A NETWORK OF HAILPADS IN SPAIN

Roberto Fraile, Lab. Física de la Atmósfera, Dpto. Física, Universidad de León, Spain
José L. Sánchez, Lab. Física de la Atmósfera, Dpto. Física, Universidad de León, Spain
José L. de la Madrid, Lab. Física de la Atmósfera, Dpto. Física, Universidad de León, Spain
Amaya Castro, Lab. Física de la Atmósfera, Dpto. Física, Universidad de León, Spain

Abstract. Hailpads are sensors which can detect the impact produced by hail, thus allowing one to determine if a particular storm gave rise to the production of hail, and if so, the caracteristics of the stones. Due to the fact that hailstorms are very typical of this area, a large number of hailpads must be installed. Furthermore, the reading of the haildents is difficult and there may be many errors if due precautions are not taken. In this work we present a design for a hailpad and a methodology which we believe will greatly diminish the reading errors. We also present the criteria used in the installation of a network of sensors. Finally, we analyze the results from a storm in the summer of 1990 in León (Spain).

1. INTRODUCTION

In order to physically characterize hail near ground-level, it is necesary to use an instrument capable of measuring hailstone parameters.

The fact that the instruments are usually very sophisticated, and thus costly, greatly lessens the quantity of data which we are able to collect. The objective is to study an aceptable number of hailstorms, and thus a dense network of sensors over a vast ground span is necessary.

Since 1986 we have been studying the incidence of hail in the Provinces of León and Zamora, and we have been using a network of observers as our main source of ground level data. Recently we have designed a network of hailpads, located in one area which suffers most from hailstorms, and this was made operative in the summer of 1990.

Historically, one of the first sources of data used for studying hail was the network of observers. These are still very useful in covering some of the scientific necessities concernig hail such as: establishing the regional meteorology of the hailstorms; damage analysis of crops caused by the stones and the determination of the relationship between the observed damage and certains parameters of the stones. In general, this information can be used to verify the effectiveness of the hail prevention methods.

The observers also inform us of the duration of the hailstorm, the percentage of surface covered by the stones, and the largest and most frequent sizes of the hailstones.

However, the data provides by the observers may be affected by a certain degree of subjectivity. Schleusener and Jennings (1960) developed the hailpad in order to satisfy the necessity of having a system capable of measuring hail objectively and economically. The pad consists of a styrofoam plate covered by a sheet of aluminum. Later, protective paints have replaced the aluminum sheet. The impact of the hail upon the styrofoam produces eliptically shaped dents whose larger and smaller axis can be related to the size of the object in question.

The calibration of the hailpad is done by dropping steel balls of different diameters on the pad, making sure that the kinetic energy of these as they hit the surface is identical to that of a hailstone of the same size. In order to do this, some approximations, especially those referring to the density of the ice and the shape of the hail, must be assumed true (Lozowski, 1978).

The main problem with this instrument is the possible overlapping of two impacts, which may make identification and measurements difficult and seems to have no quick solution. For this same reason, there could be overlapping of two or more consecutive hailstorms. This must be solved by going immediately to the area where the storm took place and changing the sensor pad. Another difficulty presented when using the hailpad is the time and effort required for reading the impacts. Some methods have been adapted to facilitate the readings, such as classifying the dents by sizes instead of taking exact measures of each. Those which do not reach a minimal size (usually 0.5 cm) are grouped together without further measurements, thus saving some time.

Many factors influence the precision of the measurements done on the hailpad, such as size, hardness, shape and impact angle, or the position of the dent on the pad, the irregularities and the very components of the sensors. In spite of the difficulties in assigning an average precision to the hailpad measurements, in as far as size distributions, percentages of ±20% have been established. Still, after a certain size there is a discrepancy between the dent and the actual size (Smith, 1989).

The wind speed which accompanies the hail -an interesting factor in determining the damage to crops- can only be approximately determined with the hailpad. It would depend on the major and minor axis of the eliptical dents caused by oblique impacts.

2. NETWORK OF OBSERVERS

The study of the physical parameters of hail was done in one of the areas of the Peninsula which suffer most from hail (Font, 1983) which extends over part of the Provinces of León and Zamora. Due to the extremely local character of this form of precipitation, it was necessary to create a suficiently dense network of observers in order to precisely deliniate the zones afected by hail. Each observer was assigned a certain territory to monitor.

