"REVIEWED"

THE NOAA ATMOSPHERIC MODIFICATION PROGRAM-- A 1995 UPDATE

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1. Introduction

NOAA's Atmospheric Modification Program owes its origins to the Weather Modification Advisory Board Report (1978), that was commissioned by the Secretary of Commerce. One of the key recommendations of that interdisciplinary panel report was the establishment of a new, vigorous research program by NOAA, which was layered on top of some pre-existing operational cloud seeding programs in the States. Concurrently, the water management community within some of the States organized to seek Congressional support for their atmospheric modification efforts. These actions resulted in the formation of the "Federal/State Cooperative Program in Weather Modification Research", now termed the Atmospheric Modification Program (AMP) to reflect the inclusion of research on inadvertent weather modification and climatic change impacts. The AMP is carried forward in the National Oceanic and Atmospheric Administration (NOAA), Oceanic and Atmospheric Research, by renewable two-year cooperative agreements with the six member states: Arizona, Utah, Nevada, North Dakota, Illinois, and Texas.. We should emphasize that the AMP Program supports a large fraction of the cutting-edge research in cloud physics and associated laboratory and field measurements in the U.S. The status of the program through 1991 was reported by Reinking (1992). An excellent review of progress in planned weather modification between 1991-1994 will soon be published by Czys(1995).

2. The Atmospheric Modification Program: Mission and Focus

The AMP research is conducted within the states' universities and research institutes, private industries and collaborating research groups within federal and state agencies (e.g., NOAA, the National Center for Atmospheric Research, and the Bureau of Reclamation). AMP seeks to be technically responsive to regional and national water resource and hydrometeorological issues, and to the needs of our user community. We start from the premise that better understanding of both natural and modified precipitation will lead to general scientific acceptance of the modification technology. The AMP results to date support the recent Policy Statements on Weather Modification issued by the AMS and WMO(both 1992). The program emphasizes physical design, application of numerical cloud/storm models and new observing technologies, and physical evaluation. The six states are now partners with the federal government in the NOAA/State AMP; indeed, the program of each state reflects its needs and interests with respect to atmospheric modification in its own climate regime. Thus, research in Arizona, Utah and Nevada is focussed on wintertime precipitation in order to secure larger and more reliable spring and summer runoff from the melt of mountain snows. The focus in Illinois, North Dakota and Texas is on precipitation from deep summertime(growing season) convection. Here, the development, testing and application of technologies to increase rainfall and, in the case of North Dakota, to reduce the damaging effects of hail are important. Illinois, at its State Water Survey, has a growing research effort in assessing the socio-economic as well as the physical impacts of climatically or purposely altered precipitation on midwestern crops of national significance. Illinois is also addressing various other aspects of inadvertent weather modification, including the effects of urban heat islands and the Great Lakes on surrounding precipitation.

2.1 Arizona AMP

This State relies on aquifers for about 40% of its water supply. However, in some areas(especially over the densely-populated region centered on Tucson and Phoenix), ground water tables are falling rapidly. Therefore, the Arizona Department of Water Resources has begun a program to encourage water conservation and possibly augment supplies in an attempt to address the 2.5 million acre-ft per year imbalance between supply and demand for renewable water. There is no operational seeding underway in Arizona at this time; however, since about 40% of the water for central and northern Arizona falls as snow over the Mogollon Rim, attention has naturally focussed on this region as a potential target area for research. Drainage of snowmelt from the Mogollon Rim goes about 50% into the Little Colorado system to the north, and 50% into the Verde and Salt river systems to the south.

The Arizona AMP Program aims to ascertain whether or not winter cloud seeding could be usefully applied in upslope weather conditions over the Mogollon Rim. A critical tool in this effort has been the development, testing and validation with real data of a computer model for winter precipitation over the western Mogollon Rim (Bruintjes et al, 1992a,1992b). One of the major goals of the Arizona AMP Program is to use this three-dimensional prediction model to increase our understanding of the parameters that control the amount of precipitation that reaches the ground. Field programs conducted during the winters of 1987, 1991 and 1992 verified one of the model's most intriguing predictions: the presence of strong gravity waves over Mingus Mountain. These waves were apparent in data from a wind profiler mounted on the top of Mingus Mountain, as well as from rawinsonde releases in the Verde Valley. Some of the waves were manifested by cloud bands containing significant amounts of supercooled cloud water(as verified by research aircraft, Bruintjes et al, 1992a). These waves may provide a key focus for precipitation development not previously noted in other orographic weather modification programs. Future research is aimed at improving the model's microphysics, and a major field program was conducted during January 15-March 15, 1995 in which the first test releases of seeding material took place. For the first time, limited seeding trials using aircraft AgI and hygroscopic flares were carried out under tightly-controlled conditions. Figure 1 gives an overview of the complex topography in the Arizona AMP field program area and facility locations.

