ORGANIZATION AND MAIN RESULTS OF THE HAIL SUPPRESSION PROGRAM IN THE NORTHERN AREA OF THE PROVINCE OF MENDOZA, ARGENTINA

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ABSTRACT

Cloud seeding activities for hail suppression using rockets are being carried out in the northern area of the Province of Mendoza, Argentina, from 1985 to 1998, with some interruptions. In the operational seasons 1993/94 to 1997/98, Antigrad Latinoamericana has conducted the Program. The target area reaches a surface of 200,000 hectares, of which 91,500 hectares are cultivated.

The technology is based in the seeding of the hail and potential hail clouds using a mixture of AgI as glaciogenic agent. The method is based in the hypothesis of the acceleration of the precipitation process or early rainout, which assumes the seeding of the area of formation of hail embryos in the periphery of the main updraft and in the area of feeder clouds, resulting in the "rainout" of smaller hydrometeors from less-mature, less vigorous clouds. The hydrometeors reach precipitation sizes prior to encountering the stronger updraughts capable of producing hail (WMP Report N° 26. WMO/TD-N° 764).

The evaluation of the effectiveness of the Program is carried out using the comparison of the historic data on damage by hail recorded in the target area in the period in which there were no activities of hail suppression. The average of hail damages to the crops during the 11 seasons with activities of hail suppression in the province of Mendoza was 4.22%, while in a period of 13 years without protection against the hail in the same area this same index was 12.45%.

1. INTRODUCTION

Cloud seeding to reduce hail damages is one of the technologies of higher interest in the present, as part of weather modification programs. As a result of the progress reached in the study of hail clouds during the last decade a transition in the work of hail suppression from the experimental to the operational field was seen in various countries. Hail suppression projects using rockets have had a wide diffusion in the 70's and 80's in the Soviet Union, China, Yugoslavia, Argentina, Brazil, Hungary and Bulgaria. Although change in the political and economic situation in the countries of Eastern Europe affected the development of the programs of cloud seeding, the total number of operational projects in these countries was 25 in 1992 (WMP Report N° 23. WMO/TD N° 686).

The improvement of the rocketry technique and the meteorological radars, the accumulation of experience in works carried out in different physical and geographical conditions as well as the application of the latest achievements in the theoretical and experimental conditions of hailstorm processes have determined the formulation of seeding technologies with very important methodological differences. Nowadays, it is almost impossible to talk about the "method of cloud seeding using rockets" without mentioning to which concrete project we are referring. This is due to the fact that not only the initial and finishing criteria of the seeding operations vary, but also the levels of temperature and the place of the introduction of the reagent, its concentration, etc. In other words, from one project to another the basic seeding methodology changes. It is precisely for this reason that the results obtained in some experimental programs (Federer et al., 1982) cannot be extended in a linear way to all programs of hail suppression which in the present time use the technology of seeding with rockets.

In our case, the seeding is carried out as function of the thermodynamic and aerosynoptic conditions which determine the type of hail formation processes, the data about their structure obtained by the radar, their dynamics of development, the

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categories of the hail and potentially hail cells.

Therefore, the objective of this article is to present a comparative analysis of the data on the seeded and non-seeded hail clouds, and also of the damages recorded during our experience in the Province of Mendoza, Republica Argentina.

2. ORGANIZATION OF THE HAIL SUPPRESSION PROGRAM IN MENDOZA

According to many of the indices of hail activity, such as the recurrence of the processes, their intensity, the number of hail cells, the duration of the almost stationary phase, the Province of Mendoza is one of the regions most affected by hail on the planet. Hail processes in the region are distinguished by their great diversity, their structure and dynamics of development, as well as by the synoptic and thermodynamic conditions of their formation. An intense heating of the surface, the irruption of the cold fronts, the penetration of tropical air from the north and northeast, together with the contrasting Antarctic cold fronts, coming from the south and southwest frequently favor the formation of unique synoptic situations, with a development of a strong convection of thunderstorms and hailstorms. In Mendoza, all the hail processes previously reported are observed, some of which have regional peculiarities that until now did not have a physical interpretation.

Hail suppression activities are being carried out from 1985 to 1998, with some interruptions. In the operational seasons 1993/94 to 1997/98, Antigrad Latinoamericana has conducted the Program. The annual period of an operational season is October 15 to the following April 15.

The applied method is based in the seeding of hail and potential hail clouds with a glaciogenic agent (a mixture of AgI) using three types of antihail rockets which are differentiated by the form in which the seeding material is dispersed, as well as in the trajectories of the flight and the effective seeding radios. The rockets Alazan-15 and Alazan-5 have an effective reach of 8 km and 11 km, respectively, and they disperse the seeding material from the tip. The rocket Crystal has an effective reach of 12 km and it disperses the reagent also from the tip, by means of 28 ejected cartridges, one at each 350 meters of flight.

The technology is based in the cloud seeding from 30 launching sites, which have 2 or 3 launchers with 12 rockets in each one. The launching sites are placed so that they can achieve the multiple cover of the target area and of a part of the surrounding territory, with special attention towards the preponderant directions of irruption of the hail processes. The target area is in the north of the Province of Mendoza and covers approximately 200,000 hectares, of which 91,500 hectares are cultivated with grape, stone fruits and, to a lesser extent, horticultural crops.

