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AN ATTEMPT TO EVALUATE HAIL SUPPRESSION IN CROATIA

Jedan način utvrđivanja učinka obrane od tuče u Hrvatskoj

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Abstract: The number of hail days in the warm period of the year, June-September, at meteorological stations, is used for the evaluation of hail suppression activities in north-western Croatia. The mean number of hail days at the station is connected with the mean number of hail days in the experimental region and the mean area covered by individual hail falls in the region (Long, 1980). The assumptions of this analysis are that the regional frequency of hail days cannot be changed by hail suppression and that the change of the mean area covered by individual hail falls is a consequence of hail suppression.

Multivariate linear regression has been chosen as the method of analysis. The frequency of hail days at stations is a dependent variable, and the year, the number of days with thunder, and the amounts of precipitation greater than 10, 20 and 50 mm, are independent variables. The assumption is that more stormy weather means more hail days in the region and that the chosen correlates can compensate the difference in the number of hail days between years in the region. The effect of hail suppression is represented by a step function, the value of which is one for years with hail suppression and zero otherwise. The regression coefficient of this function, according to analysis assumptions, reflects the effect of hail suppression.

Data from seven meteorological stations in north-western Croatia, spread over an area of 11000 km^2, have been used in the analysis. The operational hail suppression system started working in this part of Croatia in 1971, and by 1974 it spread over the whole region, so that there were years during which some stations were under the influence of hail suppression while others were not. The number of meteorological stations in the region has changed over the years, too. The first station started working in 1862 and the most recent one in 1982. Analyses have been done with data from all years with at least one working station, and for the two periods, 1937–2000 and 1945–2000. The common characteristic of all three sets of data is a very low percentage of explained variance, 15–20%, and a negative regression coefficient of the step function representing the effect of hail suppression. According to the value of this regression coefficient, the yearly mean number of days taken at all stations was 22% lower for the years with hail suppression, but it was not possible to distinguish it from the long-term trend in all cases.

Key words: hail suppression, evaluation, regression analyses

Sažetak: Učinak obrane od tuče u Hrvatskoj analiziran je korištenjem broja dana s tučom u toplom dijelu godine, lipanj–rujan, zabilježenih na meteorološkim postajama u sjeverozapadnoj Hrvatskoj.

Srednja vrijednost broja dana s tučom na meteorološkoj postaji povezana je sa srednjom vrijednošću broja dana s tučom na širem području unutar kojeg se nalazi postaja i srednjom vrijednošću površine pod tučom na dan kad je padala tuča, na istom području (Long, 1980). U ovom radu pretpostavljeno je da obrana od tuče ne može promijeniti srednju vrijednost broja dana s tučom na širem području postaje i da su promjene srednje vrijednosti površine pod tučom uzrokovane djelovanjem obrane od tuče.

Metoda obrade podataka jest višestruka regresija. Kao zavisna varijabla uzet je broj dana s tučom na postaji, a nezavisne varijable jesu godina, broj dana s grmljavinom i brojevi dana s oborinom većom od 10, 20 i 50 mm. Pretpostavka je da više nevremena na promatranom području znači i više dana s tučom, i da odabrani korelanti mogu kompenzirati promjene od go-

dine do godine ukupnog broja dana s tučom na promatranom području. Učinak obrane od tuče predočen je step-funkcijom koja ima vrijednost 1 za godine s obranom od tuče i 0 za godine bez nje. Učinak obrane od tuče određen je koeficijentom ove funkcije u jednadžbi regresije.
Analiza je napravljena s podacima sedam meteoroloških postaja s područja sjeverozapadne Hrvatske. Površina analizom obuhvaćenog područja je oko 11000 km². Na tom je području obrana od tuče počela raditi 1971. godine, samo na dijelu područja, a područje pod obranom od tuče širilo se do 1974. godine, kad je pokriveno cijelo područje. U razdoblju širenja područja obrane od tuče neke postaje su bile pod utjecajem obrane od tuče a neke ne. Broj postaja na području također se mijenjao s godinama. Prva je postaja počela raditi 1862. godine, a zadnja 1982. Analize su napravljene s podacima za sve godine kad je bar jedna postaja radila, te za dva perioda, 1937–2000. i 1945–2000. Zajednička karakteristika svih analiza jest vrlo malen postotak protumačene varijance, 15–20%, i negativni koeficijenti uz step-funkciju obrane od tuče. Prema vrijednostima tog koeficijenta regresije, srednji broj dana s tučom na meteorološkim postajama smanjen je za 22% za vrijeme djelovanja obrane od tuče, ali nije bilo moguće u svim analizama razdvojiti tu promjenu od dugogodišnjeg trenda.

