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Objective analysis schemes and their applications to hail measurements network in the Greek NHSP

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The objective of this study is to present the investigations and applicability of several objective analysis schemes and to create a detailed, representative and better resolution grid-point hailpad network system retrieved from actual hailpad measurements. The main motivation for this study is the desire to use the equally spaced hailpad measurements in order to be able to theoretically estimate the appropriate hailpad spacing by using either the Monte-Carlo simulation method or any conventional method of statistical analysis.

To meet the goal, several objective analysis methods are applied to the actual hail impact energy measurements which were obtained from the hailpad network system in the Greek NHSP during the 21st of June 1987 case study, and their effectiveness for the creation of an artificial grid-point hailpad network system is examined. Finally, comparisons between the methods themselves, and each of them against the actual hail impact energy measurements are performed, in order to determine the adequate objective analysis scheme.

Sheme objektivne analize i njihove primjene na mrežu mjerenja u Grčkom nacionalnom programu borbe protiv tuče

Predmet ove studije je prikaz istraživanja nekoliko shema objektivne analize kao i mogućnosti njihove primjene u kreiranju detaljnog, reprezentativnog sistema mreže s boljom rezolucijom, izvedenog na osnovi realnih mjerenja zrna tuče. Studija je potaknuta željom da se upotrijebe jednako udaljena mjerenja zrna tuče u cilju teoretske procjene podesnog razmaka mjerenja primjenom simulacije metodom Monte-Carlo ili bilo koje konvencionalne statističke analize.

U tu je svrhu nekoliko metoda objektivne analize primijenjeno na postojeća mjerenja energije udara tuče, provedena pomoću sistema mreže mjerenja zrna tuče u Grčkom nacionalnom programu borbe protiv tuče za vrijeme eksperimenta 21. lipnja 1987. Također je ispitana njihova efektivnost u kreiranju umjetnog sistema mreže točaka razdiobe zrna tuče. Na kraju su provedene usporedbe pojedinih metoda kao i svake posebno u odnosu na aktuelna mjerenja energije udara tuče radi određivanja adekvatne sheme objektivne analize.

1. Introduction

Since its introduction 30 years ago by Schleusener and Jennings (1960) and Decker and Calvin (1961), the hailpad network system has become an important source of hailfall data information. It is being used all over the world, particularly for the evaluation of hail suppression programs (Changnon, 1969; Vento, 1976; Strong and Lozowski, 1977; Long, 1978; Karacostas, 1984; Svabik, 1989). In spite of this worldwide use, there are two problems associated with the determination of hailfall parameters by a ground network system of hailpads. These are the accuracy and the representativeness of such point measurements, which are often encountered in geophysical investigations dealing with field observations. The second problem, mainly due to its complex nature, seems to be a crucial one. A precise, accurate and brief discussion of some important studies related to the representativeness of the hailpad measurements is provided by Waldvogel and Schmid (1982).

One of the primary objectives of the hailpad measurements is the estimation of several hailfall parameters which are necessary for the evaluation of any hail suppression program. Hence, it is desirable to know the hailpad network system capabilities of detecting information of small signals coming from the differences between seeded and unseeded ensemble. Moreover, the arrangement of the hailpads within the network domain, together with their spacing, seems to play a very important role in the detection of high resolution information related to the spatial variability of hailfall at the ground. Although this problem is generally recognized and accepted, in reality it cannot be directly overcome because of the lack of easy access to the hailpads for fast and efficient maintenance, resulting in a non uniform distribution of hailpad network system. The lack of uniform spacing could result in different localized maxima and minima, and in generally smoothened out pattern.

The design of a network system for making meteorological measurements has been the subject of interest of many researchers (Alaka, 1970; Gandin, 1970). Although the majority of this work was dedicated to the large-scale numerical weather prediction (Bergman, 1978), it was also applied in raingauge network design (Eddy, 1976) and hailpad network design (Lozowski and Wojtiw, 1979). The most of the fundamental work is based on objective analysis using optimum interpolation scheme (Gandin, 1965) and the Monte-Carlo simulation method. Since the principle of the Monte-Carlo modelling is to determine the objective sampling statistics, it is desirable to convert with the minimum computational error, a non uniform hailpad network system into a grid-point uniform one. In this way, the Monte-Carlo simulation method can objectively and easily be applied, thus providing more accurate and representative results.

