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RADAR EVALUATION OF BIG SPRING WEATHER MODIFICATION PROGRAM

FINAL REPORT
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mri **Technical Report**

RADAR EVALUATION OF BIG SPRING WEATHER MODIFICATION PROGRAM

MRI 75 FR-1380 and MRI 77 FR-1485

Submitted to
Texas Water Development Board
Post Office Box 13087
Austin, Texas 78711

Date 31 July 1977

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FOREWARD

The Colorado River Municipal Water District (CRMWD) has sponsored a cloud seeding operation to increase rainfall and, consequently, runoff into Lake J.B. Thomas and E.V. Spence Reservoir since 1971. This CRMWD weather modification effort was initially conceived as an operational project based upon the assumption that cloud seeding to increase rainfall can be effective. In 1973, the Texas Water Development Board, now a part of the Texas Department of Water Resources, was charged by the Weather Modification Act with a responsibility to promote research and development in the field of weather modification. An evaluation of the effectiveness of the CRMWD project was initiated by the Board.

The final report of that evaluation culminates three years of careful study of the seeding effects, as practiced by the CRMWD, on West Texas summertime convective clouds. Because of the wide interest in weather modification as a tool for augmenting dwindling water supplies, the report is made available in this format to satisfy the numerous inquiries that have been received about this promising new rainfall stimulating technique. The reported conclusions are those of the consulting firm performing the study and should not be construed as the views or policies of the Texas Department of Water Resources.

Effective September 1, 1977, Texas' three water resources agencies, the Texas Water Rights Commission, the Texas Water Quality Board, and the Texas Water Development Board, were consolidated to form the Texas Department of Water Resources. A number of publications prepared under the auspices of the precedessor agencies are being published by the Department of Water Resources. To effect as little delay as possible in production of these publications, references to these predecessor agencies will not be altered except on their covers and title pages.

Charles E. Nemir

Charles E. Nemir
Acting Executive Director

INTRODUCTION

Considerable interest in the evaluation of operational weather modification programs has been expressed within the State of Texas. At the heart of the interest is the ultimate development of state policies related to the use of weather modification as a water resources tool within the state.

In 1973 the Texas State Legislature appropriated funds to be administered through the Texas Water Development Board for an evaluation of the seeding program carried out near Big Spring by Atmospherics, Inc. for the Colorado River Municipal Water District. A report on this evaluation was prepared in draft form in November 1975. A final version appears as Volume I of the present report.

In 1975 funds were provided by the Texas Water Development Board to extend the evaluation study to a portion of the 1975 operational season. These funds were supplemented by the Atmospheric Water Resources Division, Bureau of Reclamation in order to expand the scope of the study. Monitoring and direction of the program, however, remained with the Texas Water Development Board. Results of the 1975 study are described in Volume II of the present report.

In view of the similarities between the two studies and the commonality in procedures and background information, the two reports have been bound together into one volume for final presentation purposes. In this way, each report maintains its own identity in terms of results and conclusions but yet the combined results of both studies are made available in a convenient form.

mri **Technical Report**

VOLUME I

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SUMMARY

An examination has been made of the seed and no-seed events carried out in the Big Spring area during the late summer of 1973 and from April to October 1974. An operational seeding program was carried out by Atmospherics, Inc. under sponsorship of the Colorado River Municipal Water District during this period. The principal evaluation tool was an M-33 radar loaned by the Bureau of Reclamation and located at Snyder. The radar, in conjunction with a raingage network, monitored the area rainfall during the seeding program. In order to examine the effectiveness of the seeding one-quarter of the candidate seeding events were left unseeded for comparative purposes.

The number of individual events during the program (36) was less than expected and insufficient to perform meaningful statistical comparisons of the characteristics of seeded and unseeded clouds. Instead, a case history approach was used. An examination of the individual seeding events indicated that approximately half of the events were treated in a manner where there was considerable doubt about the possible effectiveness of the seeding. In general, these events consisted of seeding peripheral cells around an existing rain center when the new, seeded cells frequently did not grow sufficiently for a seeding reaction to be possible.

The remaining events were seeded in a timely manner and showed evidence of changes in cloud structure which might be associated with seeding. The possibility of these changes resulting from natural variability could not be discounted, however.

Comparisons of cloud top heights, rainfall area, intensity and total cloud rainfall did not yield significant differences between seeded and unseeded events. A portion of this non-significance results from the nature of the seeded systems. All of these were associated with semi-organized cloud structures such as lines, cell sequences and large area developments. These types of systems have inherently greater natural variability and the problem of distinguishing seeded effects from natural variations is considerably enhanced.

An assessment of the total rainfall associated with seeding events indicated that only about 10 percent of the total rainfall in the area could be so related over the period of the evaluation program. Of this amount (approximately 280,000 acre-feet) only a portion is likely to have been caused by the seeding. In spite of this and because of the inherent value of the water, the seeding program might still be considered as an economic success.

Although significant results from the seeding program were not obtained, future operations in the Big Spring area and in other Texas locations should benefit from the information gained and attempts at systematic organization of the seeding results.

1. INTRODUCTION

Definitive evaluation of weather modification programs has been and continues to be an extremely challenging problem. Natural variations in rainfall productivity tend to obscure any effects which may result from advertent or inadvertent modification activities. Development and acceptance of operational weather modification techniques has been hampered by the difficulties involved in obtaining significant results from these evaluations.

Most attempts at definitive evaluations have been carried out within the framework of controlled research programs where potential benefits of the precipitation were considered to be a secondary factor. In spite of the favorable opportunities for evaluation due to optimal program design, the research programs have produced only a few examples of statistically significant results. Operational weather modification programs have generally been designed for maximum precipitation benefits and definitive evaluations have been even more difficult to obtain.

In 1973, the State of Texas, through the Texas Water Development Board, initiated a study of an on-going operational weather modification program. Purpose of the study was to aid in the establishment of state policies in regard to future weather modification activities in Texas. The particular program selected for study had been conducted in the Big Spring area during the summer months, beginning in the spring of 1971. Sponsor of the program was the Colorado River Municipal Water District (CRMWD), while the operations themselves were carried out by Atmospherics, Inc. The seeding program was designed to add run-off water to Lake J. B. Thomas and/or E. V. Spence Reservoir on the Colorado River.

In order to conduct the study within sound statistical design principles, it was necessary to afford a compromise between the dictates of a pure operational program and a research program. This compromise consisted of seeding only three-quarters of the available opportunities, with the remainder being left as unseeded comparisons. With this exception, the operational program was conducted by Atmospherics, Inc., in their normal manner.

The following report describes the evaluation study which was carried out in the late summer of 1973 and from April 15 to October 15, 1974. As a result of a wide variety of factors which are discussed in the following sections, the results of the study were not statistically significant in terms of precipitation increases. In more subjective terms, however, the study provided opportunities for examining the potential for cloud modification in the Big Spring area and generated assessments of some of the techniques involved. In addition, the study constituted an excellent preliminary source of data which will be of considerable benefit to the Hiplex program being initiated in the project area.

2. DESIGN OF THE STUDY

There are two principal factors involved in the design of an evaluation program. These are: (a) the statistical aspects of the design and (b) the measurement techniques.

2.1 Statistical Aspects

Many of the problems of evaluation of weather modification programs would be greatly minimized if it were possible to predict precipitation amounts accurately for specified days and for given cloud systems. Differences between predicted and observed precipitation amounts would then constitute a measure of the effectiveness of the seeding. The factors involved in accurate prediction of precipitation, however, are varied and diverse and their interrelated effects on precipitation are poorly understood on a quantitative basis. The classical method of handling this problem statistically is to randomize the seeding treatment so that the "uncontrolled" factors will appear equally in the treated and untreated cases.

Randomization has been used in the experimental design of most weather modification programs which are intended to be evaluated seriously. A selection procedure for a potential seeding event is established. Once the decision is made, a drawing takes place from a previously constructed set of randomized numbers or cards. These numbers or cards provide the seed or no-seed decision. In this manner, a proportion of the potential seeding events are reserved to observe the natural cloud developments.

Proportions of seed to no-seed cases vary from one project to another. Most frequently, a 1:1 seed to no-seed ratio has been used. The proportion, however, has ranged up to three seed cases for each no-seed case.

The primary objective of the CRMWD program was to increase rainfall over the Colorado River watershed. Evaluation of the program had to be considered a secondary role. A compromise of 3:1 seed to no-seed cases was therefore established between the desires for additional precipitation as against the statistical needs of the evaluation which would have dictated a 2:1 or 1:1 seed to no-seed ratio.

The technique for accomplishing the randomization was keyed, insofar as possible, to the seeding operator's standard treatment technique. Each wing of the aircraft was loaded with a set of 12 pyrotechnic flares. A number of dummy flares were manufactured by Colspan, Inc., which were, as nearly as possible, identical in appearance with the live flares. The flares were packaged in lots of 12 by MRI personnel and each lot labeled by number. The sequence of lot numbers to be used corresponded to a random set of numbers previously drawn. The pilot loaded two lots (one on each wing) for each seeding flight. Each lot (set of 12 flares) was available for use in one seeding event so that two separate events could be carried out before reloading. The pilot was free to use as many of the 12 flares as desired during one event. Unused flares were removed from the wing after each flight and repackaged in lots of 12 for future use. Each flare contained 18 g of AgI with a burning time of about 8 minutes.

A separation of 25 miles was required between individual events during the same flight in order to maintain distinct patterns from the two events. This separation requirement constitutes the major constraint imposed on the operator by the evaluation requirements. In all other parts of the seeding operation (with the exception of the no-seed events), the intention was to allow the operator to conduct the seeding activities in his normal fashion. In this manner, it was hoped that the evaluation would include the influence of the operator's skill which has presumably been acquired over a considerable period of time.

For the 1973 portion of the program, dummy pyrotechnic flares were obtained from Colspan, Inc., in which the silver iodide (AgI) content was replaced principally with potassium iodide. The flare burning characteristics were not changed appreciably, but the flame color was markedly different. This enabled the pilot to recognize the presence of a dummy flare but only after the decision had been made for the conduct of a seeding event.

Subsequent to the 1973 season, six of the dummy flares were sent to Colorado State University (CSU) for an evaluation of their nucleation activity. Results from the CSU tests showed a very wide range in nucleation ability for the dummy flares. The highest observed activity produced 10^{12} nuclei per gram of component (referenced to AgI). Most of the dummy flares tested showed much less nucleating ability. This maximum value is about one to two orders of magnitude less than the corresponding AgI flare. Calculations based on burning rate, seeding location, etc., indicate that 10^{12} nuclei per gram would produce about one ice nucleus per liter effective at -20°C within the cloud. This corresponds very closely to the background levels which have been consistently measured in the atmosphere. Seeding treatments are designed to increase the ice nuclei levels by a factor of 10-100 over background values.

In spite of the low values of nucleation activity and primarily because of the wide variations from one flare to another, the dummy flares were changed for the 1974 season. For this season, Colspan, Inc., manufactured inert flares of the same size, shape, and weight as the AgI flares. Electrical firing wires were attached in the same manner as the standard flares but no ignition occurred. This lack of ignition was obviously apparent to the pilot from his observational vantage point. Although he knew that dummy flares were being used after ignition, he was not in a position to determine this information prior to the definition of the seeding event. As a consequence, the integrity of the decision to seed in a particular situation without prior knowledge of the randomized seeding process was maintained.

2.2 Measurement Techniques

The basic design of an evaluation program required that precipitation from the treated and untreated clouds be measured as quantitatively as possible. Evaluation of the seeding may be in terms of total precipitation in the project area or as rainfall from individually treated and non-treated cells. The high degree of spatial variability in summer rainfall makes it relatively uneconomic to measure this precipitation solely by surface raingages. Gage densities of the order of one per square mile would be required throughout the area to obtain a reasonable resolution of precipitation amounts. Radar has been used in several weather modification programs to give quantitative estimates of rainfall amounts. Radar-returns from the precipitation are converted by means of an assumed drop-size distribution into rainfall intensity. Time histories of the radar derived intensities yield the total precipitation at a fixed point in the area or for a particular cell. The radar's advantages are excellent spatial and time coverage. The disadvantages result from the need to assume a drop-size distribution, from the occurrence of hail and from occasional cases of anomalous propagation. In spite of these disadvantages, the value of the radar is considerable, and the decision was made to use this tool as the primary precipitation measurement system for the Big Spring program.

The radar used in the evaluation study was a modified M-33 on loan from the Bureau of Reclamation. The 10 cm portion of the set utilized a 15-foot circular antenna which produced a 1.5° beam width between half-power points. In actual operation, the antenna completed one revolution each five-minutes at an elevation angle of 2° above the horizon. The 3 cm portion of the M-33 was operated manually to obtain radar cloud tops for clouds of interest. Return signals from the 10 cm set were recorded on video tape in analog form for subsequent processing.

The radar was located at Snyder (Fig. 1) on the eastern edge of the project area. Area coverage by the radar extended to about 50 nautical miles (nmi) radius. This covered most of the project area and, in addition, permitted some coverage in the downwind area of cloud systems which had been seeded in the project area. The operational center for the Atmospherics, Inc., radar and aircraft was at the Big Spring airport. Radio communication was maintained between the two radar sites and the aircraft.

A raingage network was located within the project area. During the 1973 season 12 recording gages were set up in the area. The number was increased to 36 in the 1974 season. These gages were arranged in twelve clusters of three gages per cluster. Each cluster was arranged in the form of a triangle with one km spacing between gages. Locations of the 12 clusters are shown in Fig. 1.

Primary purpose of the raingage clusters was to obtain calibration between the radar-derived rainfall amounts and corresponding raingage values. It was believed that the rainfall on the ground could be measured more accurately in a small area by clusters of gages than by a uniformly spaced gage system with larger spacing between gages. Although it was recognized that the number of useful comparisons between radar and raingage precipitation amounts would be reduced by use of the cluster system, it was hoped that the comparisons obtained would be more representative of area rainfall values.

In addition to the recording gages, CRMWD operated a network of 55 fencepost gages. Locations of these are shown in Fig. 1. The gages were read as early as possible on the morning of each day following a significant rain event in the area.

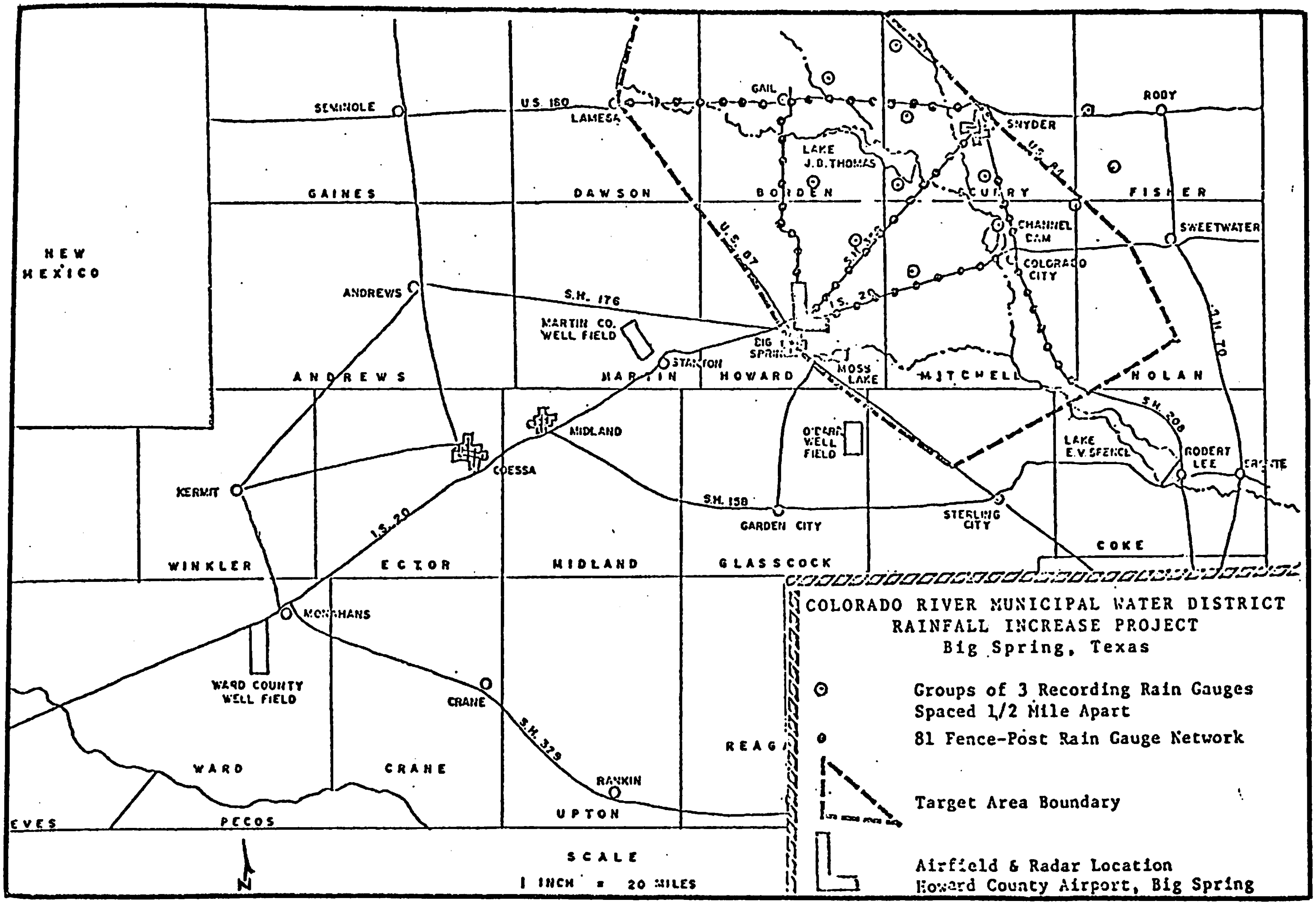

Figure 1. Location of raingage network

3. THE EVALUATION PROBLEM

There are numerous fundamental problems related to the evaluation of weather modification projects. Although it is tempting to consider a program which relates "seeded" versus "unseeded" storms, in practice summer convective rainfall, in particular, cannot be treated as simply. Two general types of problems exist. These fall into the categories of measurement problems and conceptual ones. It is useful to have a perspective on these problems during the discussion in the following sections.

3.1 Measurement Problems

Principal among the measurement difficulties is an accurate determination of rainfall amounts. Once the commitment is made to utilize radar as the main measurement tool, the possible errors involved must be kept in mind.

a. Conversion of the radar reflectivity (Z) into rainfall rate (R) requires the assumption of a specific Z-R relationship. Z-R relations have been measured extensively at many sites. Significant variations are found to exist from site to site and from storm to storm. This represents a fundamental source of uncertainty in indicated rainfall amounts which restricts the capability for detecting seeding effects. Efforts have been made to minimize this uncertainty by optimum combinations of raingages and radar measurements. The analysis of the Big Spring data has not yet been carried to this level of data treatment.

b. Operation of the radar at low elevation angles (2° elevation) inevitably produces occasional ground return ("ground clutter"). This results from power radiated at angles beyond the nominal 1.5° beam width of the antenna. The ground clutter is localized in specific areas around the radar site but can increase substantially if the ground is wet. Precipitation echoes in these areas may be indistinguishable from the ground return.

c. Propagation of the radar signals can be affected by strong air density gradients (anomalous propagation).

Typical effects are a downward bending of the radar beam which may result in increased ground clutter or a focussing of the beam so that a precipitation area may return abnormally strong signals.

d. The presence of hail in the radar beam increases the reflectivity values obtained by the radar substantially. These are erroneously interpreted as high rainfall rates unless the existence of hail is suspected.

3.2 Conceptual Problems

Evaluation of a weather modification program requires some forehand expectation of the potential effects of the seeding. The possibilities, however, are quite numerous and complex so that it is not unreasonable that a possible effect of the seeding might be overlooked. A typical complication is the maximum time interval between seeding and any potential effect of the seeding. Models and physical hypotheses do not include an understanding of these possible residual effects. An additional and frequent problem is the absorption of the seeded cell into a larger system and the difficulties in determining the effect of the seeding on the total system.

Some of the potential results from seeding are as follows:

a. A change in total precipitation from the seeded clouds. For the larger (already precipitating clouds) this generally requires an increase in the vertical depth of the cloud.

b. A change in the intensity of the precipitation. This might result from a more efficient precipitation mechanism.

c. An increase in the precipitation area. An increase in the size of the area might be realized without simultaneous increases in intensity or cloud depth.

d. Extended lifetime of the cloud system. Seeding might be carried out to generate or reinforce a propagating sequence of cloud developments.

e. Residual effects. Seeding might result in ice particles becoming available for subsequent cloud developments so that the end of the seeding effect is not easily defined.

All of these problems are inherent in the evaluation of weather modification projects and become limiting factors in the evaluation unless the seeding effects are so large that they can be detected with a simple statistical treatment. This has not proven to be the case in the Big Spring program.

Evaluation of an on-going operational program creates additional problems of a unique nature. Some of these are:

a. It is not generally possible for one aircraft to cover an area as large as the CRMWD project in terms of treatment of all available cells. As a consequence, many of the storm systems (or portions thereof) are untreated and should not be expected to show seeding effects.

b. Seeding in the CRMWD area was concentrated near the reservoirs regardless of the possible existence of more favorable conditions elsewhere in the area.

c. Operational seeding differs from a research program in that treatment of many cells is required. It generally does not permit careful selection of only those where the seedability may be pronounced. Consequently, a number of cases of low seeding effectiveness should be anticipated.

d. Operational seeding for reservoir runoff dictates that the larger storm systems be given preferred attention. In general, these are the more complex systems and the effects of seeding are difficult to detect within the natural variability of the system.

4. RADAR DATA REDUCTION

Data from the radar at Snyder were returned to Altadena in the form of video tapes of the analog radar signals. These tapes were then fed into a Biomation A/D converter which converts the radar original into 1000 bins of information each representing 150 m distance along the radar beam. The output from the A/D converter is fed into a PDP-8 computer which averages 16 successive radar pulses in each of the storage bins and records the time averages on magnetic tape. These second tapes are then processed to formulate a field of Z (reflectivity) values corresponding to the horizontal sweep through the cloud.

Fig. 2 shows an example of a horizontal field of Z-values. This figure represents only a portion of the field-of-view of the radar in accordance with the azimuth and range values shown. At the scan speed used in 1973-74 this same area would be scanned every five minutes. Letters in the figure refer to coded values of Z (in dbz and range-corrected) as shown in the table on the figure. Each letter represents an average reflectivity value over 150 m in range with an angular distance as indicated by the vertical coordinate. Z-values for every third range bin only are shown in Fig. 2 in order to make the display more compact. Intermediate values are available for areal computations of total rainfall, however.

Determination of the Z-values as shown in Fig. 2 requires calibration of the radar set in terms of absolute reflectivity values. Difficulties were encountered in calibrating the 10 cm radar with standard target techniques due to the limited elevation drive existing at that time. To achieve an absolute calibration of the 10 cm set, the 3 cm radar and the 10 cm radar were operated together, measuring a precipitation area of relatively uniform reflectivity. A previous sphere calibration of the 3 cm radar was then used to determine the absolute calibration of the 10 cm set. Internal calibration of the 10 cm radar was carried out at least once each day during the 1973 and 1974 seasons.

Following calibration of the Z-values, these have to be interpreted in terms of rainfall rate. Over a period of years and a large number of observations, an average relationship between Z and rainfall rate (R) has been determined. This relationship is based on the Marshall-Palmer distribution of raindrop size vs. number. The corresponding Z-R relation for converting Z-values to rainfall rate is given by:

$$R = .0365\, Z^{.625}$$

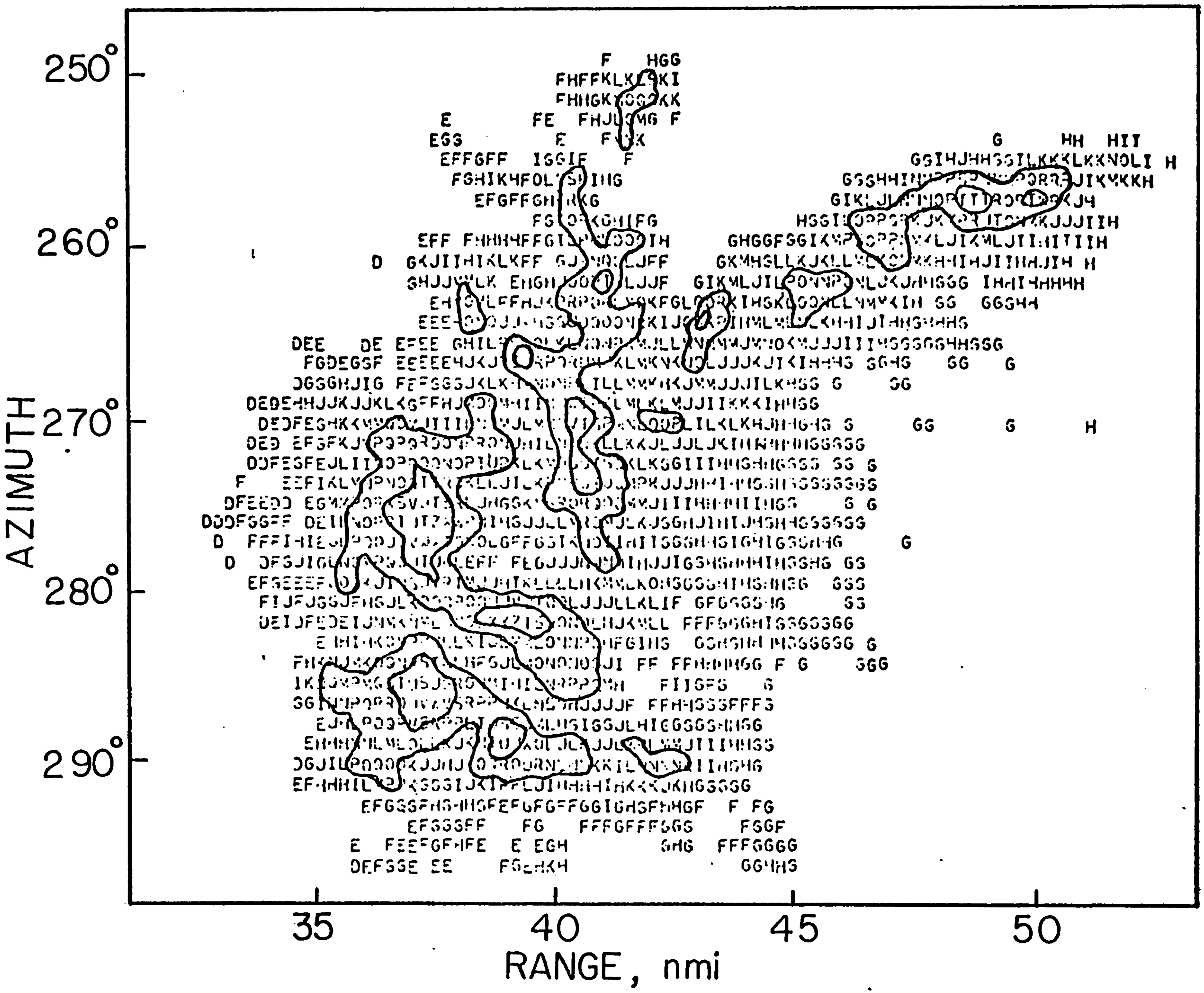

Figure 2. Horizontal radar-rainfall plot

When R is given in mm/hr and Z is in units of mm^6/m^3. The relationship between these units of Z and dbz is as follows:

$$Z\,(mm^6/m^3) = \text{antilog}\,\frac{dbz}{10} \quad .$$

Numerous attempts have been made to use radar measurements quantitatively. A leader in this effort has been the National Severe Storms Laboratory [Brandes, 1974]. A Marshall-Palmer rainfall distribution was assumed and radar-derived rainfall amounts were compared with simultaneous raingage values. Efforts focussed on techniques for adjusting the Z-R conversion based on observed raingage values which served as calibrations for the Z-R relationship. Significant storm-to-storm variations were observed which were partly attributed to propagation effects.

The Bureau of Reclamation [Takeuchi, Peace and Howard, 1975] supported an investigation involving the NSSC radar and nearby raingages to determine the effect of varying raindrop size distributions on the appropriate Z-R relations. Important variations in drop-size distribution were measured by aircraft which significantly affected the Z-R relation.

The Experimental Meteorology Laboratory of NOAA in Miami has also carried out Z-R comparisons to determine the optimum technique for converting radar data to rainfall amounts [Woodley, Olsen, Herndon and Wiggert, 1974]. For the Miami area it was concluded that the appropriate Z-R relation was given by:

$$R = .017\,Z^{.714}$$

which shows a considerable variation from the Marshall-Palmer relation.