Ključne riječi: obrana od tuče, utvrđivanje učinaka, analiza regresije

1. INTRODUCTION

The evaluation of weather modification attempts is a very difficult task, and this is particularly true for hail suppression. The great variability in time and space of the characteristics of hail falls, the difference between cumulonimbuses, the yet not completely understood processes in thunderstorms and the influence of seeding on them, are some of the reasons why the problem of evaluation of hail suppression remains unsolved. One of the conclusions at the WMO hail suppression expert meeting (WMO, 1996) was that the evaluation of hail suppression methods must be done in two stages. In the first stage, the so-called exploratory stage, physical measurements should be done to explain the processes in cumulomimbuses that cause hail growth and to find the statistical characteristics of hail falls. On the basis of this knowledge a hail suppression method can be defined together with the measurable effects of the method on the processes of hail growth. In the second stage, called confirmatory, the method is applied, measurements of those physical values that are affected by the method are done and the method is evaluated. To do only randomized experiments is not recommended, because it would last too long to reach a significant result. Many randomised experiments ended without reaching a significant conclusion. The most well-known experiment of the kind, Grossversuch IV (Federer et. al, 1986), aimed to evaluate the Soviet method, could in five years of experimentation detect only a 60% or greater reduction in hail kinetic energy. The possible effects of smaller amounts, if there were any, could not have been detected in the given time period.

An appropriate way to measure hail on the ground is by using a network of hail pads. For the evaluation of the hail suppression method, the network density should be one hail pad or more per 4 km². Measurements within the network should be done during both the exploratory and the confirmatory stage of the experiment. Many operational projects do not fulfil these conditions. If we still want to evaluate the effects of such projects, other sources of data should be used. Changnon and Schickedanz (1969) and Schickedanz and Changnon (1970) investigated the use of historical hail data, that is hail day data and insurance crop-loss data, to evaluate hail suppression projects. For the hail day data they suggested continuous seeding as the optimal experiment design, and a sequential test involving the Poisson and Negative Binomial distributions as the optimal test. They used data from Illinois, United States, and found that 13 to 37 years of seeding experiments would be needed to detect a 20% reduction in hail days, and 1 to 3 years for detecting a 60% reduction. For insurance data, the random-historical design in which all potential storms are seeded on a particular day, and 80 percent of the forecasted hail days are chosen at random to be "seeded days" is suggested as the optimum experimental design. They recommend a statistical analysis based on the sequential analytical approach or the non-sequential approach utilizing a one-sample test with the historical record as control. The duration of the experiment needed to detect a 20% reduction in the number of acres damaged in an area of 1,500 sq mi would be 11 years. For 40% and 60% reductions, 2 and 1 years are needed, respectively. The duration refers the sequential analysis. The non-sequential analysis is less efficient and the corresponding experiment durations are 25, 5 and 1 year.

There have been many operational hail suppression projects around the world that lasted several decades and, according to the above results, could be evaluated by the application of historical hail data. This has been done for several projects, although not by applying the above mentioned methods. The hail suppression project in North Dakota (US) was evaluated utilising insurance data (Smith et. al, 1997). Historical data from the target area and the control area were used and the statistical analysis was done using the multi-response permutation procedure. The reduction in hail insurance loss ratio was estimated to be about 45%. Insurance data were used to evaluate a long-lasting hail suppression project in France, too (Dessanse, 1986). In this study the trends of risk-to-loss ratio in three areas (target, buffer and control) were analysed. A bivariate test for the detection of a systematic change in mean was applied to the logarithmic function of the risk-to-loss ratio. Only in the target area a 45% reduction in the risk-to-loss ratio was found. The problem with insurance data is that all factors affecting them cannot always be accounted for, such as changes in farming practice, changes in crop type, differences in insurance policies through the years and insurance coverage of the area. There is a possibility that the results achieved by using insurance data be affected by these unknown influences.

As mentioned earlier, another kind of historical data that can be used to evaluate long-lasting operational hail suppression experiments, where a hail pad network is not available, are hail day data from meteorological stations. The problem with hail day data is that they are an indirect measure of hail suppression effects, and the area coverage is too sparse. They should be used only when there are no other, more suitable, data available. This kind of data was used to evaluate a more than 30 years long operational hail suppression project in Serbia (Mesinger and Mesinger, 1992). The ratio of average hail frequency in the hail suppression period and in the years before it, showed a 25% reduction in hail frequency. This ratio was corrected for possible climatic and hail-observing practice changes. To find the effect of climatic changes the authors used data from neighbouring regions without hail suppression projects. The final conclusion of this analysis was that 'it appears unlikely that the seeding activities have no positive effect whatsoever; and the reduction in hail frequency seems to be of the order of 15%–20%.

