A NEW HAIL SUPPRESSION PROJECT USING AIRCRAFT SEEDING IN ARGENTINA

by

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INTRODUCTION

The Province of Mendoza in western Argentina (32 S., 68 deg W.) is one of the most hail prone areas of the world. Losses to agriculture due to hail historically are >10% of total annual agricultural production. The region is known as the "Land of Wine" and the principal crops are grapes plus a large variety of fruit and vegetables (e.g. apples, cherries, peaches, apricots, plums, melons, garlic, tomatoes). The province comprises a diverse territory of mountains, upland areas, and plains. The western border of Mendoza is occupied by the main Andean cordillera, with a number of peaks above 6400m. Climatic conditions are semi-arid, and the annual rainfall for the Capital City Mendoza is 200 mm.

Hail suppression programs using Russian rocket technology have been conducted in the region since 1985 with some interruptions (Makitov 1999). A new airborne hail suppression project has now been implemented by Weather Modification Inc. (WMI) of Fargo, North Dakota for the Ministry of Economy, Government of Mendoza, Argentina. A one-year program was conducted from Dec. 4th 1998 to April 15th, 1999 to demonstrate the capabilities of airborne hail suppression techniques and methodologies. In October 1999, in response to an international request for bids, WMI was awarded a 5 yr contract to continue the operational seeding program and implement a technology transfer and research program.

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OPERATIONAL SEEDING PROGRAM DETAILS

The current operational seeding period is from October 15th to April 1st. The main radar is centrally located at Cruz Negra (33.447 deg south, 68.967 deg west) near Tunuyan. The project area covers the three agricultural oases of Mendoza-San Martin in the north, Tunuyan in the center, and San Rafael in the south. A map of Mendoza province and the target oases is shown in Figure 1. The program consists of 3 Piper Cheyenne II seeding aircraft, 1 LearJet research-seeder aircraft, two C-band weather radars with TITAN processing and display software, two Vaisala radiosonde systems, plus all the necessary staff. Two Cheyenne II are stationed at San Rafael, the

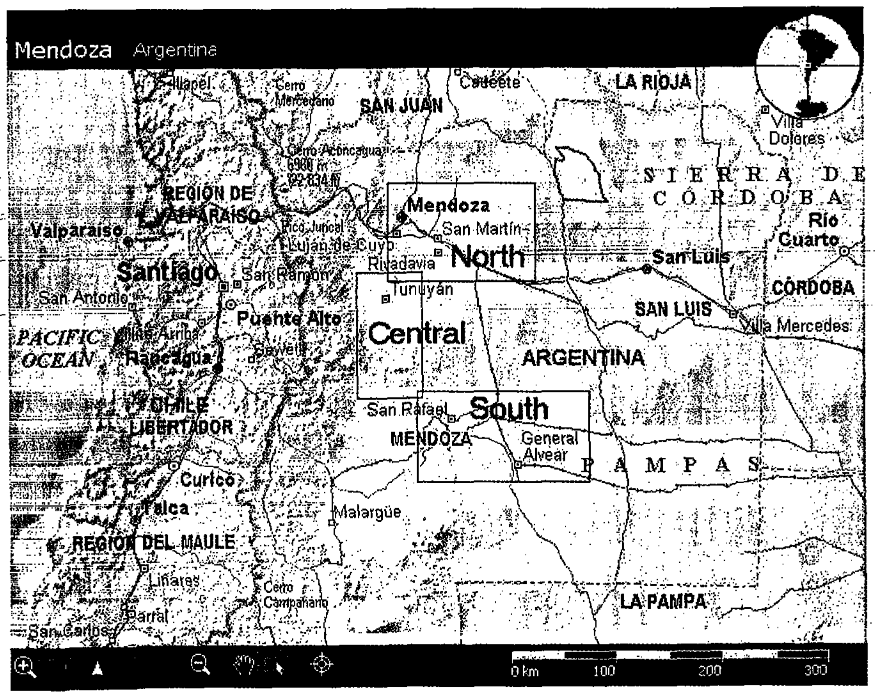

Figure. 1: Map of Mendoza Province, Argentina showing the three areas of operations: North (Mendoza and San Martin), Central (Tunuyan), and South (San Rafael).