The purpose of this contribution is to try to investigate the general problem of the representativeness of the measurements provided by the hailpad network being used in the Greek National Hail Suppression Program (NHSP). To meet this objective, it is necessary to apply a suitable objective analysis scheme, in order to combine finite number of »point« measurements and estimate the area integral of an ensemble of hailswaths. Moreover, to provide some insight information and the necessary means (grid-point network system) for the correct application of the Monte-Carlo simulation method, a technique is required to overcome the unrealistic, but sometimes unavoidable, bunching or spreading of hailpads, and provide high resolution information on the spatial variability of hail at the ground. In future studies, the retrieved grid-point network system could be the input to the Monte-Carlo simulation method, which should be used to estimate the degree of reliability of the Greek NHSP hailpad network system, and even to contribute to the redesign of an improved and more representative hailpad network system by using actual hailfall measurements.

2. The NHSP and its hailpad network system

The Greek National Hail Suppression Program (NHSP) is the first weather modification program in the modern Greek history. It began in 1984, and was designed as an operational research cloud seeding program. The main objectives were to reduce the hail damage over the three distinct agricultural areas in the northern and central Greece, and simultaneously examine and study the thermodynamic, dynamic and microphysical characteristics of the potential hail producing clouds. This randomized cross-over design, being a »piggy-back« venture on the overall operational project, was highly desirable because it provided the means for monitoring the optimal treatment for the given situation and conditions, and an opportunity to improve the meteorological understanding of the hail process present in this area of Greece (Flueck, 1976). The NHSP was carried out for five consecutive hail seasons, from 1984 to 1988. The exploratory stage covered the first three years whereas the confirmatory stage covered the last two. The relevant background and the overall design were first touched upon by Karacostas (1984). An analysis of the first two years of the exploratory randomized cross-over experiment was presented by Flueck et al. (1986), whereas an overall picture of the NHSP was fully illustrated by Karacostas (1989, 1990). Detailed descriptions concerning the operation, data collection and analysis, preliminary evaluation, training procedures of Greek personnel etc, are provided within the interim Reports issued by Atmospheric Incorporated and Intera Technologies.

The research component of the Greek NHSP is related to area A1, about 2000 km^2 in size, which is located over the north-central part of Greece. This area is equipped with 130 hailpads, with an average linear spacing of 4 km. Within the area, there are two dense network systems, with an average linear spacing of 1.5 km, which are not used in this study. A detailed description of the hailpad itself, the material used, the maintenance and particularly of the calibration procedures used is provided by Dalezios et al, (1991).

3. The objective analysis schemes

The hailpad data collected during the Greek NHSP are considered to be the prime source of objective information, and they will be used in the statistical evaluation of the hail suppression hypothesis. This discrete data set represents only point measurements and comes from an irregularly spaced hailpad network system. Hence, it is necessary to transform this data onto a regularly arranged grid-point network, and thus, knowing the energy density field between the hailpads estimate the total kinetic energy of an ensemble of hailswaths. This transformation process has often been referred to as objective analysis.

3. 1. The successive corrections method

The weighted successive corrections method was originally devised by Cressman (1959) and later modified and described in further detail by McDonell (1962) and Inman (1970).

The application of the method requires the use of a predetermined initial field of the desired parameter in order to initiate the successive corrections procedure. It is understood that the more representative and accurate the initial field is, the better results will be obtained with smaller computational effort.

In this study, the initial field is mathematically defined though equation (1), according to which the kinetic energy at each grid-point is calculated as the weighted mean of the kinetic energy values of the surrounding hailpads being within a distance d from the grid-point.

$$X_{\mathrm{gm}} = \frac{\Sigma\,[W_{\mathrm{k}}(d)\,X_{\mathrm{o}}(\mathrm{k})]}{\Sigma\,W_{\mathrm{k}}(d)}\ , \qquad \mathrm{k} = 1,2,\ldots,\mathrm{n} \tag{1}$$