The operational hail suppression project in Croatia has been going on for over 30 years. Only hail day data from meteorological stations can be utilised to evaluate its efficiency. During this hail suppression project hail day data were collected by personnel at hail suppression rocked launching stations but these data cannot be used because similar data were not collected in the years preceding the project. There have been at least two attempts to establish the effect of hail suppression in Croatia through hail day data. Gajić-Čapka and Zaninović (1993) studied the effect of hail suppression with data from three stations in the hail suppression project region. They used linear regression to find the trend for the number of hail days in the periods 1951–1990, 1951–1972 and 1973–1990. None of the trends was significant for any station. The comparison of mean values for the number of hail days during hail suppression activities and prior to these activities did not show any significant difference, either. Gelo et al. (1994) compared the mean values of the number of hail days in the warm season of the year (May–September) for two periods, 1951–1970 and 1971–1990, i.e. before and during the hail suppression project. They found that during the project the number of hail days had decreased by 35% compared to the prior period. This result was corrected for the decrease in the number of thunderstorm days. The remaining 29% decrease in the number of hail days was attributed to the effect of hail suppression.

The aim of this work is to find the effect of hail suppression activities on the number of hail days in the warm season of the year, at meteorological stations, by using the multivariate linear regression method. This method has been chosen because it gives an opportunity to study the influence of more factors at the same time. When hail day data are used to evaluate the effects of hail suppression, it is not enough to find the changes of mean. The number of hail days can change because of climate changes and some other reasons, even for unknown reasons. In the above mentioned studies, climate changes were taken into account using changes in the hail day frequency in neighbouring regions (Mesinger and Mesinger, 1992) or changes in the number of thunderstorms (Gelo et al, 1994). Both methods have been used in this work. Changes in the number of thunderstorms have been taken into consideration by using the number of thunderstorms as an independent variable in the regression equation. Climatic changes in the neighbouring region have been taken into consideration by using data from one station to the south of the project region and put in the data set used to find the regression equation.

2. THE HAIL SUPPRESSION PROJECT IN CROATIA

In the sixties, last century, farmers in Croatia started to protect their crop from hail by launching rockets with silver iodide into stormy clouds. These were the first attempts of hail suppression in Croatia. Soon, the Meteorological and Hydrological Service started to give some guidance to farmers how to choose the right clouds for seeding. In the 70's, radars started to be used for cloud detection and guidance in rocket launching. The claimed method of hail suppression was the Soviet method based on the big drop accumulation zone theory. The method was never applied completely because rockets could not reach the accumulation zone. Instead, updrafts in young cells were seeded and it was expected that they would carry the silver iodide up to the accumulation zone. Today, there is a consensus that the weak updrafts, where the hail embryos develop, should be seeded for hail suppression. In the 80's, the theory of beneficial competition in the hail-growth zone was claimed as a method of hail suppression. Again, young cells and weak updrafts were the seeding targets. However, there was a problem: the radars had only analog displays, so the cloud images were approximated with circles and it was assumed that the seeding region, which could not be seen on radar, was at the right front side of the moving cloud, except in the rare occasions when clouds are left movers and the seeding region is on the left front side. There is no systematic evidence that seeding was correct. In the second half of the 90's, radars were upgraded and digital processors were added, and one Doppler radar was both. Software for the visualisation and analysis of radar images was developed. Nowadays, radars are used to find first echoes, or early echoes, and their movement. The main updrafts are recognised from shape of echoes and echoes at higher elevations. The clouds are seeded around the main updraft. Besides rockets, ground burners are used, which should start to work at least three hours before the storms in the protected area starts.

According to this method of hail suppression, the method of beneficial competition, one of the effects of hail suppression should be the reduction of the area covered by individual hail falls. The same holds for the Soviet method. If the number of hail days in the region is not changed, the number of hail days at meteorological stations in the region is diminished by hail suppression.

During all the years of the hail suppression project, operations were on from May to September.

3. REGION AND DATA SOURCES

The region of the operational hail suppression project in Croatia is shown in Figure 1. It covers an area of about 20000 km^2. The evaluation of hail suppression has been done only for its western part, about 11000 km^2 west of the 17° E meridian. There are seven main meteorological stations with professional observers in the selected area, and their operation years are presented in Table 1.