Radar data obtained during the Big Spring program (e.g., Fig. 2) were first converted to rainfall amounts using the standard Marshall-Palmer relation. Subsequently, during the 1975 summer airborne raindrop size distributions were obtained by the MRI Navajo aircraft as a part of the Bureau of Reclamation Hiplex Program. Although there were sizable differences in the measured Z-R relations (four flights) the approximate average relation obtained was:

$$R = .025\,Z^{.62}$$

This relation represents lower rainfall values for a given radar reflectivity than given by the Marshall-Palmer relation. On the other hand, the Miami Z-R relation gives considerably higher rainfall values for a given reflectivity than the Marshall-Palmer relation. In view of the possibility of characteristic local Z-R relations, it was decided to use the observed Big Spring Z-R relation for conversion of the radar data into rainfall amounts. A comparison of rainfall rates derived from the Marshall-Palmer relation compared to the Big Spring relation is shown in Table I:

TABLE I. COMPARISON OF RAINFALL DERIVED FROM MARSHALL-PALMER VS. BIG SPRING Z-R RELATIONSHIPS

Display Code	dBZ	Marshall-Palmer R	Big Spring R
F	35	5.62 mm/hr.	3.70 mm/hr.
J	39	9.99	6.55
N	43	17.77	11.59
R	47	31.61	20.51
V	51	56.21	36.30
Z	55	99.95	64.26

Data in the table give an example of the variations in rainfall estimates which can be attributed to assumed Z-R relations. It is, of course, probable that Z-R relations are not only site dependent but may vary in different stages of an individual storm's development.

A further evaluation of the Z-R relation is shown in Fig. 3. Radar-derived rainfall values (summed over one-hour intervals) at specific gage cluster locations have been compared with the average hourly gage amounts determined from the three gages in the cluster. Good comparisons of this

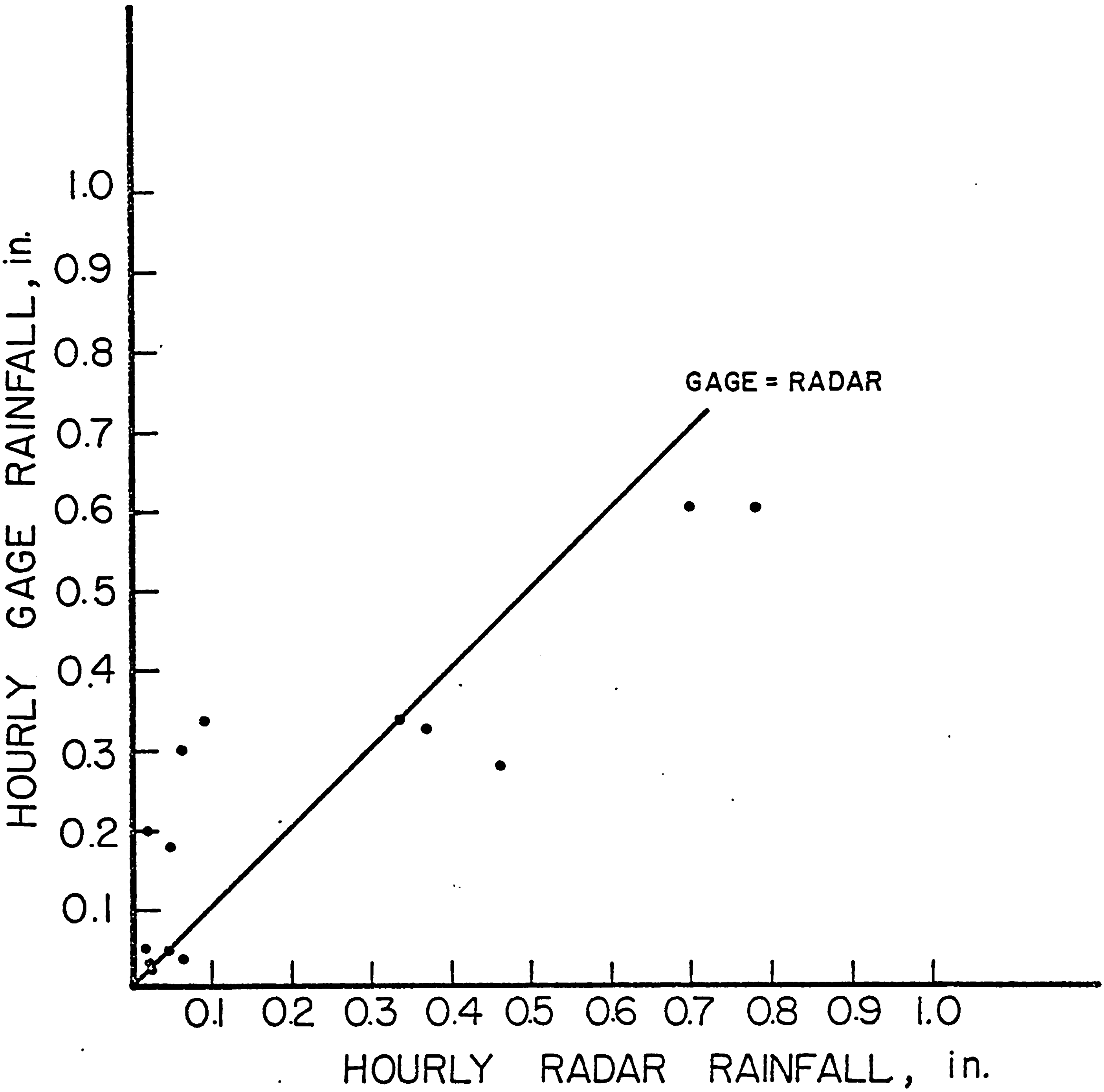

Figure 3. Comparison of Radar and Gage Measurements

type are infrequent. In many cases, the edge of the cell may pass over the gage system and the portion of the radar echo actually affecting the cluster may be in some doubt. Wind shears and evaporation below cloud base can contribute significantly to errors in the radar-raingage comparison. Results shown in Fig. 3 suggest a reasonable agreement between radar and raingage rainfall amounts and illustrate the variability in the estimates which can be expected.

Each horizontal radar section through the area of interest (e. g., Fig. 2) was processed in a similar manner. Bin data (Z-values) were converted to the appropriate rainfall value and areas associated with each bin were calculated by the computer. Total acres in the storm system and total acre-feet per hour were then printed out for each horizontal section. Fig. 4 shows the time history of the acre calculations and the corresponding acre-feet/hour values determined for the observed lifetime of Event No. 2 on August 31, 1973. Similar plots for each event were made for all valid radar data. These plots form the basis for much of the discussion in the following sections.

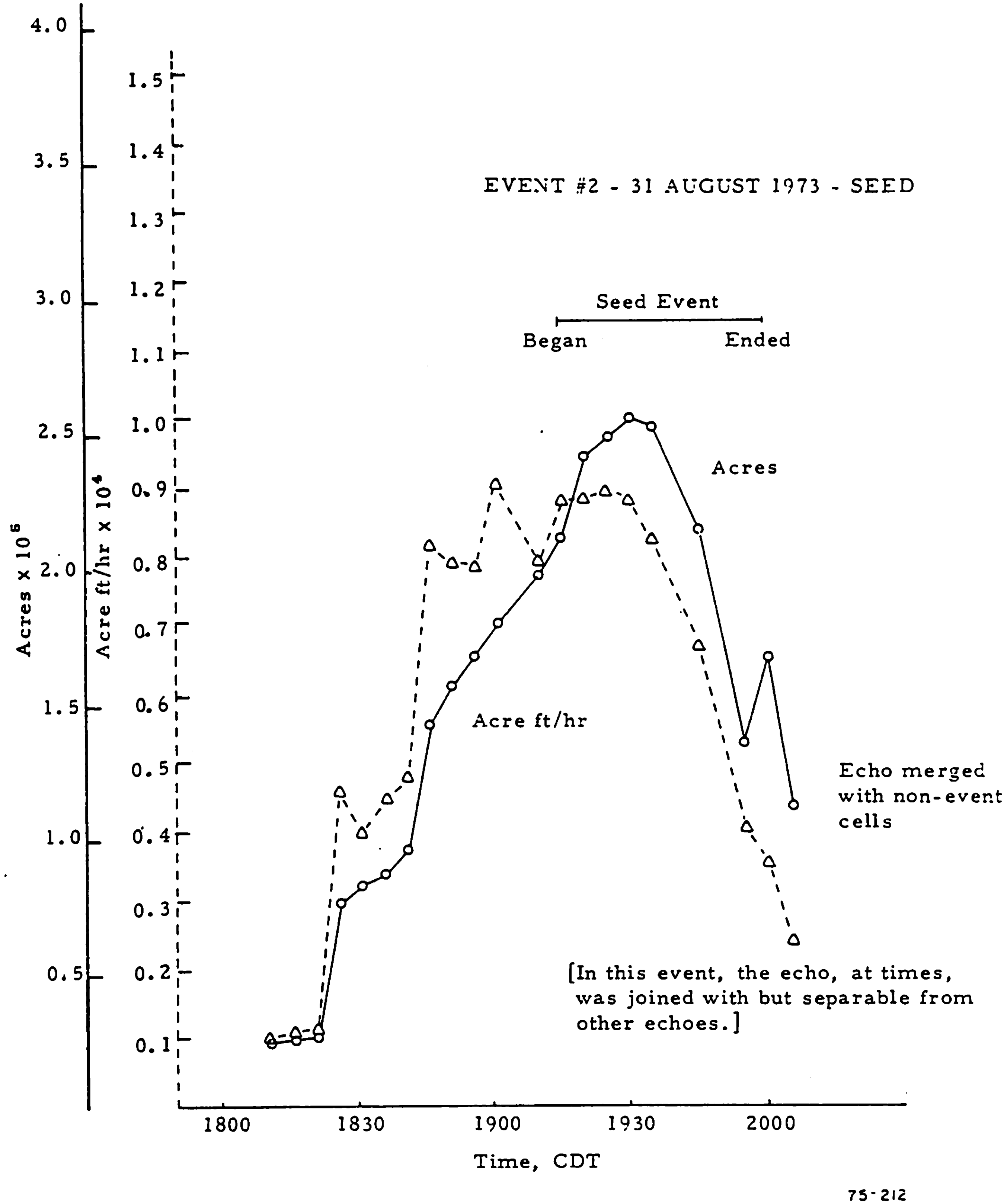

Figure 4. Time history of radar rainfall, 31 August 1973

5. OPERATIONS SUMMARY

A summary of the dates of the seeding events in 1973 and 1974 is given in Table II together with times, seed or no-seed decisions and amounts of silver iodide used. A total of 36 events were designated during the two summer seasons. The total of 10 events in 1973 resulted from a starting date of the program after August 16, 1973.

Preliminary processing of the radar data was carried out for all 36 events. In several cases, however, the radar-derived rainfall values did not prove to be useful in terms of evaluation. In some cases, the echo of interest was masked by ground return so that no quantitative values could be obtained. In a few other cases, the seeding event quickly merged into a larger storm system and became indistinguishable. In addition, on July 12 and 15, 1974, the seeded cells dissipated rapidly shortly after seeding as a result of a general decline in convective activity. All of these cases have been marked with asterisks in Table II. Rainfall time-histories for the remainder of the cases were obtained in the form shown in Fig. 4.

Designations as 6a and 6b for event numbers in Table II signify that the same cloud system was seeded more than once in its life history. On other occasions, if two or more different event numbers are shown on the same day, these have been assigned separate event numbers in accordance with the experiment design which permitted separate seeding events if the seeded areas were at least 25 miles apart.

TABLE II. SUMMARY OF SEEDING EVENTS

Year	Event Number	Date	Time	Seed Decision	Amount of AgI
1973	1	August 31	1650-1715 CDT	Seed	54 g
	2	August 31	1914-1959	No-Seed	---
	3	September 1	2010-2043	Seed	72
	4	September 4	1830-1915	No-Seed	---
	5	September 4	1918-2013	Seed	173
	6a	September 12	1639-1708	Seed	90
	6b	September 12	1810-1847	Seed	82
	7	September 12	1714-1751	Seed	90
	8**	September 12	1935-2020	Seed	154
	9*	September 21	1627-1712	Seed	108
	10**	October 10	2034-2135	Seed	190
1974	1*	April 18	1715-1857 CDT	Seed	144 g
	2*	April 21	1425-1502	Seed	90
	3	April 27	0055-0125	No-Seed	---
	4*	April 28	2340-0055	Seed	180
	5	May 9	1520-1554	No-Seed	---
	6a	May 9	1600-1635	Seed	90
	6b	May 9	1640-1654	Seed	36
	6c	May 9	1703-1738	Seed	90
	7	May 25	1705-1743	Seed	180
	8a	May 25	2015-2030	Seed	36
	8b	May 25	1950-1957	Seed	18
1974	9	June 1	2255-2330 CDT	No-Seed	---
	10*	June 11	1943-2035	Seed	126 g
	11	June 12	1834-1900	Seed	72
	12	July 3	1910-2015	Seed	162
	13***	July 12	1553-1635	No-Seed	---
	14***	July 15	1917-1940	Seed	54
	15a	July 17	1538-1600	Seed	72
	15b	July 17	1608-1630	Seed	54
	16	July 26	1945-2014	Seed	72
	17**	August 9	1710-1814	No-Seed	---
	18a	August 10	1550-1621	Seed	126
	18b	August 10	1641-1714	Seed	90
	19**	August 10	1723-1806	Seed	198
	20*	August 10	1852-1942	Seed	90
	21	August 24	1635-1700	No-Seed	---
	22	August 26	1323-1433	Seed	308
	23	August 27	1530-1620	Seed	254
	24	August 28	1625-1651	No-Seed	---
	25	August 28	1850-1930	Seed	108
	26a	August 29	1342-1415	Seed	108
	26b	August 29	1422-1442	Seed	146
	26c	August 29	1453-1514	Seed	54

* - Echo in ground return   ** - Echo merged with nearby cell or not identifiable   *** - Cells dissipated shortly after seeding.

6. EVENT CHARACTERISTICS

Characteristics of the various seeding events in 1973 and 1974 are shown in Table III. Seeding was generally carried out about 500 feet below cloud base. The seeding altitudes shown in the table consequently can be interpreted as approximate cloud bases if 500 feet is added to each of the given values.

Maximum cloud tops were observed with the MRI radar at Snyder. Comparisons between the MRI and AI observations indicate that the AI cloud top heights tended to be several thousand feet higher than simultaneous measurements with the MRI radar. It is generally recognized that radar cloud tops usually overestimate actual cloud conditions due to the finite width of the radar beam. This error is a function of range from the radar and may amount to about 2500 feet at a distance of 30 miles. Corrections for this effect have not been incorporated in the data in Table III.

Speeds and directions of cell movements were obtained wherever possible from tracks of echo centers after processing into quantitative reflectivity form. In some cases, tracking of a specific reflectivity center over a period of time was questionable due to the development of new growth centers or the lack of well-defined centers of activity. The directions and speeds of movement therefore represent best estimate values.

Data on cell movement show a strong preponderance of motion toward the southeast (northwest wind). Almost half of the observed cases showed evidence of movement in this direction. From the standpoint of organization, the data in Table III indicate that line organization occurs predominantly with higher wind velocities and translational speeds. Most (but not all) of the observed lines were oriented in a NE-SW direction and were moving to the SE. Single cells and organized clusters of cells occurred most frequently with light winds.

TABLE III. CHARACTERISTICS OF SEEDING EVENTS

Event No.	Date	Time	Seeding Alt (msl)	Max. Top Seeded	Cell Movement Toward	Speed	Comments
1	8/31/73	1650-1715 CDT	----	-- K ft	NE	18 mph	NE-SW line
2	8/31/73	1914-1959	----	31	NE	40	NE-SW line
3	9/1/73	2010-2043	7500 ft	39	WSW	8	Single cells
4	9/4/73	1830-1915	7500	29	SE	35	NE-SW line
5	9/4/73	1918-2013	8000	37	SE	22	Cluster
6a	9/12/73	1639-1708	7000	44	SE	26	Single cells
6b	9/12/73	1810-1847	7000	48	SE	25	Single cells
7	9/12/73	1714-1751	7000	47	SE	26	NE-SW line
8	9/12/73	1935-2020	7500	--	ESE	23	NE-SW line
9	9/21/73	1627-1712	7000	45	E	12	Cluster
10	10/10/73	2034-2135	9000	--	NE	34	N-S line
1	4/18/74	1755-1857 CDT	9500 ft	38 K ft	NW	5	Cluster
2	4/21/74	1425-1502	7500	47	NE	--	NE-SW line
3	4/27/74	0055-0125	7500	24	ESE	22	NE-SW line
4	4/28/74	2340-0055	5500	20	ENE	--	Cluster
5	5/9/74	1520-1554	6500	37	E	14	Single cells
6a	5/9/74	1600-1635	7500	39	E	12	Cluster
6b	5/9/74	1610-1654	7500	--	ENE	10	Cluster
6c	5/9/74	1703-1738	7500	38	NW	12	N-S line
7	5/25/74	1705-1743	7500	47	SE	22	Cluster
8a	5/25/74	2015-2030	7500	26	SE	40	NE-SW line
8b	5/25/74	1950-1957	7500	41	SE	24	NE-SW line
9	6/1/74	2255-2330	6500	36	SE	36	NE-SW line

Event No.	Date	Time	Seeding Alt (msl)	Max. Top Seeded	Cell Movement Toward	Speed	Comments
10	6/11/74	1943-2035 CDT	10,500 ft	35 K ft	SE	35 mph	NE-SW line
11	6/12/74	1834-1900	7,500	53	SE	10	Cluster
12	7/3/74	1910-2015	9,000	30	SE	20	NE-SW line
13	7/12/74	1553-1635	6,500	--	--	--	Single cells
14	7/15/74	1917-1940	11,000	--	--	--	NNW-SSE line
15a	7/17/74	1538-1600	8,500	36	SW	8	Single cells
15b	7/17/74	1608-1630	8,500	--	SW	12	Single cells
16	7/26/74	1945-2014	10,500	28	SW	20	Single cells
17	8/9/74	1710-1814	9,500	46	--	--	NE-SW line
18a	8/10/74	1550-1621	9,000	45	SE	10	Cluster
18b	8/10/74	1641-1714	8,500	40	SE	10	Cluster
19	8/10/74	1723-1806	8,500	43	SE	12	Cluster
20	8/10/74	1852-1942	9,000	46	SE	12	Cluster
21	8/24/74	1635-1700	5,500	38	NNW	20	Cluster
22	8/26/74	1323-1433	5,500	29	N	6	Cluster
23	8/27/74	1530-1620	6,500	29	NNE	12	NE-SW line
24	8/28/74	1625-1651	5,500	--	SE	8	Single cells
25	8/28/74	1850-1930	5,500	18	SE	8	Cluster
26a	8/29/74	1342-1415	4,500	37	E	10	Single cells
26b	8/29/74	1422-1442	4,500	35	E	5	NE-SW line
26c	8/29/74	1453-1514	4,500	--	N	5	NE-SW line

7. RESULTS OF EVALUATION

7.1 Timing of Seeding

Effective modification of cumulus clouds requires that the treatment be carried out within a relatively short period during the lifetime of the cloud. Effects of the silver iodide occur only after the material has reached the -5°C level in the cloud (10,000 to 15,000 feet above cloud base in the Big Spring area). Significant precipitation growth then occurs only if the updraft continues to supply moisture for a reasonable period of time after ice nucleation has taken place. About 5-10 minutes are then required for the precipitation particles to fall to the levels being sampled by the radar beam. Based on these concepts, at least 15 minutes of updraft is required from seeding at cloud base to the growth of substantial precipitation in the cloud. After 20 minutes or more it should be expected that the effects of the seeding might be apparent in the radar plots (e.g., Figs. 2 and 4). These estimates are in agreement with Simpson (1970) who calculates that a marked precipitation increase due to seeding can be expected to appear in radar observations within 10 minutes after seeding. Differences in the time estimates reflect seeding from falling pyrotechnics in Simpson's case in contrast to seeding from cloud base in the Big Spring area. In the Big Spring case, time to travel from cloud base to nucleation levels amounts to around 10 minutes.

The lifetime of many cumulus updraft areas is of the order of 20 minutes although continued updrafts of one to one-and-a-half hours may occur in larger propagating systems. If the updraft lasts for only 20 minutes, however, time of introduction of the material into the updraft at cloud base is a critical factor. Recognition of the updraft has to be accomplished early enough so that sufficient time remains for travel to the nucleation zone and subsequent precipitation growth. Late recognition of the updraft area can result in ineffective seeding.

Examination of the individual seeding cases for 1973-74 at Big Spring indicated that this problem was prevalent on a number of occasions. Two types of situations were observed. In one type the updraft turned out to be sporadic and short-lived, i.e., the cloud system did not become properly organized. Seeding of these cases is ineffective since there is insufficient time for precipitation growth in the updraft lifetime. In the second (and most frequent) situation, seeding was carried out in a well-organized updraft area but was started too late in the life history of the updraft to accomplish precipitation growth. In some of these cases the seeded cell was on the periphery of a larger storm area and the seeded cell was overcome by the general collapse of the main storm system so that its lifetime was shortened substantially.

All of the seeding events during 1973-74 were examined individually for evidence that the lifetime of the seeded cell was sufficient to permit significant precipitation growth. Generally this required at least 15 minutes of coherent updraft after start of the seeding or at least 20 minutes from the start of seeding to peak radar rainfall. The most definitive information came from time-histories of radar data (e.g., Fig. 4). Updraft reports from the seeding aircraft were also invaluable in estimating the amount of time available for the seeding material to affect precipitation growth.

Figs. 5-7 show several examples of the various relationships observed between seeding intervals and the timing of the cloud developments. In Fig. 5 the seeding began at cloud base a few minutes after peak rainfall intensity had been observed. The short interval of seeding (15 minutes) reflects the short duration of the updraft following initiation of the seeding. Under these conditions there is little chance that the seeding could have been effective in the cloud.

In contrast, Fig. 6 shows that the seeding began about 15 minutes before a marked increase in precipitation intensity and 30 minutes before peak intensity. Although it is not implied that the seeding necessarily caused the change in precipitation intensity, the cloud developments were such that the seeding material should have reached the proper levels in the cloud and <u>could</u> have influenced the precipitation process. The early stages of the evaluation analysis have focussed on segregating those cases where there was some reasonable possibility of seeding influence from those (e.g., Fig. 5) when there was little likelihood of seeding effect.