Here, $X_{\mathrm{o}}(\mathrm{k})$ is the measured kinetic energy at the k-th hailpad, X_{gm} is the estimated kinetic energy at a grid-point, m is the integer indicating the scan number, n is the number of hailpads within the radius of influence, and $W_{\mathrm{k}}(d)$ is the weighting factor defined by equation:

$$W_{\mathrm{k}}(d) = \begin{cases} (R^2 - d^2)\,/\,(R^2 + d^2)\,, & \text{if } d \le R \\ 0\,, & \text{if } d > R \end{cases} \tag{2}$$

R is called the radius of influence and provides the maximum distance where $W_{\mathrm{k}}(d)$ takes the minimum value, that is zero. A new estimated value, $X_{\mathrm{oe}}(\mathrm{k})$, of the hailstone kinetic energy at the k-th hailpad is computed by the bilinear method from the previously estimated kinetic energy values of the four surrounding grid-points. The successive corrections, which are mainly initiated after the above procedure are mathematically described by the equation:

$$X_{g(m+1)} = X_{gm} + \frac{\Sigma\, W_k(d)[X_o(k) - X_{oe}(k)]}{\Sigma\, W_k(d)}, \qquad k=1,\ldots,n \tag{3}$$

and in this study they take two consecutive scans. The $X_{g(m+2)}$ is the estimated kinetic energy at a grid-point, which takes the objectively estimated final value at the last scan. The initial radius of influence was taken to be 3.0 km. However, 0.2 km was subtracted from the radius at each scan.

3. 2. The polynomial interpolation method

The initial idea of this method was firstly suggested by Panofsky (1949) who used third degree polynomial to fit wind and pressure fields. The method was later modified to handle areas with sparse data by Gilchrist and Cressman (1954). Since that time, many scientists have used the method and modified it according to their needs.

The objective of this method as used here is to estimate the hailstone kinetic energy at a particular grid-point by applying a first degree polynomial. The polynomial coefficients are calculated by the least squares method from three hailpad measurements and their average value. The input data is inverse-distance weighted according to the second power scheme, which is mathematically expressed by equation:

$$W_k(d) = 1/(d^2 + e) \tag{4}$$

The distance of each hailpad from the grid-point is denoted by d and e takes very low value in order to avoid arithmetic overflow. It should be stated that the average value is sited at the grid-point position with very low weight. The objectively estimated value, X_g at any grid-point is given by:

$$X_g = ax_k + by_k + c \tag{5}$$

Here a, b, and c are the calculated polynomial coefficients, and (x_k, y_k) the coordinates of the grid-point.

In addition to the aforementioned described objective analysis methods, two further methods have been used in this study: the kriging and the inverse distance method.

3. 3. The kriging method

The kriging method is based on the best linear unbiased exact interpolation scheme, which computes the weighting coefficients by minimizing the variance of the hailstone kinetic energy measurements (David, 1977). It is correctly assumed that the hailstone kinetic energy measurements are realizations of a two-dimensional field. The objectively estimated hailstone kinetic energy at any grid-point is given as a function of the computed weighting coefficients. The correct application of the kriging method relies upon the variogram which defines the distance where the parameters are considered to be independent. The asymptotic value of the variogram, the sill in other words, was empirically estimated to be 3. km. and resulted from the necessity to have three hailpad measurements for the estimation of the hailstone kinetic energy.

3. 4. The inverse distance method

The inverse distance method is a weighted interpolation technique. According to it, the objectively estimated hailstone kinetic energy at any grid-point results from the three neighboring hailpad measurements which are weighted inversely proportional to the second power of the distance between each hailpad and the grid-point location.

4. Case study analysis

The 21 June 1987 case study was chosen to be analyzed because it was considered to be one of the most active days during the Greek NHSP. 35 hailpads, out of the 130 hailpads of the regular hailpad network system, were hit by hail. The hailstone kinetic energy for each hailpad was calculated and these values constituted the input data set which is to be transformed to a regular grid-point network system, according to the aforementioned methods.