Their data are stored in the Croatian Meteorological and Hydrological Service database. Before being used in the analysis, the data were checked with the original records in the observers' books, and corrected if necessary. Most stations worked in the years before the

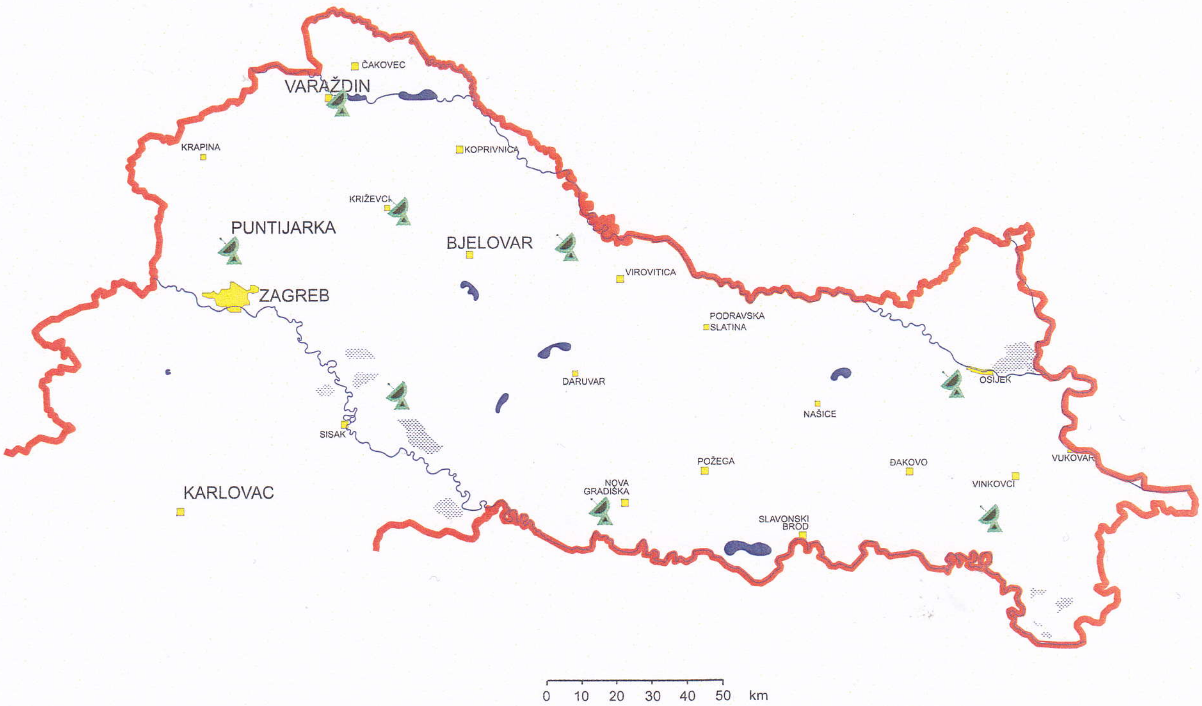

Figure 1. The region of the operational hail suppression project in Croatia and the meteorological stations. The points are the launching stations and the radar symbols are the radar stations.

Slika 1. Područje Hrvatske na kojem se provodi projekt operativne obrane od tuče s označenim meteorološkim postajama. Točke označavaju lansirne postaje, a simboli radara radarske postaje.

Table 1. Operation of main meteorological stations per year.

Tablica 1. Pregled rada glavnih meteoroloških postaja.

Station	Start of operation	End of operation	No. of years without hail suppression	No. of years with hail suppression	% of years with hail suppression
Bjelovar	1891	1910	20	0	0
Bjelovar	1946	1947	2	0	0
Bjelovar	1949	2000	52	28	54
Karlovac	1941	2000	60	30	50
Puntijarka	1960	2000	41	29	71
Varaždin	1937	1940	4	0	0
Varaždin	1945	2000	56	27	48
Zagreb-Grič	1862	2000	140	29	21
Zagreb-Maksimir	1949	2000	52	29	56
Zagreb-Pleso-aer.	1982	1997	16	16	100

start of the hail suppression project and during the hail suppression project. One station worked only in the years of the project, and one, Karlovac, is out of the project region. Within the chosen sub-region, there are another 49 meteorological stations, but they are not the main ones, and their quality of hail day data is not as reliable. The frequency of hail days at these stations is significantly lower than at the main stations, and this is the reason why their data were not used in this analysis.

4. THE DATA

As mentioned before, each year of the hail suppression project clouds were seeded from May to September. The number of hail days during these five months is important for the evaluation of the project's effects. Consequently, the number of hail days in this analysis means the number of hail days in these five months. The same holds for the number of days with thunder, and all other data. The term "hail day" has to be explained, too. It refers to the day when hail or ice pellets were observed at the station. This definition has been chosen to avoid any influence on the analysis that could come from changes in observing practices or the definition of hail days.