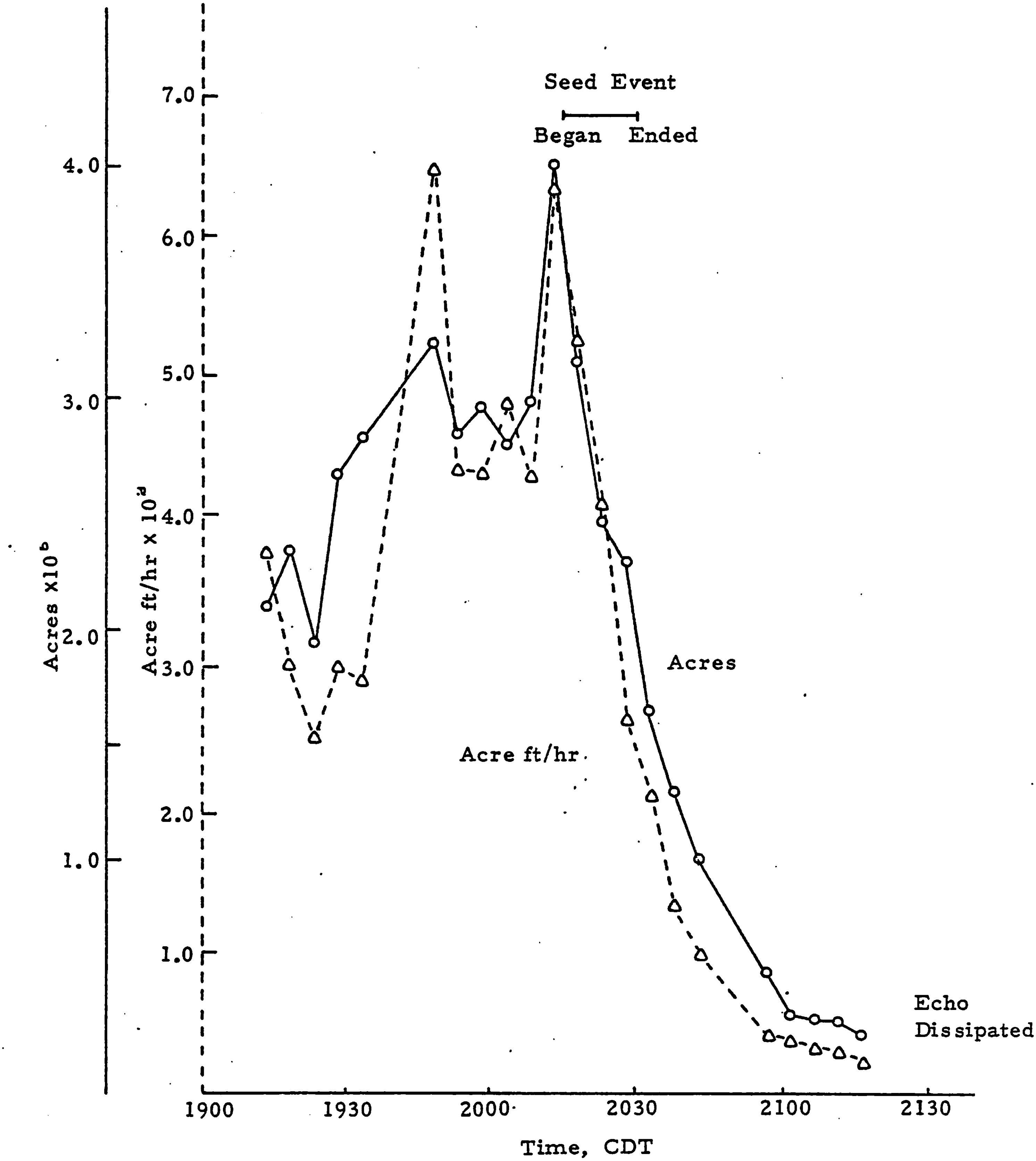

Figure 5. Time history of radar rainfall, 25 May 1974

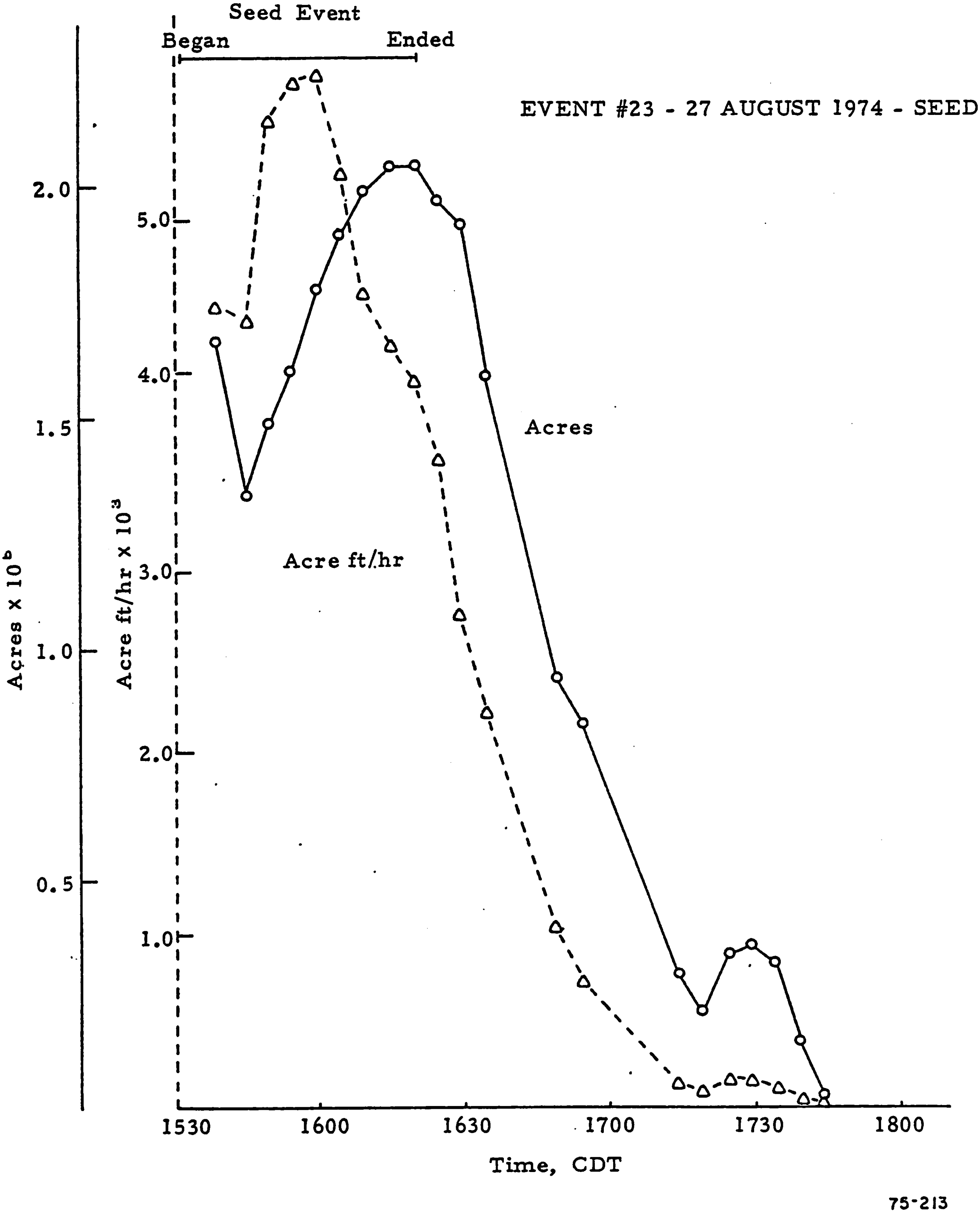

Figure 6. Time history of radar rainfall, 27 August 1974

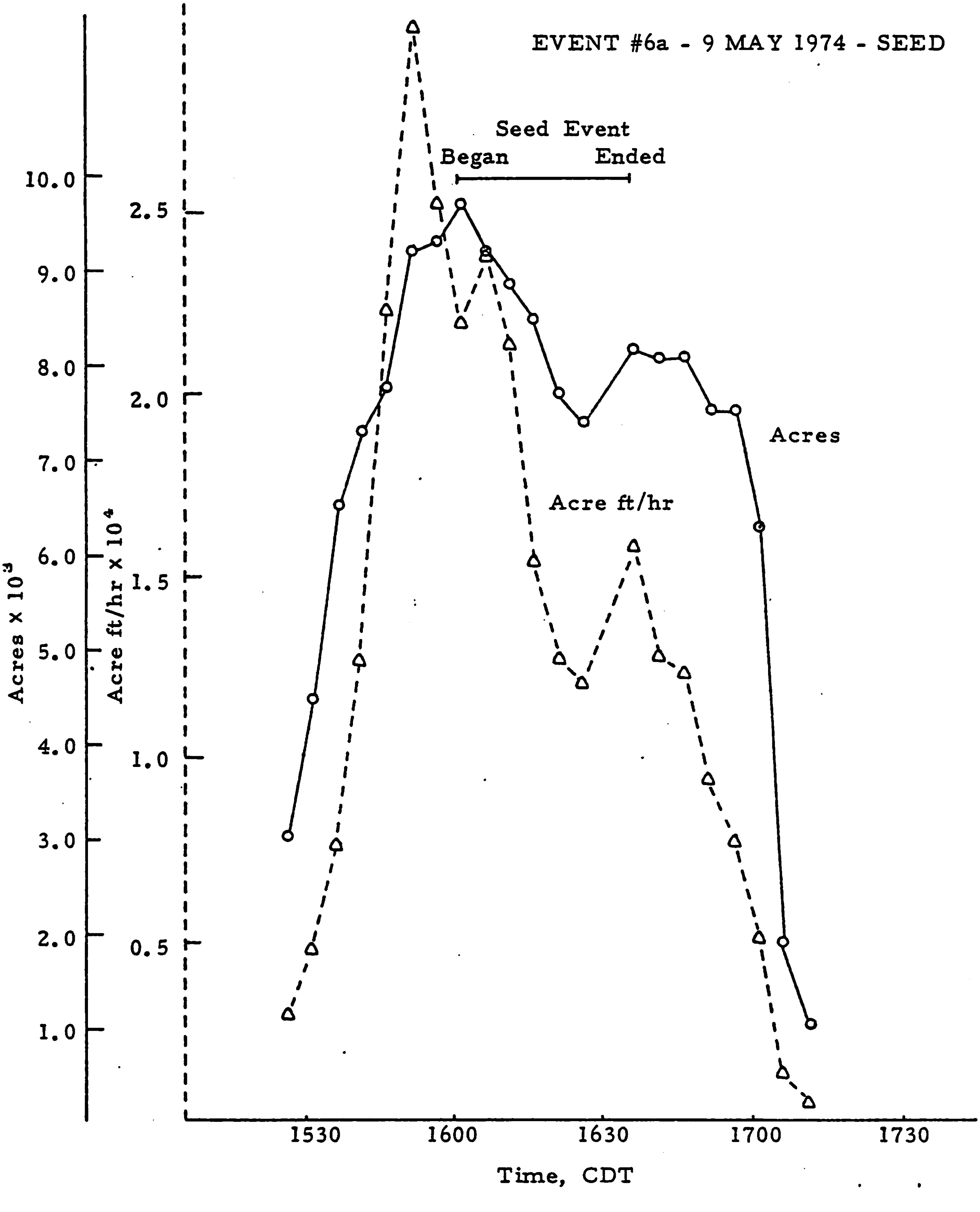

Figure 7. Time history of radar rainfall, 9 May 1974

Fig. 7 shows a somewhat more complicated case where there were two major cell developments involved. As shown in the figure, the seeding commenced about 10 minutes after the peak intensity associated with the first development. The seeding, however, was carried out in a timely manner with respect to the second development and could have influenced this portion of the system. This case serves to illustrate two features in the evaluation analysis. This pattern of seeding the second or third development in the storm sequence (rather than the first) is common to most of the seeding events examined. The philosophy of increasing the duration and area coverage of the cloud system by peripheral seeding is a useful one but apparently leads to a number of cases of ineffective seeding (e. g., Fig. 5) when the peripheral cell is not able to develop adequately.

Secondly, the data shown in Fig. 7 illustrates the complexity involved in attempts at quantitative evaluation of seeding effects. It is clear from the figure that a majority of the precipitation in the system occurred in the unseeded portion. Delineation of the portion due to seeding alone is a difficult task within this type of multi-celled cloud system.

During the 1973-74 seasons there were a total of 46 separate seeding events. In six of these events more than one period of seeding occurred per event. This contributed to the total of 44 identifiable seeding cases in the two-year period. Each of these cases was examined in terms of the timeliness of the seeding in the manner described above. In cases of doubt, the events were placed in the "valid" seeding category so that no potential effects would be overlooked.

Tables IV and V give lists of events which fell into the two categories of "Valid Seeding Events" and "Ineffective Seeding Events". Asterisks indicate that there was no detailed radar coverage (such as Fig. 4) primiarly because of ground clutter problems. As can be seen in the tables, most of these cases were placed in the "valid" category where reasonable doubt about seeding effectiveness existed.

In four of the cases shown in Table IV the designation "no effect" appears in the table. For these cases there was sufficient evidence in the data to indicate that no apparent change in the precipitation history could be associated with the seeding event. An example of this is shown in Fig. 8. Seeding occurred after the main storm intensity had peaked but within a series of cells which continued after the main storm development had started to dissipate. The first of these cells (peak at 2039 CDT) was seeded in a timely manner. The second (peak

TABLE IV. VALID SEEDING EVENTS

Event No.	Date	Time	Remarks
1	August 31, 1973	1650-1710 CDT	
3	September 1, 1973	2010-2043	No effect
4 (NS*)	September 4, 1973	1830-1915	
5	September 4, 1973	1918-2013	
6a	September 12, 1973	1639-1708	No effect
6b	September 12, 1973	1810-1847	
7	September 12, 1973	1714-1751	No effect
8b	September 12, 1973	1941-2026	
9	September 21, 1973	1620-1700	
10	October 10, 1973	2034-2135	
1	April 18, 1974	1755-1857 CDT	
2	April 21, 1974	1425-1502	
4	April 28, 1974	2340-0055	No effect
5 (NS)	May 9, 1974	1520-1554	
6a	May 9, 1974	1600-1635	
7	May 25, 1974	1705-1743	
8b	May 25, 1974	1950-1957	
10	June 11, 1974	1943-2035	
11	June 12, 1974	1834-1900	
12 (NS)	August 9, 1974	1710-1814	
19	August 10, 1974	1723-1806	
20	August 10, 1974	1852-1942	
22	August 26, 1974	1323-1433	
23	August 27, 1974	1530-1620	
26a	August 29, 1974	1342-1415	
26c	August 29, 1974	1448-1514	

* - No-seed

TABLE V. INEFFECTIVE SEEDING EVENTS

Event No.	Date	Time
2 (NS) *	August 31, 1973	1914-2010 CDT
3 (NS)	April 27, 1974	0055-0125 CDT
6b	May 9, 1974	1640-1654
6c	May 9, 1974	1703-1738
8a	May 25, 1974	2015-2030
9 (NS)	June 1, 1974	2255-2330
12	July 3, 1974	1910-2015
13 (NS)	July 12, 1974	1553-1635
14	July 15, 1974	1917-1940
15a	July 17, 1974	1538-1600
15b	July 17, 1974	1604-1630
16	July 26, 1974	1945-2014
18a	August 10, 1974	1550-1621
18b	August 10, 1974	1641-1714
21 (NS)	August 24, 1974	1635-1700
24 (NS)	August 28, 1974	1625-1651
25	August 28, 1974	1850-1930
26b	August 29, 1974	1422-1442

* - No-seed

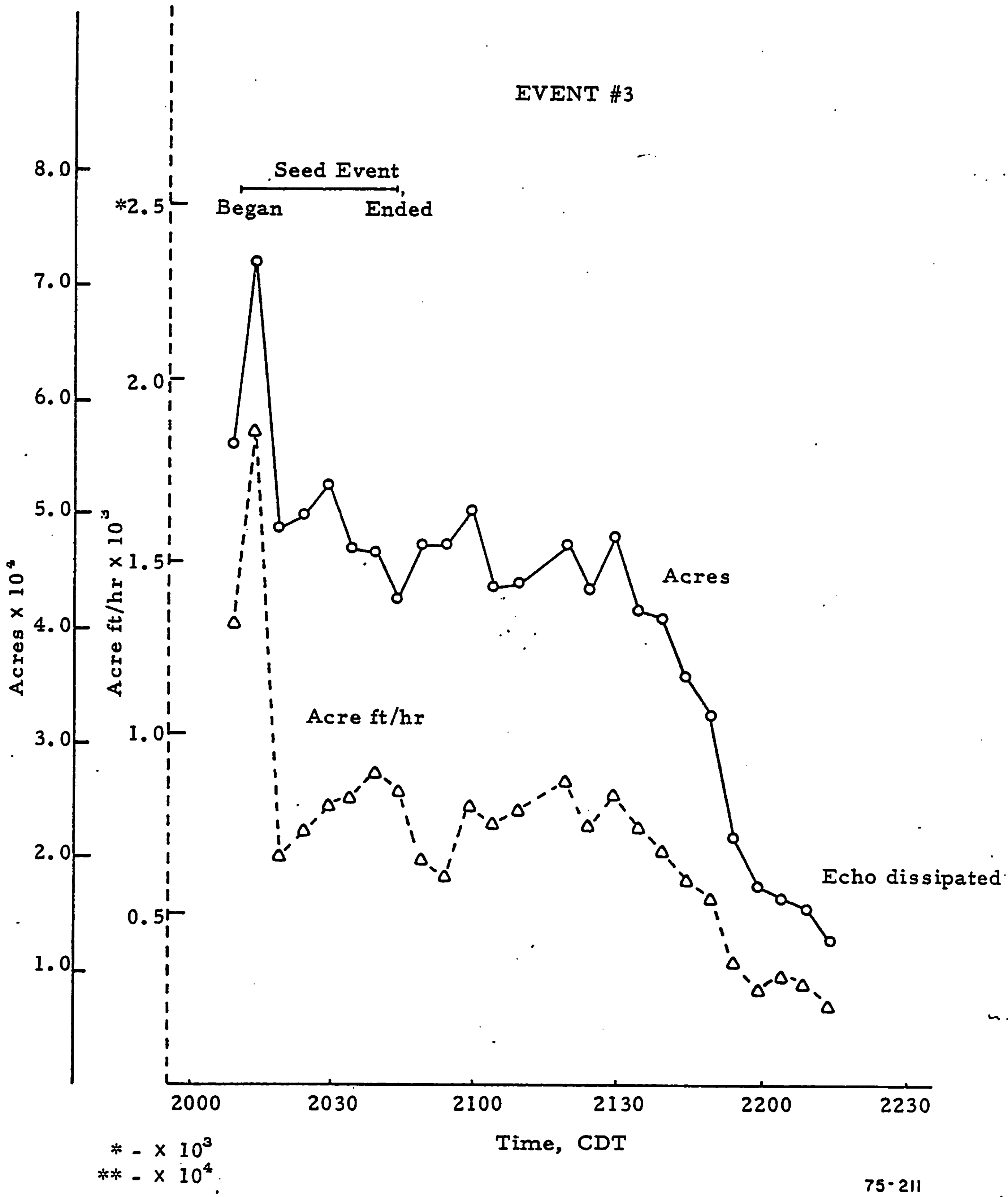

Figure 8. Time-History of Radar Rainfall, 1 September 1973

at 2119 CDT) was not seeded. The similarity in the intensity and area patterns for the two cells suggests that the seeding of the first cell was not effective.

Through the processes described above, twenty-two events (of 44 total) were classified as potential condidates for seeding effects. It is not implied that these necessarily produced additional precipitation as a result of seeding. The classification only indicates that the possible effects should be confined to these cases.

It is of interest to note in Tables IV and V that there were 10 "valid" seeding events in 1973 compared to one "ineffective" event. In 1974, however, there were 16 "valid" events versus 17 "ineffective" events. Relatively dry conditions in 1974 may have led to less selective seeding decisions and to a greater number of ineffective events.

7.2 Seeding Effects on Cloud Tops

It has been reported previously that seeding of cumulus clouds has had the effect of increasing cloud depth (higher cloud top) compared to unseeded systems. Weinstein and MacCready (1969) have found this effect in Arizona. The concept also forms the basis for apparently successful seeding in Florida (Simpson and Woodley, 1971). In both of these programs large amounts of silver iodide were used in each cloud treatment in a deliberate attempt to glaciate the cloud and increase internal cloud buoyancy ("dynamic" seeding). This was not a stated objective of the seeding in the Big Spring area and, in fact, silver iodide amounts were usually lower than used in Arizona and Florida. It is useful, however, to examine cloud top behavior at Big Spring for any possible effect of the seeding.

Table VI shows a comparison of maximum seeded cloud tops with those maximum tops observed at about the same time each day in nearby areas where seeding was not carried out.

Data in Table VI include only those cases from Table IV which appeared to be valid seeding events. These data indicate that maximum cloud tops in the seeded area were at least 5000 feet higher than in the unseeded area on six occasions. However, the reverse was also true on six occasions. The remaining cases (five) showed cloud top heights within 5000 feet for both seeded and unseeded cases.

TABLE VI. COMPARISON OF MAXIMUM CLOUD TOPS

Event No.	Date	Time	Cloud Top Heights	
			Maximum Seeded	Maximum Non-Seeded
4 (NS) *	Sept. 4, 1973	1830-1915 CDT	29 K ft	35 K ft
5	Sept. 4, 1973	1918-2013	37	27
6b	Sept. 12, 1973	1810-1847	48	55
9	Sept. 21, 1973	1627-1712	45	38
1	April 18, 1974	1755-1857 CDT	40 K ft	38 K ft
2	April 21, 1974	1425-1502	42	47
5 (NS)	May 9, 1974	1520-p554	43	37
6a	May 9, 1974	1600-1635	39	39
7	May 25, 1974	1705-1743	45	47
8b	May 25, 1974	1950-1957	36	41
10	June 11, 1974	1943-2035	41	35
11	June 12, 1974	1834-1900	46	53
17 (NS)	August 9, 1974	1710-1814	48	46
19	August 10, 1974	1723-1806	--	43
20	August 10, 1974	1852-1942	44	46
22	August 26, 1974	1323-1433	34	29
23	August 27, 1974	1530-1620	37	29
26a	August 29, 1974	1342-1415	26.	37
26c	August 29, 1974	1448-1514	30	--
* - No-seed				

It is concluded that the evidence given by the data do not support any appreciable increases in maximum cloud top heights due to seeding. This is not surprising in view of the light amounts of silver iodide used and the lack of emphasis on "dynamic" seeding concepts.

7.3 Organizational Characteristics

The 26 valid seeding events listed in Table IV have been examined individually for evidence of common characteristics. Three types of storm conditions were defined by the examination:

a. Line Organization - Lines of cumulus cells developed which were frequently associated with frontal passages or convergence lines. These were usually characterized by rather rapid rates of movement through the area. Seeding was conducted in a line pattern, usually in front of the advancing system. Objective of the seeding was to intensify the line by further developing the existing cells or by initiating precipitation in new cells along the line so that the lines propagated in a more efficient manner.

b. Cell Sequences - On numerous occasions sequences of cells developed, separated in time by 20-30 minutes each. The new cell usually formed during the collapsing stage of the previous cell and in an upwind direction according to the low-level winds. A series of three cells in sequence was a common occurrence. Objective of the seeding was to develop a more extensive area of precipitation and seeding was usually carried out on a cell-by-cell basis. Often the first cell in the sequence was not seeded while the second or third was. A comparison between seeded and unseeded cells was therefore possible.

c. Area Development - A third type of pattern was the formation of a broad area of precipitation consisting of a number of individual cells. These patterns tended to occur with lighter wind velocities. There were indications that the general, mesoscale environment was modified under these conditions to form a favorable and preferred area for cell developments. Objective of the seeding would be to continue and further develop this broad area modification.

Tables VII through IX give lists of the three types of events observed. Eleven of the cases fell into the line organization category, eleven appeared to be cell sequences and four were large area developments. It is to be noted that there was one no-seed case within the line organization events, two in the cell sequence cases and none in the area development occurrences.

The patterns described above carry certain implications in regard to their potential for evaluation. Both the line organization and the area development are essentially large, mesoscale features of the weather pattern. As such, their characteristics vary considerably from one day to another due to changes in stability, moisture, wind shear, etc. It is then difficult to compare seed and no-seed cases unless adjustment is made for these environmental differences. One technique that suggests itself is a comparison of the seeded portions of a line with adjacent, unseeded portions of the same line.

The evaluation problem is somewhat better for the cell sequence events. In this case, several cells form in time sequence within the same general area. As indicated earlier, only one or two of these sequential cell developments were seeded, leaving at least one cell for a natural comparison. In addition, day-to-day variations in the characteristics of the cell sequences were not as pronounced as the other two pattern types.

7.4 Intensity and Area Variations

It has been suggested that rainfall intensity and/or area of the cell development might be influenced by seeding. Hypotheses have been offered that rainfall intensity could increase while others have suggested that cell areas might be increased by the seeding. The data presentations shown in Figs. 5-7 afford an opportunity for examining these suggestions.

Table X gives a list of identifiable cell events during the 1973-74 period. For each of these events the radar time-history was sufficiently well defined so that peak areas, intensities and total rainfall could be determined. In some cases, the radar plots were divided into sequences of cells where the plots and associated information indicated that two or more cell developments were appropriate. An example of this is shown in Fig. 7 for May 9, 1974. This time-history was divided into two cells, one peaking at 1551 and the other at 1636. The first cell is shown in the table as a no-seed event, the second as a seeded case. Table X gives the area and intensity of the rainfall at the time of peak cell development. Intensity was computed as the total rainfall from the cell divided by the cell area at the time of the peak rainfall rate.

TABLE VII. LINE ORGANIZATION EVENTS

Event No.	Date	Time
1	August 31, 1973	1650-1710 CDT
8	September 12, 1973	1941-2026
9	September 21, 1973	1620-1700
10	October 10, 1973	2034-2135
2	April 21, 1974	1425-1502 CDT
10	June 11, 1974	1943-2035
17	August 9, 1974 (NS*)	1710-1814
19	August 10, 1974	1723-1806
20	August 10, 1974	1852-1942
26a	August 29, 1974	1448-1514
26c	August 29, 1974	1448-1514

* - No-seed (NS)

TABLE VIII. CELL SEQUENCE EVENTS

Event No.	Date	Time
3	September 1, 1973	2010-2043 CDT
4	September 4, 1973 (NS*)	1830-1915
5	September 4, 1973	1918-2013
6a	September 12, 1973	1639-1708
6b	September 12, 1973	1810-1847
7	September 12, 1973	1714-1751
5	May 9, 1974 (NS)	1520-1554
6a	May 9, 1974	1600-1635
11	June 12, 1974	1834-1900
22	August 26, 1974	1323-1433
23	August 27, 1974	1530-1620

* - No-Seed (NS)

TABLE IX. AREA DEVELOPMENT EVENTS

Event No.	Date	Time
1	April 18, 1974	1755-1857 CDT
4	April 28, 1974	2340-0055
7	May 25, 1974	1705-1743
8b	May 25, 1974	1950-1957

TABLE X. INTENSITY AND AREA CHARACTERISTICS

Year	Event Number	Date	Time	Seed Decision	Peak Intensity	Area
1973	1	August 31	1827 CDT	No-Seed	0.37 in./hr	1.3×10^5 acre
	2	August 31	1907	No-Seed	0.50	3.1
	3	September 1	2037	Seed	0.23	0.82
	4	September 4	1907	Seed	0.31	0.85
	5	September 4	1928	No-Seed	0.42	0.58
		September 4	2105	No-Seed	0.79	1.2
	6	September 12	1804	No-Seed	0.19	1.9
		September 12	1918	Seed	0.28	2.3
	7	September 12	1850	No-Seed	0.30	2.6
1974	5	May 9	1700	No-Seed	0.45	1.2
	6a	May 9	1551	No-Seed	0.39	0.90
	6a	May 9	1636	Seed	0.23	0.80
	6b	May 9	1650	No-Seed	0.35	0.40
	6c	May 9	1705	No-Seed	0.27	1.2
	6c	May 6	1755	Seed	0.32	1.8
	6c	May 9	1835	No-Seed	0.27	2.3
	8a	May 25	1948	No-Seed	0.24	0.32
	8a	May 25	2013	No-Seed	0.18	0.32
	8b	May 25	2015	Seed	0.36	2.2
	9	June 1	0032	No-Seed	0.58	3.5
1974	9	June 1	0102 CDT	No-Seed	0.44 in./hr	5.0×10^5
	11	June 12	1900	Seed	0.80	1.5
	11	June 12	1922	Seed	1.00	2.0
	11	June 12	2027	No-Seed	1.00	2.5
	15a	July 17	1550	No-Seed	0.07	0.26
	15a	July 17	1635	No-Seed	0.09	0.28
	15b	July 17	1605	No-Seed	0.04	0.71
	15b	July 17	1635	Seed	0.06	1.0
	18	August 10	1605	No-Seed	0.75	1.3
	21	August 24	1715	Seed	0.32	0.52
	21	August 24	1806	No-Seed	0.38	1.1
	21	August 24	1826	No-Seed	0.29	0.70
	22	August 26	1318	Seed	0.27	0.58
	22	August 26	1458	Seed	0.16	1.3
	23	August 27	1559	Seed	0.43	1.7
	25	August 28	1846	No-Seed	0.18	0.17
	25	August 28	1911	Seed	0.15	0.34
	26c	August 29	1416	No-Seed	0.18	0.13
	26c	August 29	1521	Seed	0.20	0.76

Table XI gives a summary of the data in Table X, segregated into seed and no-seed cases.

TABLE XI. SUMMARY OF INTENSITY AND AREA VARIATIONS

	Average Intensity (in./hr)	No. Cases	Average Area (acres)
Seed	0.33	15	1.23×10^5
No-seed	0.36	24	1.37

7.5 Total Rainfall Characteristics

Table XII shows the total rainfall amounts calculated for each of the cell events given in Table X. Total rainfall was determined by integrating under the radar time-histories as given, for example, in Figs. 5-7. Also shown in the table are the cloud depths associated with each cell event at the time of peak rainfall intensity. Cloud tops were determined by radar from the Snyder radar. If no cloud top was available at the proper time and location, no data are included in the cloud top column. Cloud top data from the AI radar although frequently available, were not used due to general differences between the Snyder and Big Spring radar top measurements.

The data in Table XII can be used to develop a relationship between cloud depth and total cell rainfall. Such a relationship was presented by Koscielski and Dennis (1972) and was subsequently used by Smith, Takeuchi and Chien (1974) in analyses of the San Angelo data. This relationship for the data in Table XII is shown in Fig. 9. Although there are numerous problems involved in defining the total rainfall from each event (radar - rainfall relation, cell definition, etc.) the relationship shown in Fig. 9 is reasonable and similar to those previously found.

Cell events designated as seeded are shown in Fig. 9 as circled data points. Although several of the seeded events suggest increase in precipitation over the values described by the best-fit relationship, there is little overall indication of substantial seeding effects.

TABLE XII. CLOUD DEPTH AND TOTAL RAINFALL CHARACTERISTICS

Year	Event Number	Date	Time	Seed Decision	Cloud Depth	Total Rainfall
1973	1	August 31	1827 CDT	No-Seed	7.3 km	4375 acre-ft
	2	August 31	1901	No-Seed	--	11,850
	3	September 1	2037	Seed	9.5	490
	4	September 4	1907	Seed	6.4	1170
	5	September 4	1928	No-Seed	8.1	1130
		September 4	2105	No-Seed	--	2515
	6	September 12	1804	No-Seed	12.4	995
		September 12	1918	Seed	--	2490
	7	September 12	1850	No-Seed	--	2400
1974	5	May 9	1700	No-Seed	--	3240
	6a	May 9	1551	No-Seed	10.7	1675
	6a	May 9	1636	Seed	8.8	820
	6b	May 9	1650	No-Seed	5.5	655
	6c	May 9	1705	No-Seed	9.1	1935
	6c	May 9	1755	Seed	--	2795
	6c	May 9	1835	No-Seed	--	2890
	8a	May 25	1948	No-Seed	8.5	265
	8a	May 25	2013	No-Seed	5.2	265
	8b	May 25	2015	Seed	--	6370
	9	June 1	0032	No-Seed	--	9885

Year	Event Number	Date	Time	Speed Decision	Cloud Depth	Total Rainfall
1974	9	June 1	0102 CDT	No-Seed	-- km	23,535 acre-ft
	11	June 12	1900	Seed	11.6	4225
	11	June 12	1922	Seed	13.7	5740
	11	June 12	2027	No-Seed	--	21,125
	15a	July 17	1550	No-Seed	4.9	60
	15a	July 17	1635	No-Seed	--	95
	15b	July 17	1605	No-Seed	2.7	20
	15b	July 17	1635	Seed	2.7	18
	18	August 10	1605	No-Seed	10.8	6567
	21	August 24	1715	Seed	8.8	460
	21	August 24	1806	No-Seed	--	2035
	21	August 24	1826	No-Seed	--	690
	22	August 26	1318	Seed	7.3	1220
	22	August 26	1458	Seed	--	1345
	23	August 27	1559	Seed	6.7	3610
	25	August 28	1846	No-Seed	--	120
	25	August 28	1911	Seed	3.3	250
	26c	August 29	1416	No-Seed	9.1	115
	26c	August 29	1521	Seed	--	785

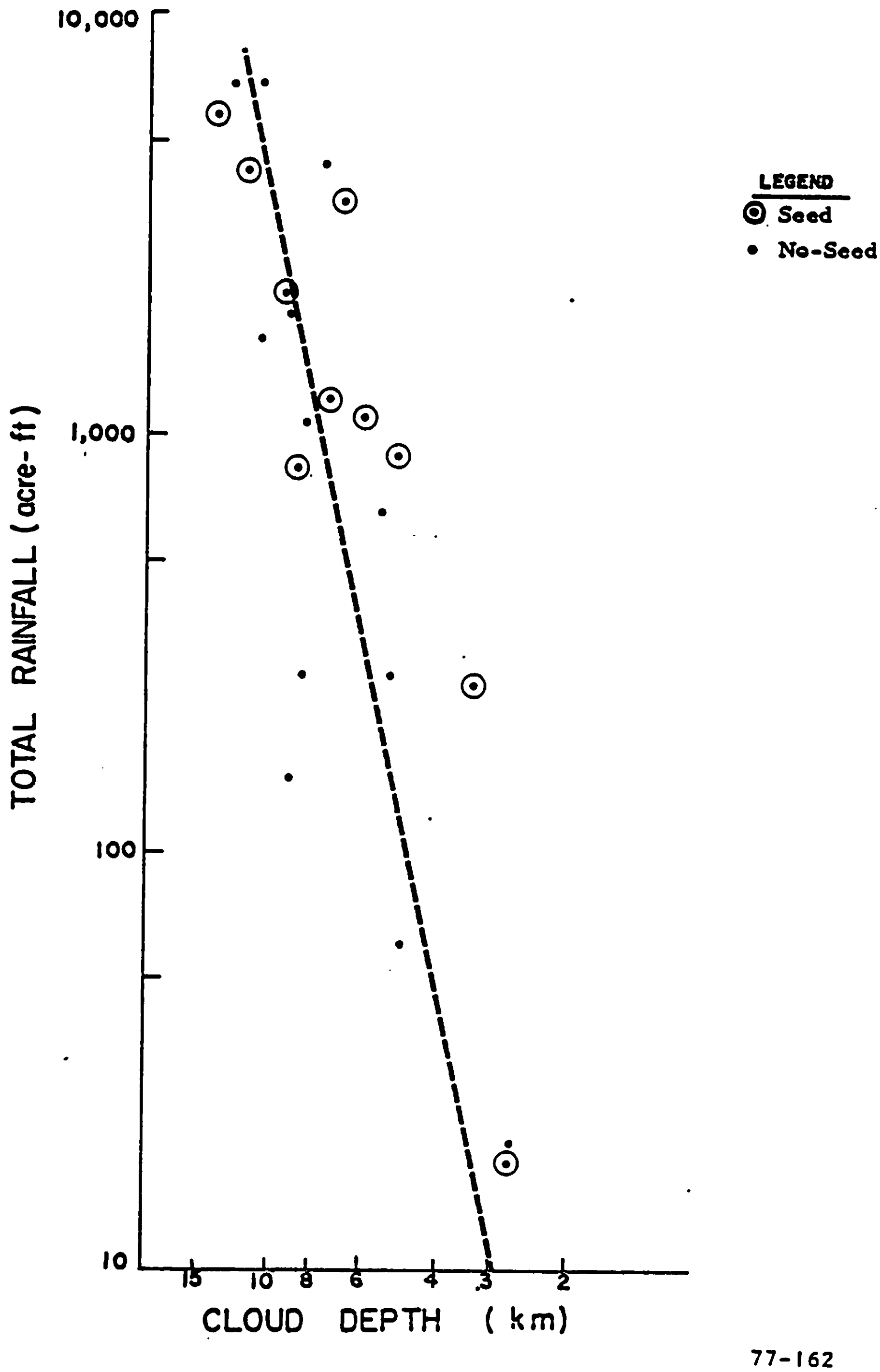

Figure 9. Relationship between cloud depth and cloud rainfall

7.6 Area Rainfall Estimates

An estimate of the total rainfall occurring in the Big Spring area can be obtained from the 81 gage rainfall network maintained by the Colorado River Municipal Water District. The network is concentrated in an area from La Mesa to Snyder to Silver to Big Spring which consists of about 4700 square miles (3×10^6 acres). This area comprises most of the project area but nearly all of the productive watershed. Average rain totals from the 81 gage system are shown in Table XIII along with an estimate of the total volume of rainfall which occurred in the above portion of the project area.