The Radar Center has two special meteorological radars MRL-5, of two different wavelengths (S band and X band). Both radars have been equipped with a computerized system of detection, processing and analysis of the information obtained by the radar, specially designed to operate over hailstorms. The system allows us to obtain in real time any type of horizontal and vertical sections of the radio echo, images of the upper and lower limits of the radio echo at any level of reflectivity of the radar, and maps of the total amount of precipitation and hail precipitation, which are expressed as projections of the levels of radar reflectivity and as isolines of kinetic energy of the precipitated hail. The seeded area is determined by the Project Manager in the computer screen, from which the software calculates the trajectories of the rockets necessary to completely cover the chosen area, selects the optimum launching sites, the type and number of rockets to be fired, and makes the necessary corrections of the firing coordinates as a function of the velocity and direction of the cloud displacement.

The Project Manager can adjust these determinations as a function of their own experience and capability. During seeding operations, the system controls the total consumption of rockets and the number of rockets available at each launching site. All the information obtained is recorded, forming a data file. At the Radar Center a local computer net is used; three of the computers receive information from the main radar and one of them from the reserve radar.

The computerized system has been improved on the basis of the experience obtained in our operational work in Mendoza. During the last season, various complements and adaptations were introduced to the system, such as the possibility of distinguishing any region of the radio echo, visualizing its parameters obtained by the radar in the screen; the possibility of displacing the seeding area outlined in the vertical section of the radio echo in any direction; the incorporation of a simulation program which recovers the file images in programmed intervals and the introduction of new algorithms which optimize the selection of launching sites when establishing the seeding areas.

The meteorological support includes data from radiosondes launched at the airport of the city of Mendoza, including the estimation of the height of the isotherm of 0°C carried out 8 times per day using a METSAT PC station; the acquisition of visible and infrared bands satellite images, as well as six types of synoptic maps, with the analysis and the weather forecasts for South America with an anticipation of up to 144 hours.

3. SEEDING HYPOTHESIS

Cloud seeding technologies currently used for hail suppression are mainly based on two physical principles: 1) beneficial competition and 2) acceleration in the formation of precipitation or early rainout. Their achievement assumes the simultaneous massive seeding of a specific surface, determining the place and the time of the seeding as a function of the thermodynamic state of the atmosphere, the information on the cloud structure obtained by the radar, and the state of development of the cloud. However, it is not always possible to rigorously establish which of the two hypothesis to use when carrying out a real seeding operation, as demonstrated when analyzing the characteristic trajectories for hailstones which grow naturally and for those which grow under the influence of the seeding (WMP Report N° 26. WMO/TD-N° 764).

The hypothesis of the early rainout, on which the technology used in Mendoza is based, assumes the seeding of the area of formation of hail embryos in the periphery of the main updraft and in the area of feeder clouds. These are the seeded areas in most of the hail suppression operational projects which use aircrafts as a way of delivering the glaciogenic agent (Rudolph et al., 1994; Smith et al., 1997). The seeding is designed to create a great number of artificial ice nuclei in this area to accelerate the natural growth of cloudy particles to reach the dimensions of precipitables particles. In these cases, the descent of the lower limit of the overhang of the radar echo and sometimes its total disappearance is ovserved. The regeneration of the hail cell is interrupted; the cloud acquires a more symmetric vertical structure, and the descent of the height of the increased reflectivity zone is detected, diminishing later the other radar parameters.

The hail and potential hail cells are divided into four categories as a function of the stage of the cloud development and the type of hailstorm, and the seeding of each cell is strictly made according to a specific method. As classification criteria, the values of parameters such as the maximum radar reflectivity of the radar echo Z max [DbZ], and the height of the different levels of reflectivity above the level of the isotherm of 0 °C (H_0)-dH_{25}, dH_{35}, dH_{45} [km], etc., are taken into account. The first radar echo generated at great height are part of the first category and are observed with particular attention when detected in the area of the main hail cell during the multicell hail processes. The clouds with potential hail warning and a tendency for rapid development are part of the second category. Hail and very strong hail clouds constitute the third and fourth categories, respectively (Reinking et al., 1994; Sanchez et al., 1998).

The seeding of cells of different categories is carried out as a function of the structure of the cloud observed by the radar, the kind of development of the process of hail formation in space, the size of the overhang of the radar echo and the velocity and direction of displacement of the radar echo. That's why the quantity of rockets necessary for the seeding vary in each particular case, being the average of rockets used per category the most demonstrative example. For instance, during the 1997/98 season, the average consumption of rockets was equal to 7.6, 19.3 and 66.8 for the categories II, III and IV, respectively.

4. COMPARATIVE ANALYSIS OF SEEDED AND NON-SEEDED HAIL CLOUDS

The questions related to the evaluation of the physical and economic effectiveness of any project of weather modification are based on specific hypothesis, since it is impossible to simply separate the natural evolution of the cloudy processes from their transformation as a result of seeding. At present, when carrying out the artificial stimulation of the precipitation, the most common practice is the realization of randomized experiments with posterior statistical evaluation of their effectiveness. It is evident that in the operational programs that protect a specific area, the possibility of any randomized seeding experiment is excluded. In this case, two traditional methods are used: the control area method and the historic series method.

