SOME POTENTIAL ERRORS IN THE IDENTIFICATION OF HAIL SWATHS AND SEEDED STORMS

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Abstract. In many hail suppression projects currently under development in western Europe, ground generator networks are deployed. The plumes of AgI emitted by these, containing high concentrations of ice nuclei, follow the wind trajectory. When an evaluation of the Project needs to be made, it is essential to be able to determine whether storms which gave rise to hailfalls were seeded or not, and to establish the exact extent of the zones affected. In this study, a discussion will be made of the criteria which need to be applied in order to avoid errors in the evaluation of seeded and non-seeded thunderstorm samples.

1. INTRODUCTION

Weather Modification (WM) applied to hail suppression entails increasing significantly the concentration of ice particles in and below the Hail Growth Zone (HGZ), which leads to a reduction in the amount of supercooled water available for hail growth. The method most widely used to achieve this, consists in adding to the Embryo Formation Region (EFR) a sufficiently rich supplement of ice nuclei (IN), which, being introduced into the HGZ, results in a greater number of small ice particles (Young, 1993).

One of the ways of increasing the number of embryos in the EFR is by adding artificial IN. There are various techniques for doing this, but at present, in the majority of Hail Suppression Projects in western Europe, a network of spatially distributed ground generators is used, which provide extensive areas over which the concentration of IN is much higher than the natural level.

It is well established that storms are predominately fed by air and the water vapor which accompanies it, both of which are drawn up from the lower levels (Foote, 1984). Once the water vapor has reached condensation level, i.e., when it reaches the cloudbase, and if the instability continues, the air and the water drops which have formed continue rising to form the cloud mass which is the site of the storm.

Given that the ground generators emit IN continually, the storms which are formed take air from the lower levels, drawing in both water vapor and the IN present in the air as they do so, so that the resulting mixture is incorporated in the ascending air currents. If the zones where the storms form and develop are fed from the environment in which the ground generators created a high concentration of IN, then the characteristics of any precipitations of hail which result, must be included in the seeded storms sample. If, on the other hand, the storms zone is fed from an environment into which the ground generators did not introduce IN, then the hailfall characteristics must be included in the non-seeded storms sample.

The trajectories followed by the IN until their entry into the area of storm influence, are coincident with the components of the wind, of which the low level component is particularly important, as it is mainly these levels which feed the storm. Therefore, in order to determine the zone seeded with IN, the trajectories which must be analyzed are those of the air masses which drew in the nucleant material from the area where the generators are sited (Sánchez et al., 1994).

In any WM Project, objective and rigorous evaluation has to be a primary aim, in order to analyze the effectiveness of the seeding carried out. Comparison between the distribution data deriving from seeded and non-seeded storms allows this evaluation to be made (Warburton et al, 1995). One of the errors which can be committed in the evaluation of hail suppression is that of supposing that an air parcel or a cloud mass has been seeded, when there in fact exists no possibility that glaciogenic agents could have been introduced into it. Obviously, precipitations associated with thunderstorms fed by natural air cannot be considered as modified precipitation. At the stage of assigning the seeded or non-seeded category to the samples, it must therefore be possible to determine whether or not they were affected by the IN emitted. In those Projects which make use of ground generators, the method of determination is therefore of crucial importance.

It is clear that great care must be taken in all Ground Generator Projects to avoid the inclusion in the data for seeded activity that which cannot have been affected by glaciogenic seeding. In addition, the determination of the extent of the zones affected by hailfall depends on the spatial resolution of the ground observation network. If the latter is inadequate, the case could arise that, where no hail is recorded in a seeded area, the data are incorrectly assigned to the sample of seeded thunderstorms without hailfall, when a denser observation network would have recorded some hailfall.

The lack of an established set of standards and code of practice among operators of WM Projects naturally gives rise to a disparity between evaluation criteria, and allows this kind of error to escape unnoticed. Clearly, the detection of errors such as these would contribute to an improvement in the quality of evaluation, and this paper therefore analyzes a concrete example recorded from WM activity in León (northwest Spain).

2. HAIL DETECTION

2.1 Introduction

Since 1986, an observation network has been continuously in operation in the province of León, detecting precipitations of hail and thunderstorm activity during the summer months. After several years of initial climatological study, from 1993 onwards a series of experimental seedings with IN was carried out, emitted from a network of ground generators installed in the area where storms were known to form most often (Sánchez et al., 1994).