TABLE XIII. AREA RAINFALL ESTIMATES

Month	Average Rainfall (inches)	Area Rainfall (acre-feet)
September 1973	3.38	8.4×10^5
April 15-30, 1974	1.92	4.8
May 1974	1.53	3.8
June 1974	0.95	2.4
July 1974	0.45	1.1
August 1974	3.66	9.1
Total		29.6×10^5

During these months the data from Table XII indicate that approximately 139,000 acre-feet were measured by radar for seeded or associated seeded events. The events listed in Table XII cover approximately half of the events which actually occurred during these months. For the remainder (not shown in Table XII) ground clutter problems and/ or incomplete time coverage by the radar precluded a rainfall estimate of the entire event. It is therefore reasonable to estimate, for the purposes of the present discussion, that about 280,000 acre-feet of rainfall actually occurred in conjunction with the seeding events during the months shown in Table XIII. Without prejudging the effects of the seeding itself, it appears that the seeding was associated with rainfall events which comprised only about 10 percent of the total rainfall which occurred in the area.

7.7 Area Rainfall Characteristics

The total rainfall for the operational periods (August 16 through September 1973 and April 15 through August 1974) for the project area have been plotted along with data from all regular reporting stations within 90 nm of Snyder. Contour maps of total rainfall for each of the periods are shown in Figures 10 and 11.

Both figures show indications of somewhat larger amounts of rainfall in the southern portion of the project area than occurred in surrounding areas. In the case of Figure 11, virtually all of the excess (12 inch maximum) along the highway between Big Spring and Colorado City occurred in August 1974. This rainfall occurred in four periods (August 4-5, 10, 11, 26). Only the storm of August 26 was clearly seeded in the area of the precipitation maximum. August 4-5 and 11 were not seeding days in the area and the several cells seeded on August 10 probably did not influence the area along the Big Spring-Colorado City highway in a substantial manner.

Although a portion of the rainfall contributing to the 12 inch maximum was not associated with seeding, a reasonable adjustment in the rainfall values to account for this nonseeded contribution would still leave a weak maximum in the area similar to that shown in Figure 10. The rainfall maps could then be used to support an indication of a maximum seeding effect amounting to approximately 2-4 inches total for the period covered by the two maps in the southern portion of the area. A more accurate estimate of the effect would require closer examination of the possible contributions of each storm.

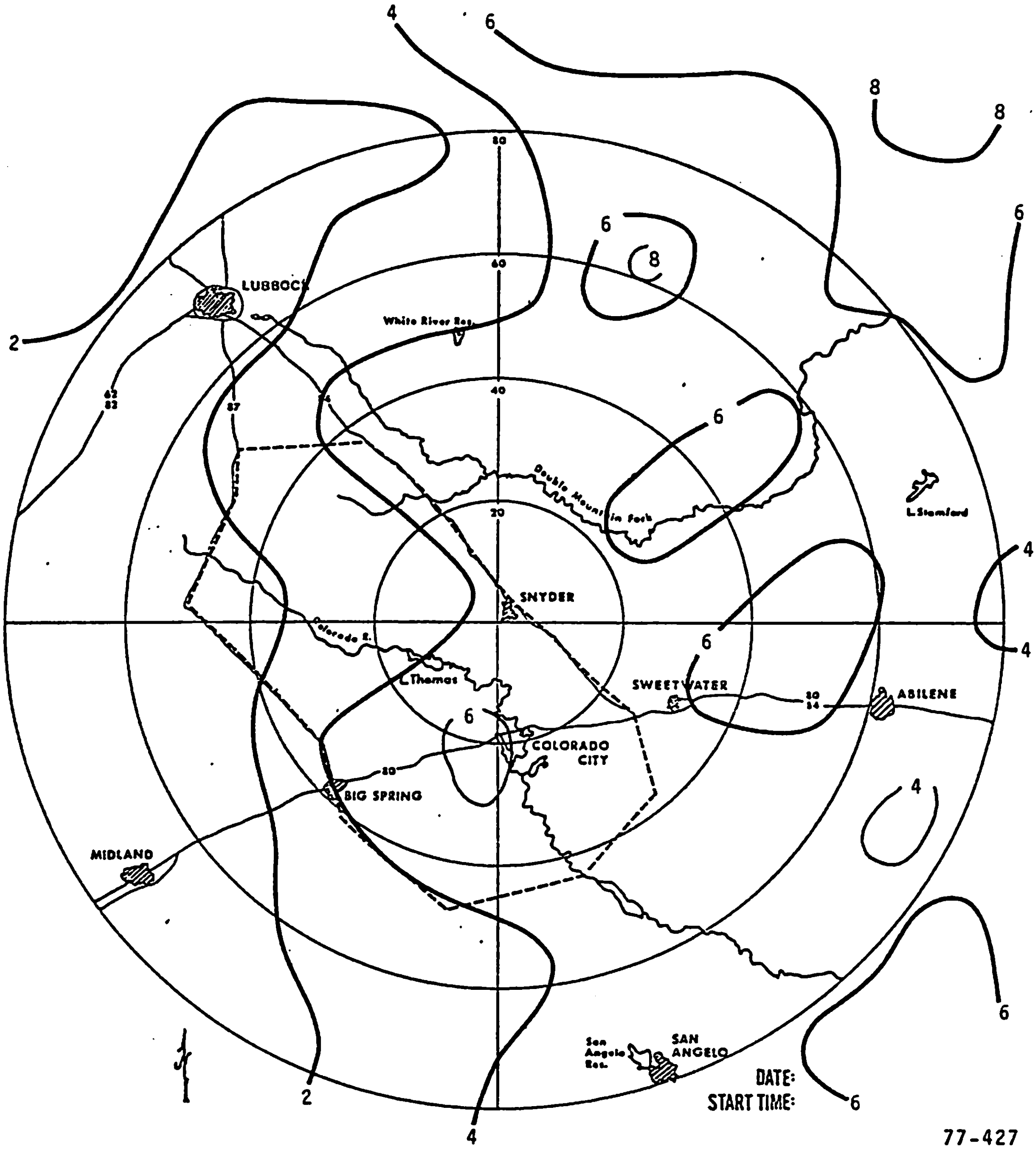

Figure 10. Total rainfall (inches) August 16-September 1973

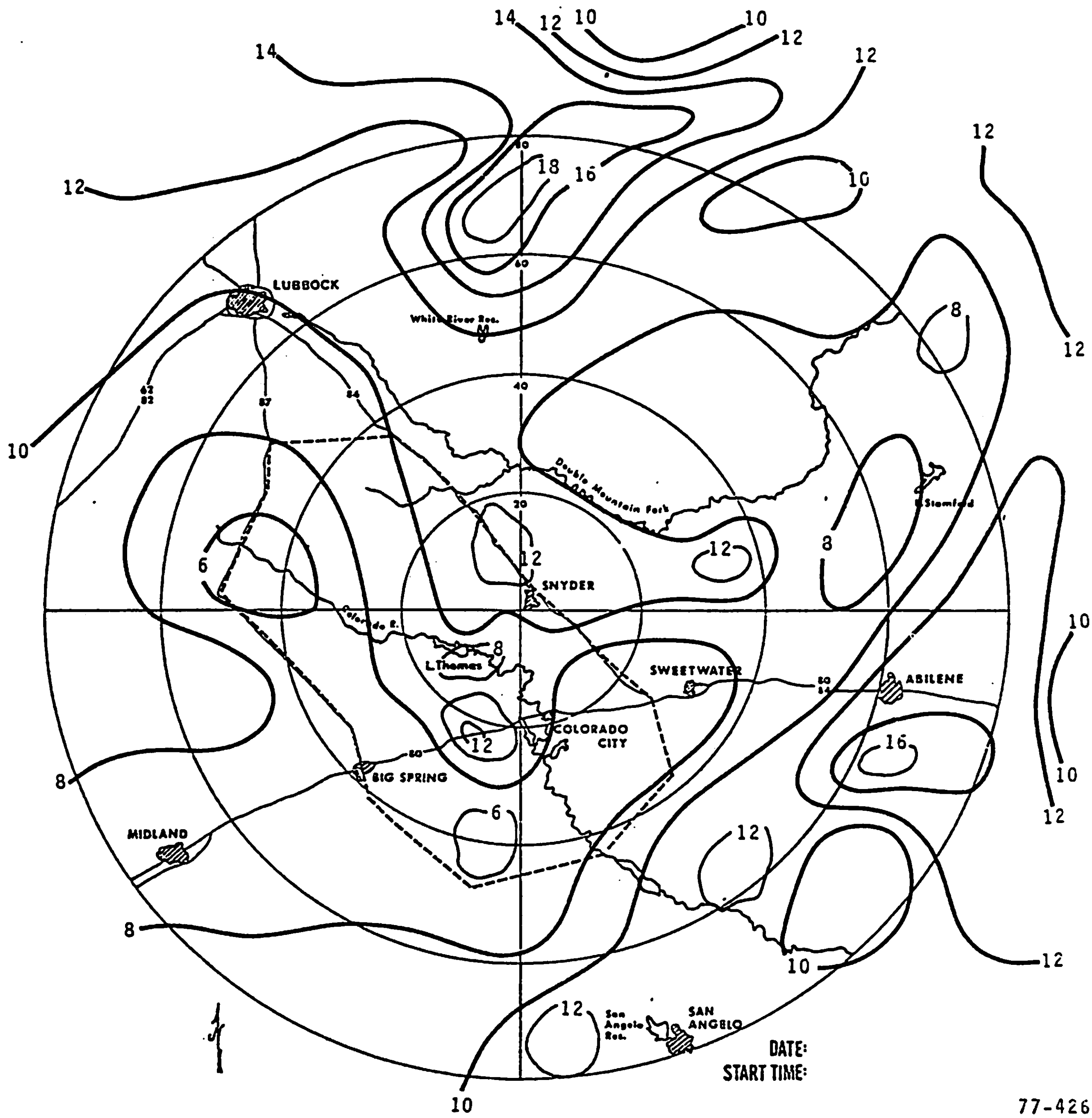

Figure 11. Total rainfall (inches) April 15-August 1974

8. DISCUSSION

Two definitive results from the study require further discussion. These are 1) the proportion of seeding events which were considered as ineffective and 2) the percentage of total area rainfall which could be associated with seeding events. In addition, the limitations of the study itself should be kept in mind.

8.1 Ineffective Seeding Events

Approximately half of the seeding events were classified as ineffective on the basis of the short cloud lifetime available after the seeding took place. There are several reasons why this may have occurred.

1. The seeding philosophy practiced by Atmospherics, Inc. in Texas calls primarily for seeding of peripheral cells around an established rain center. Purpose of the seeding is to extend the rain development in area and duration. Radar is used to vector the aircraft to the location of existing rain cells.

In a number of cases, (e.g., Fig. 5) the peripheral cells around the main rain center fail to develop adequately and the seeding material does not reach the nucleation level or does not have sufficient time thereafter to develop precipitation. The time sequence of cell developments initiated by the first rain cell is a complex organizational system and is poorly understood. It is not unexpected that some of the anticipated peripheral cell developments might not develop as fully as anticipated. This problem is made more significant by seeding at cloud base where at least 15-minutes of cloud life must exist in order for the seeding material to become effective.

This problem may have been made particularly significant during 1974 when relatively dry conditions existed through out much of the summer. In this case (low moisture in the area) the periphery cells are less likely to develop around the dissipating main cell.

2. Operational weather modification programs must, of cesessity, treat many marginal clouds where the seeding conditions may not be optimum. Research programs, on the other hand, can affort the luxury of careful cloud selection in order to achieve a more controlled experiment. On this basis, it would be surprising if a portion of the seeding events were not ineffectively treated.

3. Again, the proportion of "ineffectively-seeded" clouds increased substantially in 1974 compared to when relatively dry conditions prevailed and attempts were made to seed all available clouds of even marginal interest. 1974 cloud systems were also anomalous from the standpoint of the extensive, widespread rain system which characterized September and October 1974 and which are generally not as susceptible to seeding treatments.

8.2 Percentage of Total Area Rainfall

The results of the study indicate that only about 10 percent of the rain in the area during the evaluation period was associated with (but not necessarily caused by) the seeding events. The seeding philosophy which is based on peripheral seeding around an existing rain area permits the early existence of uninfluenced rainfall. In addition, it is frequently operationally impossible for one aircraft to be in position for optimum seeding of all cells in the area. Since some reasonable length of time is spent working with one area of cell development, it is clear that the aircraft cannot reach some of the other cells in the area which are frequently in similar growth stages. Atmospherics, Inc. believes that four aircraft might be needed to cover the area adequately. The present techniques involve only one aircraft which attempts to select the most promising clouds meteorologically as well as those whose location will contribute most to the run-off.

8.3 Limitations of the Study

There were several limitations and associated problem areas which caused certain difficulties in the evaluation study. These were:

1. The number of seeding events during the evaluation period was less than had been anticipated. A further subdivision into types of storm developments and into valid-ineffective categories brought the total number of events down to a level where a statistical perspective was not very useful. This suggested the case history approach which was subsequently followed.

2. The seeding events, by the nature of the seeding philosophy, invariably involved complex organizations of cells occurring in lines, sequences or in mesoscale areas. The mechanisms for the natural formation of these systems are not well understood. As a result, one can only speculate about the effects of seeding on the systems.

3. The accurate measurement of rainfall by radar is a formidable problem in itself. Variations in apparent rainfall rate may result from differences in drop-size distribution, anomalous propagation and/or the existence of hail in the cloud. Variations in the rain-radar relationships tend to limit the range of seeding effects which can be examined.

4. The use of case histories as a method of analysis often required more detailed data on cloud characteristics than existed. Continuous cloud-top measurements and cloud base updraft data would have helped in the description of the individual cases.

5. An evaluation of this type should start from a clear hypothesis (or hypotheses) of the expected effects of the treatment. It would then be possible to look for these effects as well as for corollary physical data associated with the effects. The present program assumed that the evaluation would include any and all possible effects. At the end of the evaluation program, consequently, there remains a nagging question of the possible existence of other effects which were not considered in the study.

8.4 Conclusions

In spite of the non-significant results of the study and the inherent difficulties encountered, a considerably better understanding of seeding programs in the area has been obtained.

Principal conclusions of the study were as follows:

1. Comparisons were made between seeded and unseeded cloud characteristics such as cloud tops, rain areas, peak intensities and total rainfall per cloud. Within the limitations imposed by the study, no appreciable differences were found between seeded and unseeded clouds.

2. It was found that approximately half of the seeding events appeared to have been seeded in an ineffective manner such that the seeding material was not likely to have effected the cloud system. The primary reason for this was the frequently limited lifetime of the cloud after seeding available for precipitation growth. Some portion of the seeding events can be expected to be ineffectively seeded within an operational program whose goal is to deliver water on the ground.

3. Only about 10 percent of the total precipitation in the area could be associated with the seeding events. Only a fraction of this 10 percent (280,000 acre-ft) might reasonably be expected to have been the result of the seeding itself. Even this relatively small portion of the total rainfall, however, may make the program an economic success.

4. A categorization of the possibly successful seeding events showed several kinds of organizational systems: lines, cell sequences and area developments. Of these, the line systems appeared to be particularly promising for potential seeding effects. The light seeding conducted by Atmospherics, Inc. may initiate precipitation in various cells along the line leading to a general intensification and enhanced propagation of the line.

Seeding of sequences of cells should also contribute to extended durations of the mesoscale systems. In some cases, however, subsequent cells in the system failed to develop sufficiently for seeding response and, in those cases, the seeding was considered ineffective.

There were some indications that large area systems developed in the seeded area under light wind conditions. Seeding may have a beneficial effect on developing these areas but in their mature stages sufficient ice is probably available and seeding may no longer be necessary.

There were several occasions which involved seeding of large, well-developed cloud systems (e.g., with tops as high as 45-50 thousand feet). In one case only 7 grams of silver iodide were used for such a system. The rationale for treatment of these large systems is not clear. Some evidence exists from work in South Dakota that these large systems produce sufficient ice internally and that they represent relatively poor targets for seeding.

9. RECOMMENDATIONS

1. Statistical evaluations of seeding events as conducted in the Colorado River Municipal Water District program are not likely to be very productive unless carried out over long periods of time. Seeding has generally involved complex, semi-organized cloud systems whose variability is large and whose response to seeding is poorly understood. A continuation of the case history examinations will probably be more fruitful over the short term.

2. The evaluation program (and probably the operational program) would be aided by more definitive hypotheses for the seeding. There should be stronger conceptual ideas on what is expected to be accomplished by the specific seeding operations.

3. It would be helpful to recognize and categorize the various types of organizational systems during the seeding operation itself. The seeding would then be conducted within a better conceptual framework from both an operational and an evaluation standpoint.

4. The radar should be operated at a slightly higher elevation angle to avoid some of the ground clutter problems. Additional Z-R relations from the aircraft sampling will help the conversion from radar to rainfall amounts.

5. The gage cluster system should be reanalyzed. The system resulted in only a small number of useable gage-radar comparisons. Consideration should be given to a uniform gage spacing.

6. In the context of case history studies, additional attention to cloud top heights, updraft time-histories, etc. would help greatly to categorize individual seeding events.

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Technical Report

VOLUME II

RADAR EVALUATION OF 1975 COLORADO RIVER MUNICIPAL WATER DISTRICT SEEDING

MRI 77 FR-1485

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ABSTRACT

A program of evaluation of the CRMWD seeding operations at Big Spring has been carried out. The period of study covered the operations in July and early August 1975. A total of 30 case studies representing six days were examined in detail. This study followed a similar examination of the operations carried out in late summer of 1973 and during 1974.

Data used in the study were obtained from quantitative radar measurements made by an M-33 radar in Snyder. The 10 cm portion of the radar provided reflectivity values at cloud base from which estimates of cell rainfall could be obtained. The 3 cm portion of the radar generated measurements of the heights of the cell tops through a series of stepped-elevation antenna scans. The data obtained were summarized in the form of time-histories of rainfall rate, rain area and height of the cell top.

A summary of the 30 cell time-histories showed that most of the events studied were parts of larger organized cloud systems which had a lifetime of several times the life of individual cells making up the system. The dominant form of organization, by far, was an elongated line of cells.

The seeding technique used in Big Spring is largely based on treatment of new cells around the periphery of an organized system. Purpose of the seeding is to extend the area and lifetime of the system. It was found that, in many cases, the cloud growth areas were being seeded after the organized system had begun a general decay cycle leading to eventual dissipation. Under these conditions, the new growth areas exist in a relatively unfavorable environment for the accomplishment of the program objectives. In these cases, little effect of the seeding could be determined.

For the remaining cases, the precipitation totals and rain areas were plotted against cloud depth in order to compare seeded and non-seeded cases. No appreciable difference was found for these cases. Possible factors contributing to these results are the possible lack of adequate amounts of AgI material in the cloud, insufficient time for precipitation growth in the cloud and unfavorable environment conditions for new cell growth.

This study and its predecessor have provided the first opportunity for detailed examination of the Big Spring seeding results. Valuable insight into cloud organization and the implications on seeding techniques have been gained. Recommendations for improvements in seeding operations include early recognition of organized systems and their life cycles, earlier seeding to coincide with the developing stages of the organized system, possible increase in AgI burn rate or longer orbiting in the cloud updraft and consideration of some exploratory seeding tests with AgI releases at cloud top. Finally, continued study and monitoring of the seeding results should lead to an optimum development of the seeding technology.

1. Introduction

Interest in the evaluation of weather modification programs has continued undiminished since the initiation of the early seeding tests in the late forties and early fifties. The limited number of definitive evaluations generated since that time is ample evidence of the difficulties involved in obtaining meaningful assessments of seeding effectiveness.

In 1973-74 the Texas Water Development Board (TWDB) initiated an evaluation study of the operational program conducted by Atmospherics, Inc. (AI) for the Colorado River Municipal Water District (CRMWD). A major purpose of the study was to assist in establishing an appropriate state policy in regard to the conduct of operational weather modification programs. In order to aid in the interpretation of the results, the seeding was randomized on the basis of three seed events for each no-seed case. In this way, it was hoped to obtain significant comparative data between seeded and unseeded clouds.

Results of the 1973-74 study were inconclusive in regard to precipitation increase. As a consequence, the TWDB with the support of the Atmospheric Water Resources Division of the Bureau of Reclamation extended the study to include a portion of the 1975 CRMWD seeding program. The period of the present study included July and the first half of August 1975. During this period a more extensive set of observational data were available than in the previous study as a result of improvements in the capabilities of the Bureau of Reclamation-Hiplex observing system.

The present report deals only with the results of the 1975 study.

2. Problems of Evaluation

A basic decision concerning evaluation technique is the choice of examining the seeding response on a cell-by-cell basis or on an area-wide basis. Most of the evaluations performed, particularly for operational programs, have been based on area-wide analyses. The measurement capabilities of the Hiplex program in Big Spring make it possible to carry out the present study on a cell-by-cell basis. This decision, however, leads to a number of problems which should be kept in mind during the following sections. Principal among these are:

a. Natural Variability of Clouds - On most summer days with precipitation in the area, there is a wide range of cloud sizes and precipitation production per cloud. Comparisons between seeded and unseeded clouds on the same day suffer from this variability and require some stratification of the cloud data (such as cloud diameter or height) to obtain a meaningful comparison.

b. Cloud Time Scale - The time scale of most summer cumulus clouds (or individual cells) is very short, of the order of 20-30 minutes. This provides only a limited time window for the introduction of the seeding material and also limits the time over which a precipitation response can be found for any given cloud. Examination of individual cloud response then requires measurements over a time scale comparable to or shorter than the cloud time scale.

c. Cloud Area Scale - Most summer cumulus clouds are of the order of 2-10 km in diameter. Measurements of the response of individual clouds to seeding requires observations over comparable distance scales.

d. Determination of Cloud Responses - There is considerable interaction between clouds of cumulus size, particularly after precipitation has been initiated in one or more of the cells. Apparent growth of the seeded cloud may be due to the influence of the surrounding clouds or the natural growth of the cell. Separation of the seeding effect from the natural development that might have occurred without seeding is the most difficult problem in evaluation.

e. Operational Constraints - A seeding program designed to be as productive as possible is not necessarily conducive to best evaluation efforts. An effective operational program should seed as many opportunities as possible. Inevitably, a number of these may be ineffectively seeded due to the inability of the aircraft to always be in the proper position at the proper time for each seeded cloud. It is inevitable, therefore, that the operational programs will appear inefficient in terms of proportions of successful events as compared to carefully designed, experimental programs.

3. Data Resources

The principal source of data used in the study was the M-33 radar at Snyder. During the 1975 season the 10 cm radar was operated constantly at a 1.5° elevation angle in an azimuth scan to record reflectivities near cloud base level. One 360° scan was obtained at approximately five-minute intervals. The 3 cm antenna was operated in a stepped elevation mode by 1.5° elevation angles from 1.5° to 12° and thence by 2° intervals to 18°. This cycle was completed once in five minutes and was used to determine radar cloud tops as a function of time. Signals from both radars were recorded on video tape. The 3 cm data were played back through a special display system and the resulting recreated picture was photographed onto 16 mm film. Using these films and the ability to examine the data on a frame-by-frame basis, the time history of a large number of precipitation cells was obtained. The 10 cm tapes were run through a digital processor at the Illinois State Water Survey where digital tapes were created. These tapes were then processed by computer into quantitative records of radar reflectivity at cloud base.

The 3 cm radar data were used to obtain individual cell-top heights for those cells of interest. As the 3 cm antenna spiraled upward the angular elevation and range of the appropriate cell-top were measured and recorded. These data provided a time-history of each cell-top during the lifetime of the cell.

Rainfall data were available from 50 recording raingages and 81 nonrecording gages in the area. These gages were maintained and read by the CRMWD. The recording gages were located in the form of 12 clusters of three each (triangular array with one km spacing between gages) and fifteen individual gages scattered throughout the area. The 81 nonrecording gages were located along the principal highway routes at about three mile intervals where they provided additional details of rainfall amounts in the area.

4. Treatment of Data

Reflectivity data from the low-elevation, 10 cm radar scans were averaged over spatial areas of dimensions about 0.5 km in radar range and 1° in azimuth. An example of one section of the radar scan is shown in Fig. 1. Each bin containing reflective elements is shown by a letter designating the quantitative reflectivity in the bin. A scale of reflectivity values is drawn at the bottom of the figure. A number of individual rain cells are shown in the figure. The most important of these is outlined by dashed lines and labeled as "Cell DD". The time history of this cell was determined in successive scans of the radar.

Also shown in the figure is a solid line marking the aircraft seeding track between 1841 and 1849 CDT where the radar measurement (Fig. 1) was made at 1844 CDT. Locations of the seeding tracks were obtained from CRMWD aircraft flight notes. Aircraft tracks of this type made it possible to examine the response of each cell examined, on a specific basis, during the time immediately following seeding.

Conversion of radar reflectivity data (Fig. 1) into rainfall estimates requires use of a "Z-R" relation, i.e., between radar reflectivity (Z) and rainfall rate (R). Numerous Z-R relations have been determined from observational data in a wide variety of conditions and locations. Z-R relations, in addition, have been found to vary significantly within the lifetime of a single rainshower. For the purposes of the present study a relation of the form:

$$R = 0.025\ Z^{0.62}$$

was used where R is in mm/hr and Z is in mm^6/m^3. This relationship was found in 1975 by averaging data collected by the MRI Navajo aircraft at Big Spring and is considered to be the most appropriate for use with the Snyder radar. It is important to remember, however, that the rainfall estimates obtained from the radar data may vary slightly, depending on the specific Z-R used and that whatever relation is used only represents an average of a large number of different relationships which can be expected to occur.