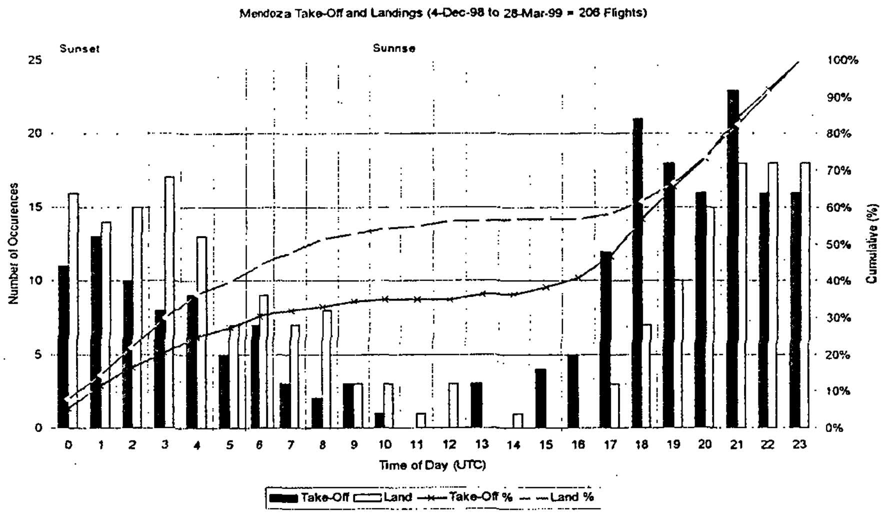

Figure 2: The frequency of occurrence and cumulative distributions of aircraft take-off and landing times for all flights as a function on time. Local time is 3 hrs behind universal (UTC) time. Approximate summer sunset *and sunrise times are indicated.*

other Cheyenne II and the Lear Jet are stationed at Mendoza. The Cruz Negra radar operates continuously. Radar images are made available on the WWW internet at 15 min intervals. All of the project's radar data, meteorological data, aircraft data, and reports are recorded onto CD-ROM for the Ministry of the Economy. The auditing of the operational program is being conducted by the National University of Cuyo in Mendoza.

CONCEPTUAL HAIL MODEL

The cloud seeding is based on the conceptual model of Alberta hailstorms which evolved from the experiments and studies of Chisholm (1970), Chisholm and Renick (1972), Barge and Bergwall (1976), Krauss and Marwitz (1984), and English (1986). Direct observational evidence from the instrumented aircraft penetrations of Colorado and Alberta storms in the 1970's and early 1980's indicates that hail embryos grow within the time evolving "main" updraft of single cell storms and within the updrafts of developing "feeder clouds" or cumulus towers that flank mature "multi-cell" and "super-cell" storms (see e.g. Foote, 1984; Krauss and Marwitz, 1984). The computation of hail growth trajectories within the context of measured storm wind fields provided a powerful new tool for integrating certain parts of hail growth theories, and illustrated a striking complexity in the hail growth process. Some of this complexity is reviewed in the paper of Foote (1985) that attempts to classify a broad spectrum of storm types according to both dynamical and microphysical processes thought to be critical to hail production. The growth to large hail is primarily hypothesized to occur along the edges of the main storm updraft where the merging feeder clouds interact with the main storm updraft (WMO, 1995).

