## THE TIME EVOLUTION OF Cb CLOUDS IN NORTHEASTERN SLOVENIA

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**SUMMARY**

Radar data collected with two radars over two periods (i.e. 10 cm radar for the 1975-1981 and the 5 cm radar for the 1985-1986 period) were used for statistical examination of some characteristics of Cb- clouds in north-eastern Slovenia. Time dependences were studied to follow the time evolution (the development and the decay) of these clouds. Typically one third to one half of the final intensity of the cloud (height, diameter, solid/liquid water content) was achieved in the last half hour before the maximum intensity and decay from the maxiumum exibited approx. the same time rate. From one half to three quarters of the variance in the data can be attributed to the time process of growth or decay; the rest of the variance can not be connected with time evolution.

**POVZETEK**

V okviru operativne, nerandomizirane obrambe pred točo v Sloveniji sta bila pridobljena dva niza radarskih podatkov za dve obdobji: z 10 cm radarjem na Žikarcah v letin 1975-1981 in 5 cm radarjem na Lisci v letih 1985-1986. Ti podatki so klimatološko obdelani in iz njih so razvidne nekatere karakteristike Cb oblakov severovzhodni Sloveniji. Tabela 1 prikazuje osnovne statistične karakteristike oblakov: njihove višine H, premera D, višine najmočnejše radarske odbojnosti H(Zmax) in vrednost te odbojnosti Zmax, ter vremenskih parametrov, ob katerih so se oblaki razvijali, hitrosti in smeri vetra v srednji troposferi, vetrovnega striženja med 850 in 500 mbar ter Showalterjevega indeksa stabilnosti. Ker se oblaki med seboj lahko močno razlikujejo, so vrednosti, ki jih obravnavamo, normirane glede na največjo vrednost za posamezni oblak. S to normalizacijo ugotovimo (tabela 2 in slike 1 do 4), da se oblaki tipično razvijajo tako, da okrog tretjine do polovice končne velikosti, premera, vodnosti (t.j. tekoče in/ali trdne vode v oblakih, kot jo ocenimo iz radarske odbojnosti) pridobijo v zadnje pol ure, preden te

količine dosežejo največje vrednosti. Upadanje intenzivnosti poteka približno enako hitro. Okrog pol do dve tretjini variance v podatkih lahko razložimo z omenjenim časovnim razvojem oblakov, preostala varianca pa ni v zvezi s časovnim razvojem.

## 1. INTRODUCTION

Slovenia is a prealpine country between the Gulf of Trieste, the Julian Alps and the flat Panonian basin. It is among the most stormy regions of Europe, with an average number of thunderstorm days observed at meteorological stations exceeding 50 events per year. Maximum thunderstorm activity occurs along the Alpine-Dinaric ridge, separating the Mediterranean and the more continental, central parts of Slovenia (Petkovšek 1987, Rink 1988).

Due to numerous storms, and due to optimistic reports from other countries, hail suppression activity was also established in the seventies in Slovenia in the region of southern Styria close to the Austrian and Hungarian borders. On average more than one day per year with hail has been recorded at meteorological stations in this region, and more than five days per year in extreme years (Kajfež- Bogataj and Rakovec, 1988). Initially the suppression was carried out with simplified radar support. In those first years clouds were observed with a 10 cm radar without computer support. Later a new meteorological 5 cm radar was installed and equipped with computer software for weather monitoring and for hail suppression purposes.

To determine the criteria for cloud seeding with AgI bearing rockets, in the 1975-81 period the height of the maximum radar reflectivity zone and the cloud height were measured. Later, in the 1985-86 period, when the 5 cm radar was installed, the criterion was based on the position of the 45 dBZ value of radar reflectivity. Data based on these criteria were archived, and this data set was used for the present study. The details of the supression system are described by Lemut (1989).

In 1987-1988 a study of the efficiency of this system was carried out using the data sets which were available for such an evaluation. Four types of data were examined, i.e. pluviographic data, data on days with thunderstorms, radar data, and the insurance company data on damage to agriculture. The appropriate hypotheses of the possible beneficial effect of suppression activity on these hail describing variables were tested. The study could not confirm the efficacy of the hail suppression system with any acceptable statistical significance (Rakovec et al. 1990).

In the present paper the time dependence of some cloud variables was studied as deduced from the available radar data for the 1975-1986 period. Due to the statistically nonsignificant difference between the seeded and nonseeded cloud cells, all the data are treated here as belonging to a unique sample set.



