"REVIEWED"

Review of Downwind Extra-Area Effects of Precipitation Enhancement

by

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Abstract. This paper discusses a) findings to date about downwind effects of cloud seeding and b) research methodologies that may be applied to advance our understanding of the subject. An important segment of the present report provides the intellectual foundation of any research effort aimed at understanding and assessing downwind effects of a precipitation enhancement project. The body of scientific knowledge presented here tells us by example what can be done to further understanding of downwind effects.

Downwind effects of cloud seeding demonstrate a strong signal according to the U.S. National Academy of Sciences (1973) There was evidence of effects at long distances well beyond where errors in seeding targeting might be expected and little evidence for decreases in precipitation downwind.

Two mechanisms for downwind effects have been hypothesized. They consist of a) downwind transport of ice nuclei and ice crystals from the seeding source, and b) dynamic invigoration of clouds by release of latent heat of freezing. Research and verification of these mechanisms in any precipitation enhancement project are required. This activity involves the tracking and observation of seeding effects into a downwind area. There will be microphysical observations of a) detrainment of ice nuclei and ice crystals from clouds seeded for the primary target area and their environs, b) transport and dispersion of the ice nuclei and ice crystals downwind, c) total budget of these traveling ice nuclei and crystals including destination sinks and residence times, d) entrainment of these particles into clouds downwind, and e) development of cloud and precipitation in the downwind clouds. The investigation may simultaneously be concerned with dynamic seeding effects including observations of a) the dynamics in and around the clouds being seeded for the primary target area, b) the interaction of these dynamics with other clouds , c) the dynamic development of these other clouds followed by d) the development of cloud and precipitation in the other clouds. It will be important to establish the physical context of both the microphysical and dynamical studies in terms of the cloud physical events occurring up to and including the precipitation being enhanced for the primary target area.

The research will use well-developed scientific tools. They include rawinsondes, instrumented aircraft, radar, precipitation gauges, satellite cloud imagery, microwave radiometry, and precipitation trace chemistry. Numerical models are important for incorporating relevant theory and would include terrain effects, synoptic and mesoscale meteorology, (gravity) wave motions, seeding material transport and dispersion, and cloud and precipitation microphysics.

In order to raise the entire level of knowledge of downwind cloud seeding effects the research of the form outlined here and in the main text should be undertaken.

1. INTRODUCTION

The U.S. National Academy of Sciences (1966a, 1966b, and 1973) reviewed weather modification science when it was about 20-25 years old. By 1973 the subject of extra-area effects of weather modification was of sufficient interest for a separate treatment to be given in the last publication. The treatment handled potential lateral and upwind effects of cloud seeding apart from downwind effects. Still, the emphasis of past and current direct and related research has been on the downwind effects. The findings of downwind research and discussion of potential future studies are the subject of the present work.

For completeness we note here the character of lateral and upwind effects of cloud seeding. Lateral effects may occur when uncertainties in wind direction misguide seeding nucleants toward the side of a target area possibly into a neighboring control area. Upwind seeding material transport is more difficult to explain although strong wind shears may be important. Dynamic seeding effects, possibly in the form of cloud propagation, may also conceivably occur both laterally and upwind. Should lateral or upwind seeding effects occur then they may affect the proper statistical functioning of target-control or crossover arrangements of experimental areas. Countermeasures should be taken by rearrangement of experimental areas, close monitoring of winds at various altitudes, and radar and/or satellite observation of cloud growth and movement.

As of 1973 the range of clouds and geography connected with downwind effects covered much of the United States. There was evidence for effects along the central and north eastern seaboard, in the midwest, in the Rocky Mtns, and along the west coast. Overseas, evidence had been found in Australia, Switzerland, and Israel. Much of this information is examined here. Also appearing here are more recent results.

Downwind precipitation effects have been observed in geographic areas and time frames that are about the same magnitude as for the primary effects intended for the target area. There is little evidence of a decrease in precipitation outside a target area.

The two main physical mechanisms so far proposed for downwind effects are as follows. One mechanism involves the transport of microphysically active seeding ice nuclei or induced ice crystals from the target clouds downwind to another area. The second mechanism involves the dynamic invigoration of seeded clouds and their movement or propagation from the target to downwind.

Potential further study of downwind effects may include the following. A field program may have specific design features aimed at revealing any downwind effects . Boundary layer, cloud, and precipitation modeling may be used to focus the important design elements of a field measurement program. Measurements may include a full range of atmospheric and cloud microphysical variables over a larger area, longer time span, and greater frequency than normally associated with cloud seeding projects.

The present review includes a broader range of projects and a longer list of investigators than previously treated. Covered are projects and findings from Australia, Santa Barbara, Florida Area Cumulus Experiment, Climax, and elsewhere. Important points of the Workshop on Total-Area-Effects of Weather Modification which occurred in 1977 and other reports are examined. This is followed by sections on more recent cloud seeding experimental studies and implications for techniques for downwind studies.

2. AUSTRALIAN EXPERIENCE

Adderley (1968) analyzed precipitation downwind of cloud seeding operations in 1966 and 1967. From historical considerations he found increases in precipitation 150-300 km downwind of the operations, of about 50 percent in Victoria and about 20 percent in Western Australia. The detection of these increases was attributed to an absence of topographic discontinuities between the operations target area and the downwind area with consequent uniform (stratocumulus and cumulus) cloudiness extending downwind throughout . In Adderley's view there was a continuing microphysical effect of the seeded silver iodide (over and above any photolytic deactivation), but additionally the seeded clouds may interact dynamically with their environment to promote cloud development downwind.

Smith, Veitch, Shaw, and Miller (1979) analyzed the first Tasmanian experiment for cloud seeding effects on precipitation. The discussion suggested drift of seeded clouds beyond the target area may have been responsible for downwind effects. These effects are akin to a small error in seeding position rather than a major effect several target area dimensions downwind. Yet, this suggests aircraft positioning is important in order for downwind effects to be avoided . That positioning will depend to a large extent on wind speeds at all levels. If the speeds are strong there is a potentially greater chance for a seeding effect to be downwind of the target area.