The weighted successive corrections method was applied to the input data and the objectively estimated hailstone kinetic energy values were calculated at each grid-point. The method was used for three consecutive scans and was applied to different scenarios. The objective of this multiprocessing was to provide a sensitivity test for the radius of influence and graphically establish the required number of scans. To accomplish this, the bilinear method was used in order to recalculate the hailstone kinetic energy at the original hailpads from the estimated hailstone kinetic energy values. In this way the root mean square error between the original and the estimated hailstone kinetic energy was calculated for the three scans and the different scenarios. It became evident that the root mean square error decreases with the radius of influence. It levels off at the value of radius of 2.6 km indicating the optimum radius of influence for the given set of data. Therefore, considering the scenario of 3.0 km radius of influence, the first two scans seem to be influenced by some aliasing. On the other hand, the third scan, compared against the other scans, all other tested scenarios and the actual hailstone kinetic energy measurements, appears to be quite accurate and representative, indicating almost no aliasing and very low root mean square error (rmse = 0.58 J).

Figure 1 depicts the isopleth analysis of the objectively estimated hailstone kinetic energy for 21 June 1987. It represents the third scan of the successive corrections method, which was initially applied with a radius of influence of 3.0 km, 0.2 km being subtracted at each scan. The dots represent the irregularly spaced sites of the hailpads within the network system. Moreover, the measured

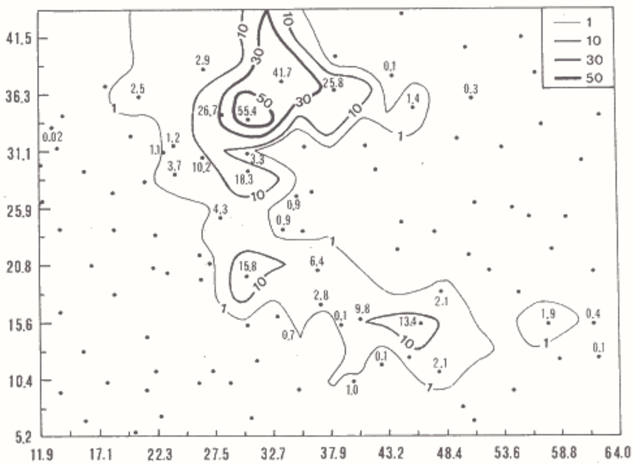

Figure 1. Isopleth analysis of the objectively estimated hailstone kinetic energy for the 21 June 1987 case study. The results have been obtained by the successive corrections method. The units of the hailstone kinetic energy are J/m^2 while the abscissa and ordinate are expressed in km.

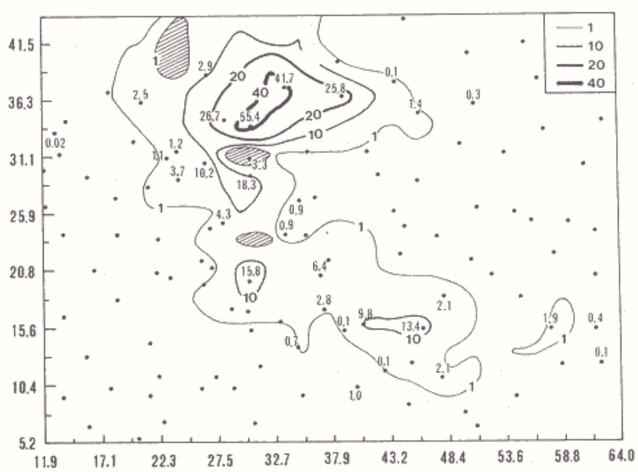

Figure 2. The same as in Fig. 1 except for the polynomial interpolation method.

hailstone kinetic energy at each hit hailpad is depicted. An examination of the measured and estimated hailstone kinetic energy values reveals a very good agreement, delineating quite accurately the large scale structure, the fine scale features and the primary maxima and minima of the hailstone kinetic energy.

Using the same set of the original data, the objectively estimated hailstone kinetic energy values for the 21 June 1987 case study were calculated by apply-

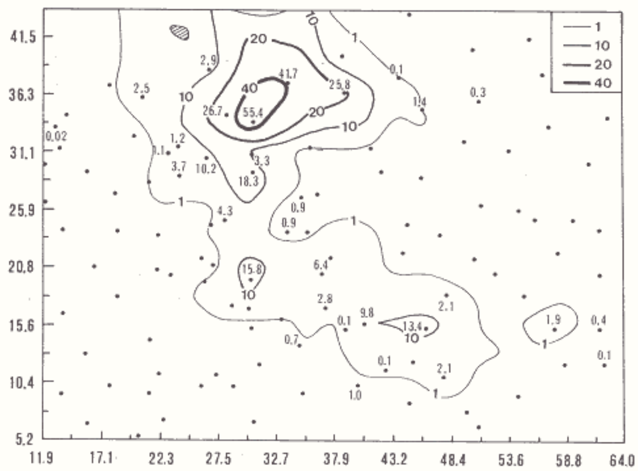

Figure 3. The same as in Fig. 1 except for the kriging method.