Due to the special characteristics of these two Provinces, which have numerous small villages, we have been able to cont on a large number of observers, who relay summer storm activities. All in all, our data source consists of more than 700 observers (one from each settlement), who send daily, from May to September, a card with the information we need. One must keep in mind that the information from one card refers to an area which, on average, is not greater than 1300 ha. The percentage of observers whose cards were sent regulary and without mistakes was 95%, wich means that the quality of the data was adequate.

3. NETWORK OF HAILPADS

The major advantage of sensory plates (hailpads) is their simplicity and low price, which allows investigators to form a network large and dense enough to insure that at least one pad will receive the impact of hail in a passing storm over a certain area.

For these reasons we decided to install this type of network as a further aid to our studies of hailstorms, in order to obtain a large amount of information about the physical parameters of the hailstones.

3.1 The LEZA hailpad

The hailpad designed in León consists of a horizontal metallic base over which is placed the styrofoam pad, appropriately painted on the upper part (in "T" form) of the vertical mast of 130 cm. The lower end is placed in the ground some 30 cm deep and anchored with cement. In this manner, measurements are taken one meter above ground level.

The pad with the material sensitive to hail impact is 30 x 30 cm and is attached to the horizontal base by a metallic frame of 34 x 34 cm, with and opening at each end. These openings are used to insert the support springs onto the base. This provide light presure over the styrofoam which assures the immobility of the sensitive pad.

Therefore, the area sensitive to hail is not the pad area of 900 cm^2, but 780 cm^2, because the metal frame leaves an area of 120 cm^2 insensitive to impacts. This area serves for individual calibration of each pad after the hailfall. In this way we prevent errors which may come from previous calibration, since this would have been considered general for all sensitive pads and would have led to mistakes. When one assumes an identical calibration of the pads, it is supposed that all the pads have the same sensibilities to impacts, and that later treatment -especially in the impregnation of the dye, as we shall see- is also identical in all the pads.

3.2 Siting

As we must assume that each hailpad is representative of the precipitation which occurs in a certain area, and that the dents of the impacts are representative of the hail precipitations, before installing a network we must consider three initial aspects:

- the extension and the zones where hail precipitation is most probable,
- the density of hailpads to be installed should be adequate so that each pad represents a sample from at least one settlement,
- the necessity of finding a network of paths and roads which allow for frecuent revisions.

Previously we spoke of the spacial distribution of hailstorms from 1986-89. In Figure 1 we can see the spacial distribution of the hailfalls. However, due to the extension of the area studied, it is not possible to maintain a network of hailpads over the entire area because, among others reasons, the lack of roads in some areas makes it impossible.

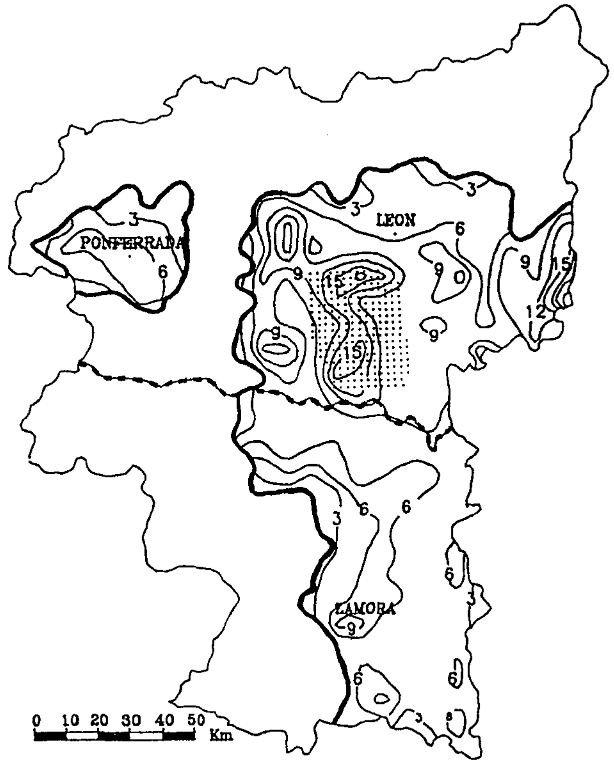

Figure 1.- The studied area is made up of a large zone on the right side (León and Zamora) and a smaller one to the left (Ponferrada). Inside each zone, the contours correspond to the number of days that there have been hail during the summers from 1986 to 1989. The dotted zone corresponds to the area with hailpads.