The hailfall detection network in the León project consists of 432 observation points distributed over 6,825 km², and complemented by 250 hailpads installed in a grid formation of 2 km between hailpads, sited where hail was known to be most frequent. As a result of the observation networks, and the analysis of the character of hailfall, the hail zone is now well defined (Fraile and Sánchez, 1989; Fraile et al., 1991; Sánchez et al., 1992, and Fraile et al., 1992). In Fig. 1, the position of each of the 432 observation points within the study area is displayed. The location of the 9 automatic generators which composes the seeding network is also indicated in Fig. 2.

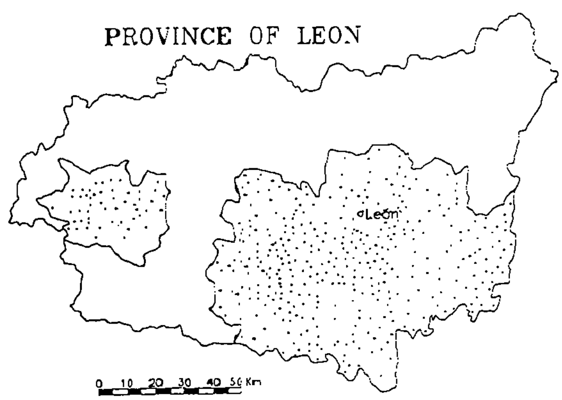

Figure 1: Study area and position of the network of observers (dots).

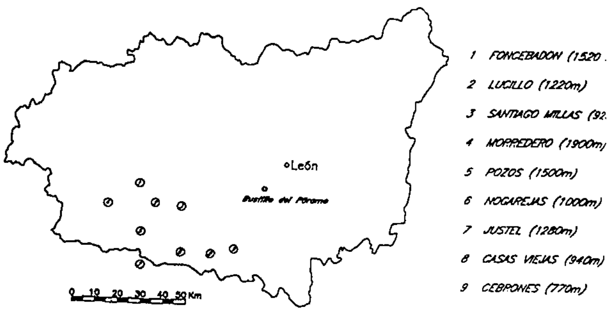

Figure 2: Location of the network of automatic ground generators.

To avoid the possibility of the cumulative damage registered in the pads deriving from two separate hail-precipitating storms passing over the hailpad network on the same day (thus complicating the task of determining seeded and non-seeded storms) the network is constantly patrolled by at least one four-wheel drive vehicle, which follows the path of a storm once it has been detected. Each hailpad is changed if it has been affected. (In eight years of operation, only once were two hail-precipitating storms detected with less than one hour's interval between them; the patrol system ensured that the pads were changed in time). Unlike the hailpads, the hail observers operate on a voluntary basis, being typically agricultural workers who work in the study zone throughout the summer months, and may be relied upon to report their observations daily. The participation of 95% of the observers can be counted on; in the event of a hail observer failing to respond, s/he is contacted by the Project operators.

2.2 The detection and determination of the extent of a hailfall

As suggested in the introduction, a potential source of error in evaluation lies in supposing that there has been no hail in zones where it has not been observed, and where there are no signs of hail detectable among the crops. A hailfall could have passed unnoticed, for various reasons:

- because it was sufficiently small in extent for no observer to report it
- because it was sufficiently weak not to affect crops, or else did not fall either over crops or over ground capable of registering its effects

In such cases of unnoticed hailfall, the evaluation of a WM Project would be seriously weakened by an error in hail detection, especially if the Project's aim was to create a reduction in the number of hail days. It is thus not feasible to try to study the behavior of hailfall if the detection network is insufficiently dense, which is the case with some meteorological organizations which rely solely on weather stations, which are at a considerable distance from one another. The present authors therefore consider it almost essential that a project employ hailpads or some kind of hail sensor, whose density over the surface area of the project may be increased at will, and far more easily than that of the observer network.

The extent of the hailfalls can also be considered as a seeding-dependent variable. It is therefore necessary to determine accurately the precise extension of the affected zones. To do so, it may reasonably be supposed that a hailpad showing impacts indicates that hail fell over the full surface of the area represented by this kind of sensor, namely 4 km². If any one of the eight adjacent sensors also shows signs of impact, it may be included in the same hailfall, and the process may be continued until the extent of the entire hailfall is defined. Once a hailfall has been identified according to this procedure, its extent can be estimated simply by multiplying 4 km² by the number of contiguous hailpads registering impact. Extent can also, of course, be estimated by the network of weather observers, using the surface area assigned to each observer who has recorded hailfall, as the unit of computation.