King, Manton, Shaw, Smith, and Warner (1979) described a prospective 5 year (1979-1983) cloud seeding experiment for western Victoria aimed in part at discovering any downwind cloud seeding effect on precipitation . Although the experiment was never conducted its design for detecting downwind effects is worth describing . The experiment had a 2000 km2 target area (with 20 pluviographs) and six upwind control areas covering about 8000 km2 (45 pluviographs). Detection of downwind effects was to be with four areas 25-75 km downwind covering a fan shaped area of about 5000 km2 and containing 20 pluviographs with 0.2 mm precipitation resolution and 1 s time resolution. The precipitation in the downwind area was to be examined historically and compared to target and control amounts to ascertain whether there were seeding effects in the downwind area as near as 1 hr downwind from the target area and at most 3-4 hr downwind.

The Australian experience suggests that studies of downwind effects of cloud seeding will be enhanced by uniform topographic and cloud fields in the downwind direction, if attention is paid to the positioning of any seeding aircraft in the embedding wind field, and if appropriate target, control, and downwind areas are considered with suitable precipitation gauges.

3. SANTA BARBARA EXPERIMENTS

Elliott and Brown (1971) described studies of downwind seeding effects in the California Santa Barbara project. Convection bands were seeded as they passed from upwind of a 3500 ft mountaintop seeding site , across the site, and downwind. Precipitation at 168 recording gauges was used to measure the precipitation from each band . Precipitation was 4 times greater from seeded bands than from not-seeded bands. When the cloud top temperature was warmer than average the seeded precipitation was greater. Both of these results occurred 150-200 km downwind of the seeding site.

A cloud and precipitation model was used to explain these results. The model predicted the movement and dispersion of the ice nucleant, its entrainment into the band and its induced production of ice particles, particle growth by diffusion and accretion in the convective updrafts, and particle drift down from the tilted convection columns. The model allowed induced ice crystals in the convection band anvil to blow out ahead of the band, fall downward, and seed clouds in the forward area ahead of the band. The model did not confirm an observed increase in duration of precipitation for seeded cases.

Brown, Elliott, and Thompson (1976) also described some findings of the Santa Barbara project phases I and II. Phase I involved ground-based pyrotechnic generators seeding clouds passing across the seeding site with randomization on precipitation bands. In Phase II seeding was with an airborne system and randomization was by storms encompassing one or more bands. In downwind areas about 150-250 km from the seeding location about 50-100 percent more precipitation was found from seeded bands. These downwind effects were located in the area where effects were predicted by a cloud and precipitation model. It was concluded that the primary cause of extra-area precipitation effects of seeding is due to an invigoration of organized convective activity dynamics with some suggestion that this occurs up to about 250 km downwind of the seeding area and perhaps 30 degrees to the right of the 700 mb mean wind flow.

The Santa Barbara experiments showed that seeded convective bands with cloud top temperatures warmer than -15C may be invigorated and provide 50-100 percent additional precipitation at a distance of 150-250 km downwind of the seeding site.

4. FLORIDA AREA CUMULUS EXPERIMENT

Simpson (1980) was concerned with observational and modeling evidence on the dynamics of cumulus clouds. She found that dynamic seeding acts to increase cloud top height and breadth . (Dynamic seeding of clouds occurs through the release of latent heat of freezing of cloud liquid water.) At the same time a downdraft is developing in the cloud leading to a gust front in the atmospheric boundary layer. This gust front acts to stimulate the production of new cumulus clouds which may merge with the seeded cloud. This work bears on the downwind effects of cloud seeding since it describes at least one mechanism for dynamic communication of one cloud to extra-areas removed from it where other clouds can develop.

Cunning and DeMaria (1981) commented on the Simpson (1980) article. They argue that a seeded cumulus cloud may grow into a cumulonimbus cloud through updrafts in the cumulus leading to a pressure deficit which forces boundary layer in under the cloud with surface convergence. This converging air rises and strengthens and broadens the updrafts and invigorates the clouds with a possible change to cumulonimbus. This process is more effective if there are adjacent cumulus clouds growing together. This process of cloud growth does not require downdrafts communicating from cloud top to base as Simpson suggested.

Simpson and Cooper (1981) replied to Cunning and DeMaria(1981) and partly reiterate their downdraft hypothesis for cloud growth. More emphasis is now placed on gust fronts interacting with strong convection including the formation of tornadoes and influences on regions of convergence and divergence.

Kerr (1982) reviewed the outcome of FACE-2 which, although not confirmatory of FACE-1, demonstrated some positive extra-area effects in rainfall measured by gauges and by satellites. The FACE researchers found that seeding may have produced increased rainfall in the FACE-2 target area and downwind . Decreased rainfall upwind may have been due to subsidence drying of the atmosphere here exceeding any positive effects of seeding.Thus there may have been a varying balance of factors increasing and decreasing the precipitation outside the target area.

Meitin, Woodley, and Flueck (1984) used the satellite rain technique of Griffith, Augustine, and Woodley (1981) to estimate the precipitation in the vicinity of the FACE target area. They found a +20 percent seeding effect downwind of the area, and a -10 percent seeding effect upwind of the target. These effects occurred within 180 km of the center of the target and within 8 hr of the initial cloud seeding time. Although the results were fairly clear in the graphical presentations, statistical support through low p-values was not strong. The paper considered a conceptual model, for the effects, that they occurred by wind transport of seeding-invigorated clouds to outside of the target. The alternative model not considered, however, was that the silver iodide is transported outside of the target area and entrained into convective clouds.

The FACE work considered the dynamic effects of a seeding-invigorated cloud on downdrafts and boundary layer pressure deficits forcing surface convergence and by extension the growth of the cloud and adjacent clouds in downwind areas. There was some evidence of increased precipitation downwind and decreased precipitation upwind with a dynamic conceptual model.

5. CLIMAX

In the Colorado Climax I experiment Grant, Chappell, and Mielke (1971) considered the change in precipitation 80-240 km downwind of the Climax target area. Downwind precipitation on seeded days exceeded that on not-seeded days by a factor of 2 or more at significance levels better than 0.05 . They hypothesized that the increase in precipitation was due to ice nucleant and induced ice crystals being transported out of colder clouds in the Climax area and being ingested in warmer clouds downwind.

Brier, Grant, and Mielke (1973) noted that downwind effects of cloud seeding on precipitation are positive rather than negative and may occur 100-250 km downwind of a primary target area. They attribute these effects to the transport, of silver iodide seeding material and ice crystals induced by seeding, to clouds in a downwind area which then precipitate. Another hypothetical cause of downwind effects is the dynamical invigoration of clouds through latent heat release and movement of these clouds downwind. Finally, they refer to Bowen (1968) who suggested precipitation wetting of the ground could moisten the boundary layer and affect cloud and precipitation downwind. They referred to studies of the Climax project which showed that the precipitation was unusually high downwind of the target area.