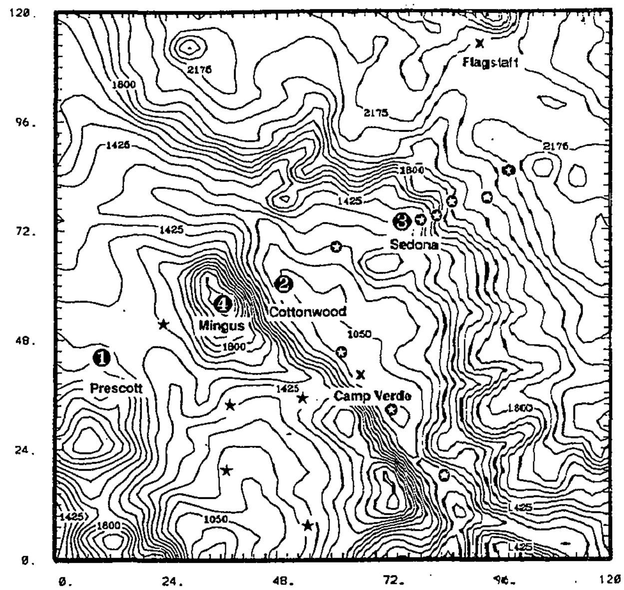

Figure 1. Overview of the Arizona Program Field area and facility locations. The Operations Center, aircraft, modelling activities, and snow sampling will be based out of Embry-Riddle Aeronautical University in Prescott ("❶"). The NOAA K_a- and X-band radars and radiometers, the Univ of Wisconsin Lidar, NASA Ames IR radiometers, and an ALERT surface weather station will all be located at the Cottonwood Airport site ("❷"). The Bureau of Reclamation microwave radiometer and an ALERT surface weather station will be located at the Sedona Airport ("❸"). Mingus Mountain ("❹") will be the location for several chaff and seeding releases, an ALERT surface weather station, and snow, ice crystal, and water vapor measurements and analysis. The other ALERT surface weather stations installed for the Program are located on both private and NFS land, and are shown in Figure 3 with "✪" symbols. Other ALERT tipping bucket rain gages not erected specifically for this project are shown by "★" symbols. Axes are in km; all locations are approximate.

Some very intense winter storms were studied with research aircraft(Figure 2); mobile sounding systems and microwave and IR radiometers;

Fig. 2. WMI, Inc. "CHEYENNE" research aircraft used during AMP-AZ winter, 1995 field program, with new hygroscopic wing-flares for test-seedings.

NASA's IR spectroradiometer; electric field mills; radar chaff cutters on Mingus Mtn. and on aircraft; an acoustic sounder; and a pair of NOAA/ETL X-band and single K-band Doppler radars, which documented a low-level jet in one case of 40 m/sec just 700 m AGL.

Additional details on the Arizona AMP results and plans are given in the papers by Sundie, 1994; Bruintjes and Betterton, 1994; Bruintjes, Clark and Hall, 1994a,b).

The Navajo Nation was added to AMP by the US Congress in 1994, with a mandate to assist them in developing a weather modification research capability. The Arizona AMP program has taken the lead in this effort, by extending the computational domain of the three-dimensional cloud model to include the north-south Chuska Mountains, along the Arizona/New Mexico border on Navajo lands. These mountains rise to over 3 km and experience signficant snowfall every winter. The orography and synoptic storm patterns appear to favor snowpack enhancement and beneficial runoff for parched Navajo farmlands through carefully-planned seeding efforts. The model will be used along with augmented observations of precipitation and other parameters to test and verify this hypothesis. We have also learned recently that the Navajo Nation has a serious flash-flood warning problem on both sides of the Chuskas, and we are working closely with the NWS Western Region to assist the Navajos to develop a coordinated warning and dissemination capability.

2.2 Utah AMP

The Utah AMP Program has a long and rich history. Its overall goals are to evaluate the effectiveness of the State operational winter cloud seeding program, and to promulgate techniques for improving that program. Previous field programs during the 1980's concentrated on the operational seeding in the Tushar Mountains of southern Utah (Huggins and Sassen, 1990). Field efforts were moved to the Wasatch Plateau(over 3 km elevation) during winter, 1989-90, because the Plateau offers logistical advantages over the Tushar Mountains for transport and dispersion investigations and microphysical studies. In particular, low-level flight through cloud systems is practical over the Plateau, and all-weather highways permit sampling on top of the Plateau (e.g., the "STARSHIP" mobile platform in Fig.3).