## 2. THE DATA

The data were sampled from the archives of the hail suppression system, in general only for the warm part of the year. Two criteria for including the data into the present study were used:

1. the cloud was so well developed (as regards its height, diameter, radar reflectivity) that it could be hail producing according to seeding criteria, and

2. at least four consecutive measurements were effected for each separate cloud (cloud cell), in this way forming a time dependent data sample (time series) of cloud characteristics.

With the data obtained with the 10 cm 3 MK-7 radar at Žikarce, 166 such clouds (or cloud cells) on 82 separate days were found in the archives for the 7-year period 1975-1981. Due to various reasons (in general due to prohibition from the air traffic control authorities), not all of these clouds were seeded: 91 of them were seeded and 75 were "natural" - i.e. unseeded. The study already mentioned (Rakovec et al., 1990) could not confirm that these two classes differed significantly, so here we are looking on all the data together. For each of the 1098 measurements at irregular time intervals the following variables were used:

a) cloud parameters:

- height of the cloud H as seen on the radar with a minimal discernable signal of -95 dBm.
- horizontal size (diameter) of the cloud D determined as the area inside the contour of reflectivity Z = Zmax-10dBm
- height of the zone of maximum reflectivity H(Zmax)
- maximum reflectivity Zmax, measured in dBm, without the range correction.

b) weather variables

- wind velocity at 500 mbar
- wind direction at 500 mbar

- wind velocity difference 500 mbar - 850 mbar

- wind direction difference 500 mbar - 850 mbar

- SSI instability index: the difference between the temperature at 500 mbar and the computed temperature of the air parcel originating at 850 mbar, being lifted adiabatically to the 500 mbar (with possible condensation process, if appropriate)

- type of cloud (frontal or non-frontal), deduced from synoptic charts subjectively, but according to criteria determined in advance.

c) time variables

- day of the year

- hour of the day.

Meteorological EEC WR 100-2/77 5 cm radar was installed in autumn 1981; in 1983 it was moved to a new location at Lisca, equipped with computer software, and in 1985 new criteria for seeding were introduced operationally. So for the 2-year period 1985-86 44 clouds on 16 separate days which corresponded to the two above mentioned criteria for inclusion in our data set were indentified in the archives. For these clouds (cells) 295 measurements were effected (163 for 22 seeded and 132 for 22 unseeded cells), again in unequal time intervals. Here the data were the same as for the 1975-1981 10 cm radar data set except for the cloud parameters (which were changed according to the new seeding criteria):

a) cloud parameters

- horizontal size (diameter) of the cloud D was defined by the contour of 35 dBZ reflectivity

- maximum radar reflectivity Zmax in dBZ, measured in the 1 km deep CAPPI layer with the base at level 1.4 km above the height of the 0 deg C isotherm.

b) and c) are the same as for the 1975-1981 period.



## 3. BASIC STATISTICS ON WEATHER PARAMETERS AND ON Cb CLOUDS

The data are mainly from the warm period of the year: from the beginning of May to the end of September, when also most thunderstorms occur in Slovenia: in the long-term average of 1951-1986 approx. 30 days with thunderstorms per year were observed at meteorological stations in the area of interest and almost all are from May to Sept. (Rink, 1988). Some examples: at the synoptic station in Maribor 36 thunderstorms per year, 32 of which occur from May to Sept., at some other stations 25:22, 27:25, 30:26, etc. We can say that the most relevant time periods for the evolution of Cb clouds are included in our data set.

Table 1 shows mean values of the variables for the two data sets. From these (and from other statistical characteristics of the distributions which are not presented here in detail) it is possible to describe the general behaviour of the cloud cells considered.

Table 1: Mean values of cloud, weather and time variables

Tabela 1: Povprečne vrednosti karakteristik oblakov, vremena in časa

| | 10 cm radar data Žikarce (1975-81) | 5 cm radar data Lisca (1985-86) |
|---|---|---|
| H height of cloud (km) | 7.5 | - |
| D diameter of cloud (km)* | 4.9* | 7.7* |
| H(Zmax) height of max. refl. (km) | 2.8 | - |
| Zmax max. reflectivity (dBm or dBZ)* | 44.6* | 45.4* |
| No. of frontal cloud cells | 64 (39%) | 25 (57%) |
| No. of non-frontal cloud cells | 102 (61%) | 19 (43%) |
| wind velocitiy 500 mbar (m/s) | 13.3 | 12.7 |
| wind direction 500 mbar (deg) | 255 | 241 |
| velocity diff 500-850 mbar (m/s) | 5.5 | 6.2 |
| direction diff. 500-850 mbar (deg) | -3.7 | 2.2 |
| SSI stability index (°C) | 0.9 | 0.5 |
| day in year | 191 | 182 |
| hour in a day | 15.2 | 16.3 |