The cloud seeding hypothesis in Mendoza is based on the concept of "beneficial competition". Beneficial competition assumes a deficiency of natural ice nuclei in the environment and that the injection of silver iodide (AgI) will result in the production of a significant number of "artificial" ice nuclei. The natural and artificial ice crystals "compete" for the available super-cooled liquid cloud water within the storm. Hence, the hailstones that are formed within the seeded cloud volumes will be smaller and produce less damage if they should survive the fall to the surface. If sufficient nuclei are introduced into the new growth region of the storm, then the hailstones will be small enough to melt completely before reaching the ground. Cloud seeding operations alter the microphysics of the treated clouds, assuming that the present precipitation process is inefficient due to a deficiency of natural ice nuclei. Cloud seeding does not attempt to compete directly with the energy and dynamics of the storm. Any alteration of the storm dynamics occurs as a consequence of the increased ice crystal concentration and initiation of riming and precipitation sized ice particles earlier in the cloud's lifetime. The silver-iodide reagents initiate a condensation-freezing process and produce enhanced concentrations of ice crystals that compete for the available, super-cooled liquid water in a storm and thereby reduce the growth of large damaging hail. The seeding also initiates the precipitation process earlier in a cloud so that cloud hydrometeors may proceed via an ice-phase (graupel) to rain mechanism instead of continuing to grow to damaging hail.

CLOUD SEEDING METHODOLOGY

Storm cells (defined by radar) with maximum reflectivity >35 dBZ within the cloud layer above the -5°C level, located within the project areas or within a 20 min travel time "buffer zone" upwind of the project areas, are seeding candidates if they are deemed to be a potential hail threat. Radar meteorologists are responsible for making the "seed" decision and directing the cloud seeding missions, incorporating the observations of the pilots into their decisions. Patrol flights are often launched before clouds within the target area meet the radar reflectivity seeding criteria. These patrol flights are meant to provide a quicker response to developing cells. In general, a patrol is launched in the event of visual reports of vigorous towering cumulus clouds or when radar cell tops exceed 20 kft height over the higher terrain along the western border on days when the forecast calls for thunderstorms with hail potential.

Cloud top seeding can be conducted between -8°C and -15°C. The 20 g pencil flares fall approximately 4000 ft (approximately 10°C) during their 35-40 s burn time. The seeding aircraft penetrate the edges of single convective cells meeting the seed criteria. For multi-cell storms, or storms with feeder clouds, the seeding aircraft penetrate the tops of the developing cumulus towers on the upshear sides of convective cells, as they grow up through the -10°C altitude.

SEEDING MATERIALS

Silver-iodide is dispensed using droppable and/or end-burning pyrotechnics. Acetone generators were also used during the 1998-99 campaign, however, they have now been abandoned due to the penalty they pose on aircraft performance. WMI now uses silver-iodide formulation flares manufactured by Ice Crystal Engineering (ICE) of Davenport, ND. The ejectable flares contain 20 gm of seeding material and burn for approximately 35 sec and fall approximately 4000 ft. The end-burning flares (BIP) contain 150 gm of seeding material and burn for approximately 5 min. The ice nucleating effectiveness of the flares manufactured by ICE, have been tested at the Cloud Simulation and Aerosol Laboratory at Colorado State University (Demott, 1999). The primary product of the laboratory characterization is the "effectiveness plot" for the ice nucleant which gives the number of ice crystals formed per gram of nucleant as a function of a range of cloud temperatures. Specified temperatures for testing in the isothermal cloud chamber are typically -4°C, -6°C, -8°C, -10°C, and -12°C. The flares used in Mendoza produce between 10^{12} and 10^{13} ice nuclei per gram of pyrotechnic between -6°C and -10°C. The new generation ICE pyrotechnic produces >10^{11} ice nuclei per gram at -4 C. Rates of ice crystal formation in the CSU isothermal cloud chamber were extremely fast (63% active within one to two minutes, and 90% active within four minutes) and the apparent ice formation mechanism was identified as condensation-freezing nucleation (Demott, 1999). Significant ice formation activity was measured as warm as -4°C. Little dependence of yield on cloud liquid water content or cloud droplet distribution characteristics is expected based on the current tests. High yield and fast acting agents are important for hail suppression since the time-window of opportunity for successful intervention of the hail growth process is often less than 10 minutes.

