DEVELOPMENT OF IMPROVED CRITERIA FOR HAIL SUPPRESSION SEEDING IN SERBIA

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Abstract. An evaluation of the criteria for hail suppression seeding in Serbia, based on temperature at the levels of the maximum of radar echo, the top of the accumulation zone and the top of the radar echo of Cb clouds, was made. The results show that these criteria were unrealistic; i.e., unreliable and uneconomical. Therefore, new criteria for hail suppression seeding in Serbia were considered. One of them is called the complex criterion and the others are based on the multiple linear regression and the logit model. The tests with these new criteria have shown that they were more selective in distinguishing between hail and no-hail Cb clouds.

1. INTRODUCTION

Hail suppression in Serbia began a quarter of a century ago based on principals similar to those developed in the former U.S.S.R. In the beginning it covered some 1,500 km^2, and a decade later it expanded to a large system covering about 35,000 km^2 of cultivated land.

The seeding criterion used from the very beginning until now was formulated by Sulakvelidze (1967). According to that criterion, a Cb cloud would be seeded if the following conditions observed by a radar of 10 cm wavelength were fulfilled:

- ambient air-temperature at the level of maximum radar echo is negative,
- ambient air-temperature at the level of the top of the accumulation zone (a space between maximum and 10 dB less than maximum radar echo) is colder than -14°C,
- ambient air-temperature at the level of the top of radar echo is colder than -28°C.

The hail suppression system operating in Serbia was based on the competition hypothesis. In the first the accumulation zone surrounding the maximum of radar echo was targeted for seeding. Later on seeding agent was injected into the layer in front of the accumulation zone bounded by the isotherms of -8°C and -12°C.

2. ESTIMATION OF HAIL SUPPRESSION SEEDING CRITERIA USED IN SERBIA

The radar and surface observations made in Serbia during 1978 were used in this analysis. This was the first year that observations were statistically elaborated and Cb's (radar echo top exceeds 6 km) classified in four categories.

The first category (I) contained Cb's which were not seeded and did not produce hail. The second category (II) contained Cb's which were seeded and produced hail. The third category (III) contained Cb's which were not seeded but produced hail. The fourth category (IV) contained Cb's which were seeded and did not produce hail. The numbers of Cb's observed in 1978 and classified according to above mentioned categories are shown in Table 1.

The most of Cb's were observed for a short time. They did not reach their mature phase or left the target area. Therefore, only cases that had been observed continuously at least 30 minutes were selected for further studies, and 431 such cases were identified. The radar observations had been repeated approximately every two minutes. From the series of observations the maximum values of the six radar parameters were analyzed. These parameters were:

1) LogZ - The logarithm of reflectivity of the maximum radar echo,
2) T_N - temperature (°C) at the level of the maximum radar echo,
3) T_{tz} - temperature (°C) at the level of the top of accumulation zone,
4) Tt - temperature (°C) at the level of the top of radar echo,

5) h-/ht- - ratio between the thickness of cold (below 0°C) and warm (above 0°C) parts of the Cb radar echo;

6) V - Volume (km3) of the cold (below 0°C) part of the radar echo.

From this analysis, we concluded that criterion for hail suppression seeding, used so far in Serbia, has a very low threshold for seeding. For that reason, it is unrealistic and uneconomical. Therefore, new criteria were developed and described in the following sections.

Table 1. Numbers of Cb clouds observed and fulfilled the criterion for seeding in 1979 in Serbia

Number of Cb clouds	Categories				
	I	II	III	IV	Sum
Observed	1450	255	65	294	2064
Fulfilled the criterion	572	226	38	244	1080

3. STATISTICAL RELATIONS BETWEEN Cb CLOUD RADAR PARAMETERS AND FREQUENCIES OF HAIL OCCURRENCE

Considering logZ data we may derive two conclusions: (1) the maximum radar echo in long lasting Cb clouds (observed at least 30 minutes) is correlated with the probability of hail occurrence; (2) regardless of the value of logZ, the probability of hail occurrence does not exceed 50%.

Concerning the temperature at the level of the maximum radar echo (T_N), three interesting characteristics may be physically important: (1) the highest frequency of the maximum radar echo of Cb clouds may be found in an interval of -11°C to -20°C; (2) the probability of hail occurrence gradually increases as the temperature on the level of maximum radar echo decreases; (3) at the temperature below -40°C the maximum of radar echo can be rarely observed.

Concerning the hail frequency connected to the temperature at a level of the top of accumulation zone (T_{tz}), the following characteristics may be seen: (1) the greatest number of Cb clouds have the temperature at a top of their accumulation zones between -16°C and -25°C; (2) no one hail occurrence was recorded when the Cb clouds had temperature at the top of accumulation zone warmer than -5°C; (3) probability of hail occurrence gradually increases as temperature at the top of accumulation zone decreases.

Hail frequency related to the temperature at a level of the top of radar echo (T_t) is shown that about 3/4 of all cases had T_t below -55°C. The probability also increases when T_t decreases.

Bibilashvily *et al* (1981) considered that the ratio of the thickness of cold and warm parts of Cb clouds (h^-/h^+) can be used to indicate hail occurrence. Thus, this ratio has been applied in Serbia and shown that over 60% of all hail cases were between 2:1 to 3:1. The increase of probability with increase of this ratio is very evident up to $h^-/h^+ = 5:1$.

The last radar parameter analyzed was the volume (V) of the cold part of radar echo. The frequency of hail occurrences related to V is shown that the greatest number of Cb clouds, over 58% of all cases, had V £ 100 km^3. Another feature which should be mentioned here, is a rather slight increase of hail probability by increase of V.