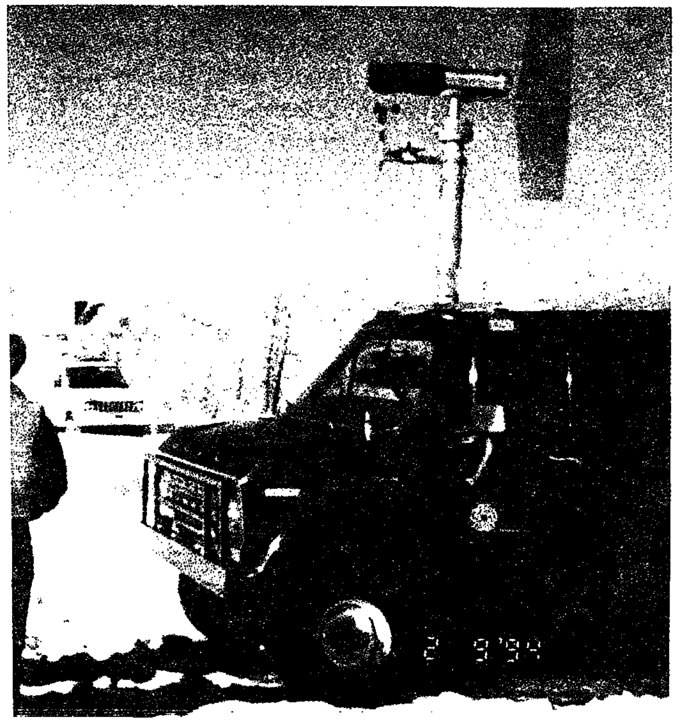

Fig. 3. AMP-Utah's mobile cloud physics vehicle with PMS cloud-particle probe.

The scientific focus of the NOAA/Utah program has emphasized research on the physical processes involved in winter orographic precipitation and its modification. Field efforts over the Wasatch Plateau continue to investigate seeding agent transport and dispersion.

The Utah field programs in the 1980's utilized new technologies such as a microwave radiometer and polarization lidar to signficantly improve knowledge concerning SLW over the Tushar Mountains. During a major winter field program over the Wasatch Plateau in 1991, both mobile and fixed microwave radiometers were used to examine the spatial variability of SLW over the barrier. In general, SLW is available during portions of many storms(Super, 1993). Traverses with a new mobile radiometer revealed a consistency in the position of a SLW maxima over the windward slope (Huggins, 1995). Sassen and Zhao(1993) show some intriguing datasets obtained on clouds with supercooled liquid in Utah using a mobile ground-based lidar system.

An adaptation of the same Clark/Hall

three-dimensional cloud model used in Arizona has been made to simulate orographic cloud formation, and transport and dispersion of seeding agents over the Wasatch Plateau (Heimbach and Hall, 1994; Holroyd et. al., 1995). Model simulations of seeding plume dispersion from sources in the valley floor and well up the windward slopes, as well as releases of a tracer gas, were compared with aircraft observations within 300 m of the top of the Wasatch Plateau. Seeding material is mainly confined to a depth of several hundred meters over the terrain, and the position of release points was critical. A unique mobile cloud physics platform, the "STARSHIP", has been used to sample natural and seeded orographic snow clouds, as it was driven along the north-south paved highway on the top of the Wasatch Plateau(Figure 3).

The Utah AMP program carried out an extensive field program during the 1994 winter over the Plateau to expand upon the 1991 observations(Super, 1994) and modelling of transport and dispersion, to document ice crystal characteristics caused by seeding,and to document the ice particle concentrations after seeding(Holroyd at. al, 1995). Figure 4 shows a remote-controlled propane generator that was used during the 1994 Utah field program at a high-altitude site(see Super et al., 1995 for a discussion of propane dispenser testing).

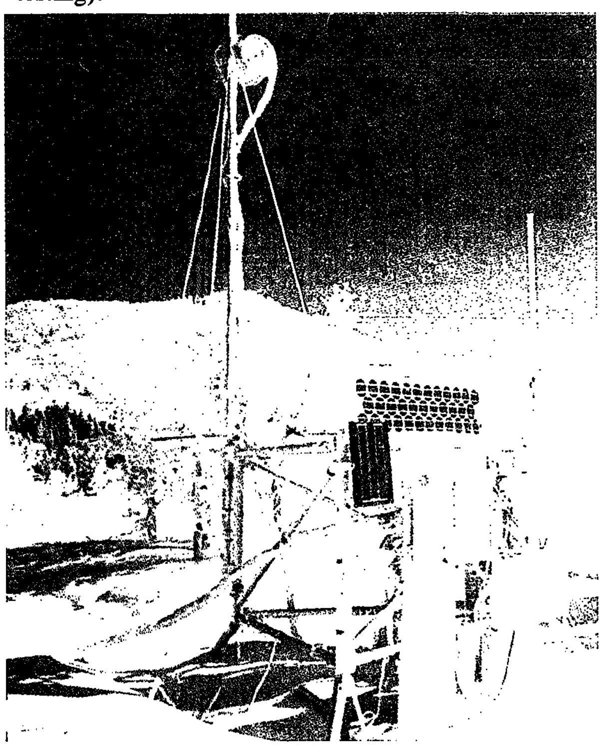

Fig. 4. Remote-controlled liquid propane generator deployed at high altitude site(2537 m MSL) on upwind slope of Wasatch Plateau.

3.3 Nevada AMP

The long-term goal of the Nevada AMP research program is to develop a method for determining whether or not snowfall enhancement occurs when orographic winter storms are seeded, using ground-based release of ice nucleating aerosols. The Nevada program has recently pioneered in the development and application of chemical tracer techniques to assess cloud seeding and targeting. These techniques, which use an Indium compound, allow the first quantitative estimates of seeding effects due to silver iodide nucleation(see Fig. 5).