Janssen, Meltesen, and Grant (1974) investigated downwind effects of the Climax I and II projects. They noted that their investigation was post hoc and as such was exploratory rather than confirmatory. In order to detect downwind precipitation effects drifting from the Climax target area various time lags ranging from 3 to 18 hours of precipitation data from hourly stations in downwind locales were considered. Significant ratios of seeded to not-seeded precipitation, with low probabilities of being due to chance, were found downwind east and northeast of the Climax area. These ratios were in the range 1.15 to 1.25 during the 3-12 hr time lag period.

The ratios were then stratified by 500 mb cloud top temperature which was taken to be close to Climax cloud top temperature. The ratios were found to be greatest with temperatures warmer than -20C. The natural ice nucleation process in such clouds may have then been less efficient and , correspondingly, artificial seeding may have been more effective. At temperatures colder than -24C there was little evidence of a downwind precipitation ratio maximum. Of particular interest was the finding that the ratio of seeded to not-seeded precipitation was greatest when the 700 mb temperature (near cloud top downwind) was in the -5C to -9C range. This was especially true when the subcloud relative humidity exceeded ice saturation at 70 percent. The increase in downwind precipitation on seed-days was thus greatest when the downwind clouds were suitable for artificial ice nucleation. This suggests that downwind effects of a precipitation enhancement project may be greatest when the clouds downwind are relatively warm (though still supercooled). With colder downwind clouds natural precipitation is produced more efficiently with little increment expected in the amount due to seeding of the target upwind.

Mulvey and Grant (1976) presented a conceptual model of how cloud seeding silver iodide and induced ice crystals could be transported downwind from the Climax experiment and interact with clouds over the Colorado Plains sloping up to the Rockies with beneficial effects. Although not all of the steps in the model are fully demonstrated there is sufficient plausibility to understand how the above interaction may develop. Phase A of the interaction involves lofting of Climax ground generated silver iodide ice nuclei into clouds upwind of the Climax target area. In Phase B the nuclei and induced ice crystals pass through the cloud over the target area and downwind where some sediment out of the cloud. Other particles continue downwind in Phase C through a series of cloudy waves stimulated by the mountainous terrain upwind. In Phase D the nuclei and ice crystals blow downwind over the upslope eastern Plains of Colorado. Then in Phase E the particles are entrained into convective features protruding upward from the extensive layer of orographically induced stratocumulus or stratus over the Plains.

The parts of this conceptual model nearer the Climax target area are better supported by observations. It is unclear, for example, how much transport of ice crystals occurs in Phases C and D downwind although the upward vertical motions in waves may redevelop the crystals from subliming ones in regions of downward motions.

It should be noted that the upslope Plains clouds may have cloud top temperatures of -16C to -11C or 4C to 9C warmer than the Climax cloud tops at -20C. As a result natural ice nuclei may be relatively inactive in the upslope clouds and precipitation processes may be limited. Any infusion of nuclei from the Climax project may beneficially augment the precipitation.

Mulvey, Rhea, Meltesen, and Grant (1977) formulated a non-dimensional indicator, largely based on meteorological rawinsonde data from Denver, Colorado, of the probability that upslope clouds over the Colorado Plains would be reached by ice crystals from the Climax experiment and that seeding effects may be present. Elaboration of the methods used in this paper may be valuable in quantitatively understanding downwind effects of cloud seeding in other regions.

The evidence that the Climax project had downwind effects came from three sources. First, precipitation increases of 15-25 percent and greater were found downwind of the project area in time frames consistent with atmospheric transport of ice nuclei and/or ice crystals from the project. Second, cloud top temperatures in the Climax area and over the Colorado Plains were sufficiently warm as to preclude active natural ice nucleation but not activation of artificial ice nuclei. Third, a combined ice nuclei and ice crystal conceptual transport and particle conditioning model was developed to explain the downwind seeding effect.

6. OTHER RELEVANT INVESTIGATIONS

Brown and Elliott (1968) examined the large scale dynamic effects of cloud seeding. Statistical studies were made of the ratio of seeded storm precipitation to not-seeded storm precipitation over, upwind, and downwind of four separate target areas. The Coeur d'Alene area in Idaho was studied in greatest detail. For cloud tops warmer than -6C the seed:no-seed precipitation ratio was greater. A geographic gap was present between the high ratio for the target and the high ratio next downwind. Hypotheses advanced for the latter ratio were

a. the seeding in the target area vicinity may release sufficient latent heat and affect the convective instability to induce a dynamic change in the downwind precipitation pattern.
b. the seeding in the target area vicinity may promote cirrus formation the ice crystals in which may blow downwind and fall downward and seed clusters of clouds there and promote precipitation formation.
c. seeding material (especially from ground generators) may be carried downwind through the boundary layer to the next cluster of clouds and seed them.

The analyses of the authors suggested there can be increases in precipitation about 150 km downwind of a target area at least in the United States.

MacCracken and O'Laughlin (1996) address a number of issues concerned with downwind effects of winter cloud seeding in California on Idaho precipitation. The view is that the 650 km separation of the two States exceeds that of about 300 km over which downwind effects are known. The complexities of atmospheric motion over this distance preclude definitive knowledge of seeding effects. Also, the 10-20 percent increase of precipitation in California could not be responsible for the 50-100 percent interannual variation of Idaho precipitation. Finally, the area seeded in California is much smaller than Idaho. The conclusion is that downwind cloud seeding effects from California do not impact Idaho.

Warburton (1971) described observations of silver in snow from Sierra Nevada cloud seeding projects and compared them against background values. He observed a smaller concentration of silver with airborne seeding than with ground generators. This may have been a function of seeding rates rather than different dispersion of silver iodide. He observed more silver in snow when seeding was 80 km from the snow sampling area but less silver when a distance of 250 km was involved. His major conclusion was that cloud seeding projects in mutual close proximity (less than 150 km apart) may affect each other through cross-contamination with silver iodide cloud seeding material. There would be a corresponding complication in analysis of precipitation for seeding effects.