The analysis of the results obtained in the 1996/97-1997/98 seasons, from this point of view, can be considered as a preliminary evaluation of the effectiveness of the work, while the posterior acquisition of experimental material on the seeded and non-seeded clouds and its statistical interpretation will allow this evaluation to acquire a greater base from the physical point of view.

An example of the development of hail clouds with and without seeding is presented where two hail clouds developed almost at the same time and under the same aerosynoptic conditions, one of which penetrates in the action area of launching sites and is seeded, while the other one moves by a parallel trajectory and goes near the target area and develops without any seeding.

In **Figure 1**, hail is expressed as isolines of kinetic energy of the precipitated hail. Cell 38, on January 20, 1998, developed north of the target area, outside the limits of the action area of launching sites. Cell 25, developed in the target area, was seed almost from the moment in which the first radar echo was detected. The estimation of kinetic energy was done by the computerized system, using the theoretical and semiempirical relationships (Z-E) (Waldvogel et al., 1978; Abshaev et al., 1985) and a special algorithm for the section of the rain region of the radar echo.

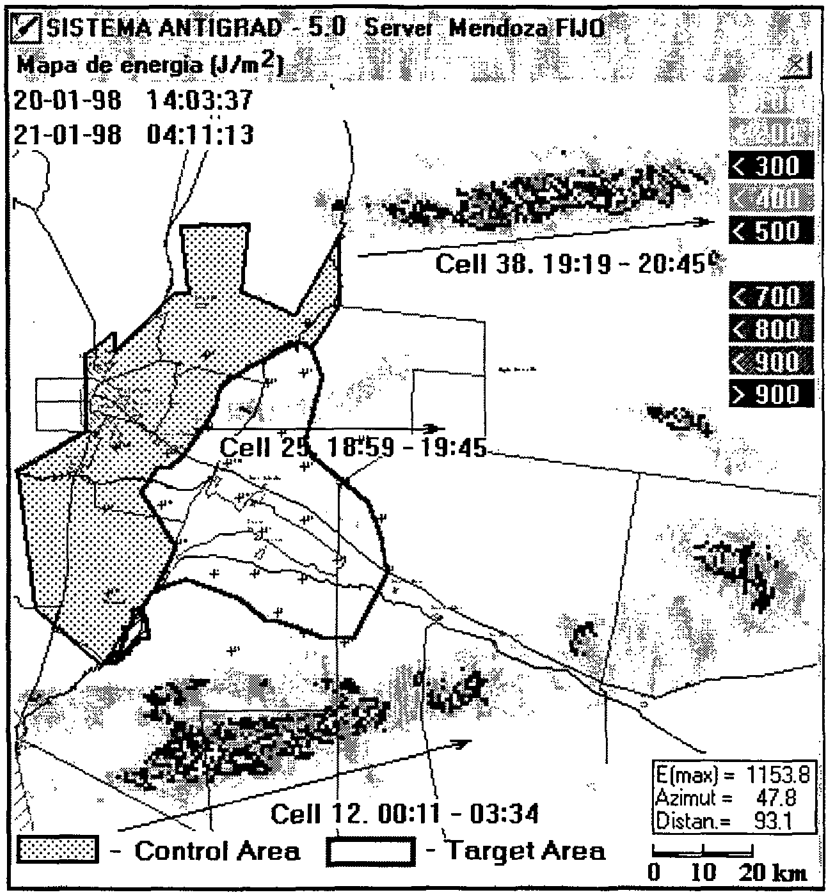

Figure 1

Fields of calculated kinetic energy of the precipitated hail on January 20, 1998, for the seeded (cell 25) and non-seeded (cells 12 and 38) hail clouds.

The cells were first detected 20 minutes apart. Cell 38 grew in natural conditions; in one and a half hours it covered a distance of more than 90 km, in 70 of which the fall of hail of great dimensions was noted. The maximum value of kinetic energy of the hail, measured by the radar, was of 1,153.8 J/m^2, which corresponds to a damage of 100% for any crop in any growing stage. 87 rockets (42 Alazan-15 and 45 Crystal) seeded cell 25, its duration was of 34 minutes, and the fall of hail of small size was observed in a reduced area, which did not produce any damages to the crops.