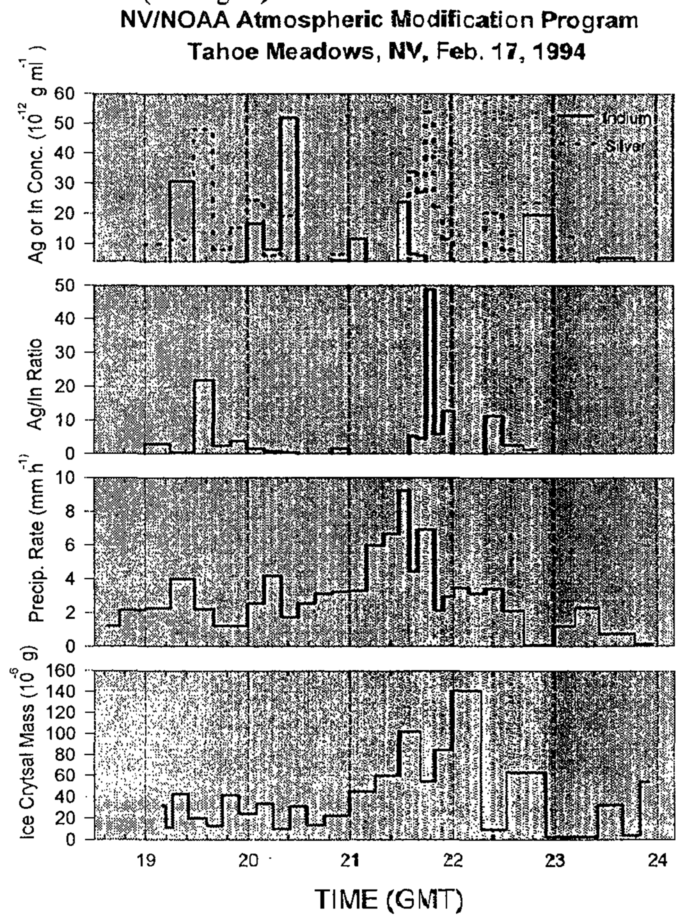

Fig. 5. Data from AMP-NV ice crystal enhancement experiment conducted at the Tahoe Meadows target site just to the east of Mt. Rose. Cloud seeding was conducted from two generator sites slightly upwind of the main Sierra Nevada Crest; both sites releasing AgI and Indium Oxide. Data suggest successful targeting during several subperiods of the experiment. Top Panel: Concentrations of silver

and indium from individual time-sequential snow samples collected at Tahoe Meadows; Second Panel: The ratio of silver mass to indium mass in the samples. Third Panel: Precipitation rate determined from the mass of the time-sequential snow samples. Bottom Panel: Average ice crystal mass determined from paired microphotographs of ice crystals and melted droplets.

Details on the Indium techniques are provided in the paper by Warburton et al(1994). The Nevada AMP Principal Investigator, Mr. Arlen Huggins, participated with one of the DRI mobile radiometers in the 1994 winter AMP-Utah field program on the Wasatch Plateau(results from the 1991 Utah field program are given by Huggins,1995). That radiometer, along with a Ka-band cloud radar from Utah-AMP will be used in a Nevada field effort being planned in the Sierra-Tahoe area during winter 1994-95. Figure 6 gives a three-dimensional portrayal of the mobile radiometer's integrated liquid water transect across the Sierra Nevada on 4 January 1994.

