over the Tushar Mountains during the winters of 1985-86, 1986-87, and 1987-88. They determined that mildly supercooled clouds developed about 73% of the time when the lidar was operated. They concluded that it is mainly the upper portions of the clouds with relatively warm bases ($T_{BASE} \geq -7$ C) that display potential for increased snowfall because they are associated with larger integrated liquid water amounts.

Relationships between storm total supercooled water flux and precipitation for four different mountain barriers were determined by *Super and Huggins* [1993]. They tested the concept that large flux storms tend to be efficient converters of supercooled liquid to ice, while small flux storms are inefficient. Supercooled liquid water flux totals were estimated from vertically integrated microwave radiometer measurements and wind speed. Large flux storms produced more snowfall. However, when normalized for storm duration, the data did not support the conclusion that large flux storms were highly efficient converters of supercooled liquid water, implying that large storms are efficient during only part of their lifespan.

Observations on 20 storm days sampled on the Wasatch Plateau were summarized by *Super* [1994]. These observations indicated that abundant supercooled liquid water existed during many hours, and a large fraction of these hours did not have snowfall. Supercooled liquid water flux exceeded average precipitation on the plateau, implying seeding potential. Aircraft measurements, using an acoustic ice nucleus counter, showed that the top of the seeding plumes were about 1 km above the plateau. Ice nucleus concentrations, adjusted to the temperature of the plume top, suggested AgI activity too low for effective seeding. This work pointed to the need for direct measurements of ice crystal concentrations in the seeded portion of the cloud to overcome uncertainty in the ice nucleus measurements, in addition to the challenge to consistently target regions of supercooled liquid water with adequate numbers of seeding-caused ice crystals.

Deshler et al. [1990] reported on cloud seeding experiments that were devoted to physical measurements of effects in central Nevada for field programs conducted from 1984 to 1986. Airborne seeding was done using either AgI or dry ice. A trajectory model was used to determine where to deploy surface instruments to watch for seeding effects. Of 36 experiments, expected seeding signatures were found by radar in 4%, by aircraft in 35%, and by the surface instruments in 17%. It was believed that the complete chain of events was documented in only two experiments in which seeding effects appeared in the aircraft measurements as high concentrations of small compact ice crystals that apparently went on to rime rather than aggregate. Dispersion of the ice crystals occurred at 1 m s^{-1}, and cloud liquid water was observed to deplete in their presence. When the seeded volume arrived at the surface, snow crystal concentrations increased, crystal habit changed to small rimed particles, and precipitation rate increased. Differences in ice particle development could not be discerned when either dry ice or AgI was used. The compound $AgI.NH_4I.NH_4.ClO_4$ burned in an acetone solution was found to be active at temperatures as warm as -6 C. *Deshler and Reynolds* [1990] presented one case study using $AgI.NH_4I.NH_4.ClO_4$ that demonstrated the warm activity temperature of the seeding material. In this study, seeding effects were observed to persist for more than 90 minutes after seeding and 100 km downwind of the seeding line.

Demoz et al. [1993] characterized the snowfall that affected the central Sierra Nevada from 1986-87 of the Sierra Cooperative Pilot Project (SCCP). They noted that ice crystal habits varied between storms and that habits reflected the temperature and moisture conditions of their growth regime. Higher precipitation rates were observed when ice crystal aggregation was present. The occurrence of riming indicated that supercooled liquid water existed below diffusional growth regions.

Chai et al. [1993] reported on chemical tracer studies conducted as part of the 1984-1985 winter cloud seeding program at Lake Almanor, California. In the technique originated by *Warburton et al.* [1985], AgI aerosol and indium sesquioxide (In_2O_3) were released from collocated, ground-based generators. In_2O_3 is a water insoluble, non-ice-nucleating substance. The purpose of making collocated releases was to differentiate between the silver content in the snow that was present from ice nucleation and that present from scavenging of the AgI. Based on aerosol emission rates, *Chai et al.* [1993] computed that if AgI is captured only by scavenging, the silver to indium ratio (Ag:In) would be 0.8. Analysis of snow samples frequently produced ratios in excess of 1.1, thereby suggesting that some of the snowfall occurred by artificial nucleation. Further analysis showed that snowfall at sites closer to the generator had higher Ag:In ratios than could be explained by a contact-freezing mechanism. *Chai et al.* [1993] suggested that the ratios could be explained if a condensation-freezing mechanism operated immediately after generation.