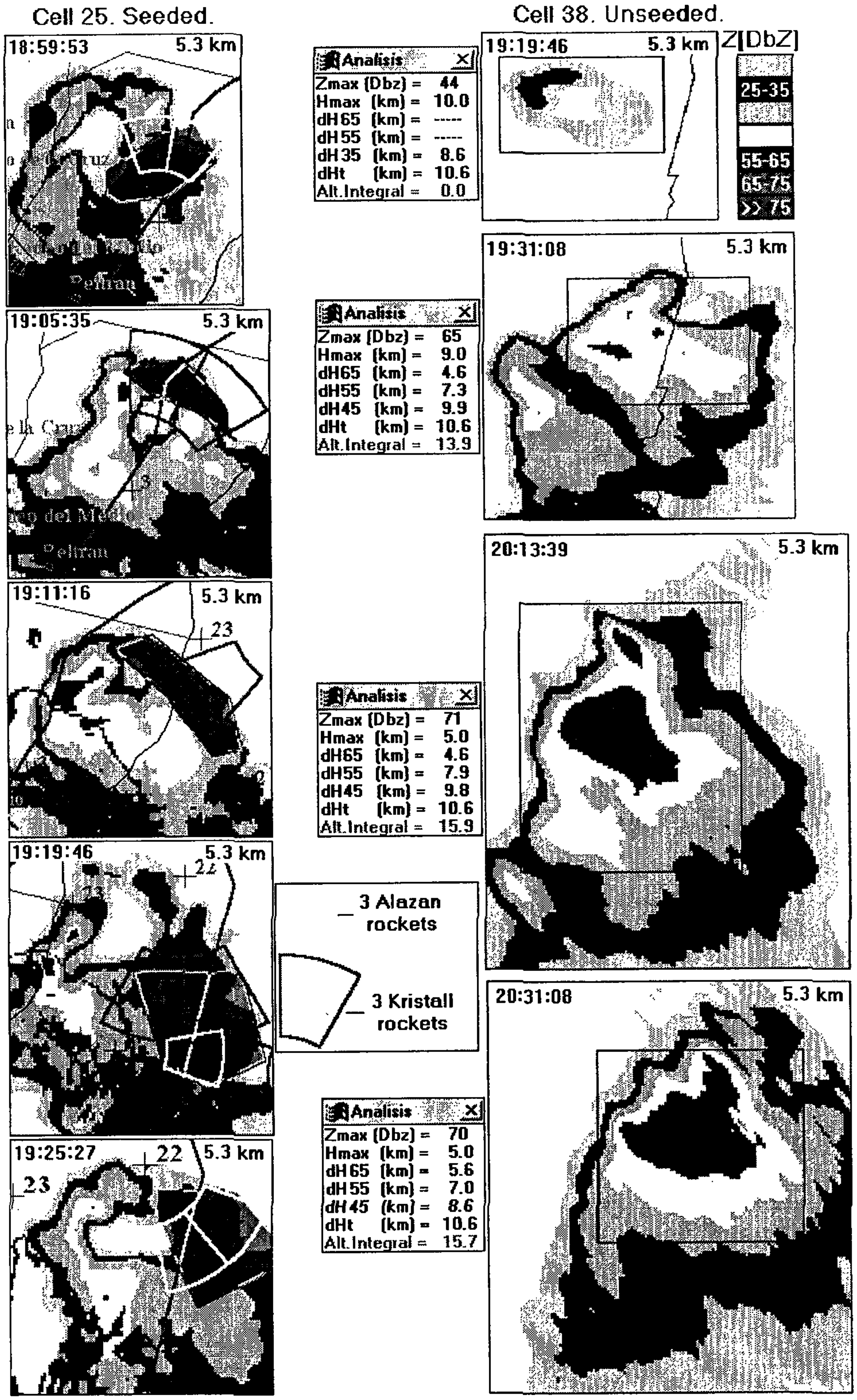

Figure 2

Evolution of the radar structure of hail cells 25 and 38. Presentation of the successive horizontal sections of the radar echo in the level of introduction of the seeding agent. The radar parameters of cell 38 correspond to the regions marked by straight angles.