* Values for 10 cm and for 5 cm radar data are not fully comparable, not only due to different wavelenths but also as the diameters of clouds are in the first case determined using the Zmax - 10dBm contour, and in the second case the 35 dBZ contour; Zmax in the first case is in dBm, and in the second case in dBZ.

### 3.1 THE CLOUD CELLS OBSERVED WITH THE 10 cm RADAR AT ŽIKARCE

Table 1 shows that Cb clouds most frequently occur in the afternoon, but they were also observed at all other hours of the day, except for some hours after midnight. Most of these clouds develop with the tropospheric flow from the western quadrant: the mean direction at 500 mbar is 255 degrees, with a mode at the 280 degrees direction, but many other directions were also observed: the standard deviation of direction reaches almost 70 degrees. As Slovenia lies in the lee of the Alps, average winds are not strong. Such characteristics are also present in our data set: 3/4 of the winds connected with Cb clouds did not exceed 15 m/s at the 500 mbar level. There are more non-frontal clouds than frontal ones: 102 against 64.

An important factor as regards the development of clouds is hydrostatic instability, as can be deduced from radiosoundings, presented here by Showalter's SSI index. An earlier investigation showed that in Slovenia thunderstorms are expected to develop if the SSI value is smaller than 3 °C (Žitnik, 1970). In our data set the mean value of SSI for all cells together is only 0.94 °C and 3/4 of all cases have an SSI value less than 3 °C. Thus Žitnik's criterion was proved to be quite acceptable.

It is known that wind shear contributes to the severity of thunderstorm clouds, especially veering in the subcloud region is positively correlated with severity (e.g. Barnes and Newton, 1982). Our data do not enable the determination of wind shear in the subcloud region, but as regards general shear in the lower troposphere, 40% of the data were collected during backing and 50% with veering (as deduced from the 500 mbar - 850 mbar wind direction difference). In most cases the velocity increased with height: the mean velocity at 850 mbar was 6.5 m/s and 13.3 m/s at 500 mbar.

The mean height of the top of the cloud was 7.5 km, but an extreme height of H(Cl) of 15 km was measured as well (most probably due to anomalous radar beam propagation). The horizontal sizes of clouds D varied from 1 to 18 km, the mean value being 4.9 km. Maximum reflectivity Zmax - representing the maximum value of the solid and/or liquid water content in the cloud - did not occur at very high levels: the mean value of the top of the maximum reflectivity zone, again for all cells together, was at 2.8 km, but a height of H(Zmax) up to 8.5 km can also be found. The values of Zmax (not absolutely calibrated) were between 8 and 72 dBm, with a mean value of 44.6 dBm.



### 3.2 THE CLOUD CELLS OBSERVED WITH 5 cm RADAR AT LISCA

In the years 1985-1986 only 44 cells corresponding to our criteria were measured on 16 different days. The data are again from the beginning of May to the end of September, but as only two years are taken into consideration, the data do not cover the whole period: e.g. there are no data from mid- August on. Most data are for afternoon hours: the mean hour is between 4 and 5 p.m., mode being at 5 p.m., missing are the early hours between 1 and 9 a.m.

It is again possible to conclude that most thunderstorm cells are observed with a general air flow from the western quadrant and only a minority of them with an easterly flow, with the velocity at the 500 mbar level being below 15 m/s in almost all cases. More frontal (25) than non-frontal (19) clouds were measured.

For 90% of the collected data the SSI index was less than 3 °C. The generally low tropospheric wind shear, as determined from the 500 mbar - 850 mbar wind, shows that veering slightly prevails over backing for all cells together. The velocity difference between these two levels was in general less than 10 m/s; only on one particular day were four cells measured with a strong velocity shear of 25 m/s. On two different days clouds developed with a wind weaker at the 500 mbar than at the 850 mbar level.