The present authors have previously made an analytical study comparing the extent of hailfalls recorded in their study zone during the summers of 1991, 1992 and 1993 (Fraile et al., 1994). Figures 3 and 4 show these hailfalls classified by extent; the first gives those detected by the observers, and the second, those detected by the hailpads. In brief, it was seen that the pads succeed in detecting smaller hailfalls than the observers, because they are capable of defining small hailfalls within what the observers consider to be an extensive one. It was thus calculated that while hailfalls of less than 10 km² made up over two thirds of the hailfalls detected by the pads, they composed less than a third of those detected by the observers.

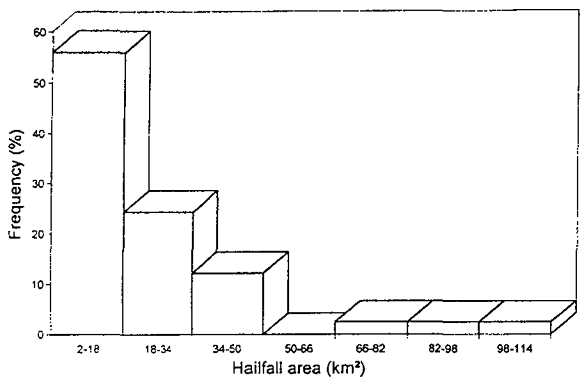

Figure 3: Extent of the hailfalls detected by the network of observers.

It is clear that some relation exists between both sources of error, between the unnoticed hailfalls and their extent. The greater the density, or resolution, of the detection network the better it will be, for it will simultaneously determine more accurately the extent of the hailfalls, and fail to register fewer unnoticed hailfalls. To visualize what is understood by the resolution of a network, two examples may be helpful, drawn from the detection networks of the León Project.

How small must a hailfall be in order to pass unnoticed? What is the minimum distance between two separate hailfalls for them to be registered as separate, and not as one? The first question depends on the network's detection capacity, and the second on its resolution, as may now be seen.

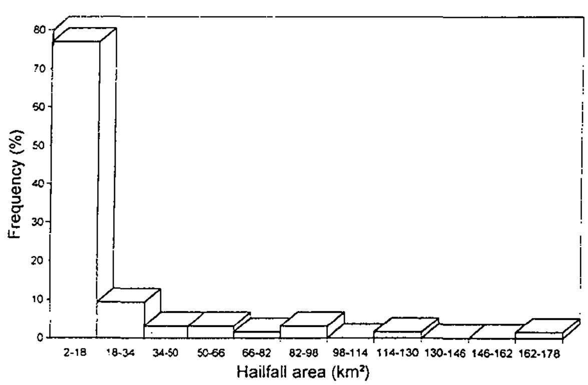

Figure 4: Extent of the hailfalls detected by the network of hailpads.

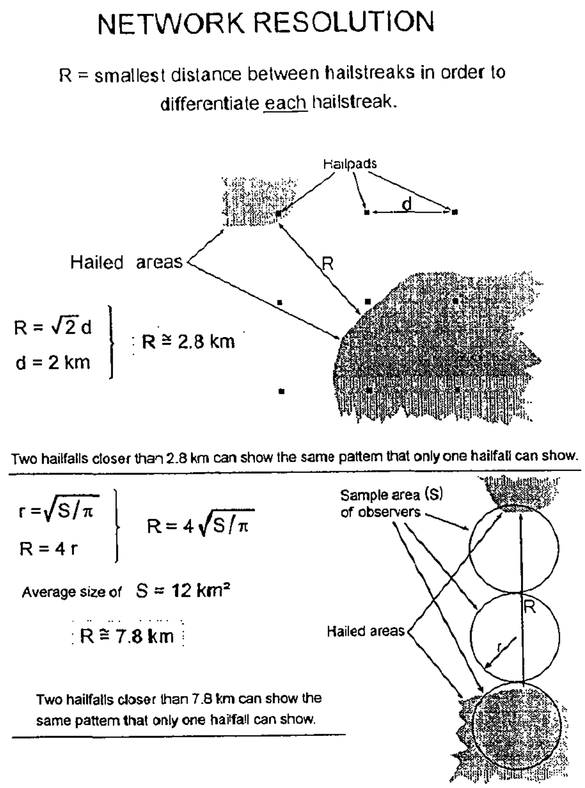

Figure 5: Scheme for the calculation of the networks resolution.