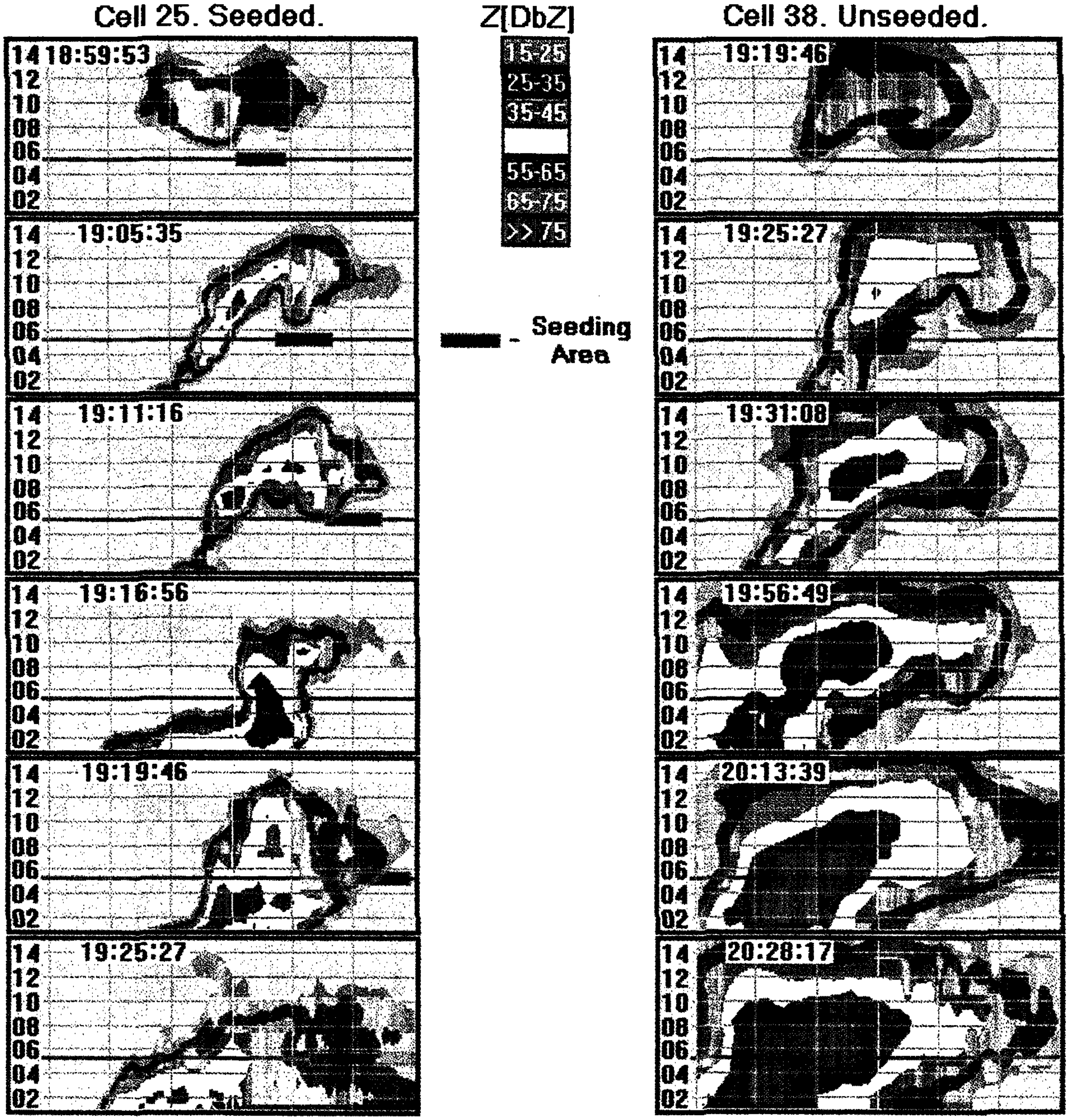

Figure 3
Vertical structure of the radar echo of hail cells 25 and 38 in a surface of maximum reflectivity of the radar.

The differences in the radar structure and in the growth dynamics of the cells are seen in **Figures 2** and **3**, where successive fragments of their vertical and horizontal sections are presented, as well as the trajectories of the introduced antihail rockets. It is interesting to notice that both cells have almost the same vertical structure of the first radio echo, recorded for cell 25 at 6:59 PM, and for cell 38 at 7:19 PM. However, the posterior development of cells differs remarkably. The development of cell 25 is subjected to a constant seeding of the frontal area of the overhang of the radar echo, at 7:11 PM its decrease is already observed, and near 7:19 PM its total precipitation and the interruption of the later cloud growth is observed.

The development of cell 38 proceeded more slowly, and just near 7:56 PM a strong nose of the radio echo of approximately 15 km in length is formed. The fragments of the vertical sections of this cell represent a classic example of a supercell hail cloud within a stationary stage. In **Figure 4**, the temporal evolution of the main radar-derived parameters are shown.