The size of the clouds, determined here as the size of the area inside the 35 dBZ contour, varied from 2 km to 22 km. The mean value was 7.7 km and the modal value 6 km. Maximum reflectivities Zmax were between 31 and 68 dBZ, with a mean value at 45.4 dBZ and the mode at 40 dBZ. The distribution was skewed to lower values.

## 4. THE TIME EVOLUTION OF THE CLOUD PARAMETERS

It is known that thunderstorm clouds have different durations: the air-mass storms have a life cycle of 20 to 40 minutes (Rogers, 1976), multicell or supercell storms can last for hours (Barnes and Newton, 1982). Here we are trying to determine the typical duration, and typical time evolution of Cb clouds as can be detected from the data measured by radar. Our intention was to study the growth of clouds to their maximum height, diameter, reflectivity, and their decay after the maxima are reached.

Our present investigation is somewhat similar to the one by Waldvogel and Schieser (1985) who tested the eventual change of kinetic energy of hydrometeors, computed from the radar reflectivity of clouds, before and after seeding for part of the Grossversuch data set. For all seeding events they could not confirm the hypothesis that after a certain delay following seeding (in which AgI should begin to act) the kinetic energy diminishes for a certain time interval (for which the beneficial effect should last). Only for the subset of seedings with the so called šuccessful rocketsŵas a rather significant reduction of kinetic energy found, which begins 5 minutes after seeding and lasts for 10 minutes. In this subcase the effect was noticeable altogether for 15 minutes after seeding.

As cloud cells characteristics change rapidly in time it is desirable to have many measurements at short time intervals. To see how sensitive our data sets are to the relatively scarce sampling, some computations of regressions (which we describe later in this section) were repeated for data sets with more data in the time series for each cell: not only 4 but at least 6, or 8 or 10 data for each cell. The results for almost all slope regression coefficients (more than 90% of them) are within the same confidence interval as computed for the original data sets (with at least 4 data per cell). So more rigorous data sets (at least 6, or at least 8 or 10 data in a time series for an individual cloud cell) do not offer statistically substantially different results. Of course, in a single case study dense sampling is more crucial than in our case of looking for the statistical behaviour of all clouds together.

The time dependencies of the cloud parameters and the regressions for the time before and after the maximum value is reached are presented in Figs. 1 to 4 (a- original data, upper parts of figures, and b- normalized data, lower parts). Normalisation here supposes that all the data for one individual cloud cell are divided by the maximum value in the time series for that cell. So the normalised values increase to the value 1 at the maximum and then decrease from unity. In this way all the data sets are unified into one sample of similar growths and decays.

The individual growths and decays are plotted for broader time intervals, while the regression lines are computed only for half hour intervals before and after the maximum. So the regression lines are not valid outside the (-30,+30) minute time intervals, but they are nevertheless plotted because inside the mentioned interval they are covered by individual lines and so invisible. The regression coefficients (which for the normalised variables nesesseraly pass through the point of origin: 0,1) are included in the figures, as well as the coeficient of determination $R^2$.

Generally one can say that scattering for all parameters is rather large, especially for the original data sets. There are great variations inside the data for separate cloud cells, but the clouds also differ very much in size and intensity. So the regressions are not strong: the coefficient of determination $R^2$ is in general below the value of 0.10 for original data.

In the case of the normalized data for all parameters the regression computations search for only one coefficient of linear regression (while the constant has the value one with a fixed intercept at the origin: 0,1), e.g. for height $H=B(t-t_o)$. The model for non-normalized data is different; again e.g. for height H we saerch for regression $H=A+B(t-_to)$. So the values of $R^2$ cannot be compared in the two cases.