Schickedanz (1977) describes the extra-area effects of weather modification due to urban-industrial complexes and widespread irrigation. The urban-industrial complexes studied in the United States have effects on summer rainfall, thunder, and hail-days. The irrigated areas have effects on summer rainfall. The area of the effect extended 1-2 times the cross-wind width of the irrigated region and 1-2 times downwind from it up to distances 200-400 km downwind. Hypothetical mechanisms considered for extra-area effects around irrigated areas, and related to artificial precipitation enhancement, included a land-sea breeze circulation set up downstream of the irrigated area, wetting of the ground by rainfall, and gravity wave generation by strong convection. Hypothetical urban-industrial downwind effect mechanisms are lifting of potentially unstable air by cold, dense air outflow from other clouds, enlargement of clouds by mergers, transport of silver iodide aerosols downwind, and ice crystal seeding of downwind clouds by cirrus blown overhead from upwind. Some of these mechanisms may operate in a mountainous area with reservoirs if one assumes that the mountains and their orographic lift are analogous to an urban-industrial complex and the reservoirs act as an irrigated area.

Although the Warburton (1971) work is a fair indication of how downwind effects may overlap, the other works are distinguished by an abundance of hypothetical mechanisms. It is the establishment of supported mechanisms which is one of the challenges facing the science today.

7. HIGHLIGHTS OF SELECTED OTHER REVIEWS

Grant, Brier, and Rhea (1977) briefly review evidence to 1977 on extra-area effects of cloud seeding. Increases in precipitation 150 km beyond target areas have been observed, and in some cases the increases have been observed at a distance as great as 300 km. These results were found in commercial precipitation enhancement operations in the eastern United States. These results have been supported by elevated concentrations of ice nuclei at distances of 50 km. It should be noted that the evidence for extra-area effects is primarily statistical. A program of physical research is needed to elucidate the sequence of physical steps necessary for extra-area effects from initial release of silver iodide from a generator, nuclei ingestion in a cloud, and transport of nuclei and induced ice particles to other clouds downwind.

Although transport of microphysical variables such as ice nuclei and ice crystals may lead to downwind effects dynamic effects on clouds related to latent heat release may invigorate clouds and also lead to additional ice production. Simplified calculations indicate that downwind production of precipitation over a succession of orographic ridges may decrease with distance and become small and inconsequential . Other evidence of extra -area effects compels one to design into a precipitation enhancement project features which will clearly reveal the existence and magnitude of extra area effects. Those features are discussed below.

Brier, Grant, and Mielke (1974) review several cloud seeding projects for evidence of extra-area effects. It is important to know the reality, magnitude, and direction of such effects since they may occur in areas where there has been no social impact planning for such effects or even no desire for them. Yet, it is recognized that in most precipitation enhancement projects there is no plan to evaluate extra-area effects either through physical measurements or statistical analyses. The projects reviewed by the authors included, for winter, several commercial projects along the east coast of the US, the Climax I and II projects and Park Range project of Colorado, the Santa Barbara II project in California, and the Israeli project. For summer there were commercial projects along the east coast of the US , Arizona I and II projects, and Grossversuch III in the Swiss Alps. Except for Arizona I and II all the projects showed positive precipitation anomalies extending out as far as 250 km downwind of the seeding area. This is an important result as it lays to rest the conjecture that seeding generally robs regions downwind of seeding of water. Still, the increases at the large distances are not explained. At smaller distances they are not surprising given the uncertainties of targeting. It should be noted that although there is a paucity of observations, upon which there can be detailed physical explanations for extra-area effects, there has been meteorological stratification of some of the results providing some understanding.

Brown, Elliott, and Edelstein (1979) have also reviewed downwind effects of cloud seeding. This review evolved from a scientific workshop sponsored by the U.S. National Science Foundation. They put these effects under the heading Total-Area-Effects i.e., extra-area effects. It was agreed that an understanding of extra-area effects is important to the beneficial application of weather modification science. Yet, most of the existing information is a posteriori, is speculative, and is based on statistical rather than physical analyses.

Still, the better quality statistical analyses (based on randomized cloud seeding programs) suggest that precipitation changes in extra areas tend to be of the same sign and magnitude as effects in a primary target area. Extra-area effects appear to be detectable as much as a few hundred kilometers from the seeding source. Beyond those distances the evidence is too weak to support any conclusions. There is little evidence that precipitation increases in a target area lead to reductions in precipitation further downwind. Two potential physical mechanisms for extra-area effects are a) transport of ice nuclei or ice crystals hundreds of kilometers downwind, and b) dynamic invigoration of convective systems with ensuing increased precipitation or, oppositely, decreased cloudiness caused by dynamic suppression.

According to the authors recommended further work would be as follows.

a. There should be a posteriori statistical reanalysis studies of past programs using more sensitive techniques in order to detect apparent changes in precipitation patterns over large areas. Valuable

information would be provided for hypothesis development and design of future weather modification field investigations incorporating study of extra-area effects.
b. To reduce the costs of weather modification field programs, in which total-area-effects are examined and which necessarily cover an area several hundred kilometers in size care should be taken in the design and proposed evaluation of the programs before inception. For example, thought should go into the temporal frequency and spatial resolution of atmospheric measurements comprising a field program.
c. Cloud physics and cloud dynamics studies should augment the present extra-area effect studies which focus more on the spatial and temporal characteristics of the seeding source and the precipitation which is apparently altered.The nominated studies should consider cloud and precipitation microphysical effects at all steps of the precipitation augmentation process. The studies should also consider the dynamics of all clouds hypothesized to be involved in the process including cloud-cloud interaction both with respect to cloud growth and cloud suppression.
d. Also of assistance to the field program - in terms of logistics, the design of the instrument measurement schedules, and interpretation of the field data - are computer modeling on the mesoscale and cloud scale of cloud and precipitation processes. This modeling can help guide and focus a cost-effective field program.

From the reviews to date it would be fair to state that extra-area effects, in fact, exist and may be found up to a few hundred kilometers downwind of a cloud seeding target area. Most of the evidence has been statistical and focused on the close-in seeding signature in a seeding project and the precipitation data. Future work should consider the cloud physics and dynamics through the region of effect with care to integrate the extra-area study into the main cloud seeding study.

In line with the previous ideas just advanced concerning the nature of extra-area, downwind studies and in the interests of efficiency of scientific investigations, it appears desirable to attach any extra-area, downwind studies to a planned or existing precipitation enhancement project aimed at a primary target area. The infrastructure and resources of that project would be utilized such as background precipitation climate studies and gauge networks (with additional gauges in the downwind area). Other resources of the main project would include meteorological analysis and forecasting. The extra-area, downwind studies would include plume dispersion tracking, physical investigations, cloud seeding models, and other topics.

Other relevant research is now discussed to provide examples of what may be done in the future in the way of extra-area, downwind studies of seeding effects.