Conversion of the radar reflectivity in each bin (Fig. 1) to a nominal rainfall rate was accomplished by the computer. These rainfall rates per bin were then summed over the area of the cell (such as Cell DD) to form an instantaneous estimate of total rainfall rate from the cell

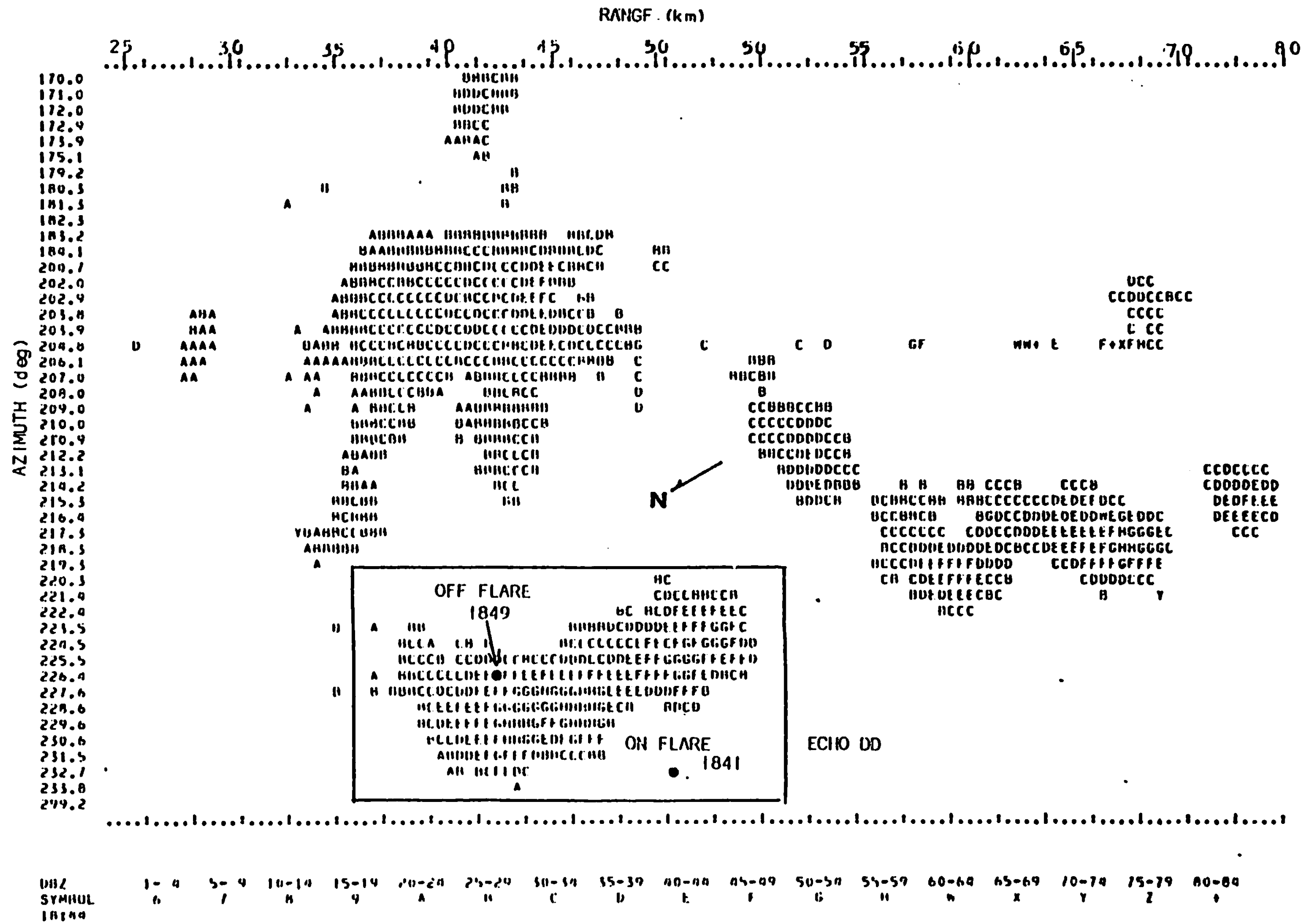


Fig. 1. BSCAN Snyder, Texas 14 August 1975 - 1844 CDT

at the time of the radar scan (e.g., 1844 CDT). The area covered by the cell was obtained, at the same time, from the number of bins containing reflective elements.

The values representing total cell rainfall rate and cell area for each scan were plotted, for successive scans, in terms of a cell time-history as shown in Fig. 2 for Cell DD. The data from Fig. 1 (integrated over the cell) represent the data points shown at 1844 CDT in Fig. 2. Also included in Fig. 2 is a time-history of the cell top as determined from the 3 cm radar, stepped-elevation scans. In the case of Cell DD, the cell top exceeded the highest antenna elevation scan for a brief period during its time-history.

A summation under the rainfall rate curve during the lifetime of the cell yields an estimate of the total rainfall from the cell. In the case of Cell DD, the estimate of total rainfall was 870 acre-feet.

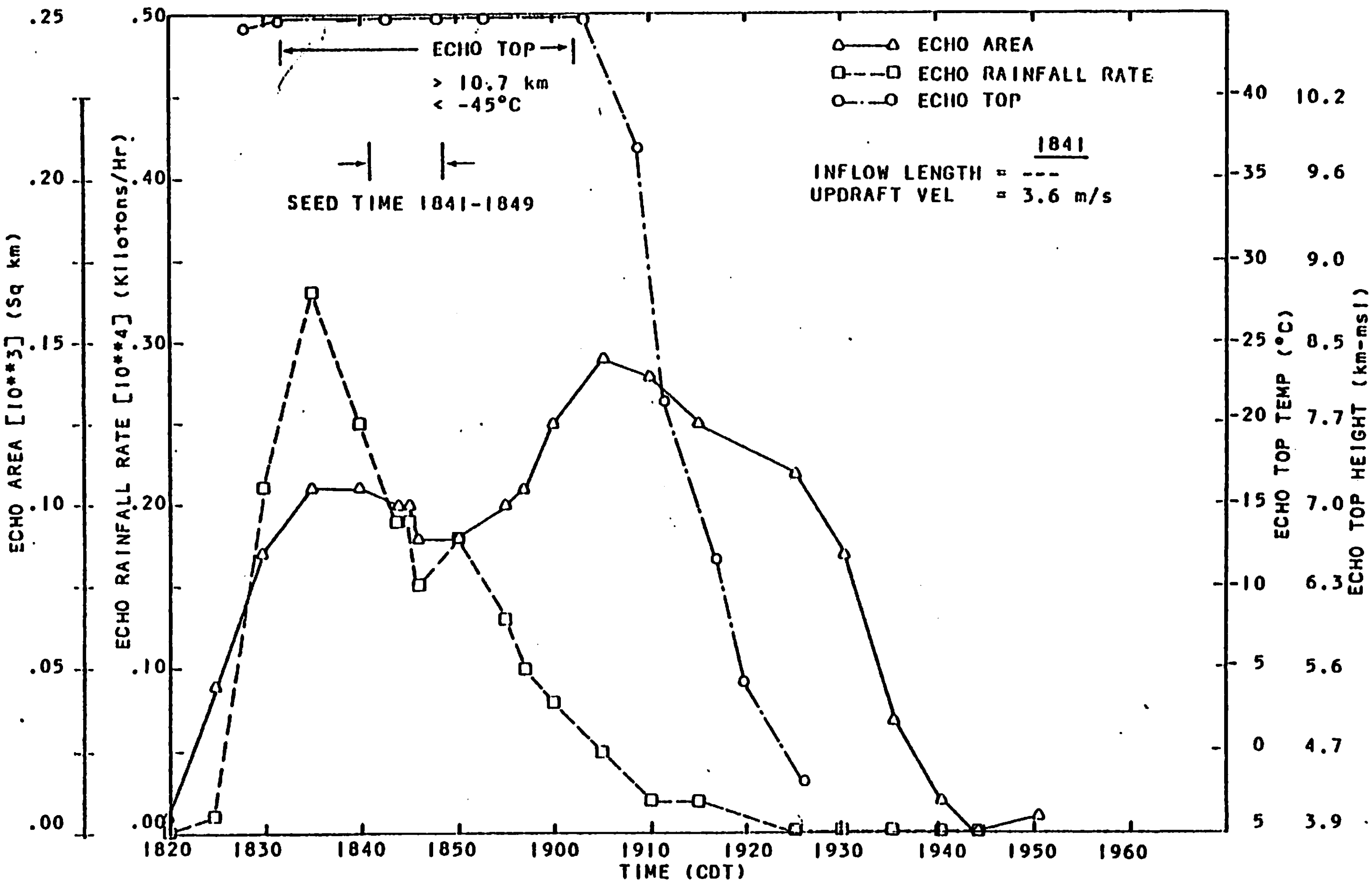
Also shown in Fig. 2 is the period of seeding for the cloud (1841-1849 CDT). This information permits a simple evaluation of the seeding period in relation to the time-development of the cell.

Similar plots (Figs. 1 and 2) were made for all cells examined and form the principal basis for the conclusions drawn during the study. Time-histories of all cells studied (e.g., Fig. 2) are given in the Appendix.

5. Selection of Cases

During the period July 1 to August 15, 1975 both radar sets (10 cm and 3 cm) were operating in an optimum manner. Selection of study cases was therefore concentrated in this time period. During this time radar data were obtained on 21 days. A total of six of these days were included in the study. The primary characteristics of these days were the occurrence of significant rain amounts and the capability of distinguishing individual cells which could be tracked over the lifetimes of the cells. In addition, some days where the seeded area drifted directly over the radar were not included since the cell time-histories were not complete. The six days studied in detail are believed to be representative of many of the seeding opportunities in the Big Spring area.

On these six days a total of 30 cells were examined in detail. Twenty-two of these cells were designated as seeded cells. The remaining



MAXIMUM ECHO AREA= .14293E+03 Sq km MAXIMUM ECHO RAINFALL RATE= .33135E+04 Kilotons/Hr

77-029

Figure 2. Echo Time History - Snyder, Texas 8/14/75
Echo DD, Seed

eight cells were selected for comparative purposes from nearby areas where there was no possibility of the seeding having affected the cell development.

Table 1 gives a list of the cells examined during the study.

TABLE 1. TABULATION OF CELLS INCLUDED IN STUDY

Cell No.	Date (1975)		Time (CDT)	Comments
A	July	11	1715-1931	Seed
B		11	1745-1921	Seed
C		11	1755-1846	Seed
D_1		11	1820-1955	Seed
D_2		11	1825-1930	No-seed
E		11	1845-2035	No-seed
F		12	1530-1720	Seed
G		12	1605-1735	Seed
H		12	1645-1810	Seed
I		19	1340-1415	Seed
J		19	1410-1828	Seed
K		19	1510-1620	No-seed
L		24	0005-0040	Seed
M		24	0005-0055	Seed
N		24	0005-0130	Seed
P		24	0050-0155	Seed
Q		24	0045-0200	No-seed
R		24	0130-0230	Seed
S		24	0145-0240	No-seed
T		24	0005-0040	No-seed
U	August	2	1515-1700	Seed
V		2	1515-1605	Seed
W		2	1535-1720	Seed
X		2	1540-1606	No-seed
Y		2	1605-1706	No-seed
Z		2	1705-1800	Seed
AA		14	1710-1810	Seed
BB		14	1715-1752	Seed
CC		14	1815-1844	Seed
DD		14	1820-1950	Seed

6. Characteristics of Precipitation Patterns

During the detailed examination of the 30 case studies of cell development, a number of general features of the precipitation were apparent. These features related to the mesoscale organization characterizing each day, the characteristics of the new growth areas associated with each system, and the life cycle of the mesoscale system itself. The following comments summarize the characteristic features of each day and serve to provide the cloud organizational framework in which each observed cell existed.

6.1 July 11, 1975

Figure 3 shows the characteristic line organization which existed for most of the day on July 11. The lines were oriented in a northwest-southeast direction and individual cell elements moved from north-northwest to south-southeast. At about 1800 CDT new cells were initiated on the west end of the line (see Fig. 3). The northwest-southeast line orientation became less pronounced and eventually became disorganized after 1930 CDT. By this time and for the balance of the observations the cells could be characterized as large, individual elements without significant organizational structure.

During the lifetime of the line organization new cells repeatedly formed on the north to northwest end of the line in spite of the general cell movement toward the south-southeast. These cells formed close to and essentially attached to the end of the existing line. After 1800 CDT when new cell growth appeared to the west of the line, the earliest cells formed close to the lines, passed through a short life cycle with new cells being formed further toward the west. This represented a downwind (relative to the surface wind) propagation of the cells but with a considerably larger distance between cells than was apparent during the earlier growth of the line.

The first clear manifestation of the line organization was about 1730 CDT. The line then continued as the dominant organized feature until 1930 CDT. The rainfall rates in the line increased to a maximum at about 1830 CDT. Thereafter, the entire system began to decline in importance accompanied by decreasing rainfall rates throughout the system.

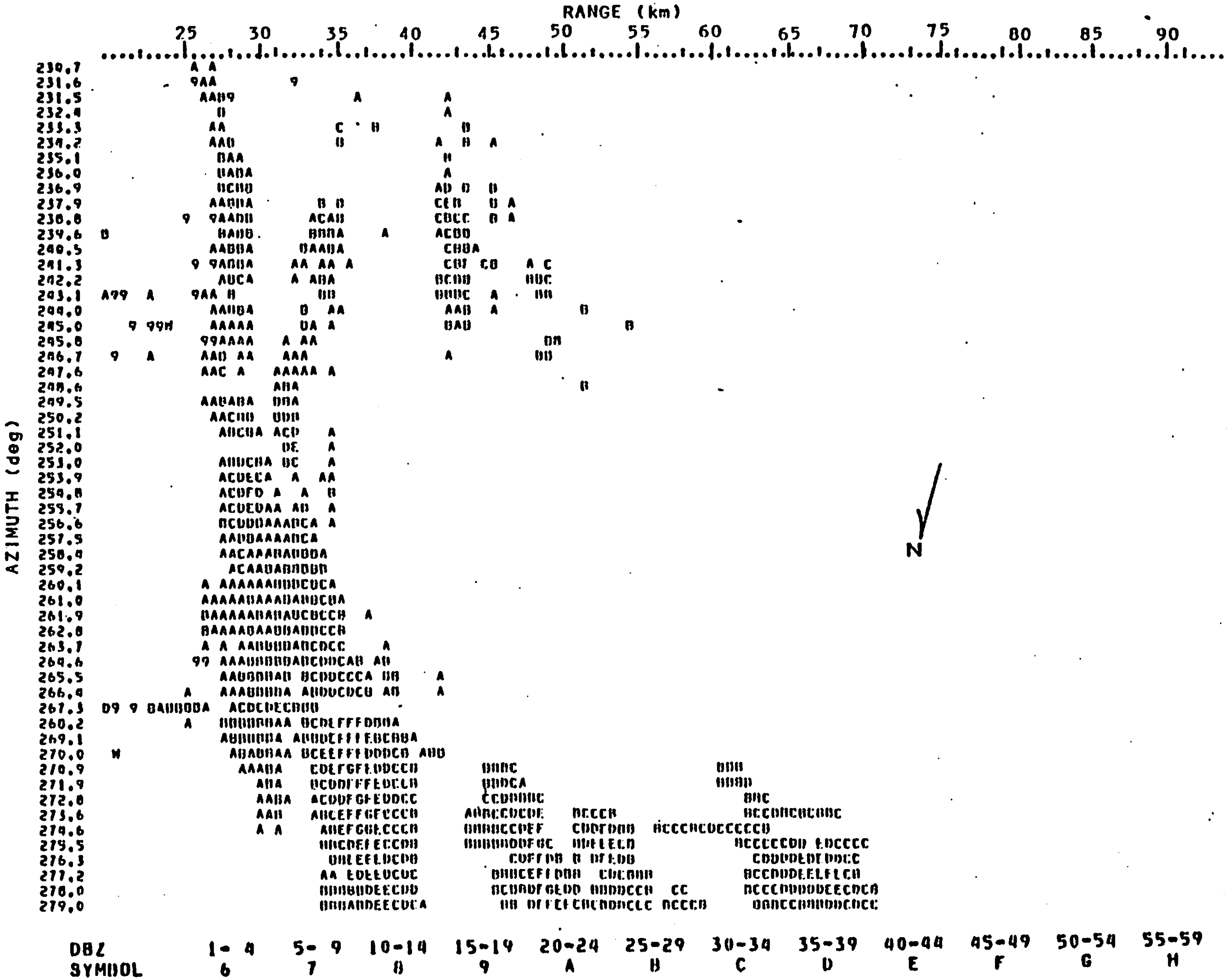


Fig. 3 . BSCAN Snyder, Texas 11 July 1975 - 1839 CDT

6.2 July 12, 1975

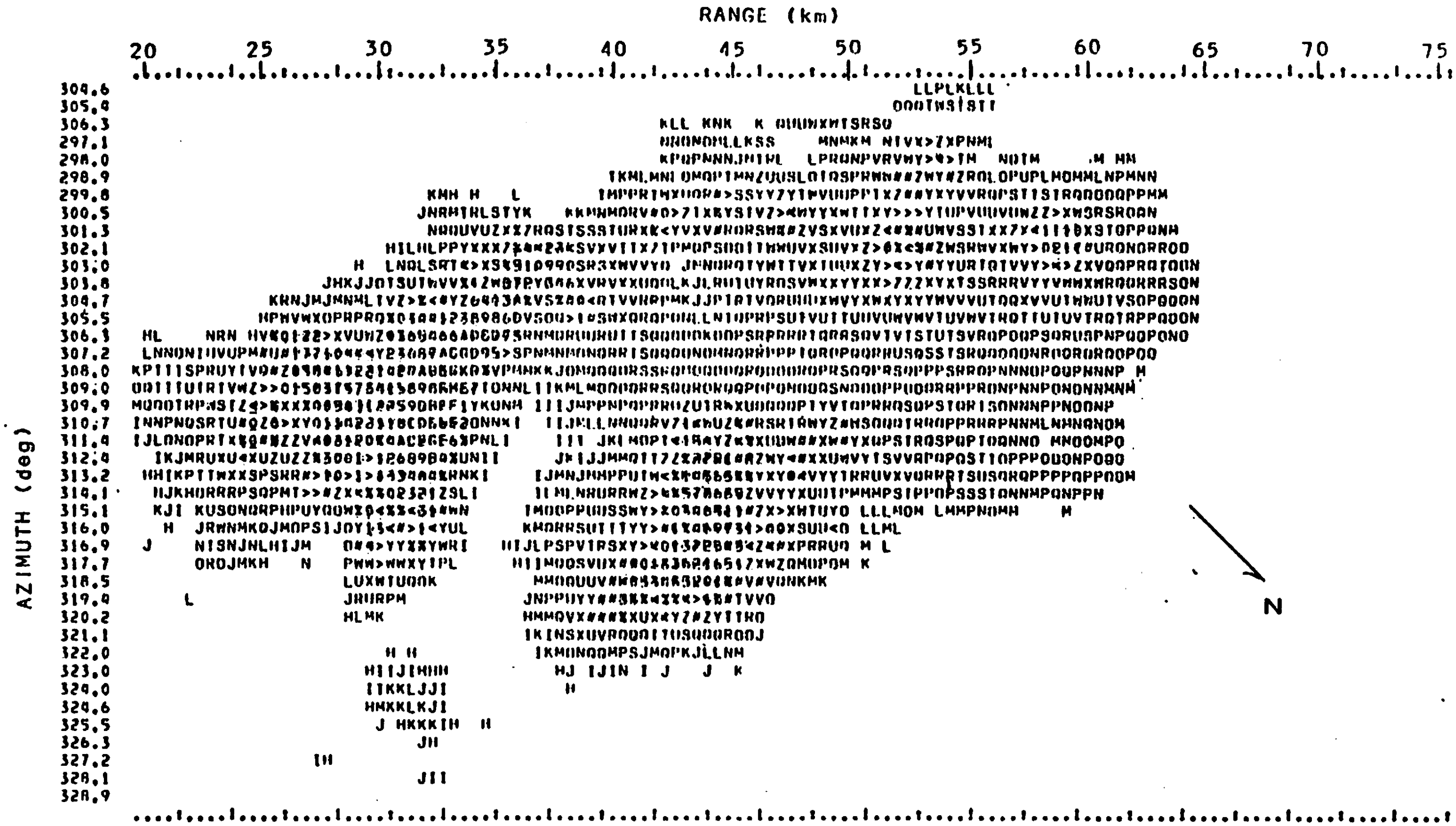
An extensive line organization, oriented WNW-ESE existed from 1450 CDT to 1600 CDT with principal growth on the south side of the line. A new area developed to the south of the line beginning about 1605 CDT and lasting until 1800. This region ultimately became a SW-NE line consisting of a series of cells, each successive cell originating to the southwest of the previous cell. Individual cells in the lines moved from the north to the south. The orientation of the original line was nearly perpendicular to the upper level wind flow. The orientation of the SW-NE line was more nearly parallel to the upper level flow. A reflectivity plot at 1557 CDT (prior to initiation of the SW-NE line) is shown in Fig. 4. The new growth area (which began about 1530 CDT) is shown toward the bottom of the figure.

The WNW-ESE line lasted from about 1451 CDT to around 1700 CDT as a recognizable entity. The SW-NE line started at 1605 CDT and the final cells in the line were still present at 1750 CDT. Both line organizations had relatively long lifetimes and rather flat structural characteristics without strong cellular activity. The associated precipitation characteristics are prolonged, widespread rain of moderate intensity.

6.3 July 19, 1975

During the early afternoon a N-S line organization developed with cells moving from the west to the east and with the line oriented nearly perpendicular to the mean wind vector. New cells developed on the north side of the line. The duration of the line organization was from about 1325 CDT to around 1450 CDT.

From 1500 CDT to 1700 CDT a series of cells in elongated lines moved from the west and southwest toward an area about 20-30 km south of Snyder. This region formed into an extensive, organized convergence area as indicated in Fig. 5. As shown in the figure there are indications of organized inflow and a hook echo in conjunction with the system. The organized pattern dominated the precipitation in the area until 1830 CDT. During the early stages of the development (1500-1600 CDT) new cells formed along lines to the west of the preceding cells (upwind). After 1600 CDT the precipitation cells became longer-lived and approached steady, moderate to heavy rain characteristics.



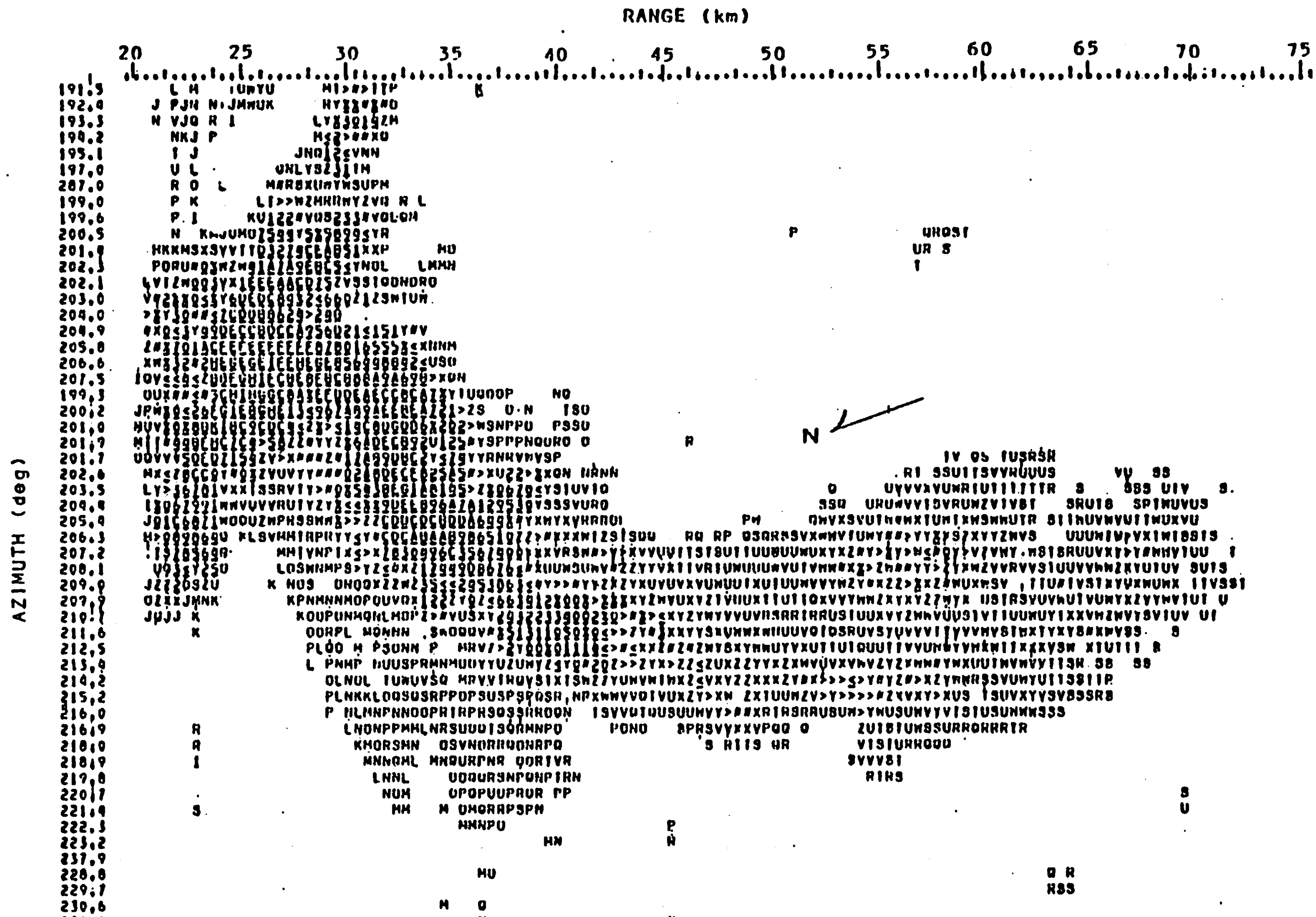
TOTAL ECHO AREA = .14902E+06 ACRES
AVERAGE MARSHALL-PALMER RAINFALL RATE = .37503E+04 ACRE-FT/HR, AIRCRAFT Z/R RAINFALL RATE = .28130E+04 ACRE-FT/HR

DBZ	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
SYMBOL	<	%	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	#	>

DBZ	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
SYMBOL	$	%	0	‡	2	3	4	5	6	7	8	9	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	#	>

15157

Fig. 4 . BSCAN Snyder, Texas 12 July 1975 - 1557 CDT



DBZ	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
SYMBOL	<	%	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	G	H

DBZ	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
SYMBOL	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	#	>

DBZ	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
SYMBOL	[illegible]	%	0	1	2	3	4	5	6	7	8	9	A	B	[illegible]	D	[illegible]	[illegible]	[illegible]	H

DBZ	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
SYMBOL	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	#	>

15:57

Fig. 5 . BSCAN Snyder, Texas 19 July 1975 - 1637 CDT

6.4 July 24, 1975

Beginning near 0000 CDT a NE-SW line of cells developed oriented nearly perpendicular to the mean wind vector. The line consisted of a series of distinct cells each elongated in a NNW-SSE direction paralleling the mean wind. New cell growth generally occurred on the north side of the line with the individual cells moving to the southeast. The line structure at 0045 CDT is shown in Fig. 6. The line had largely dissipated with flattening cells by 0120 CDT. Thereafter, until 0245 CDT the organizational structure of the cells was more of a random nature with decreasing convective activity. Peak convective activity occurred about 0025 CDT. Area activity decreased after this time.

6.5 August 2, 1975

Marked line organization was present on August 2. The orientation of the first line was northwest to southeast beginning about 1500 CDT. Peak activity occurred near 1600 CDT. The line existed until about 1700 CDT. Movement of individual cells in the line was from the north in agreement with the upper level winds. The line itself was oriented at an angle of about 45° across the wind. An example of the line at 1620 CDT is shown in Fig. 7. New cell growth occurred on the west side of the line as it moved toward the south. The line was well-organized into a nearly-steady state condition with successive cells in the line tending to merge with each other.

A second line developed parallel to and to the north of the first line around 1700 CDT. Peak activity occurred near 1720 CDT and the line gradually dissipated, ending near 1800 CDT. New growth appeared on the northwest side of the principal cells. The line itself was not as well organized or developed as the first line.

6.6 August 14, 1975

Two parallel lines of cells developed to the south and southwest of Snyder about 1700 CDT. Cell movement was from the southwest and the lines were organized along the upper level wind flow. The line to the south continued until 1840 CDT while the line to the southwest (Fig. 8) lasted until 2000 CDT. New cell growth occurred on the southwest end (upwind side) of the lines during their lifetimes. Individual cells in the line were distinctive and well-organized. By 1845 there was a tendency for small, isolated cells to develop in the vicinity of the principal organized system.