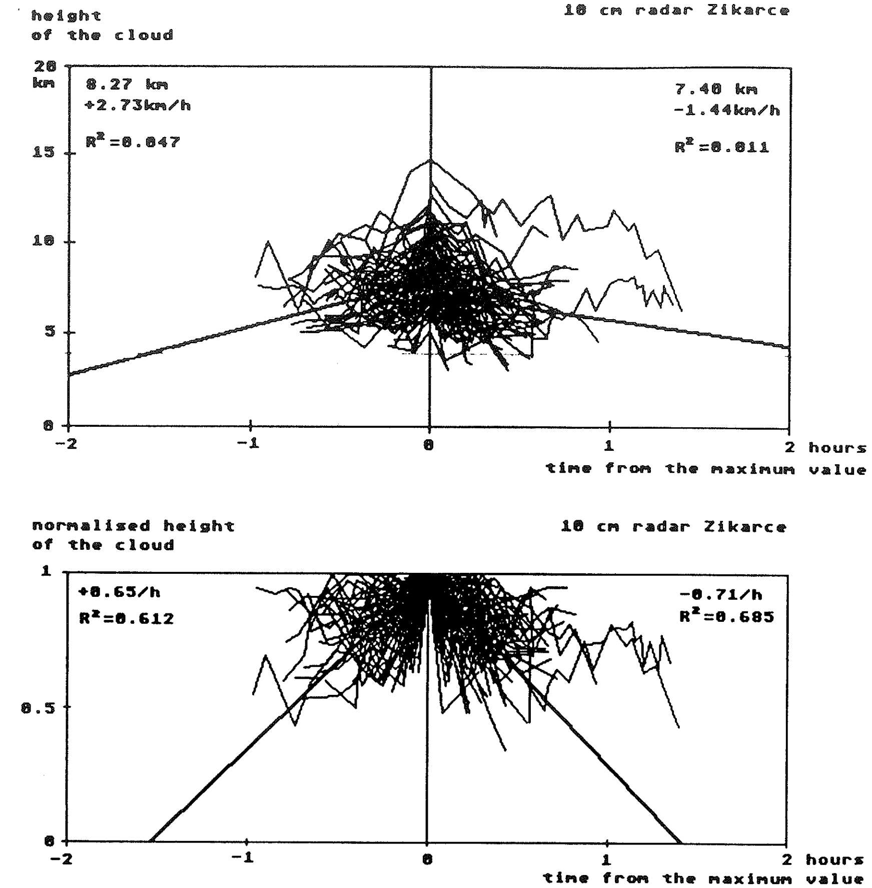



Figure 1: Time dependence of the heights of clouds, measured with 10 cm radar (1975-81) according to the time when the maximum was observed, together with the linear regression lines and regression data 30 min before and after the maximum (outside the -30,+30 minutes time interval these lines are not valid but are drawn because inside this interval they are covered by individual lines). a - upper part of the figure: original data, b - lower part of the figure: normalised data.

Slika 1: Časovni potek višin oblakov H, merjenih z 10 cm radarjem (1975-81), glede na čas, ko je bila dosežena največja višina, skupaj z linearnimi regresijami (regresijske premice in regresijski podatki) za čas 30 min pred maksimumom in po njem. Za čas pred in po njem (t.j. zunaj -30, +30 min intervala) regresije ne veljajo, so pa črte narisane zaradi preglednosti, kajti znotraj tega intervala jih prekrivajo črte individualnih potekov); a - zgoraj: originalni podatki, b - spodaj: normalizirani podatki.