Detection capacity: Let a network, like the hailpad network, be considered, with a relatively small sample area, 2 km from each of the adjacent sensors. It is clear that a hailfall of less than 2 km in diameter could pass unnoticed. The case of the observer network is different, which although, ideally, supplying information on all kinds of hailfall, in reality is only capable of detecting those hailfalls directly perceived by an observer, or of which s/he has been informed.

Spatial Resolution: This is the smallest distance between hailfalls at which they may still be detected as separate. It clearly has to do with the separation of the sensors. In Fig. 5 the resolution of the hailpad network, at 2 km interstices, is depicted graphically, and that of the observer network, for which a sample area of an average 12 km² has been supposed. The shaded areas represent areas of hailfall. For both networks, the distance R of separation, is the smallest which may obtain for hailfalls to be considered as different. It can be seen that R is not the same in both cases: it is estimated at 7.8 km for the observer network, while the hailpad network has a resolution of 2.8 km.

Obviously, if the distance between hailed areas is greater than R, the hailfall will be counted as separate. If the distance is less than R, they may also in some cases be registered as separate, but this will depend on geometrical considerations, on the position and shape of the hailed area with respect to the sensors, and it cannot be assumed with confidence that all hailfalls distanced less than R from one another will be distinguished.

When hail suppression activity is being planned, therefore, it is essential to have the widest possible knowledge of the climatology of the target area, and to position an observer network, or better still, a hailpad network, in accordance with the results of the climatological study. An inaccurate design could fail to register smaller hailfalls when in fact they should be incorporated in the data sample for hail days, despite not being extensive.

3. THUNDERSTORM TRAJECTORIES AND NUCLEANT PLUME TRAJECTORIES

The detection of the movements and in particular the trajectories of storms can be achieved by various methods. Very often, radar is used, or in default of that, the images from satellite stations, which despite not providing the detail of radar, have the advantage that the images are simple and economical.

The trajectories which storms follow are closely related to the horizontal wind component, especially in the middle levels (Castro et al., 1989). On days of storm activity, especially if severe, the horizontal wind component varies as altitude above ground level increases, and so windshear increases. However, the variation in wind direction is normally most intense in the lower levels, diminishing as altitude increases.

The determining of mesoscale air trajectories has been done using data provided by the network of tropospheric radiosondes. Meteorological Centers such as the European Center for Medium Range Weather Forecasts can supply the trajectories of air masses which have been tracked at different levels, for periods of several hours. The trajectory of an air mass which gave rise to particular precipitations of hail can thus be reconstructed. For this study, a selection has been made of a storm situation for which the area affected by hailfall was identified, along with the time period, and the trajectories followed by the storms, using infrared (IR) images from the METEOSAT satellite. The data have been acquired from a Primary Data User Station and therefore are calibrated and the images have been corrected geometrically. An overlay has been made of the Province of León, in order to locate the storms geographically. Lastly, the tops of the storms have been classified according to a system which allows their temperatures to be identified (Fig.6).

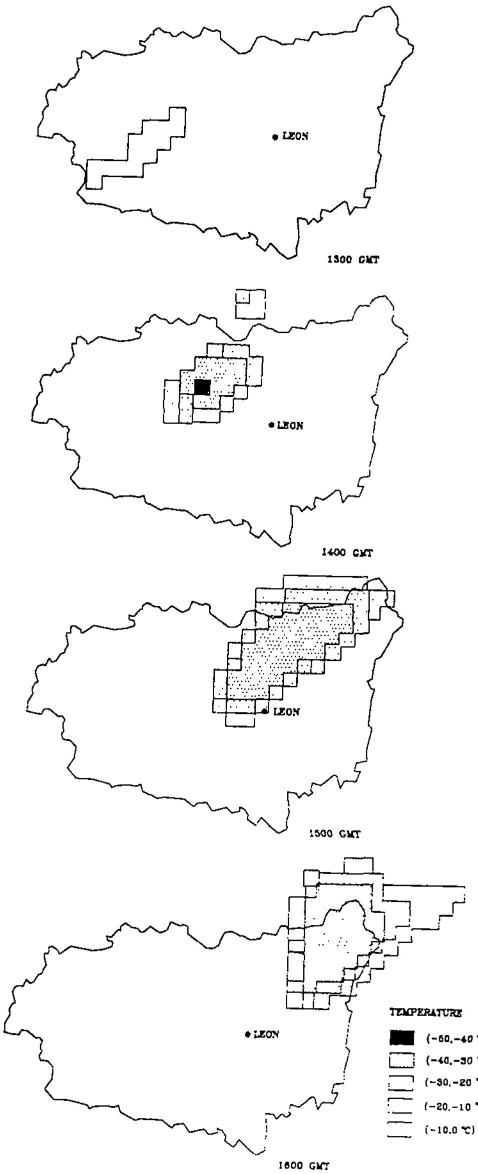

Figure 6: METEOSAT IR images on June 20, 1994. Pixels corresponding to the tops of the hailstorm analyzed are classified according to its temperature.