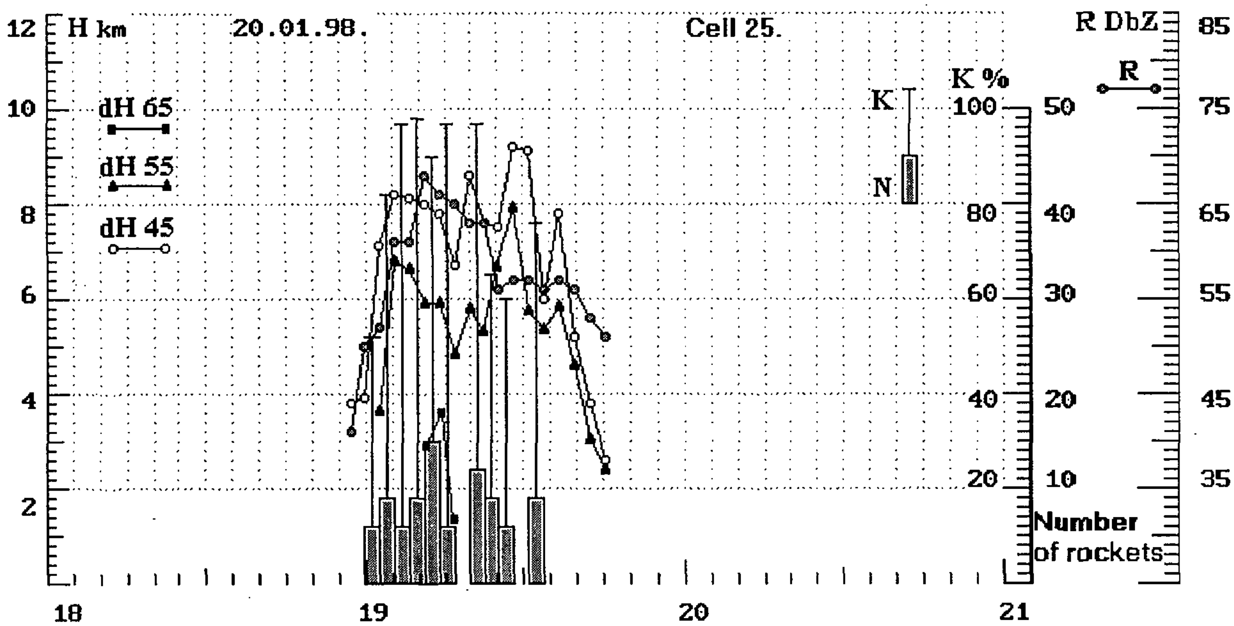

Figure 4

Temporal evolution of the main radar parameters of cell 25 on the bottom of the histogram of the introduced anti-hail rockets. The values dH_{65}, dH_{55} and dH_{45} correspond to the heights above the level of the isotherm of 0 °C of the regions of the radio echo, limited by contours with a radar reflectivity of 65, 55 and 45 DbZ, respectively.

It is evident that from this analysis conclusive evidence on the effectiveness of the method is not possible. However, through these examples, the general results of seeding operations in the study season are outlined.

5. ANALYSIS OF THE OPERATIONS' EFFECTIVENESS

Hail suppression activities are being carried out from 1985 to 1998, with some interruptions. In the operational seasons 1993/94 to 1997/98, Antigrad Latinoamericana has conducted the Program. The annual period of an operational season is October 15 to the following April 15. The temporarily interruption of the Program in the seasons 1992/93 and 1995/98 were due only to financial problems of the client.

The organization of the hail suppression program in Mendoza, outlined in the Section 2 of this paper, has been used just in the operational seasons 1996/97 and 1997/98. That's why we consider that the results obtained during such period, by using the computerized system, are most reliable, without mistakes due to subjective reading of the radar data by the operator.

The comparison of crop damages between the target and control areas shown in Figure 1, was done considering the similarity and coincidence of the climatological conditions, and the regularity on the repetition of hail processes, according to the radar data obtained since 1974 as well.

The only difference consists in the relationship between the total and the cultivated land on the above mentioned areas. The target area reaches a surface of 200.000 hectares, of which 91.500 hectares are cultivated, since in the control area the figures are of 220.000 and 50.000 hectares, respectively. Nevertheless, this is the only obtainable control area, considering that the defense is carried out in a local oasis.

5.1. Randomization:

In the 1997/98 season, a comparative analysis of hailstorms and of the damage caused by them in the target area before and during cloud seeding activities was carried out for the first time. In that season, hail suppression operations due to administrative reasons outside the project began on December 20, and not on October 15 as in anterior seasons. Hailstorms which developed in the target area before December 20 represented, in some manner, an independent selection of storms developed in a natural way which could be compared with a selection of seeded hail clouds. To compare the data about crop losses on the season 1997/98, before and after the initiation of the operations, it's necessary to consider that during January and the first half of February the maximum peak of damaging hail is registered, as well as the maximum repetition of hail processes.

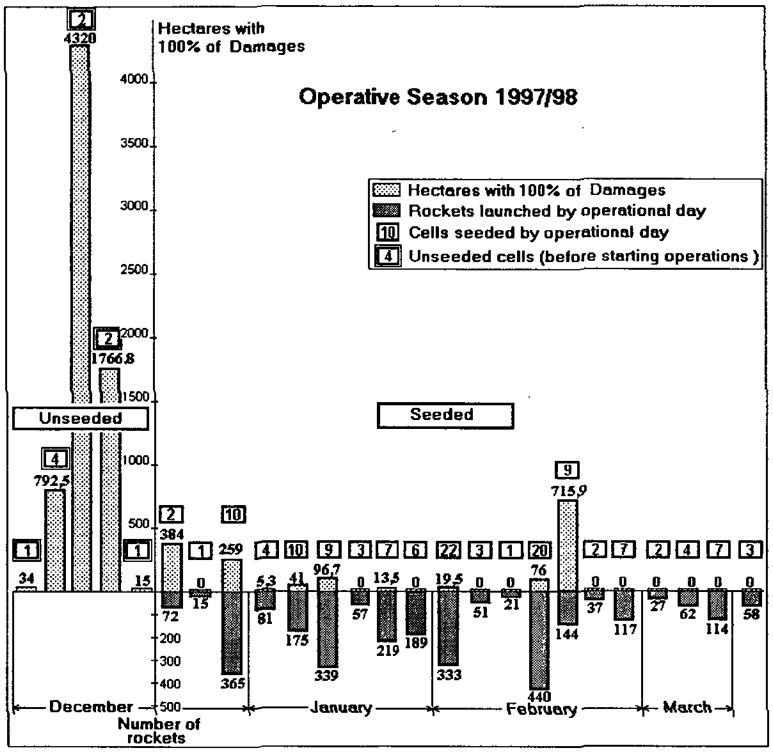

Figure 5

Distribution of hailstorms, damages estimated at 100%, and number of rockets fired in the season 1997/98