1998-99 FLIGHT STATISTICS

During the demonstration project of 1998-99, two hundred and ten (210) aircraft flights (515 flight hours) were conducted on 64 days between the period Dec. 4th, 1998 and March 28th, 1999. Of these, 161 flights (437 hrs) were seeding flights, and 41 flights (66 hrs) were for weather surveillance only. There were 111 night time flights (286 hrs) and 99 day-time flights (229 hrs). The distribution of take-off and landing times according to the time of day is shown in Figure 2.

Cloud seeding was conducted on 52 days. The seeding consisted of 18,480 droppable/ejectable flares (369,600 gm seeding material), 2,015 burn-in-place flares (302,250 gm seeding material), and 642 litres of acetone solution (11,096 gms of silver-iodide). The total mass of seeding material released was 682,946 gms.

Operations were conducted in the north oasis on 32 days, dispensing 268.5 kg of seed material. There were 10 days with reported hail damage in the north. Operations were conducted in the central oasis on 24 days, dispensing 126.9 kg of seed material. There were 9 days with reported hail damage in the central oasis. Operations were conducted in the south oasis on 34 days, dispensing 287.4 kg of seed material. There were 16 days with reported hail damage in the south.

ATMOSPHERIC CONDITIONS

A summary of some of the most important atmospheric parameters measured by the radiosonde balloon launched daily at 16:00 UTC (13:00 local time) at the Cruz Negra radar site is given in Table 1. The period for this summary is from Dec. 6th, 1998 to March 31st, 1999 inclusive. The data are summarized for all days, days with thunderstorms, and days on which damaging hailstorms occurred.

Each of the 22 days with hail damage was forecast as a hail day by the project meteorologists using the index called the CDC (Convective Day Category) as defined by Strong (1979). Storm cloud base heights averaged between 8-10 kft and the average temperature at cloud base was 8°C to 12°C. Pilots usually reported that the feeder cloud bases were between 10-12 kft. Severe hail storms tended to have the lower and warmer cloud bases. The average surface dew point on days with hail was 11.46°C and the presence of high surface humidity was a good predictor of severe storms.

The average -10°C height (used for a common seeding altitude) was in the range 18 - 19 kft. The mid-level winds were typically southwesterly (from 250-260 deg true) and the average storm cell speed was 12 - 14 kts. A common observation from the soundings was the dramatic increase in the wind speed above 20 kft, which corresponds to the height of the Andes Mountains. The mountains have a dramatic effect on storm formation that is not fully understood. The mountains are believed to cause a capping inversion which helps to suppress the premature release of convective instability, but also are thought to provide a lifting mechanism for triggering thunderstorms after sunset, possibly through the formation of a low-level-jet stream and Bernoulli type effect. More research is required into the effects of the mountains on the hailstorms in Mendoza.

Table 1: Summary of important atmospheric parameters measured by the radiosonde balloon launched daily at 16:00 UTC (13:00 local time) at the Cruz Negra radar .