8. PLUME DISPERSION TRACKING

Plume volumes are important as they can be used to predict the concentration of ice nuclei transported downwind and provide an understanding of the downwind seeding effect. Isaac, Schemenauer, Crozier, Chisholm, MacPherson, Bobbitt, and MacHattie (1977) provide an example of such research in cumulus clouds near Yellowknife, Northwest Territories, Canada.

Hill (1979) recommends that any cloud seeding project measure turbulent dispersion in its own clouds. He found greater dispersion in a horizontal direction and less in a vertical direction which was attributable to nonisotropic turbulence.

According to Grandia, Davis, and Renick (1979) a key factor in successful seeding is the repeat time between repeated seeding of the same part of the target in order that some overlap of successive dispersing plumes be achieved. Downwind, where plumes have dispersed and are larger, the repeat time will not be as important except insofar as maintaining a high concentration of seeding material.

Hill (1980) made field measurements of the dispersion of airborne released silver iodide in orographic clouds with limited turbulence . The horizontal dispersion of the plume was proportional to downwind distance from the initial seeding line and was about 10 times the vertical spread of the plume. Had convection been present larger dispersion of the material in both directions would have been expected.

Stith, Griffith, Rose, Flueck, Miller, and Smith (1986) describe the spatial distribution of SF6 tracer in cumulus clouds. A horizontal plume remains fairly narrow for much of its rise through a cloud until it reaches a turbulent region near cloud top. Broadening of the plume occurs here where vigorous mixing and entrainment occur. Seeding in a project desirably occurs where there is sufficient turbulence to broaden the plume.

Holroyd, McPartland, and Super (1988) described studies over the Grand Mesa of western Colorado which showed that silver iodide ground generators situated high on the windward slopes of the mesa or silver iodide airborne generators released ice nucleating material which reached horizontal positions over the mesa . Valley locations for the ground generators were inadequate because of trapping or pooling of the released material beneath an inversion. Actual lifting over, rather than flow around, the mesa will depend on the topographical aspect presented to the winds and any stability at altitude. It is important to document the mesoscale atmospheric conditions with rawinsondes near the study area.

It should be recognized that convective turbulence may carry some bubbles of ground-generated seeding material up over the orography. Plume turbulent expansion may affect whether and when plumes from multiple ground generators will merge and act to seed the clouds thoroughly downwind. Plume merger is also a consideration in back-and-forth crosswind seeding runs with an aircraft so far as run length and the repeat time go. Plume studies predict the volume that would be seeded in front of target clouds and the size of that volume downwind of the target. If seeding material is correctly released to augment precipitation in a target area material will be consumed there and there will be less material having any effect downwind.

Heimbach (1990) described field investigations of the dispersion and concentration of ice nuclei of airborne released " acetone burner" silver iodide plumes and wing-tip "flare" plumes. The burner plume was more distinct and maintained a higher concentration of ice nuclei. Photodeactivation of the burner nuclei (composed in solution partially of NH4I) was not a factor. The acetone burner material was a factor of 25 cheaper than the flare material. This was because the burner produces approximately 100 times more ice nuclei per gram of silver iodide than the flares. This work demonstrates the greater efficiency of acetone burners than wing-mounted flares and, potentially, a greater downwind effect.

Levin, Krichak, and Reisin (1997) model the transport of inert tracer material into clouds of the type encountered in the Israeli cloud seeding experiment. They find that seeding along a stipulated crosswind seeding line upwind of the target area will likely be effective only if the seeding is done directly into updrafts of clouds passing overhead. Seeding would be less efficient and more variable into clouds upwind or downwind of the seedline. This bears on downwind seeding effects.

The dispersion studies indicate a cloud seeding plume expands downwind of its release location. A decreasing concentration of seeding material is thus expected. The repeat time between seeding events determines the overlap downwind of plumes and the extent of seeding coverage. Field studies of plume dispersion can use SF6 tracer material in addition to silver iodide cloud seeding material although the concentration (and potential downwind effect) of the latter depends on the generation method. Dispersion studies in mountainous regions depend on the topography, atmospheric motions and stability, and the method for generating the seeding material.

9. PHYSICAL STUDIES

Hobbs and Radke (1973) and Hobbs (1975a, 1975b) discussed transferring snowfall eastward downwind across the north-south trending Cascade Mtns of Washington State. Drier conditions prevail on the east side. It was hypothesized that overseeding on the west side would produce ice particles smaller than natural which would fall further east downwind of the mountains. A clear cut positive seeding effect was the formation of a high concentration of smaller ice crystals downwind within a contrasting natural background of low ice particle concentrations. The ice particles prevalent in the east are unrimed while rimed ice particles are prevalent in the west. West of the Cascade Range liquid water droplets were present beneath a more tenuous volume of diffusion grown ice particles aloft while east of the range the droplets were absent with only ice particles aloft. Cloud seeding would induce additional of the downwind ice particles by ice nucleation of ice crystals and by freezing of the droplets upwind.

Calculations can be made of precipitation particle trajectories terminating on the east side depending on wind speeds and particle fall speeds at a range of altitudes. Positioning of cloud seeding and scientific aircraft in a downwind study are dictated by established ground site observation positions and calculations of "back" trajectories of the particles to infer the cloudy region where the seeding aircraft would have to be positioned for the seeding-induced particles to reach the ground sites.

In addition to ground and airborne microphysical observations supporting the snow redistribution other hypothesis verification may come from silver-in-snow concentrations and high freezing nuclei counts found in the melted snow. A practical kind of evidence is precipitation rate at the ground sites.

The work of Hobbs (1975a and 1975b) clearly demonstrated the kind of physical approach available to studies of cloud seeding effects in downwind directions from a primary target area.

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Locatelli, Hobbs, and Biswas (1983) described a field investigation and analysis of an altocumulus layer ($T \sim -17C$) producing dendrites in fallstreaks which naturally seeded and rimed in a lower stratocumulus ($T \sim -5C$) layer and increased in precipitation rate. Needles were produced when the stratocumulus was seeded with dry ice. The work illustrates the microphysical interaction of cloud layers and the potential effects of seeded clouds on lower, downwind clouds.

Elliott, Shaffer, Court, and Hannaford (1978) analyzed the Colorado River Basin Pilot Project. The project was designed to avoid seeding downwind areas such as Silverton, Ouray, and Telluride in Colorado as their residents did not wish more snowfall. The design eliminated certain wind directions for seeding. Ground generation of silver iodide ice nucleant was used but transport was confused in some cases with the material drifting away in some directions and back at a later time. Clearly the downwind effects depended on the actual wind velocity history. These irregular winds would have resulted in no seeding in some "seed" cases and in contamination (seeding) of some nominally not-seeded days.