4. DISPERSION OF NUCLEANT MATERIAL EMITTED BY GROUND GENERATORS

The emission of AgI is carried out by the generator network, for which the characteristics, siting and operative system have been described by Sánchez et al. (1994). Numerous meteorological soundings have been carried out in the area where the network is located, in order to understand the characteristic atmospheric conditions under which the dispersion of nucleant material takes place. The results may be summarized as follows:

- during the normal functioning period of the generators (1000-1700 GMT), inversions were not detected in the lower layers.
- given the position in which the generators were sited, windspeed frequently reached values between 4 and 6 m/s, and in the majority of cases, was greater than 3 m/s.
- applying the Pasquill (1974) classification system to the meteorological conditions of the study zone, allowed atmospheric stability to be classified as between type C and type D, though on certain occasions type B was also registered.

The emission of AgI is continuous. Windspeed and trajectory can be determined from the information provided by the European Center for Medium Range Weather Forecasts.

The background concentration of IN is known, as a result of various measuring sessions which have established the intervals within which the natural concentrations of IN in the study zone normally fall (Castro et al., 1996). These data were made use of to fix the number of generators required, and the emission rate, which was designed to increase the concentration of IN by between 1 and 2 orders of magnitude.

Bearing in mind the known conditions of dispersion of nucleant material emitted by the generator network –namely, the emission rate, and the types of atmospheric stability which obtained during the dispersion period– the terms of the Gaussian plume model for non-urban terrain (Gifford 1960), may reasonably be applied.

Under the conditions of dispersion already described, the angular width formed by the plume, which contains the nucleant material, in practice varies between 5° and 10° –similar results to those obtained by Auer et al. (1970)–, and the concentration of AgI at 20 km or more from the generator diminishes by 2 orders of magnitude. The dispersion model has not yet been fully calibrated, but diverse measurements at ground level using a cloud chamber, carried out over three summers (Castro 1996), have made it clear that the concentration of nucleant material in the plumes ceases to be significantly different from natural levels at a distance of more than 20 km from the generator, or at angles of greater than 7° or 8° deviation from the initial line of emission.

In view of the above, it may be concluded that for plumes to contain sufficient concentrations of nucleant material to seed storms, an extension of less than 20 km is required and a dispersion angle of less than 20°. Storms passing over plumes which fulfil these criteria, may be considered as seeded. It is possible that storms passing over the area covered by such plumes some time after original generation has stopped, might also be considered as seeded, due to the concentration of IN remaining in the atmosphere, but conclusions have not been drawn on this head since the necessary data on temporal persistence of AgI has not been collected.

5. CASE STUDY

June 20 1994 has been selected. In Fig. 7 a small zone may be seen affected by hail which fell at around 1400 GMT. The European Center was asked for a reconstruction of the trajectories of the air masses at surface level –corresponding to 900 hPa approximately– and likewise for 500 and 200 hPa. In Fig. 7 the position of the air mass at the time and place when it produced the hailfall is represented, and also the positions which it held at 0900, 1000, 1100, 1200, 1300 and 1400 GMT, respectively. It may be seen that trajectories of the air mass at the three levels coincide considerably, as there scarcely 20° of variation between them.

In the same way, in this Figure the position of the seven ground generators activated from 1000 to 1600 GMT is represented. A total of 800 g of AgI were emitted. The other two ground generators were not activated because of operational problems.