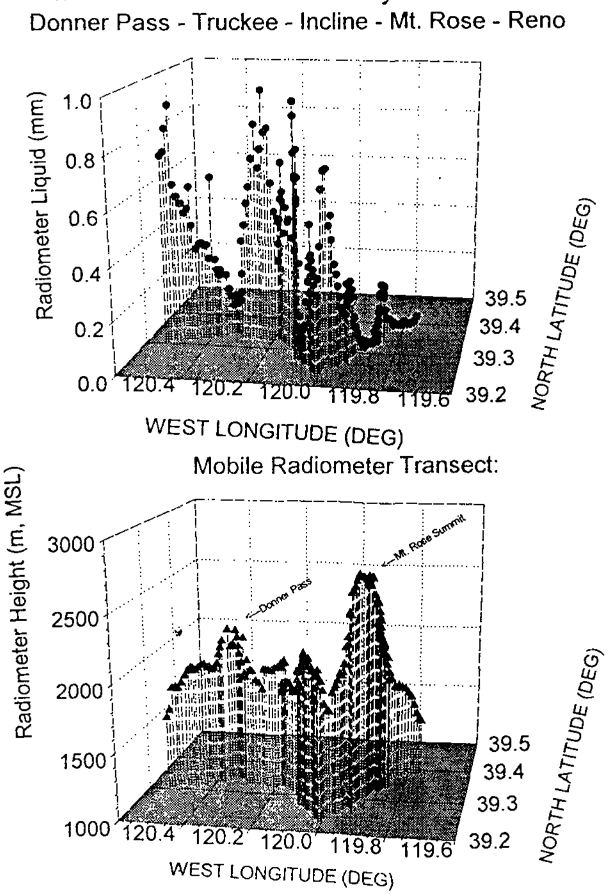

Fig. 6. Distribution of integrated liquid water depth over the Sierra Nevada, as measured on 4 January 1994 by AMP-NV. Transect began to the west of Donner Pass on I-80 and then passed through Truckee, CA and Incline Village,NV. before proceeding over Mt. Rose summit and back into Reno,NV. Top Panel: Integrated liquid water depth by radiometer position; Bottom Panel: Radiometer height by position as determined by GPS. Donner Pass on the main Sierra Nevada barrier and the Mt. Rose Summit at the crest of the Carson Range are noted.

. Future plans include a greater emphasis on measurements of the air flow over and around the Tahoe Basin(using both special surface remote stations and the new WSR88D data from Reno), and application of an appropriate three-dimensional cloud model to this same region.
Additional research is also contemplated on microphysical and chemical studies of snowfall enhancement over the Sierra-Tahoe mountains.

3.4 North Dakota AMP

The long range goals of the North Dakota research in weather modification are: (1) to determine the conditions under which convective rainfall can be enhanced by cloud seeding, (2) assess the feasibility of reducing hail damage through cloud seeding, and (3) improve the understanding of the atmospheric water processes and hazards in northern Great Plains thunderstorms. A study of North Dakota crop-loss insurance data to assess hail damage within and outside the seeding target area has been made by Smith et al(1994). The North Dakota AMP program has recently focussed its research on investigations of transport and diffusion processes in convective clouds, using the release and detection of sulfur hexafluoride gas to trace air motions in the clouds. Ice-phase cloud seeding agents (silver iodide) are sometimes released simultaneously with the tracer, so that any seeding effect can be attributed unambiguously to the actions of the seeding agent. The first North Dakota Thunderstorm Project (NDTP) was carried out in the Bismarck, N.D. area during the summer of 1989. A major new technique, termed TRACIR(TRacking of Air with CIrcular-polarized Radar), uses the NOAA dual-circular-polarization Doppler radar to follow chaff released from aircraft in a developing convective cloud system. Consecutive scans of the storm at frequent intervals allow determination of the movement and dispersion of the chaff through even precipitating clouds(Martner et al, 1992). Thus, for the first time, we can obtain detailed estimates of the transport and dispersion of seeding agents in a cloud. Over 50 publications have resulted from NDTP.

During the summer of 1993, the North Dakota AMP Program carried out its most ambitious field program to date, the North Dakota Tracer Experiment (NDTE). Two Doppler radars (one a NOAA X-band and the other, the University of No. Dakota C-band), three research aircraft, a mobile sounding system and other data were obtained to address links in a conceptual model for hydrometeor development. Figure 7 gives some preliminary NOAA/ETL X-band Doppler with chaff results from one of the best-documented hailstorms, which devastated a Airstream trailer congregation at the Bismark airport.
Three different cloud models were used operationally during the project, and will also be tested using these rich data sets.

DOPPLER RADAR DETECTION OF MESOCYLONE CIRCULATION IN A SEVERE HAILSTORM

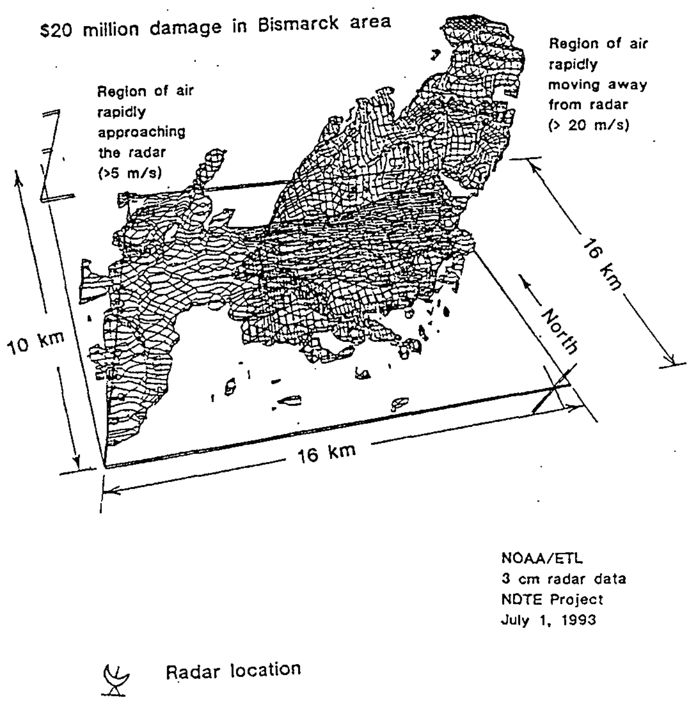

Fig. 7. Three-dimensional depiction of the tilted mesocyclonic circulation in a severe thunderstorm, as observed by the NOAA/ETL Doppler radar. Surfaces enclosing regions of strong radial velocity toward and away from the radar are indicated by the wire-cage contouring lines. The data for this volume scan were obtained during the NDTE on July 1, 1993, at 1737-38 CDT, appprox. one hour before the storm inflicted millions of dollars of hail damage in Bismarck.