		All Days		Thunderstorm Days		Hail Damage Days	
Parameter	Units	Average	StdDev	Average	StdDev	Average	StdDev
FCST CDC	None	-0.20	1.75	0.73	1.53	1.71	0.72
Precip. Water	In	0.72	0.19	0.79	0.20	0.90	0.19
0 deg ht.	Kft	14.22	1.55	14.36	1.41	13.90	1.65
-5 deg ht.	kft	16.51	1.39	16.54	1.34	16.13	1.55
-10 deg ht.	Kft	18.77	1.33	18.71	1.31	18.50	1.49
Cloud Base Ht.	Kft	9.01	2.63	9.13	2.49	8.06	1.92
Cloud Base Temp.	Deg C	8.70	4.55	9.83	5.07	12.28	3.85
Max. Storm Top	Kft	31.63	9.30	35.76	7.35	39.29	3.47
Temp. max.	Deg C	30.47	4.74	32.21	3.93	32.36	3.87
Dew Point	Deg C	8.30	3.94	9.42	4.27	11.46	2.60
Convective Temp.	Deg C	31.73	7.01	32.71	5.10	30.63	4.56
Total Totals Index	None	44.65	7.95	48.16	6.02	52.14	3.85
Lifted Index	None	0.49	4.00	-1.56	3.40	-3.64	2.13
Storm Direction	Deg true	252.58	64.00	258.62	58.80	278.35	47.21
Storm Speed	knots	15.40	8.65	13.66	6.06	12.82	4.64
Cell Direction	Deg true	250.33	64.03	255.36	63.63	262.53	71.68
Cell Speed	knots	15.60	8.88	14.00	6.51	12.76	5.01
700 mb wnd. Dir	Deg true	192.38	132.52	196.45	133.40	172.41	137.20
700 mb wnd. Spd	knots	8.80	5.28	9.68	5.86	10.41	6.49
500 mb. Wnd. Dir.	Deg true	260.56	45.21	268.15	38.41	274.29	38.50
500 mb. Wnd. Spd.	knots	25.21	12.57	24.98	13.23	23.47	11.34
300 mb. Wnd. Dir.	Deg true	260.71	50.83	265.35	41.31	273.24	34.77
300 mb. Wnd. Spd.	knots	48.37	21.33	48.61	21.56	50.88	25.30
Outlook CDC	none	-0.13	1.52	0.44	1.18	0.52	1.17

LEAR JET RESEARCH-SEEDER

The Lear Jet research-seeder aircraft conducted five research experiments and four seeding missions during February and March 1999 to characterize the microphysical conditions of the clouds, to confirm the microphysical seeding effects, and to demonstrate its superior ability to seed clouds. More research flights have been conducted in 2000. The Lear Jet is equipped with 408 flares and has the performance to move quickly from storm to storm and seed many storms during a single mission. The cloud physics instrumentation consisted of a PMS-FSSP and OAP-2DC and was able to measure the atmospheric conditions, cloud variables such as the cloud droplet and ice crystal concentrations and sizes, and microphysical responses to seeding.

Liquid water contents > 1 g/m^3 have been measured at temperatures as cold as -38°C. The liquid water contents decrease rapidly at temperatures colder than -38°C as an apparent result of homogeneous freezing of the water droplets. The cold temperatures by the Lear Jet have confirmed an abundant supply of super-cooled water for hail stone growth through a very large vertical extent as a typical occurrence in Mendoza storms.

Droplet concentrations as measured with an FSSP-100 vary between 300 and 600 cm^{-3} just above cloud base indicating a continental airmass. Cloud bases are generally between +8°C and +12°C. The limited observations to date indicate that the coalescence process is not active in convective clouds in the area. This was further supported by radar measurments that indicate that the first echo usually develops at temperatures colder than –10°C. The cloud droplet mean-volume-diameter at –10°C is approximately 15 um, and at –20°C approximately 25 um. These are characteristic of continental clouds, however, from these limited observations, it is not possible to determine the presence or absence of low concentrations of large drops (e.g. drizzle drops of 100 um diameter) and their effect on the growth of hail in these clouds.