For each meteorological station, each year of operation (May–September), is represented by eight values. These are: the year, the state of the hail suppression project, the number of hail days, thunderstorm days, thunder days, and the number of days with precipitation exceeding 10 mm, 20 mm and 50 mm. These quantities are connected with convective instabilities; a higher value of any of these quantities, except the year and the hail suppression period, should be a sign of more convective instabilities in the particular year and a greater possibility of more hail days. The state of hail suppression is represented by a step function, being 0 if the station was out of, and 1 if it was inside the project region in a particular year. The list of variables is given in Table 2. A definition of the variable "hail suppression" is given in Table 3.

The data set consists of the records of eight values, each for one station and one year. Each record is considered to be an outcome of the same process. With this assumption all geographical and climatic differences between the stations have been disregarded. Doing so, and, as there are certainly some differences between meteorological stations, we have accepted to have a certain amount of variance unexplained. But the primary goal of this study is to find the effect of the hail suppression project on the number of hail days at these stations. If the effect is found with this assumption, it means that it is strong enough to be detected. The greatest influence is caused by the difference in station altitudes. Data from one mountain station (Puntijarka, 988 m) have been used, and as there are more hail days at more elevated stations, these data are opposing the expected effect of hail suppression.

Table 2. List of variables describing the hail suppression season at a station.

Tablica 2. Popis varijabli koje opisuju sezonu obrane od tuče na jednoj postaji.

Name of variable	Description of variable
YEAR	Year
HS	Hail suppression
THSTORM	Number of days with thunderstorm in the hail suppression season
THUNDER	Number of days with distant thunder or thunderstorm in the hail suppression season
PREC10MM	Number of days with precipitation over 10 mm in the hail suppression season
PREC20MM	Number of days with precipitation over 20 mm in the hail suppression season
PREC 50MM	Number of days with precipitation over 50 mm in the hail suppression season
HAIL	Number of days with hail or ice pellets in the hail suppression season

Table 3. Definition of the variable "hail suppression".

Tablica 3. Definicija varijable obrane od tuče (OT).

HS	Condition
0	Year when the station is outside the hail suppression region
1	Year when the station is inside the hail suppression region

Table 4. Correlation coefficients.

Tablica 4. Koeficijenti korelacije.

	YEAR	HS	THSTORM	THUNDER	PREC10MM	PREC20MM	PREC 50MM	HAIL
YEAR	1,000	0,624	0,013	0,138	0,131	0,070	0,110	-0,070
HS	0,624	1,000	0,077	0,138	0,026	-0,030	0,040	-0,109
THSTORM	0,013	0,077	1,000	0,644	0,255	0,179	0,035	0,259
THUNDER	0,138	0,138	0,644	1,000	0,133	0,032	-0,015	0,006
PREC10MM	0,131	0,026	0,255	0,133	1,000	0,738	0,396	0,254
PREC20MM	0,070	-0,030	0,179	0,032	0,738	1,000	0,458	0,232
PREC 50MM	0,110	0,040	0,035	-0,015	0,396	0,458	1,000	0,071
HAIL	-0,070	-0,109	0,259	0,006	0,254	0,232	0,071	1,000

To prove the assumption that the changes of independent variables reflect the same changes of probability for hail days and to find the relations between them, the correlation coefficients among all the variables used in the analysis have been computed for the whole data set (Tab. 4). The number of hail days is positively correlated with the number of days with thunderstorm, thunder and precipitation exceeding 10, 20 and 50 mm. It is negatively correlated with the year and hail suppression. The number of hail days has the strongest correlation with the number of thunderstorm days and the number of thunder days. The correlation with the number of days with more precipitation is low and, in particular, the correlation coefficient with the number of days with precipitation exceeding 50 mm is negligible. For further analyses, it is important to note that the correlation coefficient between the variables YEAR and HS is very high. This is no surprise because the hail suppression project started after 1970 and its area was extending over the years. This correlation is bad for analysis because the influence of long-term climatic changes can be mixed with the influence of hail suppression. There are high correlation coefficients between thunderstorm and thunder days and the number of days with precipitation exceeding 10 mm, 20 mm and 50 mm, as well.