Stewart and Marwitz (1982a) described observations of seeded thin, low liquid water stratiform cloud showing the evolution of ice nuclei, liquid water, and small and large ice crystals. The work illustrates how to make airborne cloud microphysics studies near an initial seedline and as it moves downwind.

Huggins and Rodi (1985) demonstrate an analysis of seeded and not-seeded clouds based on aircraft and radar for a primary target area and downwind.

Deshler and Reynolds (1990) observed physical seeding effects 100 km downwind of a seedline created on the west side of the Sierra Nevada. The seedline was repeatedly sampled as it passed to the east and showed enhanced ice nucleus concentrations and some particle growth. When the aircraft finally withdrew from the seedline about 10 per cent of the artificial ice nuclei were still available. This work clearly demonstrates the long distances (100 km) over which seeding material can be transported downwind.

Deshler, Reynolds, and Huggins (1990) describe multi-year field experiments involving CO2 and AgI cloud seeding and an instrumented aircraft, a radar, and ground instrumentation aimed at documenting the steps in the chain of physical events from cloud seeding to extra precipitation on the ground. The methods may be useful for a primary target area and downwind.

The field investigations methodology in the Sierra Cooperative Pilot Project particularly is applicable to primary target area cloud and precipitation studies and is likely useful for downwind studies as well. They have set a good example of the steps to be taken and explain the limitations of such work.

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Super, Boe, Holroyd, and Heimbach (1988) describe the experimental design and instrumentation used in focused precipitation enhancement studies in Colorado and Montana. The experimental design involves seeding upwind of an orographic cloud over a mountain and measuring changes in the cloud and its precipitation using instruments in an aircraft or on the mountain. This paper provides a useful example of how to set up a surface and aircraft based study of seeding effects in a primary target area or downwind.

Super and Heimbach (1988) describe aircraft and other observations of seeded supercooled winter clouds over a downwind Montana ridge. Seeding conditions and data were present enough times in the reported work to engender confidence that precipitation could be enhanced over the "downwind ridge" study area. The procedures of the work would be worth noting as a good example of physical studies that may be made of cloud seeding in mountainous regions and downwind.

Super and Boe (1988) described cloud seeding experiments over the Grand Mesa in Colorado which demonstrated that ground-based and airborne acetone silver iodide generators can yield a precipitation rate above natural values. The cloud seeding method and the cloud microphysics analysis verifying this kind of work are straightforward in principle but are only now feasible with the equipment and instrumentation that have become available.

Super (1990) reviews the current status of winter orographic cloud seeding in the Intermountain West of the U.S. The review includes the structure of orographic clouds, the physical chain of events when cloud seeding leads to additional snowfall, seeding material generation and activity, the spatial distribution of cloud supercooled liquid water , the transport of the silver iodide into the supercooled liquid water zone, and the relative position of successive airborne silver iodide seedlines that may merge with the aid of atmospheric turbulence. This review demonstrates the feasibility of documenting the steps in the physical chain of events leading to seeded precipitation downwind as well as near the target area.

Holroyd, Heimbach, and Super (1995) describe microphysical ice particle concentrations from a silver iodide plume release into clouds over the

Wasatch Plateau of Utah. The plume was readily transported up and over the windward slope but was so narrow as to suggest close 5 km cross-wind spacings of generators would be required for effective seeding operations assuming suitable atmospheric conditions. Seeding appeared to promote snow crystal aggregation and to increase snowfall slightly. Modeling of the event showed moderately good agreement with the data analysis.The study demonstrated how microphysical field analyses and mesoscale modeling studies can be used together to support cloud seeding investigations near and downwind from a mountain target area.

Super (1995) describes studies near the Wasatch Plateau of Utah of silver iodide cloud seeding material transport and dispersion and effects on clouds. Although comprehensive seeding coverage with more closely-spaced generators of greater activity may influence downwind seeding effects the cloud temperature there may prevent or allow seeding material activation and is thus important.

Heimbach and Hall (1996) discuss ice nucleus measurements and modeling of cloud seeding material transport and dispersion over the Wasatch Plateau of Utah. The modeling showed a gravity wave was present upwind of the Plateau and could have transported seeding material upward through an inversion into the normal orographic flow. The descending warming part of the wave could have produced sublimation over the eastern downwind part of the Plateau. From this and other evidence (Heimbach, Hall, and Super, 1997) gravity waves may play an important role in seeding material transport and dispersion near a mountain target area and downwind.

The studies in the Wasatch Plateau and elsewhere of the transport and dispersion of seeding material into clouds indicate the topographic and atmospheric conditions for varying seeding effects in a near primary target area as well as in presumed downwind locations. The investigation methodology involving instrumentation as has been applied in this work shows how to accomplish an advanced downwind study. We now consider the contribution of seeding models.

10. SEEDING MODELS

Elliott (1981) has described a seeding effect targeting model. The airflow over the Sierra Nevada as modified by the barrier and as subject to atmospheric stability is calculated. A curtain of dry ice or silver iodide falling flares is inserted in the upwind side of the model. Ice nucleation by dry ice in the curtain occurs immediately and ice nucleation by silver iodide occurs as the curtain rises up the mountains. Subsequently there is growth and fallout of the precipitation particles . Within the cloud there are updrafts and downdrafts and associated turbulence which disperse the precipitation particles until they occupy the entire cloudy mass. The particles then follow calculated trajectories to the mountain surface. A model such as this could be used to track seeding effects downwind of a target area and estimate the amount of precipitation.

Stewart and Marwitz (1981) have examined how a crosswind curtain of ice nuclei and induced ice crystals evolves in upwind-downwind width and tilt as it blows downwind in a sheared atmospheric layer. The authors consider the downwind evolution and footprint of the seeding curtain.

Stewart and Marwitz (1982b) describe theoretically the broadening of a column of ice particles growing in a sheared environment. High concentrations of small particles are present on the upwind edge of the column, and low concentrations of large particles are present on the downwind edge of the column. Atmospheric measurements confirmed these size predictions. Less obvious was an observed lower particle concentration on the downwind side . Although windshear and fallspeed can broaden a column it is recognized that turbulence and vertical motion effects will be equally important for column broadening. This work helps understand where to find seeding effects with an aircraft and the nature of the ice particles reaching the surface in a downwind environment.