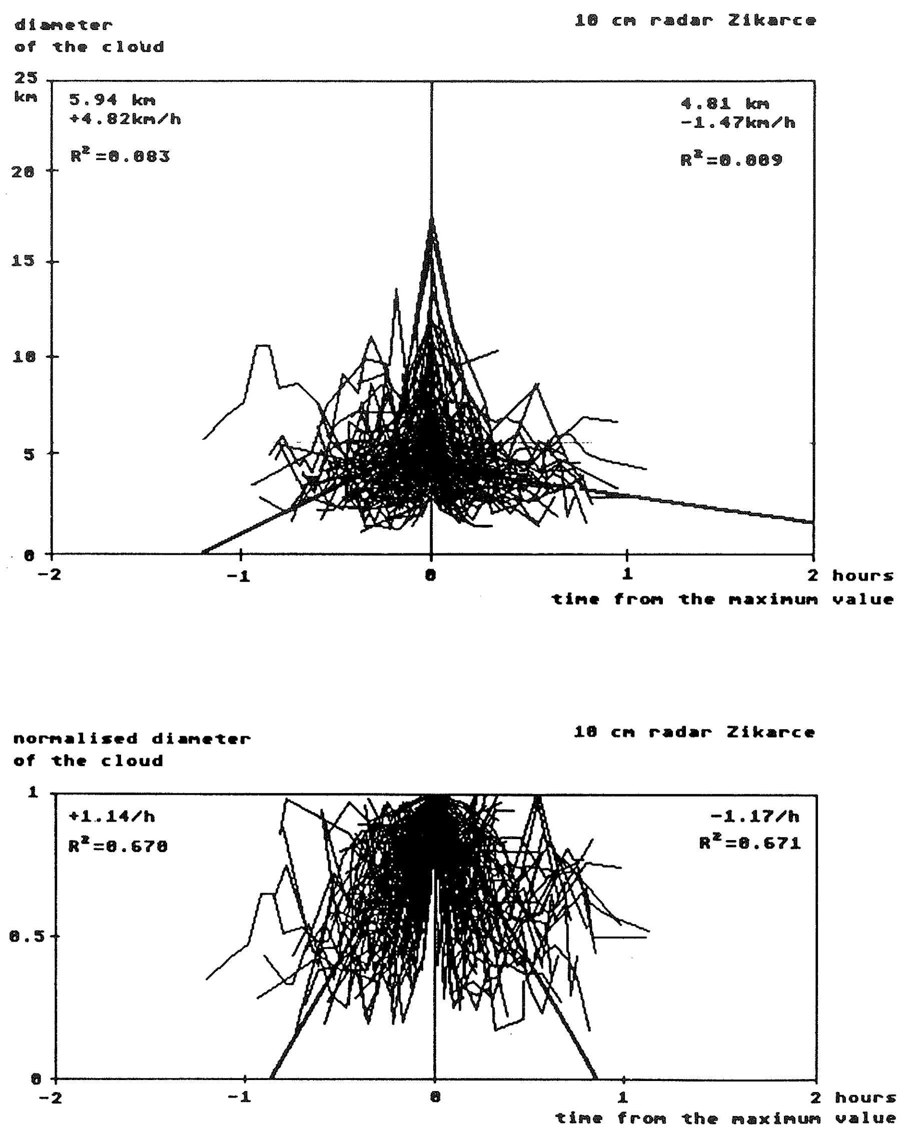



Figure 2: As Fig. 1, but for the cloud diameter.
Slika 2: Kot Sl. 1, toda za premer oblaka D.