5. ANALYSIS OF THE HAIL SUPPRESSION IMPACT ON HAIL DAYS BY MULTIVARIATE LINEAR REGRESSION

The method of multivariate linear regression assumes a linear dependence between the dependent variable Y and a number of independent variables, x_i, which is expressed by the regression equation:

$$Y=b_0 + b_1x_1 + b_2 x_2+ \ldots + b_rx_r + \varepsilon \qquad (1)$$

where ε is a residual, and b_i the regression coefficient which must be chosen to minimise the residual. Most commonly, the least square method is used to find the coefficients. The goodness of fit is given by R^2, defined as the ratio of variance of the dependent variable derived from the regression equation and the variance of observed values of the dependent variable. It has values between 0 and 1. $R^2=0$ means that the regression equation does not explain the relation between the dependent and independent variables, or that there is no relation between them. $R^2=1$ means that the relation is functional. R^2 is called "coefficient of determination", but when it is expressed in percentage it is often called "explained variance".

According to method of hail suppression, one of the consequences of cloud seeding is a reduction in the mean value of the area covered by individual hail falls. The mean number of hail days at the station, or the point number of hail days, is proportional to the number of hail days in the region and the mean area covered by individual hail falls and it is inversely proportional to the area of the region (Long, 1980). In the case where there are too few points where hail was detected, the number of hail days in the region and the mean area of individual hail falls depend on the density of the stations in the region; the greater the number of stations, the greater the number of detected hail days in the region. With more stations in the region, the mean value of the area of individual hail falls is more accurate. Within the region of this study, there are very few stations, 7, in an area of 11000 km^2. For this reason, no estimation of the number of hail days in the region or the mean area of individual hail falls was attempted. So, the only measurable value that could be used to analyse the effect of hail suppression is the number of hail days. Its mean is proportional to the mean area of hail falls, and should reflect its changes, provided that the changes in the number of hail days in the region are compensated. This task should be accomplished by using those independent variables in the regression analysis that are positively correlated with the number of hail days in the region. As seen in the table of correlations coefficients, these are the number of days with thunderstorm, the number of days with thunder, the number of days with precipitation over 10 mm, the numbers of days with precipitation over 20 mm and the numbers of days with precipitation over 50 mm. Some of these variables are very weakly correlated to the number of hail days, and some are strongly correlated between themselves. This means that some have no influence on the number of hail days if we put them in the regression equation, and the others must not be in the regression equation at the same time.

The state of hail suppression is given by the before mentioned step function, which is used as an independent variable in the regression analysis, representing the effect of hail suppression. The year is introduced as an independent variable, too. It is highly correlated with hail suppression and these two variables should not appear in the regression equation at the same time. Besides, the changes of conditions for convective instabilities from year to year and long term changes should be compensated by changes in the other independent variables. The year is still retained as an independent variable because we want to find the best regression equation, the one with the greatest explained variance and, if the inclusion of the year in the regression equations increases the explained variance, it remains an independent variable.

The dependent variable is the number of hail days, not its mean over the stations. This means that the variance of the dependent variable will be greater, while it rises inversely with the number of stations in the region (Long, 1980). The mean value is not used because in such a big region as ours the probability for hail strikes is not everywhere the same, and the mean value will not decrease the variance. Finally, the prime interest of this work is to find the existence of the influence of cloud seeding on hail suppression. If it exists, it must affect the data from all stations in the same way, and this should be seen in the regression equation.

To find the best regression equation, three equations were analysed for the given set of data. These were the equation which takes all seven independent variables and two equations built by forward and backward stepwise methods, respectively. The best regression model of the three was considered the one which yields the highest value of corrected R^2 (unbiased predictor of R^2).

Computations were done with the STATISTICA software package. The used version of STATISTICA uses the assumption of the normality of data in the significance analysis. Data on hail day frequencies were tested for normality by means of the Kolmogorov-Smirnov test and χ^2 test. The results are as follows:

Kolmogorov-Smirnov: $d = 0.2123025$ $p < 0.01$

$\chi^2 = 755.9836$ $df = 10$ $p = 0.000000$

These results show that the data do not fit to the normal distribution and the results of the regression coefficients significance analysis will not be reliable. Other distributions were tried too, and only the Poisson distribution fitted the data according to the Kolmogorov-Smirnov test, but not according to the χ^2 test. As hail day data are best fitted with the Poisson distribution, it would be better to use the Poisson regression model. It was not done here, this has been left for later work, and the results presented here are considered to be preliminary results.

The results of the multiple regression analysis are presented in summary tables. In the first column of the summary tables is the number of cases (records) used in the analysis and the names of the predictors, the other columns are BETA, B, stand. error of BETA, stand. error of B, T and p-level. Column B shows the regression coefficients and column BETA the regression coefficients for standardised variables. In column T are the values of the T-variable for testing the significance of the regression coefficients and p-level is the p-value of T. In the following chapters, regression coefficients are considered significant if their p-values are less or equal to 0.05. Variables with significant coefficients are significant factors influencing the number of hail days.