In order to complete the three requirements, of surface area of 1000 km^2 is enough for our study, thus making it possible for the labor of a dedicated team to care for the sensors. In fact, in numerous studies similar to ours, the networks extend over areas of 640 to 2000 km^2, with densities which range from 0.11 to 0.93 km^{-2} (Changnon, 1977; Vento, 1980; Sackiw, 1989; Morgan, 1990). For a hailstorm like the ones that usually affect our area, we have designed a network in which, on average, there are ten pads which receive impact. Therefore, the density of our network is 0.25 km^{-2} or, in other words, we would have one hailpad for each 4 km^2. In the design of the network we tried to establish a homogeneity which was more difficult to achieve in the terrain due to the characteristics of each zone. In this form we tried to draw a regular network with square units 2 km long on each side.

Once the zone, extension and density of the network of hailpads was established, we proceded to determine over a map with a scale of 1:50000 the theoretical points which should correspond to the position of each pad, according to the principles mentioned in the previous paragraph. Finally we searched for the roads and paths closest to each point, assuring that the pad could be seen from the path.

3.3 Installation and maintenance

In this manner we placed each of the 250 hailpads over the terrain, according to the maps. Later, a few days before the beginning of the study, the sensor pads were mounted on each hailpad. At the same time, ideal routes for periodic checks were planned. Each styrofoam pad had marks which identified its position in the network and its orientation.

In the case where no storm activities were measured, the regular maintainance required that each sensory pad be changed once a week, always taking note of the revisions and substitutions made.

On the days of activity, the radars installed in the University of León (X band) and in Bustillo del Páramo (C band) direct the actions of the mobile team. These centers remain in comunication with the vehicles using radio stations. This way if a storm which may produce hail can be detected over some point in the zone to be studied, this information is immediately communicated to the maintainance personnel so they can move to the affected area. In this manner the immediate inspection of all pads which may have received hail impacts can be carried out.

In any case where storms have caused hail over a large area, the network maintenance team, usually consisting of two people, is reinforced. All pads which received impact are gathered and replaced by fresh ones.

3.4 Calibration of the material

As previously stated, each pad collected with hail impact dents is calibrated in order to prevent errors caused by possible differences in the resistance of each pad or the blackening of the non-impacted surface.

The calibration consists in dropping six steel spheres, of diameters between 5 and 20 mm -which is the most frequent size of the hail- on the surface of the pad in such a way that they arrive at the surface with the same kinetic energy that a hailstone of the same size would have. In order to make the calculations, it must be supposed that the hail reaches the ground with a final velocity which, after some approximations, we have supposed to be:

$$v = \sqrt{\left[\frac{4}{3}\;\frac{\mu_h\, g}{\mu_{ah}\, C_d}\right] D}$$

where μ_h is the density of the ice, μ_a that of the air, g is the gravitational acceleration, C_d is the aerodinamic coefficient or drag coefficient, and D is the diameter of the hailstone.

Concerning the parameters g, μ_h, μ_a and C_d, the values were taken in the following form:

* for the density of the air, data concerning the barometric pressure and temperature were measured on the days when hailstorms were detected between 1986 and 1988 in León and Zamora. With these data, the air density was calculated according to the atmospheric standard of the ICAO. The result was 1.08 mg/cc.
* for the density of the ice, we used the value 0.90 g/cc.
* the C_d coefficient was made in relation to the radius of the hailstone, following the results compiled by Dennis (1980). A good approximation is the function in the form

  $$C_d = a\ D^b$$

  where D is the diameter of the stone in mm. The best adjustement turns out to be the parameters a = 0.79767 and b = -0.07888.
* the gravitational acceleration was calculated (Handbook of Chemistry and Physics, 1973) for 42º 20' latitude and corrected for an altitude of 850 m. The value was $g = 9.8012\ m/s^2$.

4. MEASUREMENT OF THE IMPACTS

4.1 Program for calculation

To highlight the dents, the smooth surface (no impacts) was darkened with black printer's ink, applied with a rolling pin over the surface of the pad. This impregnation method does not insure homogeneity, nor the amount of dye extended, nor the pressure of the rolling pin over the pads.

In effect, the same impacts can appear larger if too little ink was used, or if too little pressure was applied, and they can appear smaller if more pressure was used on the roller pin or if a heavy hand was used with the dye. Although in either of these cases the error is not great, individual calibration eliminates this error.