Initial studies by the Arizona NOAA-AMP have focused on snowfall over the Mogollon Rim from which much of the state obtains its water. The Arizona NOAA-AMP research has focused on the development, testing, and validation of a 3-dimensional, nested grid model (the Clark/Hall model) of air flow and cloud and precipitation development [*Bruintjes et al.,* 1992a; 1992b]. The Clark/Hall model has predicted the development of cloud bands with significant amounts of supercooled water in association with strong gravity waves. The presence of gravity waves has been verified with wind profile data obtained in field programs conducted in 1987, 1991, and 1992. Gravity waves have not previously been noted in other winter orographic weather modification programs. These modeling studies also give a fairly detailed estimate of the transport, diffusion, and targeting of the seeding material.

The Clark/Hall model used in Arizona has also been used to simulate cloud formation, and transport and dispersion of seeding material over the Wasatch Plateau [*Bruintjes et al.*, 1992a]. Model runs combined with results of SF_6 tracer and ice nucleus counter measurements have indicated that the ground based seeding plume does under certain conditions reach desired cloud levels, but it also can be confined to shallow depths making the release point critical to transport to cloud regions with desired supercooled liquid water. *Super and Huggins* [1992a] investigated the targeting of ground-released AgI using the generator network of the Utah operational project. A low percentage (< 15%) of the bulk snow samples from ten surrounding target locations had silver concentrations above background. Consistently poor targeting and/or low generator output were attributed to the low percentages. *Super and Huggins* [1992b] reported on aircraft missions flown to track AgI plumes in the Utah program. Valley floor and canyon mouth generator sites were tested using collocated releases of and AgI. Four of five missions indicated that the tracer gas and AgI were not transported over the barrier to intended cloud regions. Ice nucleus measurements indicated limited effectiveness for the generator and seeding agent being used. *Super and Holroyd* [1994] reported on several aircraft missions to monitor plumes of AgI and SF_6 tracer gas, and microphysical changes caused by seeding. An obvious enhancement of ice particle concentration was noted in one mission with a high-altitude ground-based release.

Because supercooled liquid water often occurs at temperatures too warm for conventionally generated AgI to be effective, *Reynolds* [1991; 1994] investigated the use of liquid propane to augment snowpack from winter storms. When released as a fine spray, liquid propane vaporizes and cools the air to temperatures well below that required for homogeneous ice nucleation, and thereby should be very effective at air temperatures near 0 C. Field experiments were conducted as part of the Lake Oroville Runoff Enhancement Project (LOREP) in the Sierras of northern California to document transport and dispersion of propane-generated ice crystals using SF_6 as a tracer. Aircraft tracking of SF_6 indicated that the upper part of the plume rose to elevations about 500 m above the release point and that the lower portion of the plume could descend into the valley. Of 35 seeding plumes intersected, only 11 showed evidence of seeding effects. This was attributed to a lack of supercooled liquid water. Although the use of liquid propane requires further testing, it showed some promise as an alternative to AgI in that it effectively generated ice crystals on a day with air temperature near 0 C, and at least one precipitation enhancement was noted at a precipitation gauge directly in line with an aircraft observed seeding plume.

Rangno and Hobbs [1993] further reanalyzed results of the Climax I and II winter orographic cloud seeding experiments. Climax I and II were randomized cloud seeding experiments conducted by Colorado State University scientists in the Colorado Rockies during portions of 11 winter seasons from 1960 to 1970. They concluded that the precipitation statistics which indicated a high correlation between 500-mb and cloud top temperatures were unrepresentative of long-term climatology. They also concluded that the timing and selection of the control stations had affected the results in that once the control stations were selected (mid-way through the experiment), a strong positive effect on precipitation can be noted prior to the selection, but no indications of seeding effects could be found thereafter.

Weil et al. [1993] investigated the relative dispersion of ice crystals in seeded cumuli using data collected as part of the High Plains Cooperative Program (HIPLEX). They compared observed dispersion of ice crystals to results from a stochastic model. They found that for short times after seeding, the predictions and observations suggested a dispersion of the plume directly proportional to the time difference, rather than proportional to the turbulent kinetic energy dissipation rate and the time difference. This was attributed to the large initial dispersion of the ice crystals.

Long and Huggins [1992] reported preliminary results from the first Australian Winter Storms Experiment (AWSE) conducted in 1988. The experiment was initiated to complement operational activities and to assess precipitation-enhancement opportunities from winter cyclonic storms that interact with the Baw Baw Plateau that is upwind of Melbourne's main reservoir water-supply catchment. Initial work has focused on computation of radiometrically determined horizontal supercooled liquid water flux (f) and vertical precipitation flux (p) in the target area. To the extent that the radiometric measurements are representative of cloud conditions, much lower f/p-ratios were computed for northwest winds and higher ratios for southwest winds, implying potentially more suitable supercooled liquid water conditions during periods of southwest winds. However, as has been made evident in other winter orographic experiments, extended periods of high supercooled liquid water flux are associated with low amounts supercooling.

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