6. RESULTS OF THE MULTIVARIATE LINEAR REGRESSION

Main meteorological stations, all years

The results for the best regression model for the whole set of data (1862–2000) are given as a summary in Table 5. The model was obtained with the forward stepwise method and has a very small explained variance, only 15%. The variables with significant coefficients at 0.05 level are thunderstorm, thunder and hail suppression. The number of thunderstorm days has a positive coefficient and the greatest absolute value of BETA. It is the most important factor influencing the number of hail days. The positive correlation between the numbers of hail days and thunderstorm days is well known from studies done all around the world. The other two variables have negative coefficients. The negative coefficient for the variable THUNDER could be explained as: more days with distant thunder means fewer thunderstorms at the station. Because of the great positive value of the correlation coefficient between THUNDER and THUNDERSTORM, the same model, but without THUNDER, was tried. The explained variance dropped to 12%, THUNDER and HS retained their significance. In both models, the coefficient of variable HS is negative, which suggests a reduction in the number of hail days at the meteorological stations due to the effect of cloud seeding for hail suppression.

The variables YEAR and hail suppression, HS, are highly correlated. If just one of them was significant in the best model, their relative importance was tested by replacing it by the other one. In the regression model for the years 1862–2000, HS is significant. By replacing it with YEAR, the explained variance was 0.8% lower but YEAR did not become significant.

To see the importance of HS and YEAR in the best regression equation, both were dropped out of the model until the best regression equation was found. The equation has the same variables as in Table 5, only without HS. The explained variance is 0.97% lower and this is the amount of hail suppression affecting total variance.

Main meteorological stations, analyses per periods

Due to the gradual increase in the number of main stations, the result of the analysis could be influenced by data from some stations more than from others. Two shorter periods were analysed to avoid this problem. The first period is 1937–2000. It was chosen because since the year 1937 there were two or more main stations in the region. The second period is 1945–2000. It was chosen because since the year 1945 there were three or more main stations in the region. For each period, the regression summary tables for the best models are presented in Tables 6a and 7a. Hail suppression does not appear in either of the best regression equations for the two periods, but YEAR, which is highly correlated to HS, appears, and it is a significant factor. The explained variances are 18% and 20% for the first and the second period, respectively. As YEAR and HS are highly correlated, the variable YEAR was dropped out from the analysis while HS was retained. The results are given in Tables 6b and 7b. For the years 1937–2000, the explained variance is 0.02% lower when YEAR is replaced with HS. For the second period, 1945–2000, the explained variance is 0.8% lower. For both periods HS is a signifi-

Table 5. Results of the multivariate linear regression analysis of data from the main meteorological stations for all the years of operation. The corrected determination coefficient R^2 is 0.1477.

Tablica 5. Rezultat analize višestruke linearne regresije podataka glavnih meteoroloških postaja za sve godine rada. Korigirani koeficijent determinacije R^2 iznosi 0,1477.

N=458	BETA	Stand. error of BETA	B	Stand. error of B	T(452)	p-level
Intercept			-0,238770	0,28	-0,85	0,39
THSTORM	0,38	0,06	0,070037	0,01	6,32	0,00
THUNDER	-0,25	0,06	-0,036585	0,01	-4,22	0,00
PREC10MM	0,19	0,05	0,061069	0,01	4,17	0,00
HS	-0,11	0,05	-0,341246	0,14	-2,41	0,02

Table 6. Linear regression results for the 1937–2000 period. The corrected R^2 for table a) and b) is 0.182069 and 0.181883, respectively.

Tablica 6. Rezultati linearne regresije za razdoblje 1937–2000. Korigirani R^2 za tablice a) i b) jesu 0.182069 odnosno 0.181883.

a)

	BETA	St. error od BETA	B	St. error od B	T(357)	p-level
Intercept			19,43366	9,32	2,08	0,04
THSTORM	0,20	0,05	0,063593	0,02	3,81	0,00
THUNDER	0,44	0,07	0,082661	0,01	6,34	0,00
PREC10MM	-0,34	0,07	-0,05099	0,01	-4,99	0,00
YEAR	-0,11	0,05	-0,01005	0,00	-2,12	0,03

b)

	BETA	St. error od BETA	B	St. error od B	T(357)	p-level
Intercept			-0,21475	0,32	-0,68	0,50
THSTORM	0,18	0,05	0,058614	0,02	3,52	0,00
THUNDER	0,46	0,07	0,086549	0,01	6,65	0,00
PREC10MM	-0,35	0,07	-0,05292	0,01	-5,23	0,00
HS	-0,11	0,05	-0,32634	0,16	-2,10	0,04

Table 7. Linear regression results for the 1945–2000 period. The corrected R^2 for table a) and b) is 0.19822922 and 0.19030243, respectively.