3.5 Illinois AMP

The State of Illinois is third nationally in agricultural cash receipts ($4 billion/yr) and second in agricultural exports. The most critical need is for precipitation optimization, stabilization, and long-range prediction to ensure moisture at critical periods of the growing season. Thus, the AMP focus in Illinois is on agricultural response to both purposeful and inadvertent alterations in precipitation, and on convective cloud physics. Research in the Illinois program is perhaps of the broadest of the six AMP States, and has a 14 year history. Future plans include continuing studies of cloud and precipitation processes; joint Illinois participation in the summer, 1995 AMP-Texas field program on convective cloud rain enhancement with new hygroscopic seeding flares; inadvertent modification of weather and climate conditions in Illinois and the Midwest; and the effects of altered weather and climate conditions. Figures 8 and 9 illustrate some new results on inadvertent weather modification, i.e. the urban 'heat island' effect. Figure 8 reveals a greater incidence of cloud-to-ground lightning flashes downwind from St. Louis, especially in the afternoon and early evening.

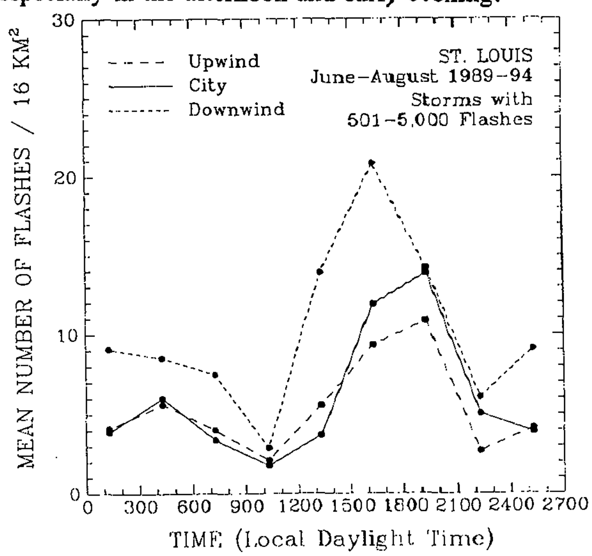

Fig. 8. Frequency of cloud-to-ground lightning flashes(per 16 sq. km) at St. Louis, MO for areas upwind of the city, over the city(urban area) and

downwind(east) of the city. Results reveal greater downwind incidences, particularly in the afternoon and early evening.

Over a larger urban area sample, Figure 9 suggests that cities adjacent to the large Great Lakes(Chicago, Detroit, Milwaukee and Toledo) showed no increase and a slight decrease in lightning. All other cities exhibited downwind increases in lightning.

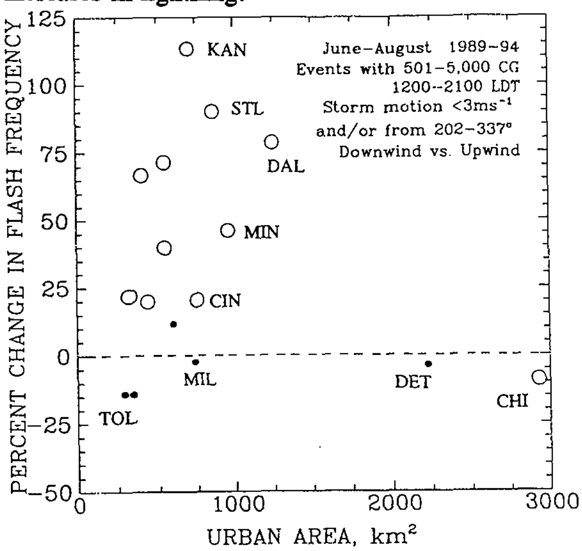

Fig. 9. Percent change of cloud-to-ground lightning flash frequency, from the west upwind to the east-downwind areas for 16 midwestern cities for June-August 1989-1994. Lightning events of a moderate size(501-5,000 flashes), occurring during afternoon hours, and moving slowly or with a westerly component were included. Open circles refer to statistically significant differences and closed circles to non-significant differences. Note that cities adjacent to the large Great Lakes (Chicago, Detroit, Milwaukee and Toledo) showed no increase and a slight decrease, while all other cities exhibited downwind increases in lightning.

Two exploratory seeding experiments were carried out in Illinois during 1986 and 1989(termed PACE), using the dynamic seeding approach(Westcott et al, 1993). The findings so far, using radar and cloud physics aircraft data, have shown some distinct limitations of this approach to Illinois agricultural productivity(Czys et al, 1993). Weather modification efforts on convective clouds in Illinois is greatly complicated by the fact that much of the rainfall occurs in association with severe weather and/or after dark. A comprehensive evaluation of the convective cloud modification efforts to date in Illinois, and possible future directions is given by Changnon et al(1994). Figure 10 shows that before cloud treatment, there was no sense of organization in the relationship between dynamically-seeded cumuli and rainfall.