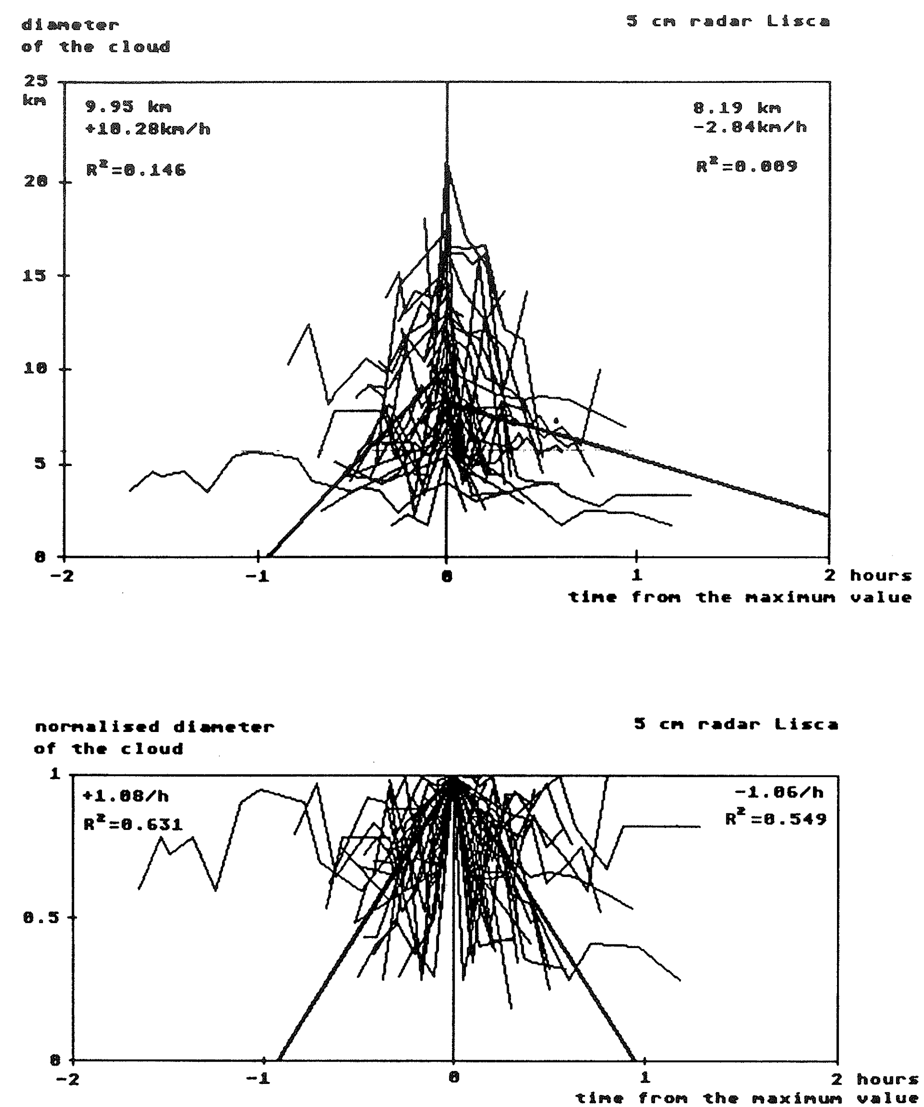
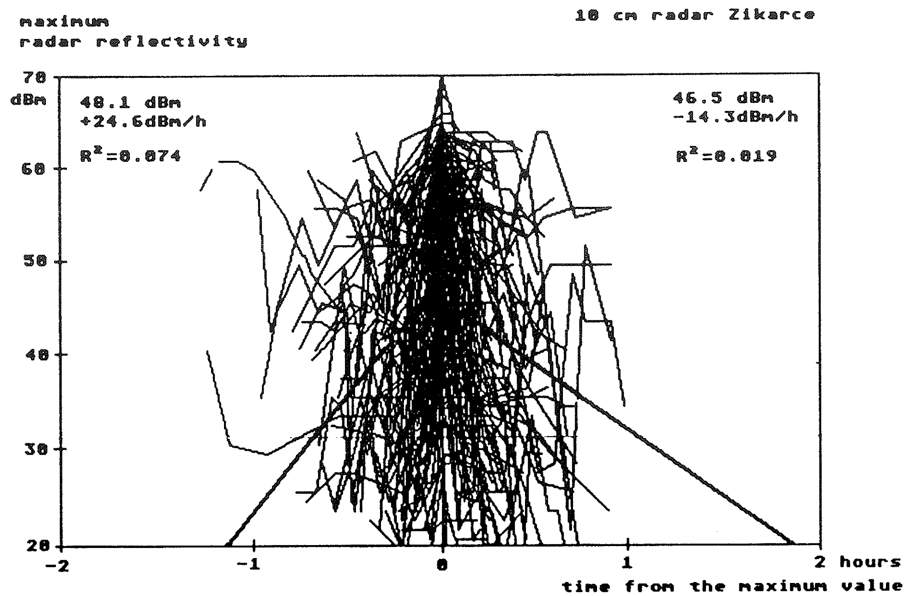



Figure 3: As Fig. 2, but measured with 5 cm radar (1985-86).
Slika 3: Kot Sl. 2, toda merjeno s 5 cm radarjem (1985-86).



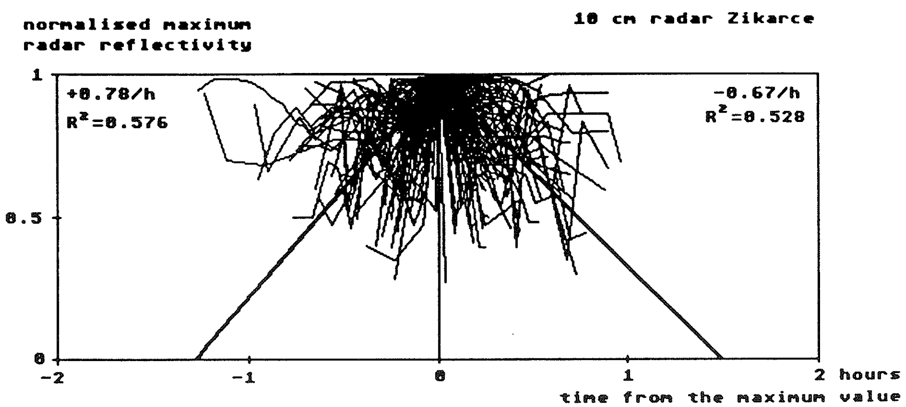




Figure 4: As Fig.1, but for maximum radar reflectivity.

Slika 4: Kot Sl. 1, toda za največjo radarsko odbojnost Zmax.