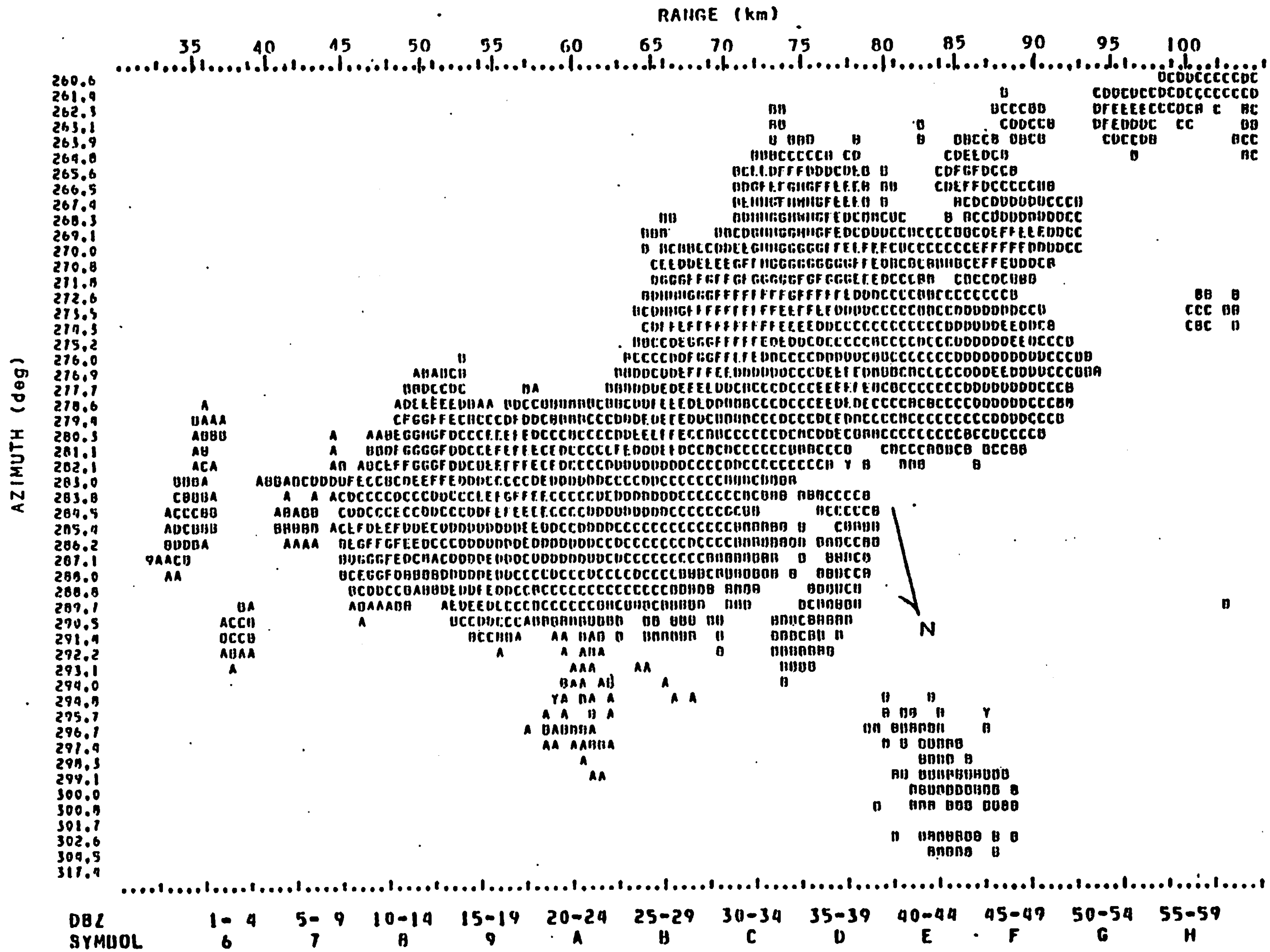


Fig. 6 . BSCAN Snyder, Texas 24 July 1975 - 0035 CDT

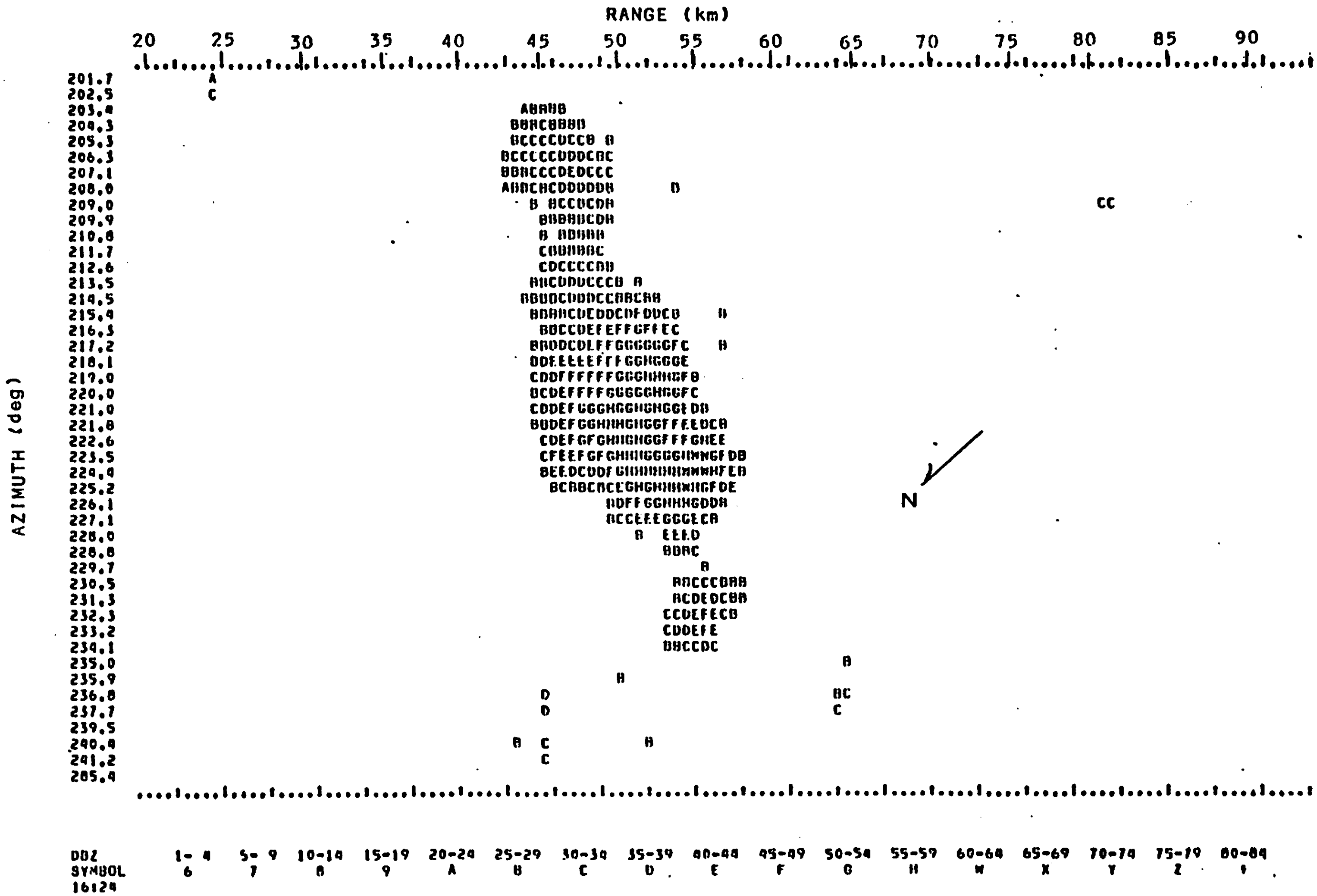


Fig. 7 . BSCAN Snyder, Texas 2 August 1975 - 1624 CDT

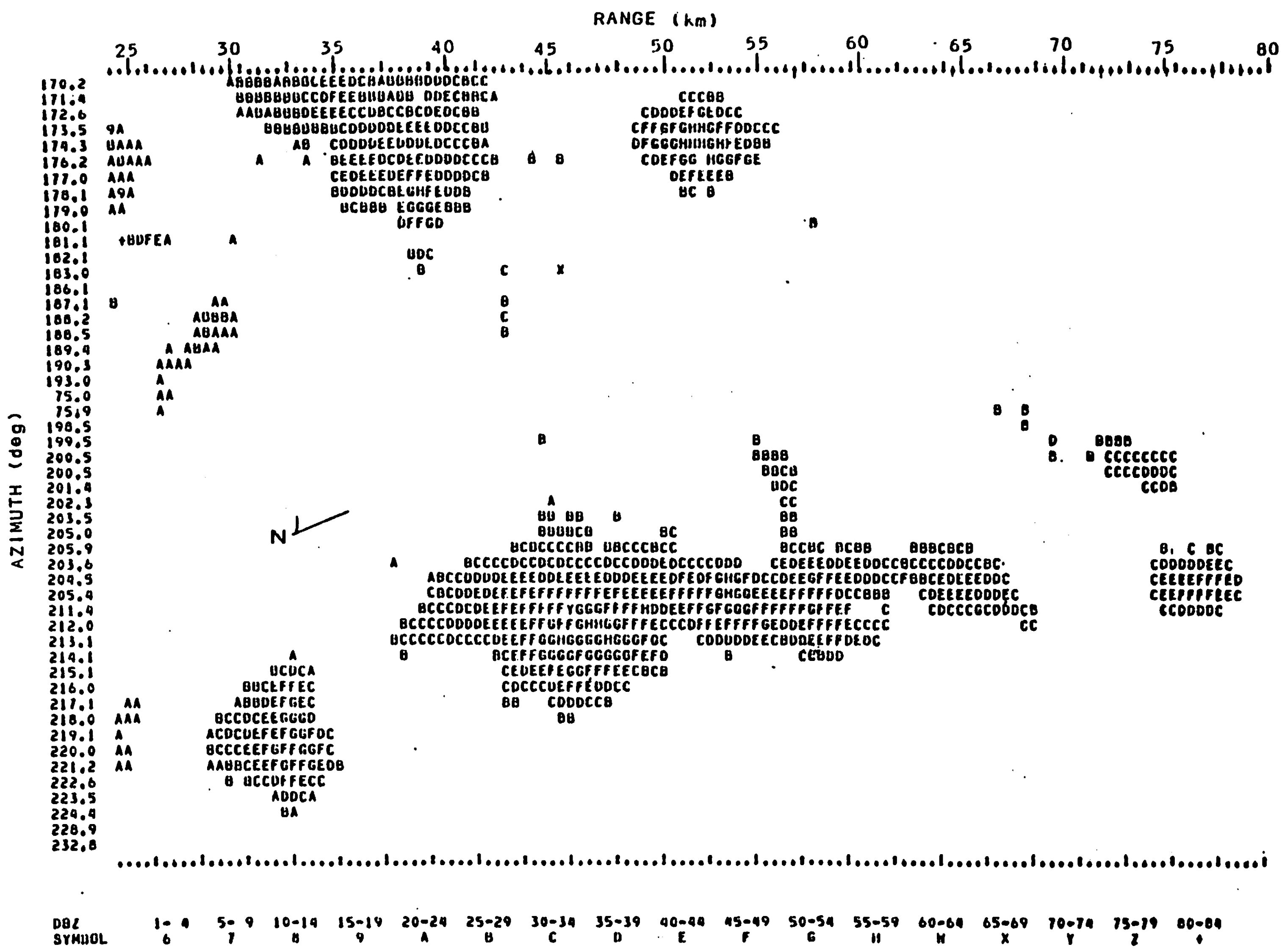


Fig. 8 . BSCAN Snyder, Texas 14 August 1975 - 1802 CDT

7. Analysis of Results

7.1 Timing of the Seeding Events

Time-histories of all 30 case studied are given in the Appendix. These plots include the history of the precipitation rate, area and cloud top as a function of time. Also shown is the period of seeding relative to the time-development of the cell.

Figure 9 illustrates one example of a relationship between seeding time and cell development. Peak rainfall rate for Cell A occurred at 1820 CDT while the seeding was carried out between 1823 and 1830 CDT. Minor cell developments in the system had peaked previously at 1730 and 1755 CDT. Subsequent to the seeding another cell development occurred with a cell top maximum at 1834 CDT and a peak rainfall rate between 1830 and 1839 CDT. Thereafter, the entire system underwent a general collapse with no major evidence of new cell developments. It is of interest to note the marked increase in precipitation area beginning about 1830, reaching a maximum area at 1855. This feature is characteristic and indicative of the final decay stages of the organized system when the earlier, localized convective activity decreases but spreads out over a wider area.

The base of the cell in Fig. 9 was 2.7 km msl and the top eventually reached 6.2 km. At an average updraft speed of 5 m/s (1000 ft/min) within the cloud the seeding material would take about 700 seconds to reach the -10°C (6.2 km) level in the cloud. Given another five minutes for the seeded rainfall to fall to the cloud base, any seeding effect should be visible at cloud base in about 15 minutes, although some variability due to variations in updraft speed should be expected.

According to this time criterion for the seeding effect to appear, there is some possibility that the rainfall rate observed at 1837 (Fig. 9) might have been influenced by seeding but only a marginal case can be developed. In any event, the remainder of the precipitation history for Cell A was not likely to have been affected. The total precipitation from the system (area under the curve in Fig. 9) of 284 acre-ft might include a few percent contribution, at most, which could be attributed to the seeding.

Figure 10 illustrates another case of a cell time-history. In this case, the peak rainfall rate occurred at 1731 CDT and there was no indication of subsequent cell development in the history of the system.

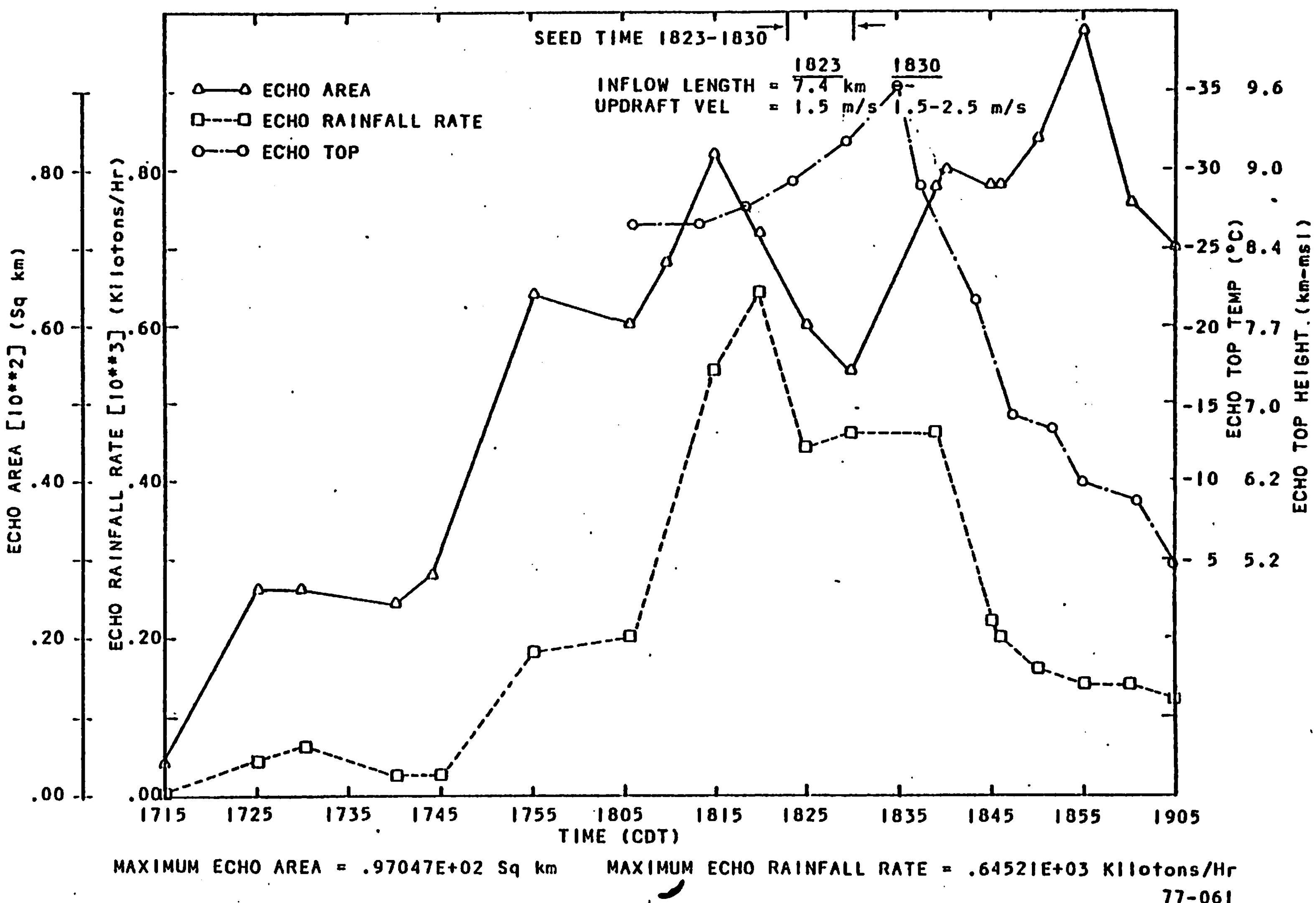


Figure 9. Echo Time History - Snyder, Texas 7/11/75
Echo A, Seed

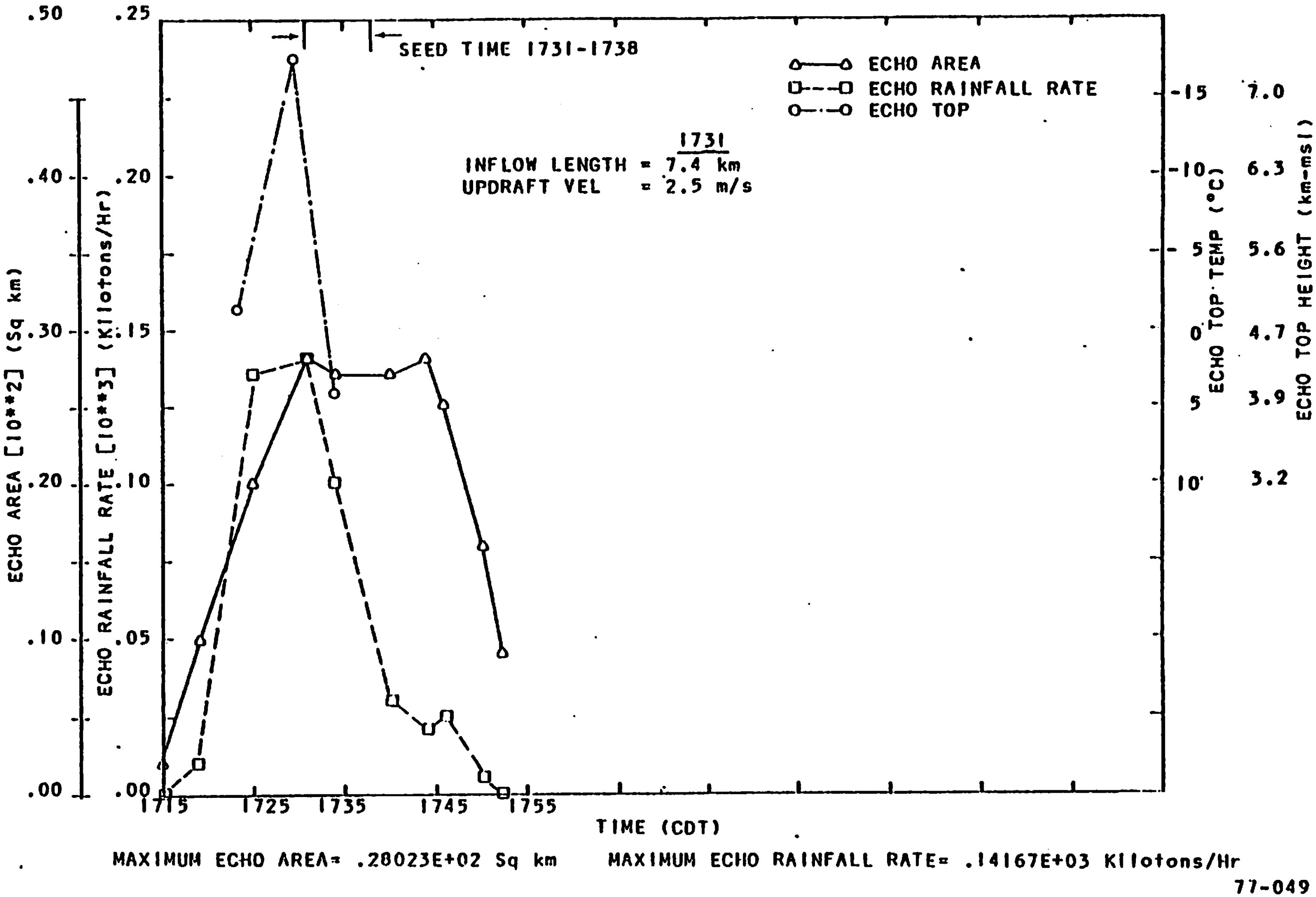


Figure 10. Echo Time History - Snyder, Texas 8/14/75
Echo BB, Seed

Seeding occurred from 1731-1738 CDT. From the time criterion described above (about 15 minutes for the effect to appear at cloud base) there is no significant possibility of the seeding having affected the cell precipitation.

Figure 11 illustrates a different type of cell history. Two distinct peaks in rainfall rate occurred corresponding to two principal cells in the system. Seeding was initiated at 1540 CDT, immediately after the initial peak and about 14 minutes before the second peak. It is reasonable to expect that the seeding material might have affected the second precipitation development but again on a somewhat marginal basis. The second cell produced a total of about 42 acre-ft so that productivity of the seeding would not have been great.

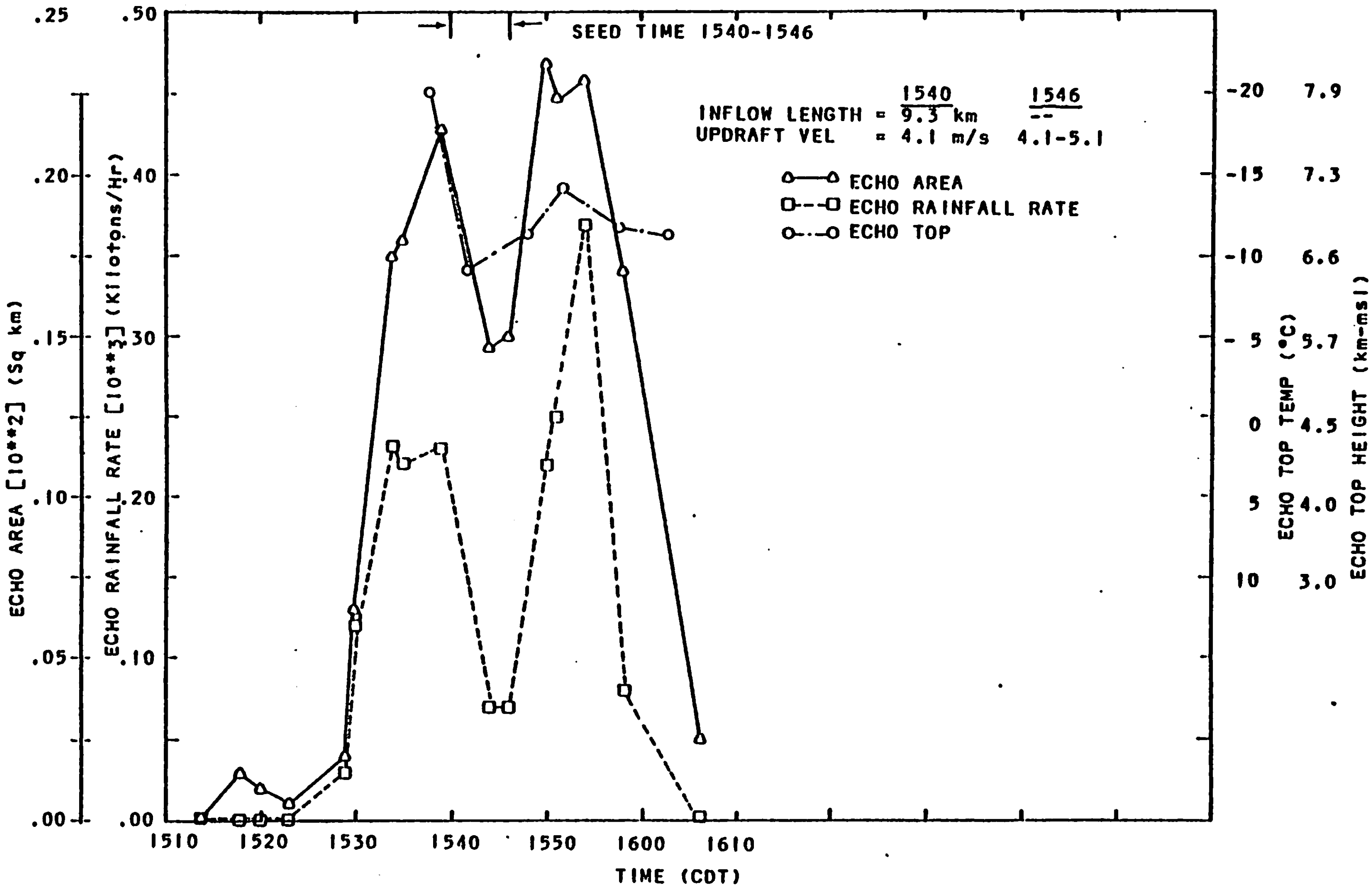
Similar case study examinations were made for each of the 30 cells studied. The 22 seeded cases were then divided into those where the timing of the seeding could have led to a precipitation effect and those where there was no significant possibility of such an effect. The following cells include the cases of possible effect:

POSSIBLE SEEDING EFFECTS

Cell	Date (1975)	Seeding Time (CDT)
A	July 11	1823-1830
F	12	1623-1637
H	12	1724-1732
I*	19	1358-1405
L*	24	0009-0016
U	August 2	1558-1601
V	2	1540-1546
AA	14	1708-1715

* Seeding effect in different cell

In the remaining 15 seeding cases studied it was not possible to associate the seeding with any significant change in the precipitation history. These conclusions were drawn from examination of the time-histories (e.g., Figs. 8-10) and, in addition, the scan-by-scan plots



MAXIMUM ECHO AREA = .23243E+02 Sq km MAXIMUM ECHO RAINFALL RATE = .37116E+03 Kilotons/Hr

77-058

Figure 11. Echo Time History - Snyder, Texas 8/2/75
Echo V, Seed

(e.g., Fig. 1) of the reflectivities related to the seeding locations. The latter studies provided an opportunity to search for nearby adjacent cells which may not have been used in the time-history plots but might have been affected by the seeding. This brought to light the two cases shown by asterisk in the preceding table.

7.2 Top Temperatures of Seeded Clouds

Table 2 shows the lowest observed top temperatures for all of the cell cases for which top measurements could be obtained. In the balance of the cases the top could not be distinguished adequately due to large range from the radar or due to attenuation from intervening cells.

For those cases with adequate top data, four of the cells showed coldest temperatures warmer than -10°C. When consideration is given to a time requirement for nucleation and growth to precipitation size, coldest top temperatures of warmer than -10°C do not provide adequate time for precipitation effects to develop. Although only four of the seeded cells showed this problem, it is apparently a factor to be concerned with in future seeding operations.

7.3 Precipitation Results

Table 3 shows a summary of the observed cells in terms of maximum area. These data have been plotted in Figs. 12 and 13 where maximum cloud depth is used as an indicator of total cell precipitation and/or peak rain area.

Similar plots were made by Dennis, et al. (1974) in an analysis of the Cloud Catcher seeding program in South Dakota Best-fit lines for the Cloud Catcher data are also shown in Figs. 12 and 13. In Fig. 12 the difference between the South Dakota and Texas best-fit lines appears to be attributable to a slightly different Z-R relation for transformation of radar reflectivity into rainfall rate. The slight difference in the two Z-R relations used tends to produce slightly lower rainfall amounts in South Dakota at high rainfall rates. The difference noted in Fig. 13 between the South Dakota and Texas best-fit lines results from a difference in definition of "rain area". In the case of South Dakota the area was defined as being enclosed by the 30 dbZ contour. For Texas all reflectivities over 20 dbZ were counted as a part of the rain area. The Texas rain areas are therefore considerably larger than the South Dakota areas for the same cloud depth although the slopes of the lines are similar.