AGI SEEDING CASE STUDY

On 2-March-2000, a seeding experiment was conducted on an isolated cumulus-congestus cloud. The convective cloud base on this afternoon was at 9300 ft MSL with a temperature of 8°C. The first penetration was made at 21:11:27 UTC, at a temperature of -10 C, approximately 1000 feet below the growing cloud top. There was no natural ice detected so the cloud was seeded during the penetration with 7 ejectable flares (ICE, 20 gm AgI type). The cloud continued to grow so the Lear Jet climbed to -14°C for the second penetration at 21:13:59 and a spike in the ice concentration from the 2DC probe was observed inside the cloud. The King liquid water content and the 2DC ice concentration for cloud pass number 1 and 2 are shown in Figure 3. The first pass had a peak liquid water content of 2.2 g/m^3 and no ice. The second cloud penetration had a peak liquid water content of 1.9 g/m^3 and a maximum one second ice concentration of 902 /L. The 2D images show that the high ice concentration seeding signature consisted of mostly 100 micron diameter thin plate-like crystals. This is the fastest response to silver-iodide seeding that the authors have ever measured within a cloud and verify the fast ice nucleation rates measured in the CSU cloud chamber. The older formulation TB1 silver-iodide flares typically took approximately 6 min before the ice signature was detected using 2DC probes (Krauss et al., 1987). The new formulation ICE probes, therefore, represent a significant decrease in response time in the life-cycle of precipitation development for continental clouds.

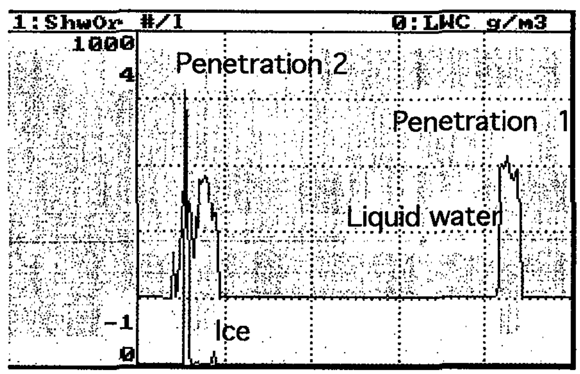

Figure 3: The King liquid water content and the 2DC ice concentration for cloud pass number 1 (right) at 21:11:27, and cloud pass number 2 (left) at 21:13:59.

The third cloud penetration was made at the -15°C level at 21:17:50 and a peak liquid water content of 1.5 g/m^3 and peak ice concentration of 788 /L were measured. The King liquid water content and the 2DC ice concentration for cloud pass number 2 and 3 are shown in Figure 4. The 2D ice crystal images for a portion of penetration 3 are also shown. The ice crystal seeding signature was splitting the updraft core of the cloud and depleting the liquid water. In contrast, the first natural ice is most often detected at the edges of the cloud.

The 4th cloud penetration was made at 21:17:50 at the -14°C level and recorded a peak liquid water of 1 g/m^3 and a peak ice concentration of 162 /L. The 5th cloud penetration was made at 21:20:37 at the -16°C level and recorded a peak liquid water of 1.5 g/m^3 in a newly developing turret, but a liquid water concentration of 0.6 g/m^3 in the older, seeded portion of the cloud. The peak ice concentration was 82 /L. in the seeded portion but essentially zero in the newly growing portion. The 6th cloud penetration was made at 21:22:55 at the -14°C level and recorded a peak liquid water of only 0.2 g/m^3 and a peak ice concentration of 84 /L. The King liquid water content and the 2DC ice concentration for cloud pass number 5 and 6 are shown in Figure 5. A radar echo of 20 dBZ had formed at this time.