Table 2 presents the coefficients of determination $R^2$ and regression coefficients B according to the model $H=B(t-t_o)$. In this table the increase of a coefficient of determination is obvious (from the menitoned value of approx. 0.10 to values between 0.50 to 0.60 approx.) and the normalisation seems to be justified.

Table 2: Regression characteristics of normalised cloud variables 30 min before and 30 min after the maximum value ($R^2$ - coefficient of determination, B - regression coefficient)

Tabela 2: Regresijske karakteristike normaliziranih sprememnljivk, ki opisujejo oblake za čas 30 min pred in po tem, ko le-te dosežejo maksimum ($R^2$ - koeficient determiniranosti, B - regresijski koeficient).

| | before maximum value $R^2$ | B (1/30min) | after maximum value $R^2$ | B (1/30min) |
|---|---|---|---|---|
| a) 10 cm radar data Žikarce (1975-81) | | | | |
| H | 0.612 | +0.32/30min | 0.685 | -0.36/30min |
| D | 0.670 | +0.57/30min | 0.671 | -0.59/30min |
| H(Zmax) | 0.482 | +0.48/30min | 0.757 | -0.62/30min |
| Zmax | 0.576 | +0.39/30min | 0.528 | -0.34/30min |
| b) 5 cm radar data Lisca (1985-86) | | | | |
| D | 0.631 | +0.54/30min | 0.549 | -0.53/30min |
| Zmax | 0.604 | +0.26/30min | 0.578 | -0.30/30min |

In such a normalised presentation the intensity (height, size, solid and/or liquid water content, which is represented by radar reflectivity) of clouds have a more determined growth and decay. According to the t-test of differences all trends (all regression coefficients) are significantly different before and after the maximum - at the confidence level of 95%. So in spite of irregularities there is a quite well expressed growth and decay, and some characteristic time of growth or decay can be deduced from the data, as follows.

Cloud height: on average 32% of the maximum height is reached in the last 30 minutes before the average maximum, and 61% of the variance in this time interval can be attributed to the process of growth, and the same holds for decay (Fig. 1, for 10 cm radar data).

Cloud size (diameter): on average most (57%) of the growth occurs in the last 30 minutes and 67% of the variance can be attributed to the process of growth in time, and again very similarly for decay (Fig. 2 for 10 cm radar data). A somewhat similar growth is obtained for the smaller data set from the 5 cm radar (Fig. 3). The rate and the determination of decay are similar.

Analogous conclusions can be obtained by looking at the maximum radar reflectivity, representing the value of solid and/or liquid water content (Fig. 4 for 10 cm radar data set): here the average rate of growth is 39% in the last 30 minutes before the maximum is reached (and 26% for the smaller, 5 cm radar data set); similarly for decay. The determination is aprox. 50 - 60%.

What can we say as regards the position of the area with maximum solid and/or liquid water content? As can be deduced from the height of the maximum reflectivity zone, this also has some time evolution: on average it starts in somewhat lower layers, then it moves upwards and (with falling precipitation) agan decreasses towards the ground.

## 5. CONCLUSIONS

Radar data collected with two radar installations in two time periods (i.e. 10 cm radar for the 1975-1981 and 5 cm radar for the 1985-1986 period) were used for statistical examination of some characteristics of Cb-clouds in North-Eastern Slovenia. The data were collected for the operation of a non-randomized hail suppression project. This poses some restrictions on the quaility of the data set.

The climatology of the general weather conditions in which Cb develop is presented in Table 1. The main attention in this article was devoted to the time evolution of clouds. The time dependencies of the cloud variables height of the cloud H, diameter of the cloud cell D, height of the maximum radar reflectivity zone H(Zmax), and the value of maximum reflectivity Zmax (representing the position and the inensity of the solid and/or liquid water content in the cloud) were studied for this purpose. The different dynamics of individual Cb clouds (due to different macro- and meso-meteorological conditions), complicated micro-physical processes in clouds, etc. all cause the variables that have been studied to vary not only during the life cycle of the cloud cell, but also from case to case. Therefore the normalization was applied.

With this normalisation one can conclude that typically one third to one half of the maximum intensity of the cloud (height, diameter, solid/liquid water content) is achieved in the last half hour before the maximum is reached, and the decay from the maximum exibits approximately the same time rate. Between one half to three quarters of the variance can be attributed to the time process of growth or decay; the rest of the variance cannot be connected with time evolution.



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Remark: This paper was prepared for publication in 1990 and only revision and some editing was made for publication in 1994.

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