TABLE 2. LOWEST TEMPERATURES OF CELL TOPS

Cell	Seed or No-seed	Date (1975)	Time (CDT)	Lowest Temperature (°C)
A	S	July 11	1834	-11
B	S	11	1755	- 8
C	S	11	1805	-12
D_1	S	11	1850	3
F	S	12	1610	-14
G	S	12	1637	-17
H	S	12	1707	- 2
I	S	19	1349	-11
J	S	19	~1715	<-45
N	S	24	0035	<-45
S	NS	24	0157	-31
U	S	August 2	1625	-34
V	S	2	1539	-21
W	S	2	1549	-27
X	NS	2	1546	-17
Y	NS	2	1634	-40
Z	S	2	1714	- 7
AA	S	14	1733	-24
BB	S	14	1729	-17
CC	S	14	1821	-17
DD	S	14	~1850	<-45

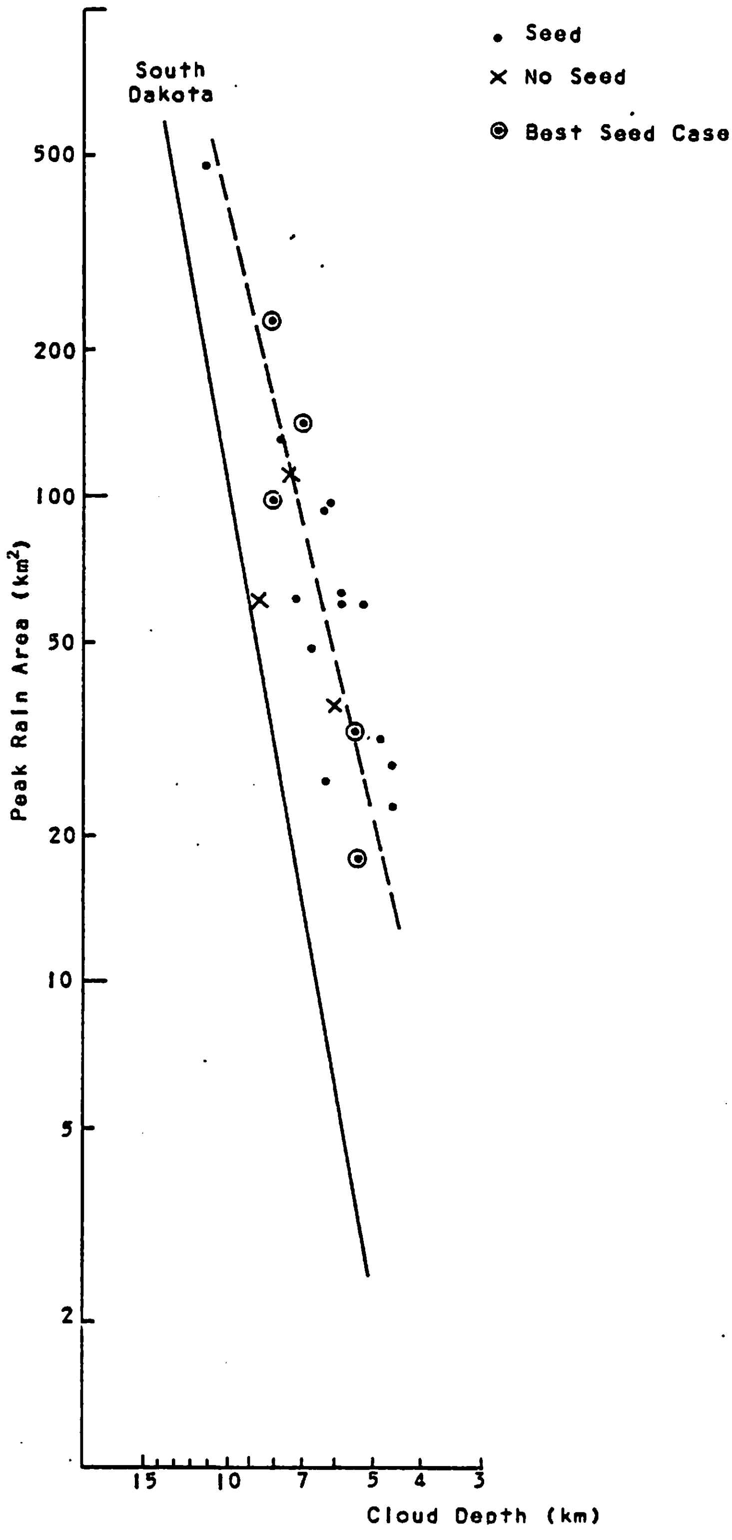


Fig. 13. Relationship between cloud depth and peak rain area.

The data points in Figs. 12 and 13 have been divided into seed, no-seed and "best-seed" cases. The "best-seed" cases include cells F, H, U, V, and AA where it was determined that the seeding material was released at an appropriate time and location for a possible effect to have occurred. From the results shown in Figs. 12 and 13 there is no significant difference between the seed, no-seed, and best-seed cases in regard to total rainfall amount as well as peak rain area.

One of the possible reasons for the lack of apparent seeding effects in Figs. 12 and 13 may be the relatively small amounts of seeding material actually available to each of the "best-seed" cells. The following table gives the seeding times and amounts for each of these cells:

TABLE 4. SEEDING TIMES AND AMOUNTS PER CELL

Cell	Seeding Duration (minutes)	Seeding Amount (AgI) (g)
F	14	35.0
H	8	20.0
U	3	7.5
V	6	15.0
AA	7	17.5

In all of the cases it is likely that only a portion of the total AgI released actually got into the updraft and had an opportunity to be effective within the cloud. This, together with dilution of the material in the updraft in the cloud leads to relatively low concentrations available at nucleation levels.

7.4 Area Precipitation Characteristics

Total rainfall amounts within 90 nm of Snyder, Texas for the period July through August 16, 1975 have been plotted and contours of equal rainfall totals drawn (Figure 14). Data from the recording gages and the CRMWD fencepost gages were used to define the pattern inside the project area while the regularly reporting National Weather Service stations were used outside the project area.

Two large centers of rainfall maxima are shown in the figure. One of those is located slightly northeast of Big Spring and the other near Colorado City. Comparison of the stations in the maximum rainfall area with those immediately adjacent indicated that contributions to the maxima originated principally on July 19 and August 14 and 15.

Most of the excess rainfall contributing to the maximum northeast of Big Spring occurred when the seeding aircraft was not aloft. In particular, very substantial amounts of rainfall occurred in this area in the early morning hours of July 20, August 15 and 16 when no seeding was taking place. These rainfalls were shown in the fencepost gage records as having occurred on the previous day. For the maximum near Colorado City the largest contribution to the maximum occurred late on July 19 when a storm seeded northwest of Lake Thomas moved through the Colorado City area. Other contributions to the maximum also occurred during the early morning hours of August 15 and 16.

If the portion of the rainfall associated with non-seeded events were removed from the rainfall totals, most of the maximum northeast of Big Spring would disappear. Near Colorado City, however, an excess rainfall of 2-4 inches compared to the surrounding area would remain. This excess results almost entirely from the heavy storm of July 19 which moved through the area from the northwest.

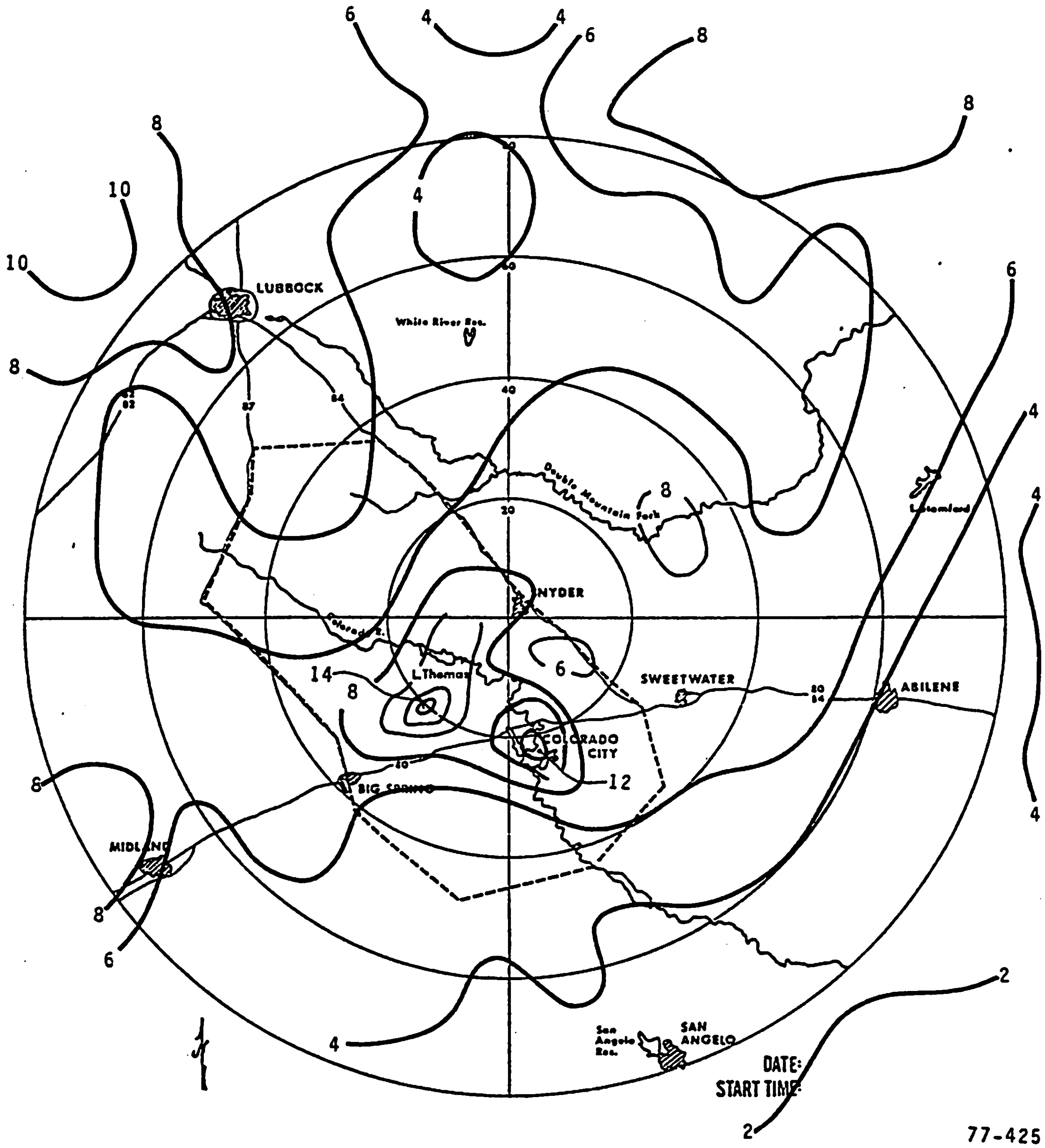


Figure 14. Total rainfall (inches) July-August 16, 1975

8. Discussion

The foregoing sections have not been able to delineate any significant effects attributable to seeding within the 30 cases examined for July-August 1975. In eight of the cases the seeding treatment was delivered at an appropriate time and location for the seeding effects to take place. However, in these cases, the total rainfall amounts attributable to seeding are likely to have been small compared to the total rain in the area but may, of course, have been of real benefit to the project area. The results shown in the preceding sections (particularly Figs. 12 and 13) differ from those reported elsewhere (e.g., Dennis et al., 1974) and it is of importance to examine the differences in the operational programs which might contribute to these differences in results.

The following comments describe some of the possible contributing factors which may have led to the present results.

1. Data Sample - Only 30 cases on a total of six days were examined in the present study. More favorable seeding results might very well appear on other days with somewhat different cloud conditions. The present results, however, do agree in principle with the studies of the 1974 data although the present report had more definitive data available for use.

2. Seeding Technique - The Big Spring program is designed to seed periphery cells which are formed, in succession, after a primary cell (or cells) has appeared on the radar. The purpose of the seeding is to extend the area and lifetime of the active precipitation region. This inevitably leads to the type of seeding pattern shown in Fig. 10 in which the seeding started at or slightly after the peak rainfall rate had already occurred at cloud base. It is precisely at this time (and because of this precipitation surge) that another updraft can occur adjacent to the precipitation cell. Unless the secondary cell is able to grow into precipitation stage, results such as shown in Fig. 10 will occur. The small proportion of appropriately seeded cases suggests that the secondary cells only occasionally develop to precipitation size. This leads to an apparent inefficiency in seeding effectiveness which is indicated in the preceding sections.

3. System Lifetime - It became apparent in the present study that there were two time scales of precipitation development present in the data. The first (and shorter) scale is related to the lifetimes of the

individual cells. Selection of the cases to be seeded seems to be strongly related to the period of peak development of the system as evidenced by the radar. In many cases, the seeding occurred after the system itself had started to dissipate. Under these conditions, the secondary clouds on the periphery of the system do not have the proper environment for growth.

4. Seeding Delivery Mode - Seeding at cloud base places a great burden on the selection of clouds to be seeded and particularly on the ability to recognize the proper cloud during its early stages of growth. Approximately 10 minutes of active growth must occur in order for the seeding material to be carried from cloud base to the effective levels. In a number of seeding cases the updraft does not continue long enough to assure this opportunity for effectiveness.

5. Seeding Amount - The amount of AgI material actually introduced into the clouds may frequently be relatively small. In some cases, only one pass (as part of a long line) may take place under the cloud. If the output of the pyrotechnic flares is assumed to be 6×10^{10} nuclei per minute effective at -8°C, use of an estimating technique developed by Smith, Chien and MacCready (1968) indicates a peak concentration of less than 0.1 per liter at the -8°C level if seeding took place at the 10°C level. Lower concentrations would be expected at off-centerline locations in the cloud.

By way of comparison, the Cloud Catcher program in South Dakota (Koscielski and Dennis, 1972) utilized pyrotechnic burn rates which were a factor of 10 larger than employed at Big Spring. A similar cloud base seeding program in Arizona (Weinstein and MacCready, 1969) burned an acetone-AgI solution which produced over two orders of magnitude more nuclei effective at -8°C. Total seeding amounts per cloud were of the order of 120 to 240 g of AgI in Arizona and 240 to 280 g in the Cloud Catcher work. These amounts are generally larger than those used per cloud in the Big Spring program.

9. Conclusions

1. Many of the seeding events observed show evidence of being seeded after the main precipitation activity had started to decrease. In a number of these cases there were no later cells of much significance which could have been associated with or attributed to the seeding.

2. The system of selection of seeding cases by radar frequently leads to initiation of the seeding during the dissipation stage of the organized system. Under these conditions, stimulation of new cell growth becomes particularly difficult.

3. In a number of cases, this seeding technique effectively provides seeding material to the new growth areas formed during the collapse of earlier precipitation cells. By waiting until well-developed systems appear on the radar, however, there is not only substantial danger of seeding during the system collapse but a substantial portion of the rain in the area cannot ever be affected by the seeding. This, in effect, limits the seeding opportunities in the area by waiting until well-developed cells or systems are present.

4. The results of the present study should not be construed to mean that effects of seeding in the area do not exist. The techniques used in the evaluation are not sensitive to small variations and effects may have occurred in areas which were not examined. The conclusion reached in the study suggests that a substantial portion of the rainfall in the area during the seeding periods, however, was not affected by the seeding.

5. Prior to this study and its predecessor, there had been little or no opportunity to examine the results of the seeding program in Big Spring in any detail. A very considerable amount has been learned during the study which should be useful in future operations. The recommendations in the following section are aimed in this direction. It is hoped that the CRMWD program can continue to carry out the vital seeding operations which can form the basis for development of a steadily-improving seeding technology.

10. Recommendations

1. Attention should be directed toward the life cycle of the organized cloud system so that seeding can be concentrated in the developing stages of the system rather than the dissipating stages.

2. Serious efforts should be made to seed earlier in the cell (or system) lifetime to avoid the problem of timing the seeding to the proper stage of cloud development.

3. Attempts should be made to introduce larger amounts of AgI into each cell of interest. This might be accomplished by more orbits at cloud base and/or by increasing the burn rate of AgI.

4. Consideration should be given to seeding at cloud-top levels, at least on an exploratory basis. This would minimize the problem of delivery of the material at the right time and in the proper amount.

5. Efforts should be made to monitor the results of the seeding in some systematic manner so that continued development of the seeding technology can take place.

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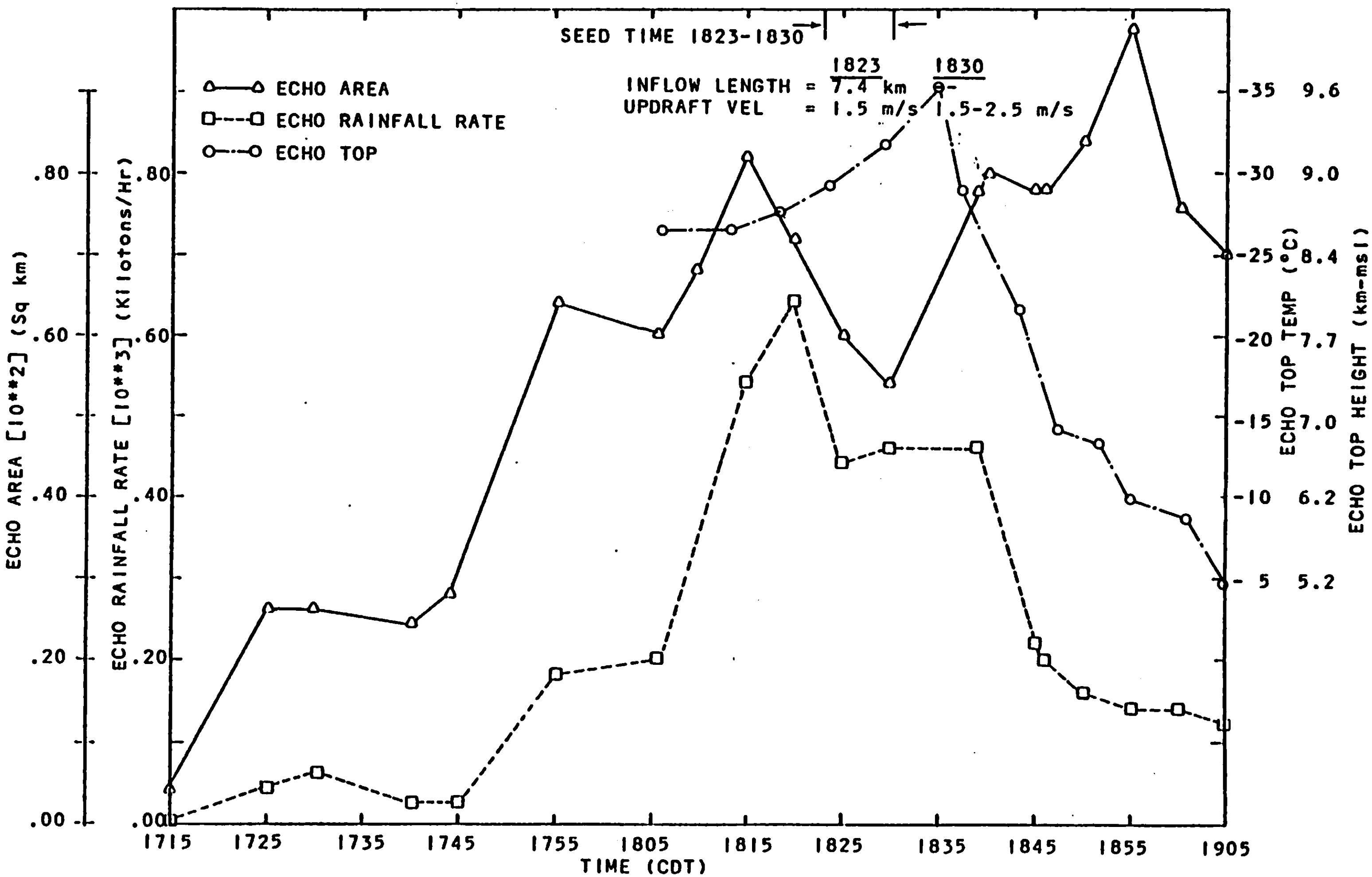
Weinstein, A. I. and P. B. MacCready, Jr., 1969: An isolated cumulus cloud modification project. J. Amer. Meteor., Vol. 8 No. 6, 936-947.

APPENDIX

TIME-HISTORY PLOTS OF CASE STUDIES



MAXIMUM ECHO AREA = .97047E+02 Sq km MAXIMUM ECHO RAINFALL RATE = .64521E+03 Kilotons/Hr

77-061

Figure 1a. Echo Time History - Snyder, Texas 7/11/75
Echo A, Seed

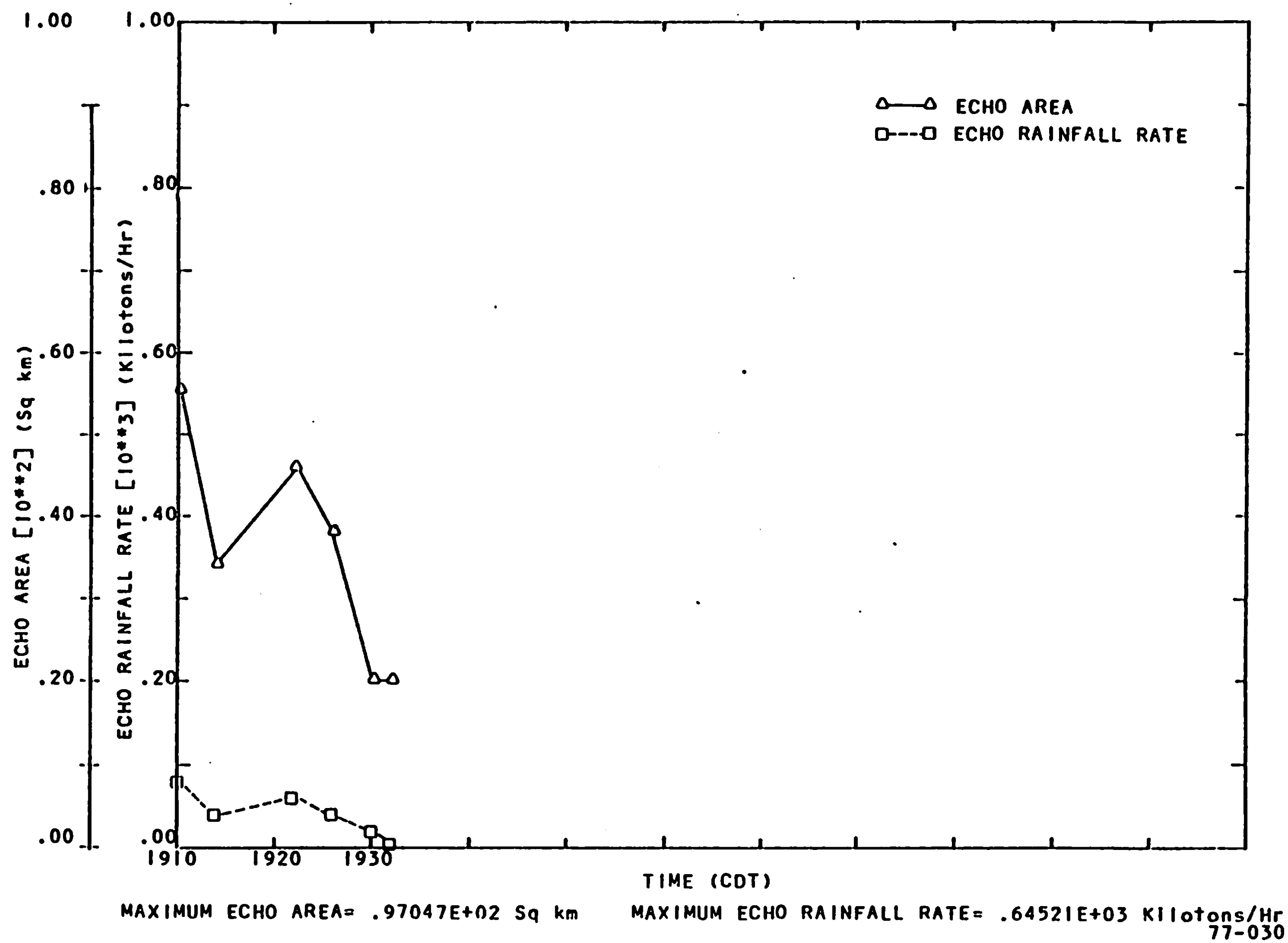
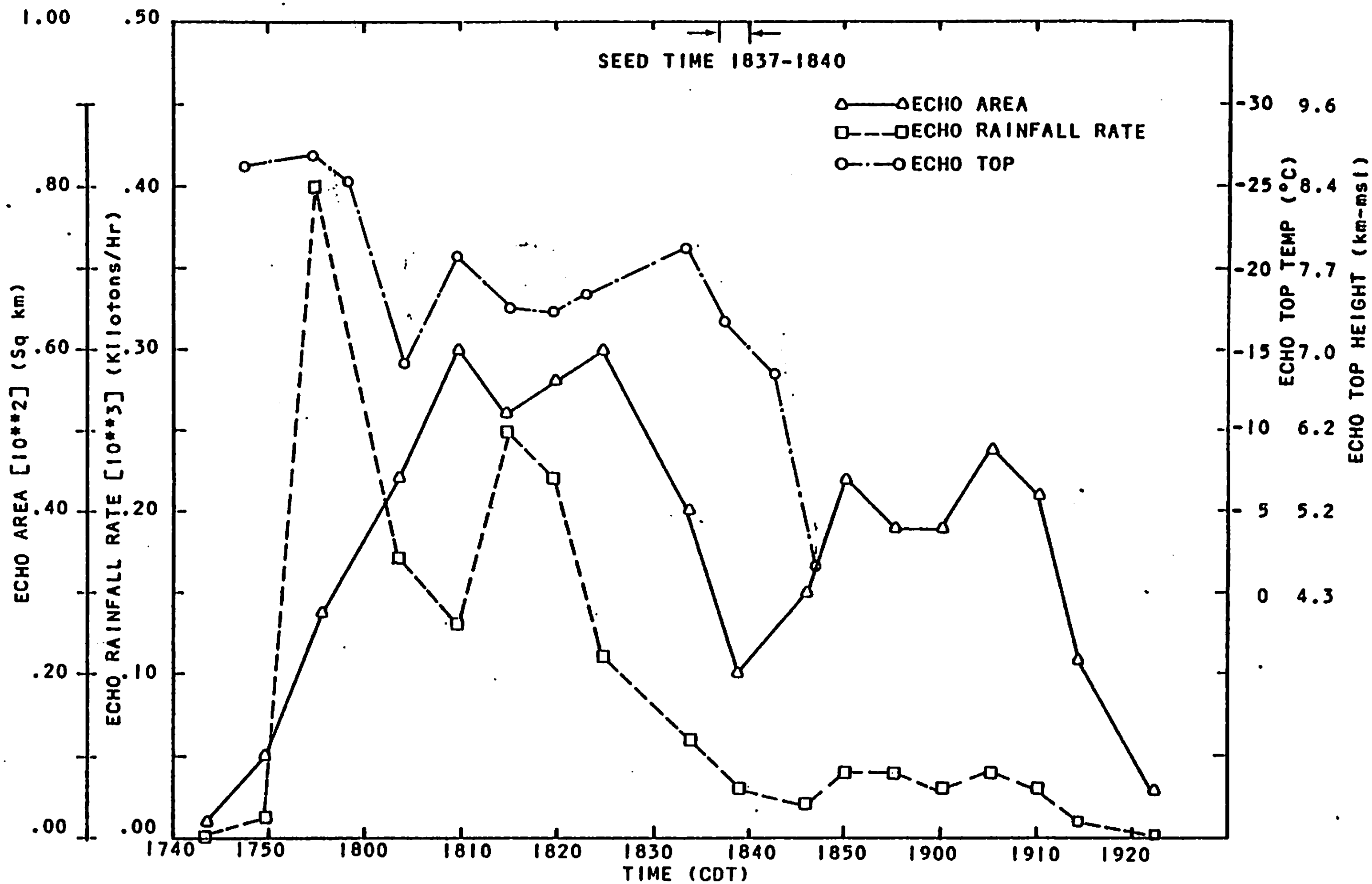


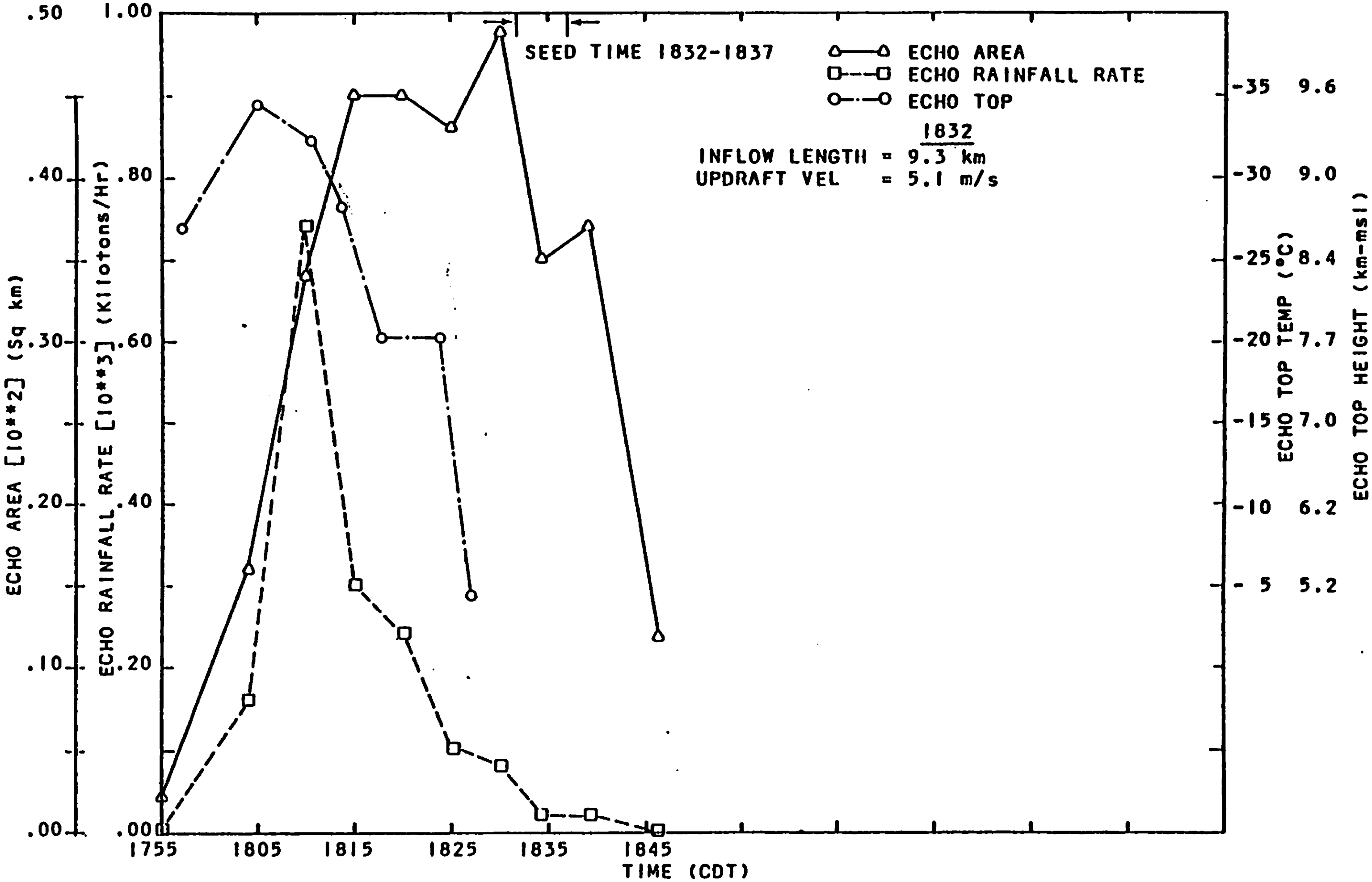
Figure 1b. Echo Time History - Snyder, Texas 7/11/75
Echo A, Seed (Continued)