Why the individual calibration of each plate? Let us suppose we have a previous calibration, good for all the hailpads. Between the calibration plates and the others, once they are prepared for measurement, there could -and do- exist small differences with relationship to the impact resistance of the material, and specially, with the dye impregnation. It is very difficult to achieve an identical dyeing in all pads, since variations in the pressure of the printer's wheel or different quantities of ink are always present on the sensor.

We believe that for any one of this causes -or for all three- the dye can enter each of the 0.5 mm dents, for example, in less quantity than in the calibration pads. In this case, all the calculated hail sizes would be aproximately 1 mm larger than actual size. This would lead to a precipitated ice mass larger than the actual size by 73 and 16% in hailstones of 5 and 20 mm, respectively. In the same manner, the calculations done for the energy would yield higher values of 100, 40 and 20% in hailstones of 5, 10 and 20 mm.

At the time of measuring the dents, we have worked with a photocopy of the impacted surface of the pads in order to preserve the hailpad from any degradation due to manipulation. The image can be digitalized and thus processed by the computer, totally automated. However, one must keep in mind that, after a hailfall, the dents can be overlapped forming a composition which differs considerably from the almost circular dents with no intersection, ideal for automatic processing after being passed to the scanner. This problem has lead us to the choice of a non-completely automated reading system to prevent the inherents errors concerning the hiding of some of the impacts.

To read the hailpads we have used a table digitalizer, with a resolution of 0.02 mm whose maximum error is 0.2 mm. Using a program we measure the maximum and minimun diameters of the dents, keeping in mind that the hailstones can cause impacts in oblique form, thus resulting in almost elliptical dents.

The entries of the program are extremes of the maximum and minimum axis of the impacts, introduced in automatic form from the table. In order to perform the calculations for energy densities and sizes, the program needs the results from eight calibration dents from the hailpad being measured (the 5 mm sphere is dropped three times to reduce the error); with this it makes a linear regression which is the calibration line. After this result, the logic support will calculate, for each dent, the diameter of the stone that made the dent and its kinetic energy. At the same time, it will store all of the data in a file able to be computer processed in the future, such as classification of sizes, energies, etc.

Although the measurement is performed on a photocopy of the pad, the person making the measurements always has the original plate within view to consult, when necessary, cases of overlapping or deteriorations not due to hail. A single plate must be entirely measured by the same person so that eventual systematic errors are always on the same side when measuring the impacts of the hail as well as the calibration dents.

To prevent possible errors in measuring the hailpads, the impacts were measured by different people. No significant differences were found.

This measurement system provides results without significative differences versus other methods of direct measurement, with the advantage of having the results in a computer data base for easy manipulation.

4.2 Precision of the measurement

The dents are measured with the help of a digitalizer table of a precision of 0.2 mm. For the reading, two points, A and B corresponding to the extremes of the minimum are marked by the coordinates (x_A, y_A) and (x_B, y_B).

From this data, the reading and storage program which we have designed directly calculates the diameter. If we suppose that the coordinates are affected by maximum indetermination equal to the precision of the pad, the error of the diameter h of the dent would be

$$\text{Error (h)} \leq \frac{2\delta}{h} \left[|x_A - x_B| + |y_A - y_B| \right]$$

where δ is the precision of the apparatus (0.2 mm, as we saw).

The bracket value in the above expression is always less than or equal to $h\sqrt{2}$ (the equality is for circular dents) for which we can write

$$\text{Error (h)} \leq 2\sqrt{2}\,\delta \approx 0.57 \text{ mm}$$

How does this possible error -due to the precision of the apparatus- affect the data calculated later? That is, what exactness are the resulting sizes, mass and energy of the hailstones going to have starting from the measurements of their dents ?.

If every pad is judged by its own calibration, the truth is that parameters a and b from the linears regressions D = a h + b (where D is the diameter of the hailstone), always take values of about 0.97 and 2.5 mm respectively. Here it is obvious that the diameters will be affected by approximately one half milimeter. This precision does not depend on the diameter, which is why the relative error diminishes as the magnitude of D increases, and is always less than 10 %, corresponding to 5 mm hail.

As far as mass is concerned, the relative maximum error is three times that of the diameter, thus possibly leading to 33% for small diameters. As comparative data, we point out that it is less than 16% and 8% in sizes of 10 and 20 mm respectively.

The exactitude of the energy (which depends approximately on the fourth power of the diameter), is not as good. Thus the hailstones of 5, 10 and 20 mm would have a maximum indetermination of energy of 46, 22 and 10% respectively.