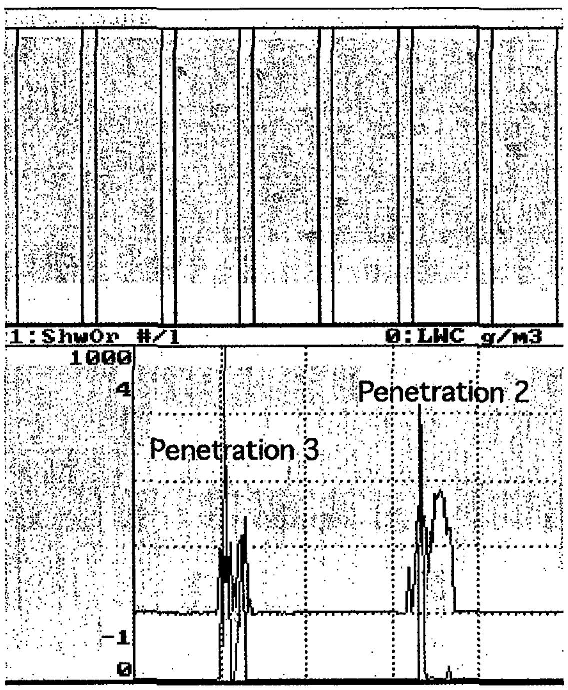

Figure 4: The King liquid water content and the 2DC ice concentration for cloud pass number 2 and 3. The 2D ice crystal images for a portion of penetration 3 are also shown. The distance between vertical lines for 2DC probe shadow images is 800 microns.

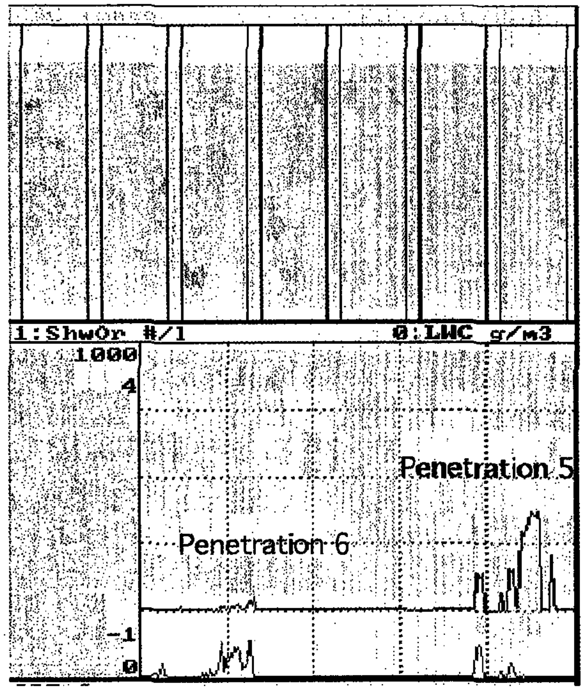

Figure 5: The King liquid water content and the 2DC ice concentration for cloud pass number 5 and 6. The 2D ice crystal and graupel images for a portion of penetration 6 are also shown.

The evolution with time of the ice size spectra for the cloud penetrations number 2 to 6 (after seeding) is shown in Figure 6. The high concentrations of ice and growth to large sizes are clearly shown. The legend indicates the average ice concentration across the ice plume during the penetration. This single cloud seeding experiment confirms the effectiveness of the ICE flares and supports the beneficial competition and cloud liquid water depletion steps in the conceptual hail suppression model.

CROP DAMAGE EVALUATION

Crop damage statistics obtained from the Ministry of Economy (Direccion de Prevencion de Contingencias) indicate that the 1998-99 season had the lowest hail damage in the last 10 years. The damaged area for 1998-99 was 41% of the previous 9 year average. Furthermore, only 33% of the year's damage occurred after the seeding project begin, since 67% of the damages occurred before Dec. 4th, 1998. A graph of the area of hail damage (equivalent to 100%) for the three oases since 1989-90 is shown in Figure 7. The season *was not unusual in climatic terms with respect to* precipitation and temperature, however, it may be that the 1998-99 season may have had below normal storm intensities and frequency of severe hailstorms. Preliminary indications for the 1999-2000 season indicate many more severe storms, therefore, the area of hail damage will certainly be greater for the second seeded season. The airborne seeding effectiveness can not be evaluated using these measures in only one or two years, therefore, no conclusions regarding the effectiveness of the seeding are made at this time.