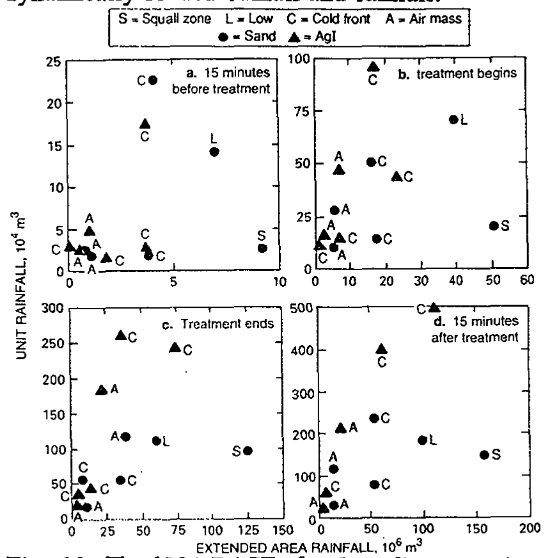

Fig. 10. The 1989 PACE cloud seeding experiment in Illinois involved dynamic seeding of growing cumuliform clouds in groups, or units, and the rainfall from the 6 units treated with AgI was compared with that from 6 units treated with a sand placebo. In this graph, the relationship of the unit-area rainfall(for seeded[treated] and non-seeded units) and that of the extended area (all the other rainfall surrounding the units) is shown for four times, from 15 min before treatment (upper left) until 15 min after treatment.

However, by 15 minutes after AgI seeding, two of six treated units had large values of unit rainfall (relative to extended area amounts). Both cases were with cold fronts, as designated.

With regard to agricultural impacts of purposeful precipitation modification, AMP-Illinois field experiments on agricultural plots have examined how additional water applied during different crop growth stages might affect yields. Figure 11 shows shifts in applications during stage 6 of corn growth for four years. Surprisingly, increased amounts of water had only minor influences on corn yields.

3.6 Texas AMP

Texas was added to the existing five States participating in AMP by the U.S. Congress in 1992. Its research is focussed on summertime convective cloud systems over the semi-arid, agricultural

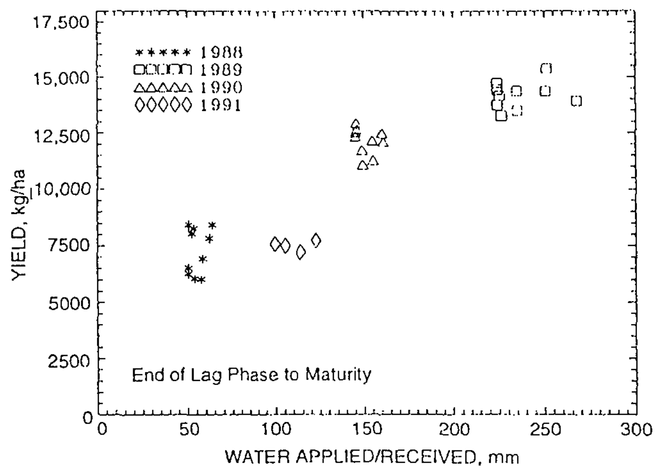

Fig. 11. Illinois field experiments on agricultural plots have examined how additional water applied during different crop growth stages affect yields Here, shifts in applications during stage 6 of corn are shown for four years. Increased amounts had only minor influence on yields.

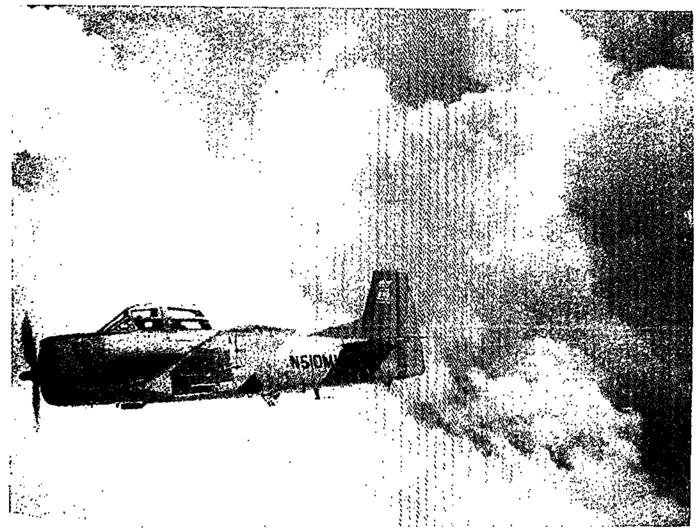

Fig. 12. The South Dakota School of Mines T-28 armoured cloud physics research aircraft, flying cloud-penetration mission on August 15, 1994 during AMP-TX field program southeast of Big Springs.