In **Figure 5**, the distribution of hailstorms with damaging hail, and rockets fired during the season are shown. In that figure, we can clearly observe that when there was a seeding, damages were significantly smaller. Moreover, all the storms developed over the target area prior to the beginning of the hail suppression operations caused damages, while in the 20 days with cloud seeding there were damages recorded in 9 cases and only in 3 of them they exceeded 100 hectares. Only 10 non-seeded hail cells before the beginning of the operations caused losses of 6,913.3 hectares, while 132 seeded hail cells damaged 1,626.9 hectares, calculated at 100% of damages. This comparison can be considered, in a cautious manner, as the results of an experiment of "forced" randomization, since all hailstorms, seeded or non-seeded, penetrated the target area in an autonomous way.

5.2. The control areas analysis:

The comparison of damages in the target area with damages in the control area corresponds with the analysis of the effectiveness of the work (Section 4).

It is difficult to choose an absolutely identical region for the control area, because the seeding is carried out in a local oasis, most of it surrounded by non-cultivated lands. The data on the damages in some cultivated areas, which were not part of the target area, could have some interest for the comparison. The area of comparison indicated in **Figure 1** is of approximately 220,000 hectares, but the percentage of cultivated lands here is considerably smaller than in the target area. In **Figure 6**, the distribution of damages produced by hail in the season 1996/97 in the target area and in the control area, as well as damages produced in the season 1997/98 before and during the defense are shown.

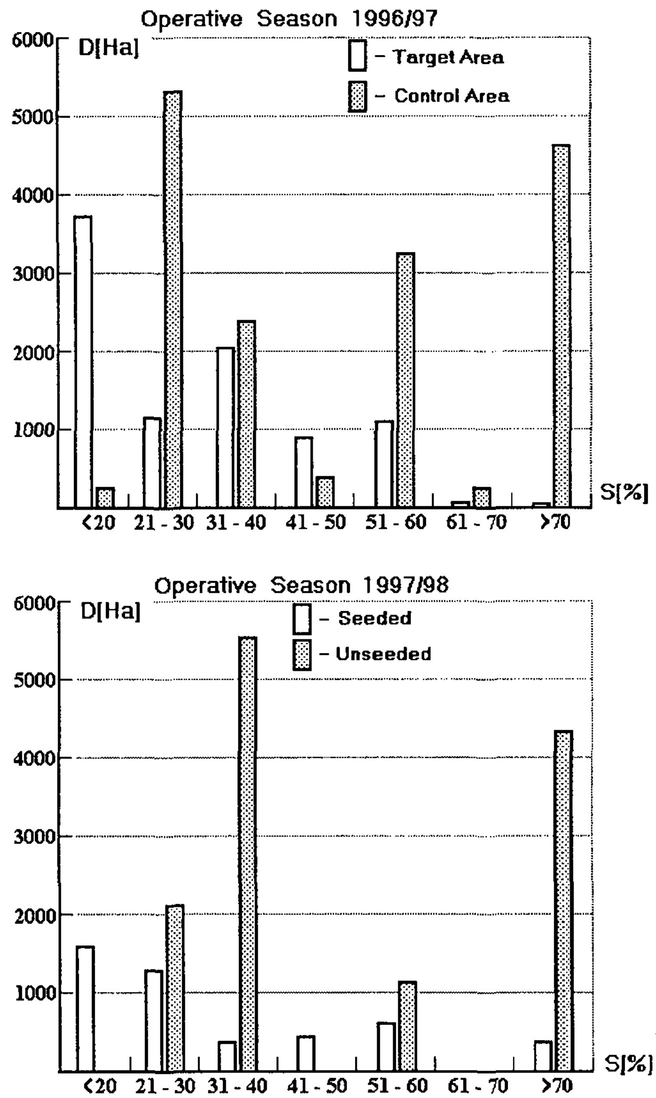

Figure 6
Distribution of percentage of damages for seeded and non-seeded hailstorms in the seasons 1996/97 and 1997/98

In the first season, hail damage in the target area, considered at 100%, reach to 2,653 hectares, while in the bordering area they reach to 8,342 hectares. An even more evident difference is seen in the areas with losses higher than 60 %. In the target area, the amount of hectares with damages exceeding 60% was of about 50 times less than in the control area, although the total surface of cultivated lands in the area under seeding is considerably greater than in the surrounding area.

In the second season, a great difference is observed when comparing areas with losses of 70 to 100%. Losses of these proportions reached in the period without seeding 4,329 hectares, while during the whole season of cloud seeding operations they reached 427 hectares, i.e., 10 times less. In other words, besides the reduction of total damages, in the target area we can see, as a result of the seeding operations, a redistribution of the areas with different percentages of damages, with a tendency towards a sudden decrease of the direct damages higher than 60%.

5.3. Historic series analysis:

A comparative analysis of the data recorded during many years in the current protected area on damage recorded in the period without hail suppression activities with the data obtained during hail suppression seasons gives a more precise idea on the decrease of the mean percentage of losses and the variation of its minimum and maximum values. The most reliable data that we have on hail damages recorded in the province of Mendoza without cloud seeding operations, have been obtained by the Provincial Institute of Agricultural Insurance, and correspond to a historic series of 13 years, from 1952 to 1965. Moreover, such data were obtained using the same criterion on evaluation of damages that are being used at the present.