Tablica 7. Rezultati linearne raegresije za razdoblje 1945–2000. Korigirani R^2 za tablice a) i b) jesu 0.19822922 odnosno 0.19030243.

a)

N=346	BETA	St. error from BETA	B	St. error from B	T(340)	p-level
Intercept			28,81655	10,41	2,77	0,01
PREC10MM	0,17	0,08	0,055849	0,03	2,21	0,03
YEAR	-0,14	0,05	-0,01472	0,01	-2,78	0,01
THSTORM	0,37	0,07	0,074016	0,01	5,52	0,00
THUNDER	-0,34	0,07	-0,05349	0,01	-5,08	0,00
PREC20MM	0,08	0,08	0,040202	0,04	1,04	0,30

b)

N=346	BETA	St. error from BETA	B	St. error from B	T(340)	p-level
Intercept			-0,08374	0,33	-0,25	0,80
PREC10MM	0,21	0,05	0,067456	0,02	3,92	0,00
THSTORM	0,41	0,07	0,081341	0,01	6,10	0,00
THUNDER	-0,36	0,07	-0,05785	0,01	-5,57	0,00
HS	-0,11	0,05	-0,34312	0,16	-2,16	0,03

cant factor. The importance of the variables HS and YEAR was tested, too. Both were dropped out from the analysis and the best regression models were $b_0 + b_1x_1 + b_2 x_1 + \dots + b_r$. For the data of the first period, the explained variance was 1.1% lower and for the second period 1.7% lower.

Reduction in the number of hail days by hail suppression

In the multivariate linear regression equations for all three periods, the coefficients of HS are similar, -0.341246, -0.32634 and -0.34312. Their meaning can be explained by the influence on mean value of the hail day frequency over all stations and all years. We get this mean value by using the regression equation and substituting each variable by its mean value. If this is done only for years with hail suppression, and as for these years HS is 1, the hail suppression variable adds to the mean exactly the value of its regression coefficient. If there was no hail suppression in those years, HS would be 0 and the mean would be equal to the mean with hail suppression minus the coefficient of HS. So, we can calculate the mean number of hail days with and without hail suppression. The difference is equal to the coefficient of HS. The mean number of hail days over all stations and years when hail suppression was operational is 1.18. We can calculate the mean in case there was no hail suppression by subtracting the regression coefficients. The values for the three periods are 1.521246, 1.50634 and 1.52312, respectively. The corresponding changes in the number of hail days in percentage of the number of hail days without hail suppression are -22.43%, -21.66% and -22.53%. We can say that during the hail suppression project the number of hail days diminished by about 22% due to the seeding of clouds. Unfortunately, this effect cannot be distinguished from the long-term trend, except for the data from 1862–2000. The Karlovac meteorological station was out of the hail suppression project area all the time and its data can be used to see the long-term trend in the region. The mean numbers of hail days for data from Karlovac are 0.90 and 0.97 for the years 1941–1970 and 1971–2000, respectively. Comparing this two means we can conclude that in the region nearby the region of the hail suppression project there was no negative long-term trend. This can suggest that hail suppression is a factor influencing the number of hail days and not the long-term trend, but one station is not enough to represent changes in the whole region. A more thorough investigation of hail suppression activities in Croatia should be carried out to get a more reliable answer. More should be learned about hail climatology in the region, too.

7. CONCLUSION

The number of hail days at meteorological stations during the hail suppression season, May to September, has been analysed. The region analysed was the western part of the hail suppression region in Croatia, 11000 sq km.

The hail suppression effect on the hail day frequency was analysed by the multivariate linear regression method. Since the number of stations had constantly been changing, several periods were analysed. The longest period was 1862–2000, and the other periods were 1937–2000 and 1945–2000. The regression equation was computed using data from all stations for the period analysed. The joint feature of all regression equations is a small percentage of explained variance, between 15% and 20%.

Hail suppression is a significant factor when all data are used, i.e. data for the years 1862–2000. When data from shorter periods are used, the years 1937–2000 and 1945–2000, the long-term trend is as much significant as hail suppression, and it is not possible to distinguish between the two. This is a consequence of the great correlation between the year and hail suppression, and is also a deficiency of this method when applied to our data.

The results of linear regression led to the conclusion that the number of hail days in the years with hail suppression is about 22% lower due to hail suppression.

The multiple linear regression is not the best suited model for analysing the data, since the hail day data do not fit well into normal distribution. Therefore, the results presented must be considered to be preliminary. In future work, the Poisson regression model should be used to get more reliable results.

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