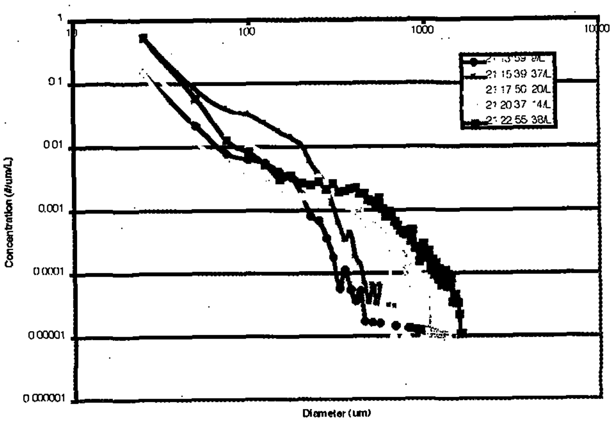

Figure 6: The evolution with time of the ice size spectra for the cloud penetrations number 2 to 6 (after seeding).

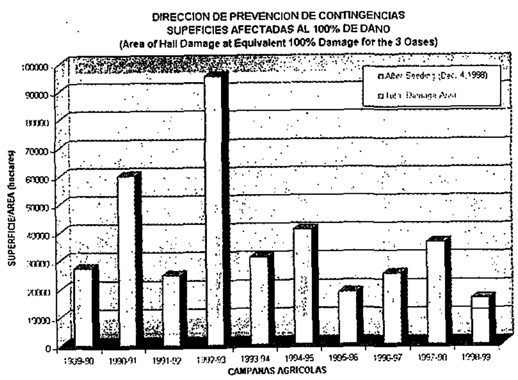

Figure 1: Area of hail damage (equivalent to 100% damage) for the three oases since 1989-90. The damage area before seeding and after seeding began on Dec. 4th, 1998 is shown separately for the past season.

PHYSICAL STUDIES

Physical studies formed a small but important part of the first two years activities and will hopefully continue in the future. Although hail suppression has shown signs of success in the past (WMO statement on Weather Modification; AMS Statement on Weather Modification), the technology is as yet not scientifically established and there is room for improvement. It is therefore important that studies to investigate the effectiveness of hail suppression and the economical impacts continue in Mendoza. In considering the outline of a possible future research program two primary objectives have been identified;

- **Objective A**: To learn more about the nature of hailstorms, both natural and seeded in order to provide:
1. Evidence for the effectiveness of hail suppression seeding
2. Evidence for the economic benefit of hail suppression (cost benefit analysis)
3. A basis for improving the effectiveness of hail suppression

- **Objective B**: To educate and train a new generation of scientists in Argentina to carry on this research in the future.

As part of the current five year program, four professors from the Universidad de Cuyo in Mendoza have been integrated into the program and two students are currently working with WMI staff in the program. In addition, eight Argentine pilots are flying as co-pilots on all the seeding missions.

CONCLUSIONS AND RECOMMENDATIONS

In conclusion, airborne seeding technology and hail suppression seeding concepts and methodologies were successfully demonstrated during the summer of 1998-99. Considerable knowledge and experience were obtained regarding the hailstorms of Mendoza. In addition, the people of Mendoza have learned a lot about the capabilities and methodologies of aircraft seeding operations. Preliminary results indicate that the 1998-99 hail damage to crops in the province of Mendoza was the lowest during the last ten years, however, the second season is experiencing above average hailstorm frequency and damage, therefore, it is much too early to draw any conclusions regarding the effectivenss of the airborne seeding program at this time. A research and evaluation program must now be implemented to determine the impact of the seeding on the frequency and occurrence of hail.

The Lear Jet has already conducted several research missions within high altitude cloud regions that have not been possible in the past. Some seeding signatures were detected, however, more microphysical measurements are required to document the concentrations of super-cooled water, especially at temperatures colder than -20 C. *Much more data is required to characterize the* initiation and evolution of the natural ice concentrations and the effect of seeding on the supercooled liquid water of the storms. Furthermore, more research is recommended to determine the variety of effects that the mountains have on the formation, structure, and characteristics of hailstorms. A research and technology-transfer program is being implemented to address these issues during the next four years.

Acknowledgements: The authors wish to thank the Ministry of Economy, Government of Mendoza for their support of the operational program and scientific studies.

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