No reliable data are available from the period 1965-1984. The period with action comprises 11 seasons of cloud seeding activities, from 1985/86 to 1997/98.

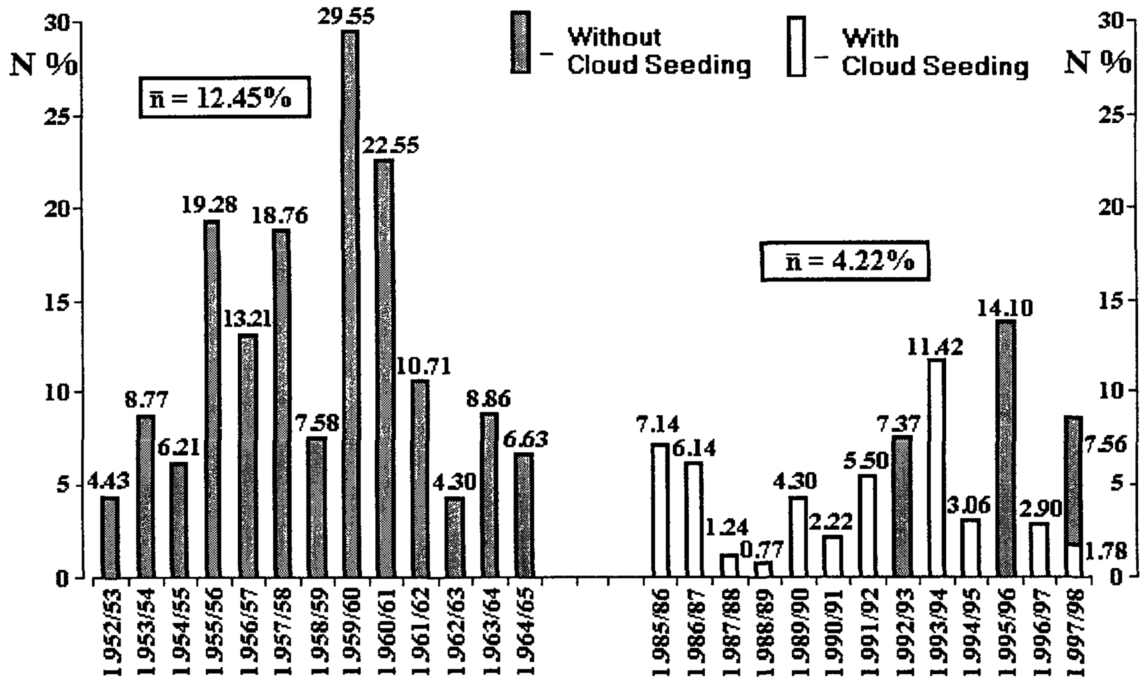

Figure 7

Distribution of the percentage of losses of the crops in the target area, without cloud seeding (1952/53-1964/65, according to official data from the Provincial Institute of Agricultural Insurance) and with cloud seeding (1985/86-1997/98, according to official data from the Ministry of Economics of Mendoza).

In **Figure** 7, the distribution of the relationship between the affected area, estimated at 100%, and the total of the cultivated area for the periods with and without seeding can be evaluated. As it can be seen in the figure, the mean percentage of losses decreased from 12.45% to 4.22%, the maximum from 29.55% to 11.42%, and the minimum from 4.30% to 0.77%. It is important to notice that the minimum percentage of losses of the crops without cloud seeding (4.30%) exceeds the mean percentage with cloud seeding (4.22%). It is natural that a more accurate comparison of these data could be possible with a greater number of seasons with cloud seeding in the considered area.

6. SUMMARY

The 1996/97 and 1997/98 seasons of hail suppression activities in Mendoza were characterized by a totally new organization of the work, the use of the computerized system of action, the local computing net, three types of antihail rockets and extended meteorological support. All these factors constitute the basis of the new project, which represents one of the last variants of the cloud seeding technology by using rockets. The great volume of experimental material obtained on the seeded and non-seeded clouds, as well as on the damages produced by them, requires a detailed physical and statistical analysis. This is necessary, 1) for the future improvement of the project and, 2) because it will allow us to judge with more reliability the possibilities of the method as a whole.

The preliminary results presented in this paper clearly demonstrate the differences in the evolution of the seeded and non-seeded hailstorms, the decrease of the total losses by hail in the target area in comparison with the control area, and the redistribution of the percentage of damages towards a sharp reduction in the areas with losses higher than 60%. As it is an operational program for the protection of a specific area, the future development of the methods of evaluation of the results of the seeding operations should obviously be based on data recorded by a terrestrial net of hail pads, placed in the target area, as well as in the cultivated and non-cultivated parts of the surrounding area. In this way, a more detailed and physically supported evaluation of the effectiveness of the seeding operations will be possible, taking into account the modification of the characteristics of the microstructure of the precipitated hail.

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