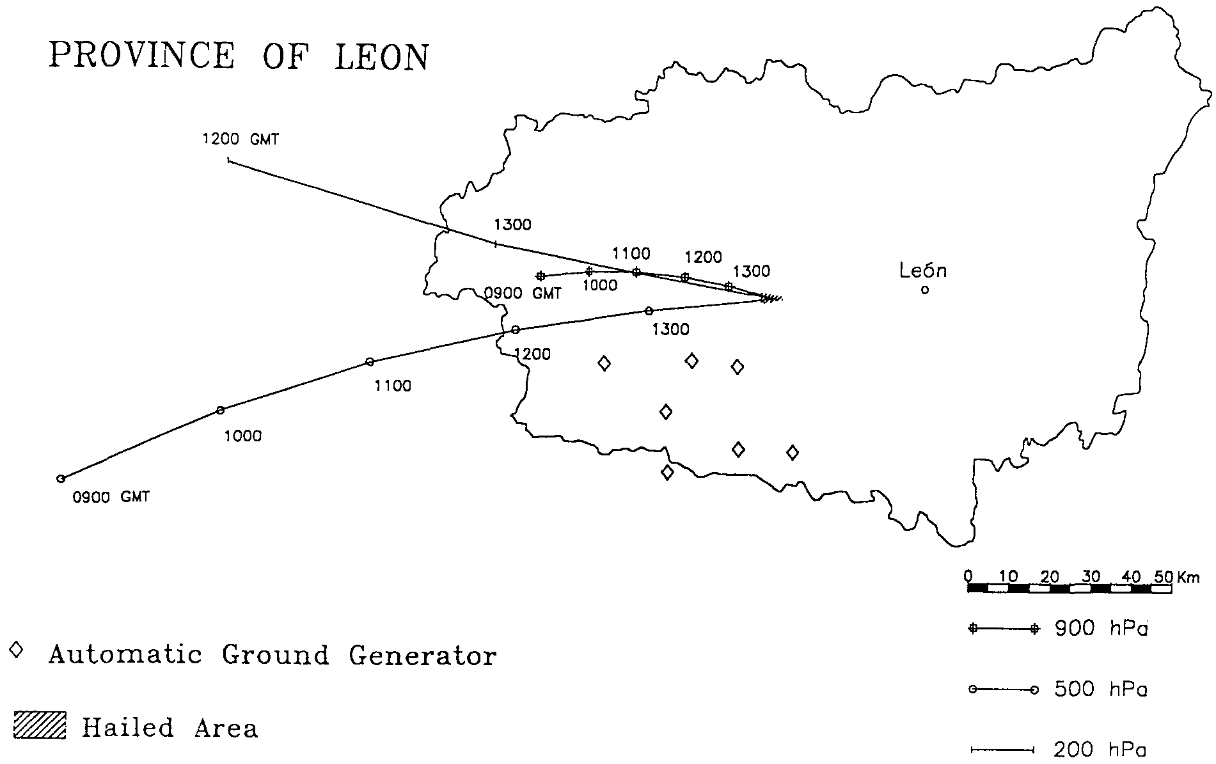

Figure 7: June 20 1994. Hailed area and back trajectories arriving at the time and place of the hailfall for the 900, 500 and 200 hPa levels. Positioning of the seven ground generators activated is also shown.

With the help of the IR images from the METEOSAT, the temperatures have been analyzed of the *tops* of the storm which produced hailfall, between 1300 and 1600 GMT. Using this straightforward method, it can be established that the storm trajectory coincides more or less with the trajectory of the air mass at the 500 hPa level.

Consequently, the hail recorded at 1400 GMT was produced by the hailstorm formed not very far from the Morredero ground generator (see Fig. 2 and 7). The trajectory of the hailstorm kept away from the network of generators activated. Therefore, there is only a slight possibility that artificial ice nuclei could have been introduced into it. So, it is very difficult to assume that the number of embryos were significantly increased and, hence, the hailstorm analyzed must be considered as natural and non-seeded and included in the non-seeded sample.

6. SUMMARY

- The efficacy of any hail suppression project is determined by comparing the characteristics of hail proceeding from seeded cells with that from non-seeded cells.
- The extension of hailed areas can be modified by hail suppression activities. Therefore, in the design of a hail detection network particular care must be taken to ensure that it offers the necessary detection capacity and spatial resolution.
- The declaration of a day as a day of seeding activity does not imply that all the storms (in the project zone) were seeded that day. This is also true of projects using ground generators.
- The storms can only be considered seeded if they have passed over zones where the concentration of AgI is above a certain minimum threshold.

- These zones can be determined by means of analysing the dispersion of seeding material, which depends on the meteorological conditions, and especially on windspeed. The simplest method consists of identifying a circular section with its center at each generator, whose radius and angle of dispersion may be calculated using a Gaussian model.
- The trajectories of air masses are significant for the following reasons:
    - ◊ at the 900 hPa level, they indicate the direction of propagation of the seeding material
    - ◊ at the 500 hPa level and above, they indicate the storm's direction of advance.

7. ACKNOWLEDGEMENTS

This work was supported by Excma. Diputación Provincial de León and Consejería de Agricultura (Junta de Castilla y León) as a part of PALA.

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