On the basis of the above derived analysis, it may be concluded that all radar parameters show direct statistical relation to the probability of hail occurrence. However, the lower and upper thresholds could not be found. It means that hail may occur in very low values of some parameters and, on the other hand, hail may not occur in the highest values of some radar parameters.

4. THE COMPLEX CRITERION

In the most hail suppression areas in the former U.S.S.R. an estimation of the hail-fall probability was made from a complex criterion. This criterion is based on the evidence that each radar parameter has a lower threshold below which hailfall could not occur and an upper threshold above which hailfall will occur. Between these thresholds there is an interval in which the probability of hailfall occurrence increases with a distance from the lower and approaching to upper threshold. Bibilashvily *et al* (1981) showed that the most reliable estimate of the possibility of hailfall may be obtained when a mean value of all radar parameters is used.

The values of complex criterion calculated for Serbia show that even the lowest values of some radar parameter are associated with some probability for hailfall. Also, for the highest values of the radar parameters, the probability for hailfall appearance did not reach 100%. In spite of that, the rise of the complex criterion values, i.e. the probability of the hailfall, with a rise of the mean values of radar parameters, is very smooth.

5. CRITERION BASED ON MULTIPLE LINEAR REGRESSION

Multiple linear regression relates one variable P, called the dependent variable or predictant (here the probability of hail) to n other variables X_i, called the independent variables or predictors (here radar parameters). The result is an equation which can be used for estimating the predictand as a linear combination of the predictors (Glahn and Lowry, 1972):

$$P = k_o + k_1X_1 + \ldots + k_6X_6 \qquad (1)$$

where the k_i's are determined such that sum of squares of the estimation errors is a minimum on the dependent sample of size N (here N=431) and X_i denotes a predictor classified so that:

$x_i = 0$ when this radar parameter value does not favor the hailfall (Y_1);

$x_i = 1$ when this radar parameter value favor the hailfall (Y_1).

Here the independent variables X_i are used as binary having the value below (0) or above (1) its median.

In the second application of the multiple linear regression technique, instead of dividing predictand and predictors in two classes, we used their observed values.

6. CRITERION BASED ON LOGIT MODEL

The logit model provides a mean of fitting a sigmoid or S-shaped curve when the dependent variable (Y) is binary and the independent variables X_i are continuous. The estimation equation for 6 independent variables can be written (Glahn and Bocchieri, 1975):

$$P(Y=1/X_1,X_2,¼,X_6) =$$
$$= 1/[1+\exp\text{-}(k_o+k_1X_1+k_2X_2+¼+k_6X_6)] \qquad (2)$$

The logit model has been applied here in three different waves. Firstly, the independent variables X_i are used as binary having the values below (0) or above (1) its median. The second way, in which the logit model was applied, the observed values were fitted in Eq. (2). The third way of the logit model used in this paper was the fitting of the probability equation by standardized values of the predictors (radar parameters).

7. THE SELECTIVITY POWER OF DIFFERENT CRITERIA

A comparative verification of the above described criteria was performed on the radar observations of Cb clouds and surface observations of hailfall for the period April-October 1979 in Serbia. These data were not used in formulation of hail suppression seeding criteria. In that period 337 Cb clouds, which had been observed at least 30 minutes, were taken into consideration. According to surface observations, 118 of them produced hail.

The lowest level of selection we have if we assume that each Cb cloud has the same probability to produce hail. In such a uniform probability (UP) distribution, each Cb cloud observed in 1979 had 35% probability to produce hail. Thus, if we take any two groups of Cb clouds, the X^2- test and correlation coefficient between those producing and not producing hail will be zero.

The second criterion verified was originally formulated by Sulakvelidze (SC) and so far used in Serbia. According to that criterion, the test applied here showed that 49 out of 337 Cb clouds did not fulfill this criterion, but 5 of them produced hail. On the other hand, 113 out of 288 Cb clouds which fulfilled criterion produced hail. The x^2- test was 15.5 and the correlation coefficient was r=0.21. These are the lowest values among the criteria considered in this paper.

The criteria based on multiple linear regression used as binary /MR(B)/ or observed radar value /MR(0)/ and on logit model /LM(B), LM(0)/, as it is shown in Table 2, gave essentially higher x^2 and r values than the criterion formulated by Sulakvelidze.

The complex criterion (CC) has shown better results than any other criterion except the logit model using standardized values /LM(S)/ of the radar parameters as predictors.

Table 2. The selectivity rank of criteria for hail suppression seeding

Criteria	Criteria unfulfilled		Criteria fulfilled			
	Cb with hail	Cb with no hail	Cb with hail	Cb with no hail	x^2	r
UP	0	0	118	219	0.00	0.00
SC	5	44	113	175	15.5	0.21
LM (B)	22	100	96	119	24.2	0.27
MR (B)	21	99	97	120	25.1	0.27
LM (R)	24	110	94	109	28.6	0.29
MR (R)	25	119	93	100	34.4	0.32
CC	18	110	100	109	39.8	0.34
LM (S)	31	141	87	78	44.6	0.36

8. CONCLUSIONS

In an effort to improve the hail suppression operations in Serbia, we evaluated the seeding criterion originally formulated by Sulakvelidze, which has been so far used in Serbia. The verification indicate that two thirds of the Cb clouds which fulfilled this criterion do not give hail. That shows that Sulakvelidze's criterion is not an efficient one - seeding when no seeding is necessary.

In order to improve the criterion, three different types of methods were studied. These are: (1) complex criterion; (2) criterion based on multiple linear regression, and (3) criterion based on the logit model.

This study has shown that the most reliable hail suppression criterion is a criterion based on the logit model, which uses the standardized values of the six radar parameters as predictors. The complex criterion was found to be the second most reliable. The criterion based on multiple linear regression was found to be the least efficient.

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