ing the polynomial interpolation method. The resulting isopleth analysis is presented in Figure 2. Although Figures 1 and 2 are similar, it is apparent in Figure 2 that some local maxima and minima are overestimated, and the major maximum is underestimated. This is probably due to the aliasing because a transfer of energy takes place between the neighboring hailpads. This aliasing problem may result from the cumbersome first degree polynomial, as opposed to a second degree polynomial, which is expected to produce better results. In addition, the root mean square error between the original and the estimated hailstone kinetic energy was found to be 1.74 J, by a factor of three higher than the one obtained by the use of the successive corrections method.

Figures 3 and 4 illustrate also the isopleth analyses of the objectively estimated hailstone kinetic energy as obtained by the kriging and the inverse distance methods, respectively. The two figures show similarities, particularly in the large scale structure. In spite of the smoothed out features, the large scale structure seems to be quite reasonable. However by comparing the fine scale features between th two figures and against the actual measurements one concludes that the analysis in Figure 3 does not appear to be as representative as the one presented in Figure 4 and particularly in Figure 1. This is probably due to the aliasing, which seems to be significant in the analysis illustrated in Figure 3, and even more significant in that depicted in Figure 2. It should also be mentioned that the results produced by the kriging method are quite similar to those produced in the first scan of the successive corrections method. Verification of the aforementioned aliasing problem is the misrepresentation of the maximum estimated hailstone kinetic energy value, which is apparent in Figure 3 and particularly in Figure 2.

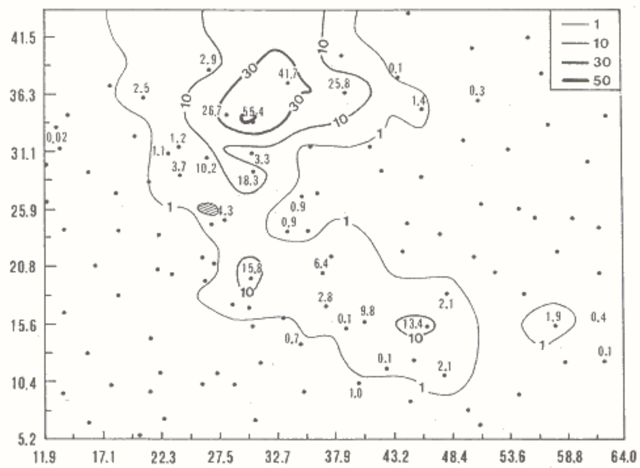

Figure 4. The same as in Fig 1. except for the inverse distance method.

5. Summary and concluding remarks

The hailstone kinetic energy as it is measured in the Greek NHSP comes from an irregularly spaced hailpad network system and represents only point measurements. The transformation of this data set onto a regularly arranged grid-point network system was performed through four distinct objective analysis methods. The transformation was required for future estimation of the area integral of the total kinetic energy, a parameter necessary for the evaluation of the NHSP, and moreover to provide the means for the correct application of the Monte-Carlo simulation method, a technique necessary for the estimation of spatial variability of hail at the ground.

Applying the four objective analysis method to the measurements obtained during the 21 June 1987 case study, isopleth analyses of the estimated hailstone kinetic energy values were presented and critically evaluated. The successive corrections method seems to give the best results. The polynomial interpolation method suffers from significant aliasing problem. This is probably due to the first degree polynomial used. Although the results from the kriging method and the inverse distance method show similarities, the latter appears to be more adequate. Further examination and objective evaluation would be necessary and desirable.

An acceptable grid-point network system, like the one retrieved from the third scan of the successive corrections method, would be the necessary input to the Monte-Carlo simulation method, used to estimate the degree of reliability of the Greek NHSP hailpad network system.

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