King (1984) calculated the elapsed time to reach the surface of a seeding effect started at -15C in stratiform cloud . He showed that the two most important variables controlling the elapsed time are the liquid water content and the cloud depth. Greater values for both variables will accelerate the precipitation development and particle fall to the surface. The paper provided information on where to position an aircraft for correct targeting of an experimental target area and to avoid downwind seeding.

Rauber, Elliott, Rhea, Huggins, and Reynolds (1988) describe a diagnostic technique for targeting of airborne seeding experiments over the wintertime Sierra Nevada. Adequate targeting requires

a) reproducing the airflow across the mountains across the seeded cloudy region,
b) reproducing the growth and the fallout trajectories of ice particles created by seeding,
c) predicting the location of aircraft seeding to produce effects at the target
d) accounting for dispersion of a seeding curtain due to vertical wind shear and particle fall velocity variations,
e) initializing the technique with field data , and
f) running the technique in real time (~ 3 min).

The diagnostic technique was evaluated through comparison of 1) predicted wind fields with those measured by aircraft, 2) ice particle growth rates within seeded cloud regions with predicted growth rates, and 3) radar echo evolution within seeded clouds with predicted particle trajectories.

With the present diagnostic technique better weather modification targeting should become available that should significantly reduce the chance of seeding in undesired locations, for example, downwind where residents may not wish augmented rainfall.

Heimbach and Hall (1994) compare the three-dimensional "Clark" cloud model with measurements of SF6 and silver iodide ice nuclei over the Wasatch Plateau of Utah. The model and measurements show that a) seeding material can be confined to a depth of several hundred meters over terrain, b) horizontal and vertical positions of the seeding release point are critical for targeting, with the best release on the windward slopes of the barrier to take advantage of terrain-forced motions, and c) pooling of seeding material can occur in valley areas. The apparent agreement of the model with measurements suggests using it or a similar model to predict near and long distance downwind transport of seeding material.

Li, Farley, Orville, and Rife (1996) applied a three-dimensional (3D) time dependent (TD) cloud and precipitation model to ascertain silver iodide ground generator locations for seeding supercooled liquid water in Black Hills clouds and increasing precipitation. By comparing the silver iodide and modeled SF6 plumes it was possible to learn where and the extent to which the silver iodide is activated. This fundamental result illustrates the capability of a 3DTD cloud model to predict where a silver iodide seeding aircraft should be located in order to seed effectively an orographic cloud or downwind clouds.

Modeling is useful in predicting where downwind of seeding an effect on precipitation will occur. The modeling must allow for atmospheric motions over terrain, ice nucleation, the factors controlling microphysical particle growth and motion through the atmosphere, and derived trajectories. A variety of models is available.

11. TRACER AND SILVER IN PRECIPITATION

Lacaux, Warburton, Fournet-Fayard, and Waldteufel (1985) describe radar, precipitation amount, and precipitation silver measurements of hailstorms studied as part of Grossversuch IV in Switzerland. The combination of these data allows estimates of how well hailstorms were seeded (seeding quality) and of the residence times of the silver iodide in the hailstorms. The residence times usefully indicate how long silver iodide may have acted.The availability of residence times shows that silver analysis of precipitation combined with data from other instruments, and comprehensive analysis provides useful information on how long silver iodide may have acted in primary or downwind cloud.

Warburton, Young, and Stone (1995) released silver iodide and indium oxide trace chemicals into snowstorms and measured the amounts in snowfall. Less indium was measured since scavenging processes were solely operating while more silver was measured since ice nucleation was also operating with the silver iodide . The combined use of indium oxide and silver iodide demonstrates a method for evaluating ice nucleation effects of silver iodide whether in a primary target area or downwind . Recent advances in this kind of work appear in Stone and Huggins (1996)

Warburton, Stone, and Marler (1995) discuss snowfall chemistry techniques which bear on a) how well a snowfall target area or downwind area may have been treated with silver iodide , and b) the extent to which wind velocities in the seeding vicinity may have been appropriate for seeding material transport. If the silver concentration in snow is above a threshold established for a geographic area (4 ppt in the Sierra Nevada) then the silver was involved in the precipitation process either by scavenging or ice nucleation. Evidence in this paper is that 75 percent of such excess silver is due to ice nucleation processes rather than scavenging. If the silver concentration is at or below the threshold then seeding did not produce that snowfall. The authors show that a large fraction (40 percent) of the snow falling in some target areas was seeded. In other cases the silver fraction was small and nucleation would not have been much involved. Similarly, control area silver in snowfall may have been below the threshold but in other cases it could have been large. This mixture of possible results would have been due to variations in low-level and high-level winds affecting silver iodide transport and dispersion. A conventional statistical analysis of seeding effects on snowfall amount is thus likely to show a smaller seeding effect than actually occurred.

The tracer and silver in precipitation studies lead to conclusions that silver iodide seeding may not be as regular as heretofore believed with atmospheric motions and transport affecting the extent to which seeding occurs whether for a target area or downwind.

12. DEACTIVATION OF SILVER IODIDE

Fukuta (1973) notes that photolytic deactivation of silver iodide smoke due to ultraviolet light in the environment may limit how far downwind seeding effects may occur. Shortly after this paper was written silver iodide seeding solution containing ammonium iodide came into favor and has been found to have little deactivation. Downwind effects with it may be greater (Super, McPartland, and Heimbach, 1975).

Super (1974) used an NCAR acoustic ice nucleus counter to measure concentrations of silver iodide nuclei released into prevailing westerly flow over a north-south mountain ridge from two ground generators. This ridge was upwind of a parallel downwind ridge where the seeding was intended to affect the precipitation.The upwind ridge forced the released silver iodide material orographically into the atmosphere sufficiently far upwind of the downwind ridge for there to be significant turbulent diffusional broadening of the plume. This experiment used a silver iodide plus ammonium iodide solution undergoing little photolytic deactivation to promote temporal continuity of the data and downwind effects.

Super, McPartland, and Heimbach (1975) measured the flux of silver iodide ice nuclei at positions 50-100 km downwind of silver iodide plus ammonium iodide ground generators using an NCAR acoustical ice nucleus counter. The measurements suggested the silver iodide became deactivated at the rate of about a factor of two per hour or less. This indicates there may be significant downwind seeding effects with this nucleant.