cloud systems over the semi-arid, agricultural regions of west Texas. The program has two objectives: to quantify the amount of additional rainwater and runoff that is generated when summertime convective clouds are seeded using the dynamic seeding approach; and to understand the behavior of convective clouds in order to predict the impact of the various cloud seeding methodologies will have on these clouds. A conceptual model for the dynamic seeding hypothesis, as applied to both seeded and nonseeded clouds in Texas has been developed by Rosenfeld and Woodley (1993). Results of a program supported by the Bureau of Reclamation in the 1980's have been reported by Rosenfeld and Woodley (1989). Randomized cloud seeding experiments conducted in 1987 and 1989-90 in conjunction with a State operational program resulted in 183 convective cells(about half seeded and half nonseeded). Dynamic seeding from aircraft increased the areas of the cells by 43%, the durations by 36%, and the rain volume ratios by 130%. The principal dynamic effect of the cloud seeding was the increased mergers of cloud cells.

Another modest field program was carried out in the Big Springs, TX area in late summer, 1994 to obtain additional seeded/nonseeded cases, with emphasis on documenting the microphysics, using the South Dakota School of Mines T-28 aircraft(Fig. 12) and remote sensors.

The T-28 aircraft penetrations of experimental cloud units showed several cases of abundant liquid water with large convective updrafts(some greater than 2 g m-3 and 10 m/s, resp.).

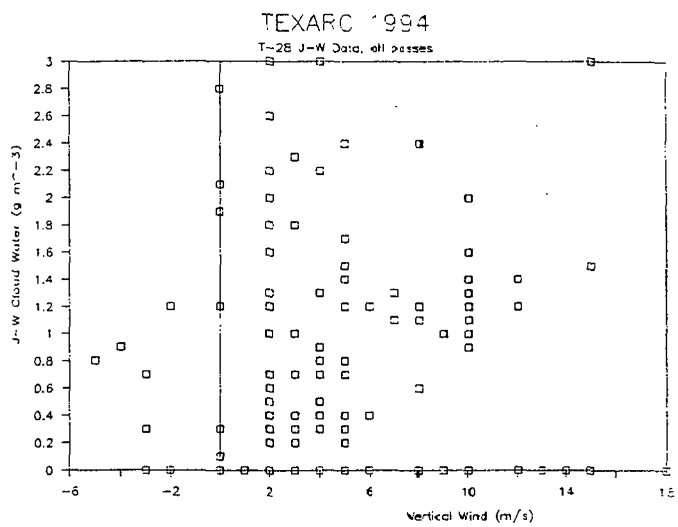

Fig. 13. Plot of J-W cloud water vs. convective updrafts in 1994 AMP-TX field program by T-28 aircraft penetrations of experimental convective cloud units.

Digital data were also archived for the first time on the NWS NEXRAD at Lubbock.

4. Weather Modification Impacts from the Modernization of the U.S. National Weather Service

The National Weather Service(NWS), NOAA is in the midst of a $2 billion Modernization program. While the total number of offices will be reduced overall at the completion and certification of the Modernization, there will be 116 modern Weather Forecast Offices(WFOs) equipped with new observing and data processing and display technologies. In addition,

NOAA has installed and operated a 29-station Wind Profiler Demonstration Network over the Central U.S. for 4 years now. These instruments are vertically-pointing, fixed array Doppler radars(405 mHz frequency) that produce virtually continuous tropospheric wind profiles, from about 0.5-16 km. NOAA laboratories have also pioneered in the development of smaller, transportable boundary layer wind profilers(915 mHz frequency), that are used in field experiments. One of these systems was used very successfully during the 1991 Arizona AMP field program. A key new technology component of the NWS Modernization is the WSR-88D(NEXRAD) Doppler radar, which has been deployed at over 100 of the eventual 116 WFO sites. This narrow-beam, 10 cm wavelength Doppler radar has characteristics and advanced data processing summarized by Golden(1989) and Golden et al(1990). It provides high-resolution, three-dimensional volume scans refreshed every 6 min. The WSR-88Ds also provide a synthesized vertical wind profile, using the VAD technique, averaged over the volume scanned above each radar every 6 min. NEXRAD data has already been used in AMP-TX and AMP-AZ field programs over the past year. Together, the wind profilers and WSR-88Ds have many applications to both research and operational weather modification programs in the U.S. In addition, we can now produce high-resolution (1 km or better) hourly, six-hourly and storm-total maps of precipitation accumulation. The WSR-88D software also permits the acquisition and blending of remote raingage data under each radar umbrella in real-time, once the new AWIPS-90 processing system is deployed. We will also be to track seeding materials released from aircraft or the ground much more accurately, using WSR-88D and wind profiler data. Finally, in concert with the FAA and Defense Department, NWS is deploying over 1200 Automated Surface Observing Systems at large and small airports in the U.S. These new in-situ and remote sensor data, when blended appropriately and assimilated into mesoscale cloud models, will permit highly detailed real-time predictions of cloud and precipitation development, as well as more accurate estimates of transport and dispersion of seeding plumes.

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