In conclusion, let us remember that the errors which have just been calculated are exclusively a consequence of the precision of the measuring apparatus, without entering into considerations of the exactitude of the data taken as the expresion of the final velocity, nor even the corrections of the aproximations used to arrive at this expression.

5. CASE OF JUNE 27, 1990

On this day, 21 hailpads with impacts were collected. Of these, 14 corresponded to the same hailfall, whose results we will now discuss.

The radar installed in the middle of the area detected the storm at 1:14 p.m. (Z), moving NE at speed of 35 km/h. At approximately 1:30 pm, the 10 dbz perimeter entered the hailpad network. Twenty minutes later, the northwestern border of the studied area was under the influence of 54 dbz. The maximum reflectivity of the storm (60 dbz) was reached at 2:09 pm, right above the zone were the largest hailstones were detected (18.6 mm).

Using lineal interpolations between sensory pads, isolines of maximum sizes, as well as number and energy per surface unit were drawn. These curves are shown in Figures 2, 3 and 4. As wind velocity was not taken into account, these energies are due solely to the vertical component of the velocity.

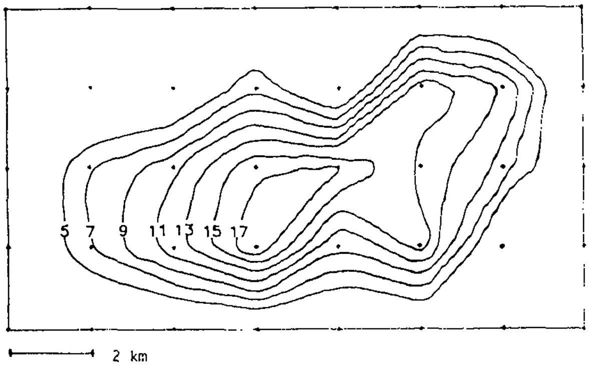

Figure 2.- Contours corresponding to maximum sizes (in mm) found. Dots represent hailpad sites.

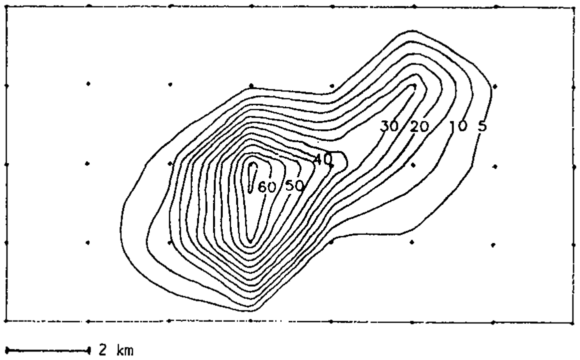

Figure 3.- Contours of the energy density (J/m²) are shown.

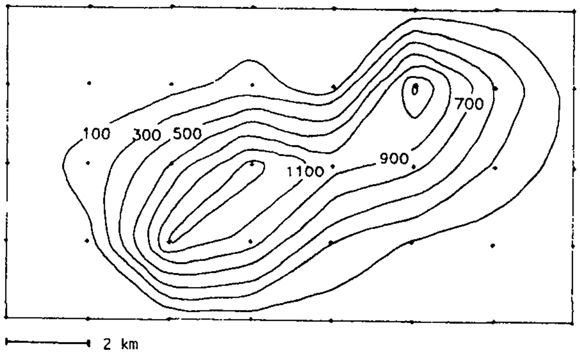

Figure 4.- Contours corresponding to the number of hailstones per square meter are shown.

The largest sizes were registered near the middle of the hailstorm zone, which does not exactly coincide with the area where the most stones were precipitated. Also, only a few hailpads received the largest part of the kinetic energy.

Supposing that each hailpad represents 4 km², we can speak of total quantities for this hailfall. Thus, the total number of hailstones larger than 5 mm is 3.6×10^{10}, which add up to an energy of 9.98×10^{8} J. All together, 11.2 tons of ice were precipitated.

Let us remember that the mass and energy calculations were done for each stone, without having to group them in any particular class. What results would we have obtained if we would have grouped the stones in different classes ? Let us make the calculations using four cases, two using a classification with intervals of 1 mm, and the other two using intervals of 4 mm.

If the class is of 1 mm width and the average diameter D_m and N (number of stones in this class) are known, we must now calculate the mass and energy of the size D_m hailstone and multiply by N, adding the results of all the classes.

But it is most common, when one does not measure the exact size of each stone, to ignore the average of the diameter of each class, being able to simply take the center of the intervals (5.5 mm, 6.5, 7.5, etc.).