13. RELATED WORK SUPPORTING DOWNWIND STUDIES

Huggins (1995) describes the use of a mobile microwave radiometer to measure the liquid water in clouds upwind and over a north-south trending mountain barrier. The liquid water increased from the west up the windward slope as condensation exceeded precipitation and decreased with evaporation and precipitation in the air descending east from the summit downwind. The supercooled liquid water was located mainly on the windward side of the mountain barrier. Ice crystals created by seeding there must follow trajectories through this windward liquid water. The mobile radiometer is excellent for delineating and measuring the amount of cloud supercooled liquid water over various terrain features and can determine whether there are seeding opportunities in a primary target area or downwind.

Huggins (1996) described a combination of radiometer , radar ,aircraft, and surface studies of orographic clouds over the Wasatch Plateau which had been seeded with silver iodide for precipitation enhancement. From the data sets an internally consistent conceptual model was developed of cloud and artificial precipitation formation over and downwind of the plateau.

Orr and Klimowski (1996) described an X-band reflectivity and circular polarization diversity radar study of the transport of chaff released from the top of Mingus Mtn in Arizona. Chaff tracking could reveal whether cloud seeding material could enter stationary gravity waves viewed as containing cloud liquid water. These case studies showed how the chaff plume location and dimensions depended on atmospheric stability and wind speed and on distance downwind.

Reinking and Martner (1996) showed how chaff observations may reveal the location and dimensions of volumes containing cloud seeding material and induced ice particles and their variations temporally and downwind.

14. CONCLUSIONS

The foregoing material has, first, shown evidence of downwind effects of precipitation enhancement by cloud seeding. Second, there has been a presentation of cloud microphysical and other studies for verifying cloud seeding effects. The techniques in these studies may be used in downwind effects studies also.

It is worthwhile quoting from National Academy of Sciences (1973, pp. 128-129) to capture the essence of the challenge still facing the weather modification scientist today. " The long-standing question of whether seeding in one target area could influence precipitation downwind has generated an additional subset of questions. The evidence suggesting some kind of propagation of effect to downwind distances distinctly greater than were assumed likely only a few years ago is now strong enough to pose very pressing questions. The evidence cannot yet be viewed as fully conclusive, but it argues urgent need for searching inquiry into the reality of, and the nature of, these apparent downwind anomalies that have appeared as temporal concomitants of a number of seeding experiments and operations. And the evidence suggestive of atmospheric responses in sectors not under influence of any simple advection action (i.e., the upwind or lateral sectors, relative to seeding sites) calls for equally careful scrutiny. The scientific payoff that could conceivably lie in these puzzling indications could be quite great."

The U.S. National Science Foundation 1977 workshop on the Total-Area-Effect of weather modification summed the situation to that date. It concluded that effects appear to be detectable as far as a few hundred kilometers from the seeding source. Further out the evidence is too weak to be conclusive. There is little evidence that precipitation increases in a target area lead to reductions in precipitation further downwind. Two physical mechanisms for effects may be a) transport of ice nuclei or ice crystals hundreds of kilometers downwind, and b) dynamic invigoration of traveling convective systems with ensuing increased precipitation or, oppositely, decreased cloudiness caused by dynamic suppression.

The American Meteorological Society (1992) in its current policy statement on planned and inadvertent weather modification has noted that "there are indications that precipitation changes, either increases or decreases, can also occur at some distance beyond intended target areas. Improved quantification of the extended (extra-area) effects is needed to satisfy public concerns and assess hydrological impacts." The American Meteorological Society (1998) reiterated this position.

From the above it is clear that study of downwind effects of precipitation enhancement is a task with scope and promise requiring scientific attention employing the full array of field investigative techniques, theory, and modelling.

From the material presented above it is possible to describe the salient features of a study of downwind effects of cloud seeding. It is assumed that the study would be more efficiently and economically conducted as part of a project aimed at precipitation enhancement in a primary target area. As such, the infrastructure and scientific resources of the primary project would be available to support the downwind study. The main features of the downwind study would be the following.

1. Understand the natural climate in and around the proposed precipitation enhancement project. Look for interrelations and correlations between the climates of different subareas of the project area including the target, control, and downwind areas under consideration. Define the terrain, its influence on climate, and the likely precipitation interactions among cloudy areas. Quantify the project terrain and surface water effects on precipitation using as analogs urban/industrial complexes and irrigation areas.

2. Devise a first-order cloud seeding methodology in terms of seeding materials, temporal frequency and spatial pattern of seeding, and choice of airborne seeding or seeding from valley or ridge terrain. Refine the desired seeding methodology with cloud and precipitation models and preliminary field investigations of seeding material transport and dispersion. Consider subsets of methodologies likely to promote or prohibit downwind effects.

3. Develop precipitation gauge, polarimetric radar, and satellite remote sensing methodologies for separately and jointly estimating short-term and long-term precipitation patterns and integral measures in the experimental primary target area, in downwind areas, and in project control areas.

4. As part of physical studies of the clouds, define and understand the populations of ice nuclei, ice particles, and liquid hydrometeors, the processes affecting their characteristics and their temporal and spatial distributions. Use in-situ, airborne, and remote sensing methodologies to define the environmental airflow. Where applicable consider the dynamical and microphysical effects of gravity waves on precipitation development. Employ the NCAR acoustic ice nucleus counter in studies of ice nucleus dispersion, and employ radar-chaff in studies of ice particle growth and transport. From this,

develop a body of knowledge of turbulent dispersion of seeding material plumes and precipitation plumes in and out of clouds. Apply the microwave radiometer to measure supercooled liquid water near the seeding target and downwind areas and serving as an environment for ice particle nucleation and growth. Correlate the supercooled liquid water with the nuclei and radar dispersion studies and use to improve calculations of particle growth in seeding plumes such as curtains. Evaluate the potential of silver-in-precipitation studies including a total silver budget study and combine silver data with winds and with cloud microphysics

5. Develop an up-to-date cloud and precipitation microphysical and dynamical model for real-time field project support in the control, target, and downwind areas. Incorporate dispersion of ice nuclei and hydrometeor plumes. Devise methods for incorporating a variety of field data in the model or for comparing the model with data to advance understanding.

6. Conduct social-economic-political-legal studies related to precipitation enhancement activities that may affect downwind areas particularly.

It should be noted that the downwind studies described above and the work in Sections 8-13 would be of an advanced kind compared to the scientific research methodologies of the 1960's, 1970's, and early 1980's which first indicated downwind effects. Hence, progress in assessing the magnitude of effects and the causes are likely with new knowledge generated with modern methodologies.

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