However, there is no unanimity when it is time to choose the interval of the class. In fact, some studies use a 4 mm class. As in the previous case, the average value of the diameter of each class may or may not be known.

For the hailstorm of June 27, 1990 data, we have compared some of our results with those which we would have obtained if we would have made separate classes as described above. The resulting data is shown in the following table 1.

Classification	**mass** (tons)	**energy** (J)
Continuous:	11.2	9.98×10^{8}
1 mm intervals:		
Average diameter	11.2	9.95×10^{8}
Interval center	11.2	10.01×10^{8}
4 mm intervals:		
Average diameter	10.8	9.35×10^{8}
Interval center	12.1	11.04×10^{8}

Table 1.- The discretisation effect of hailstone diameters in the calculation of the mass and the energy.

The largest difference of the discrete classifications with the continuous is always less than 11%, which is approximately the same as what Vento (1984) found.

As we can be seen, the consequences of applying discretisations are not relevant, even more true if we keep in mind that the precision of the digitalizer table used to make the classification measurements can have an error spoken of earlier. In this case, the non-precision in calculating total mass and energy is 15.6 and 18.4 % respectively. Anyway, by using a continuum of sizes one is able to eliminate a clear source of errors.

However, it is not possible to study the size distribution without discrimination. Therefore, we have chosen 1 mm intervals starting at 5 mm, and essayed an exponential distribution, taking the average diameter of each interval as an independent variable. In Figure 5 the experimental points are shown, along with the line segment which is closest, with a regression coefficient, r = 0.988.

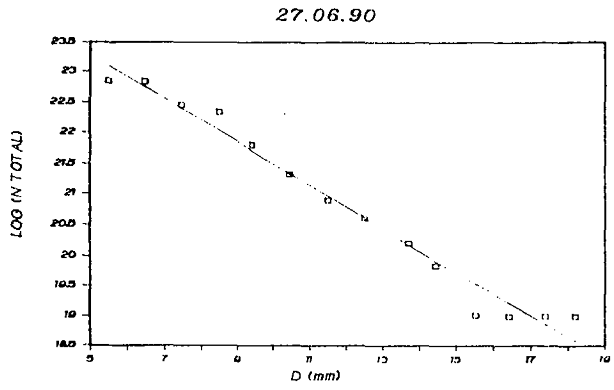

Figure 5.- Logarithm of the quantity of hailstones per interval, and the closest line.

We have also made these adjustments for each pad, but the results are not the same. Two of the pads have impacts no larger than 7 mm, so only two adjustment points could be made for these sensors. Of the other 12, three had an r coefficient below 0.7, and four coefficients were larger than 0.9. In general, all of the sensors with few impacts have correlations which are not at all acceptable. The adjustments of the pads with large hailstone impacts are not that good either.

6. REFERENCES

Changnon, S.A., Jr., 1977. The scales of hail. J. Appl. Meteor. 16: 626-648.

Dennis, A.S., 1980. Weather modification by cloud seeding. Academic Press, Inc., NY, 267 pp.

Font, I., 1983. Climatología de España y Portugal. (Climatology of Spain and Portugal). INM, Madrid, 296 pp.

Handbook of Chemistry and Physics, 1973. CRC Press.

Lozowski, E.P. and G.S. Strong, 1978. On the calibration of hailpads. J. Appl. Meteor. 17: 521-528.

Morgan, G.M., 1990. La grandine. (Hail). E.R.S.A., Gorizia, 148 pp.

Sackiw, C., 1989. Dense network analysis. In: Greek national hail suppression program. 1988 annual report. National Agricultural Insurance Institute, Athens.

Schleusener, R.A. and P.C. Jennings, 1960. An energy method for relative estimates of hail intensity. Bull. Amer. Meteor. Soc. 41: 372-376.

Smith, P.L. and A. Waldvogel, 1989. On determinations of maximum hailstone sizes form hailpad observations. J. Appl. Meteor. 28: 71-76.

Vento, D., and G. Morgan, 1980. A study of the direction of wind accompanying hail in Colorado, Illinois, Italy, and Switzerland, and of wind-caused variations of hailfall on an ultra-fine scale hailpad network containing obstacles to windflow. Preprints, Third WMO Sci. Conf. on Weather Modification, Clermont-Ferrand.

Vento, D., 1984. The discretisation effect of hailstone diameters in the analysis of the hailpads. Proc II International Conf. on Hailstorms and Hail Prevention, Sofia, September 1982, 318-324.