MAXIMUM ECHO AREA= .59057E+02 Sq km   MAXIMUM ECHO RAINFALL RATE= .70425E+03 Kilotons/Hr

77-039

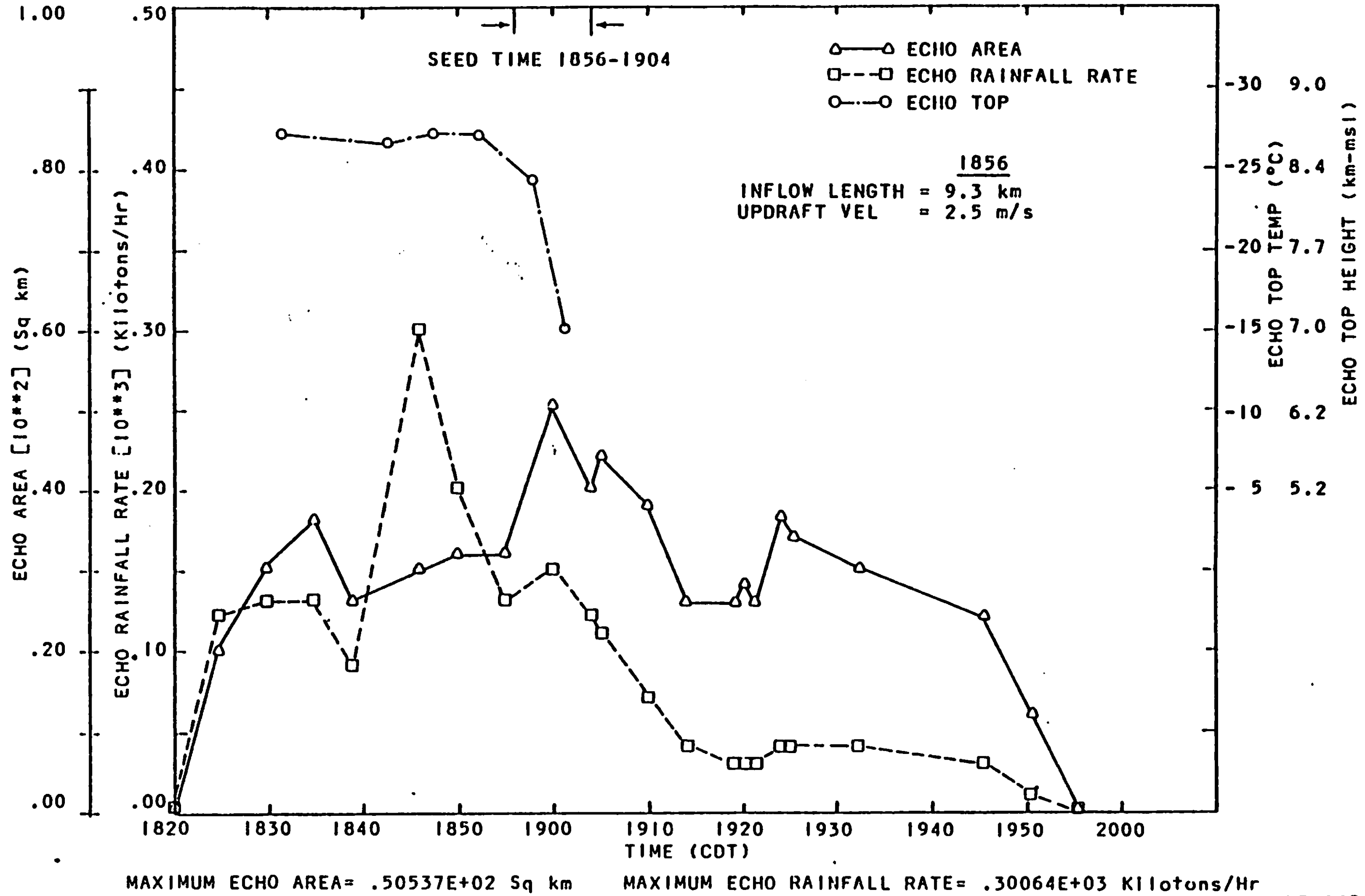
Figure 2. Echo Time History - Snyder, Texas 7/11/75
Echo B, Seed



MAXIMUM ECHO AREA= .48323E+2 Sq km   MAXIMUM ECHO RAINFALL RATE= .73200E+03 Kilotons/Hr

77-041

Figure 3. Echo Time History - Snyder, Texas 7/11/75
Echo C, Seed



77-043

Figure 4. Echo Time History - Snyder, Texas 7/11/75
Echo D_2, Seed

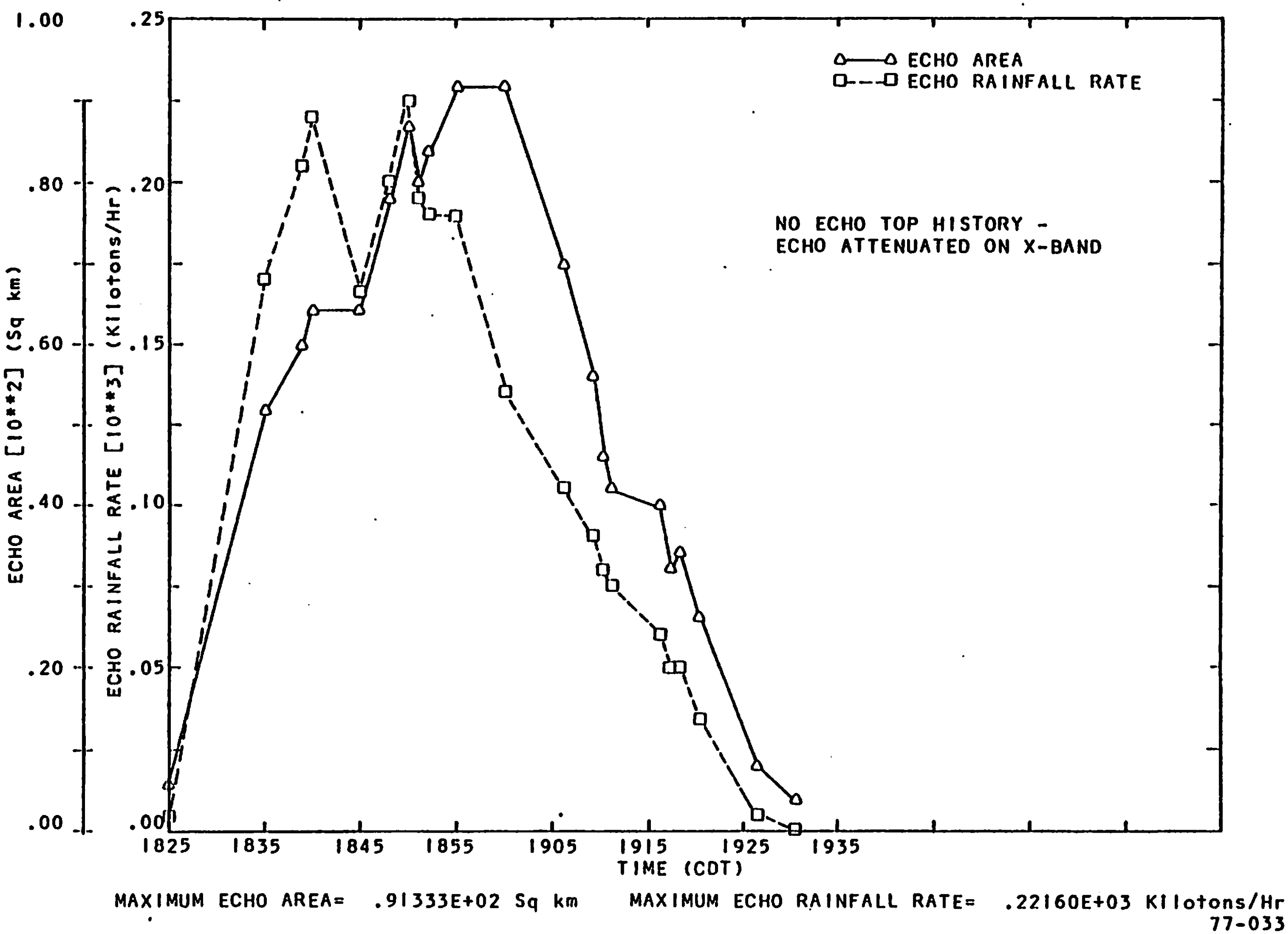


Figure 5. Echo Time History - Snyder, Texas 7/11/75
Echo D_1, No Seed

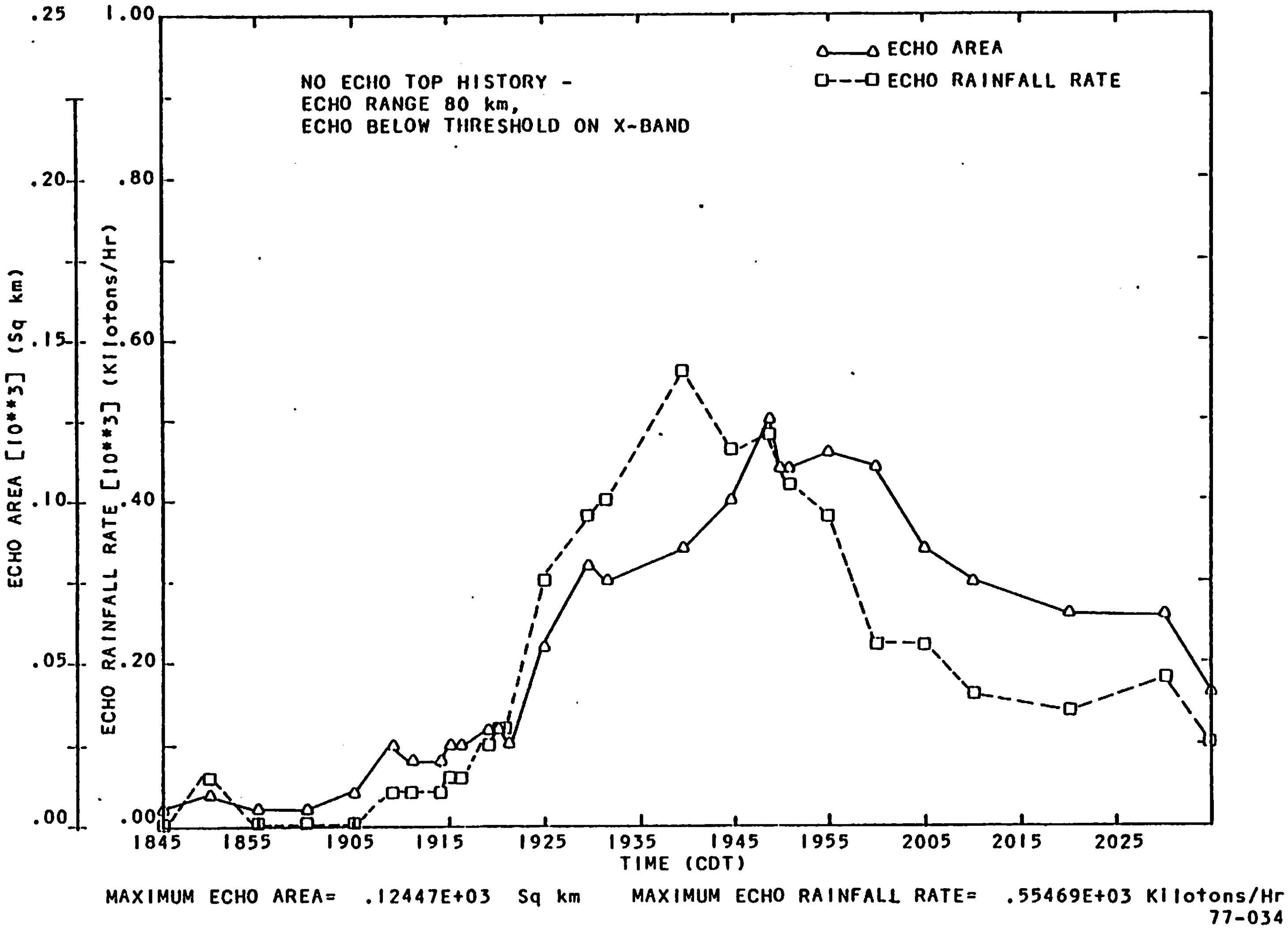
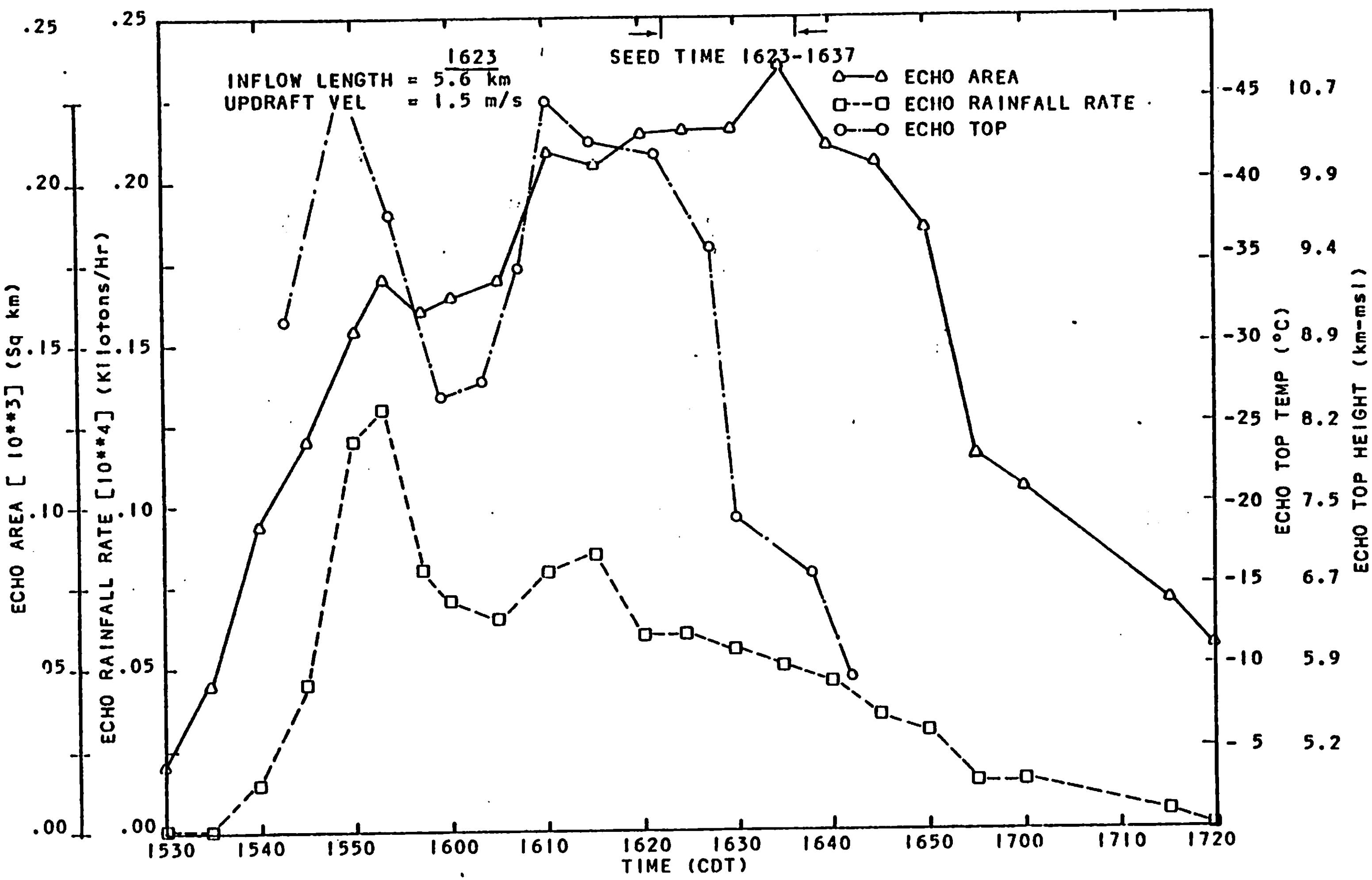


Figure 6. Echo Time History - Snyder, Texas 7/11/75
Echo E, No Seed



MAXIMUM ECHO AREA= .23431E+03 Sq km   MAXIMUM ECHO RAINFALL RATE= .12920E+04 Kilotons/Hr

77-040

Figure 7. Echo Time History - Snyder, Texas 7/12/75
Echo F, Seed

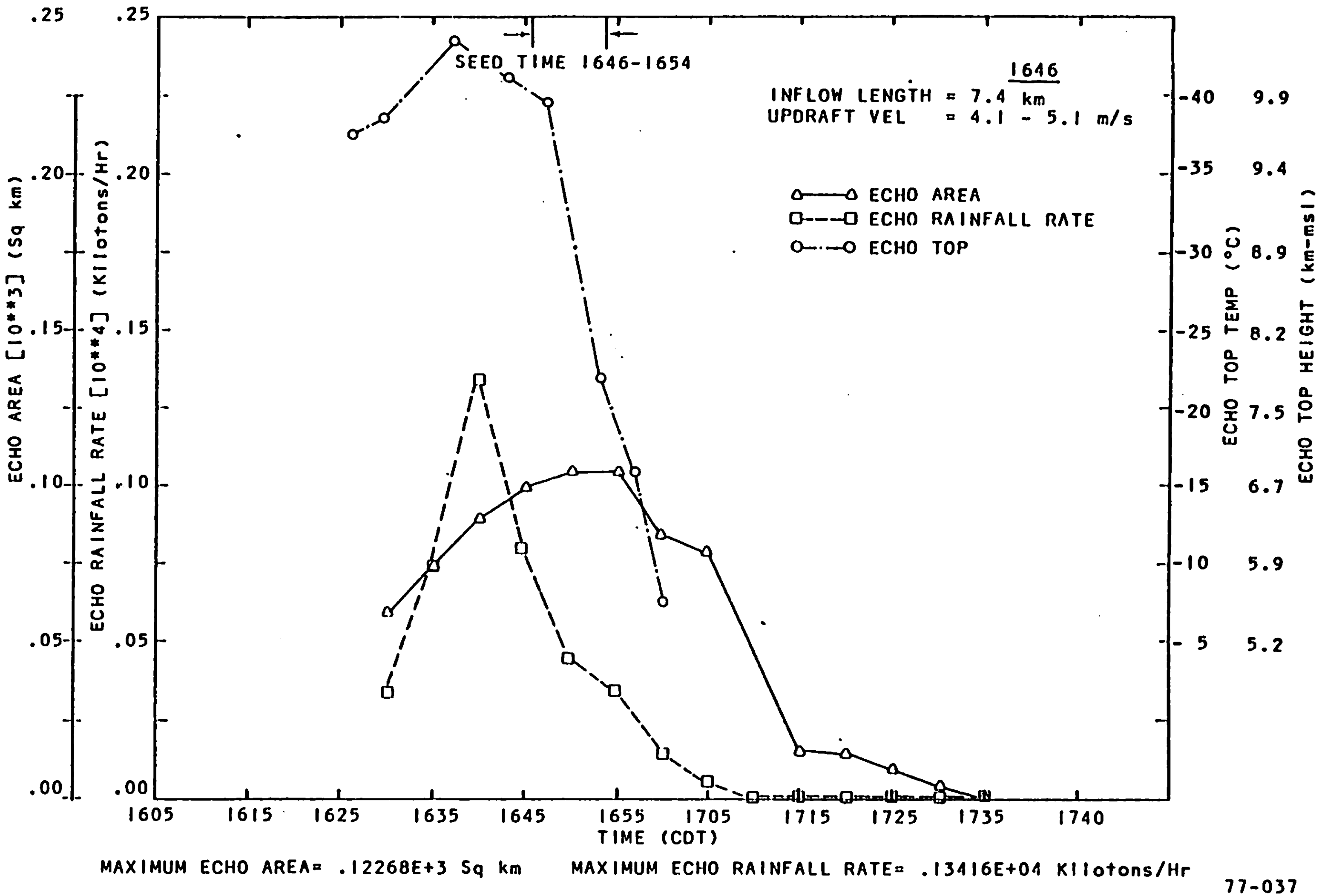


Figure 8. Echo Time History - Snyder, Texas 7/12/75
Echo G, Seed

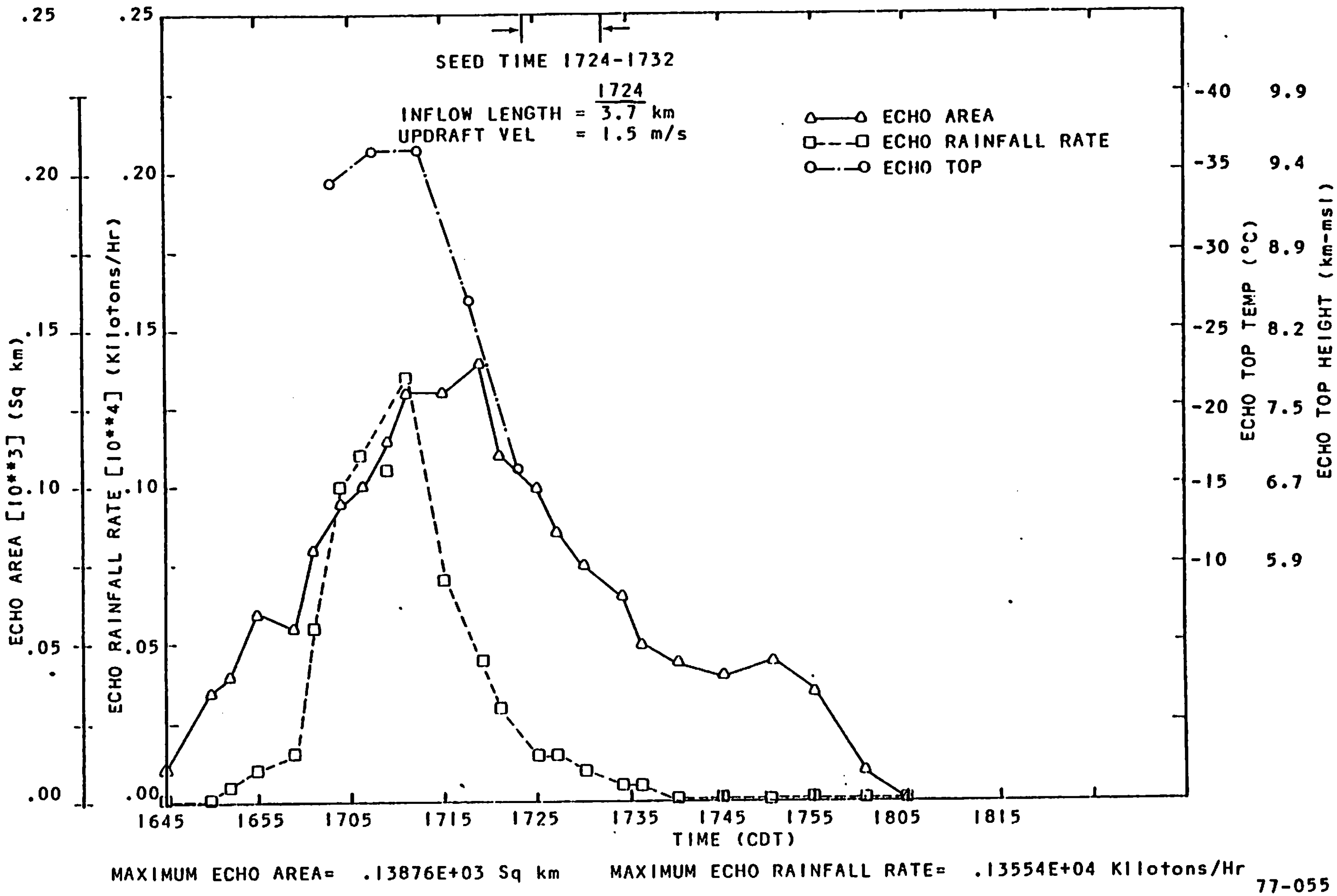
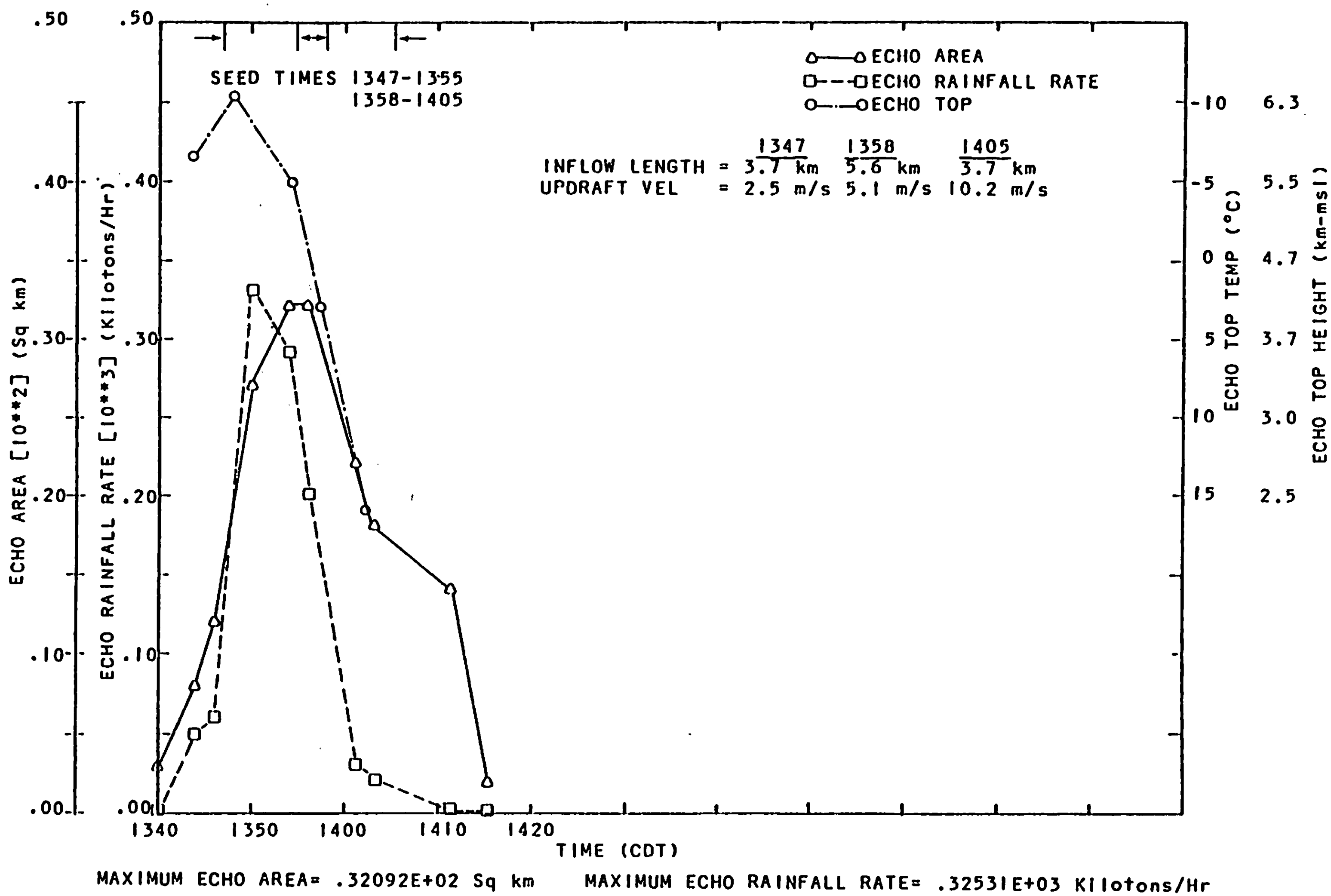


Figure 9. Echo Time History - Snyder, Texas 7/12/75
Echo H, Seed



77-036

Figure 10. Echo Time History - Snyder, Texas 7/19/75
Echo I, Seed

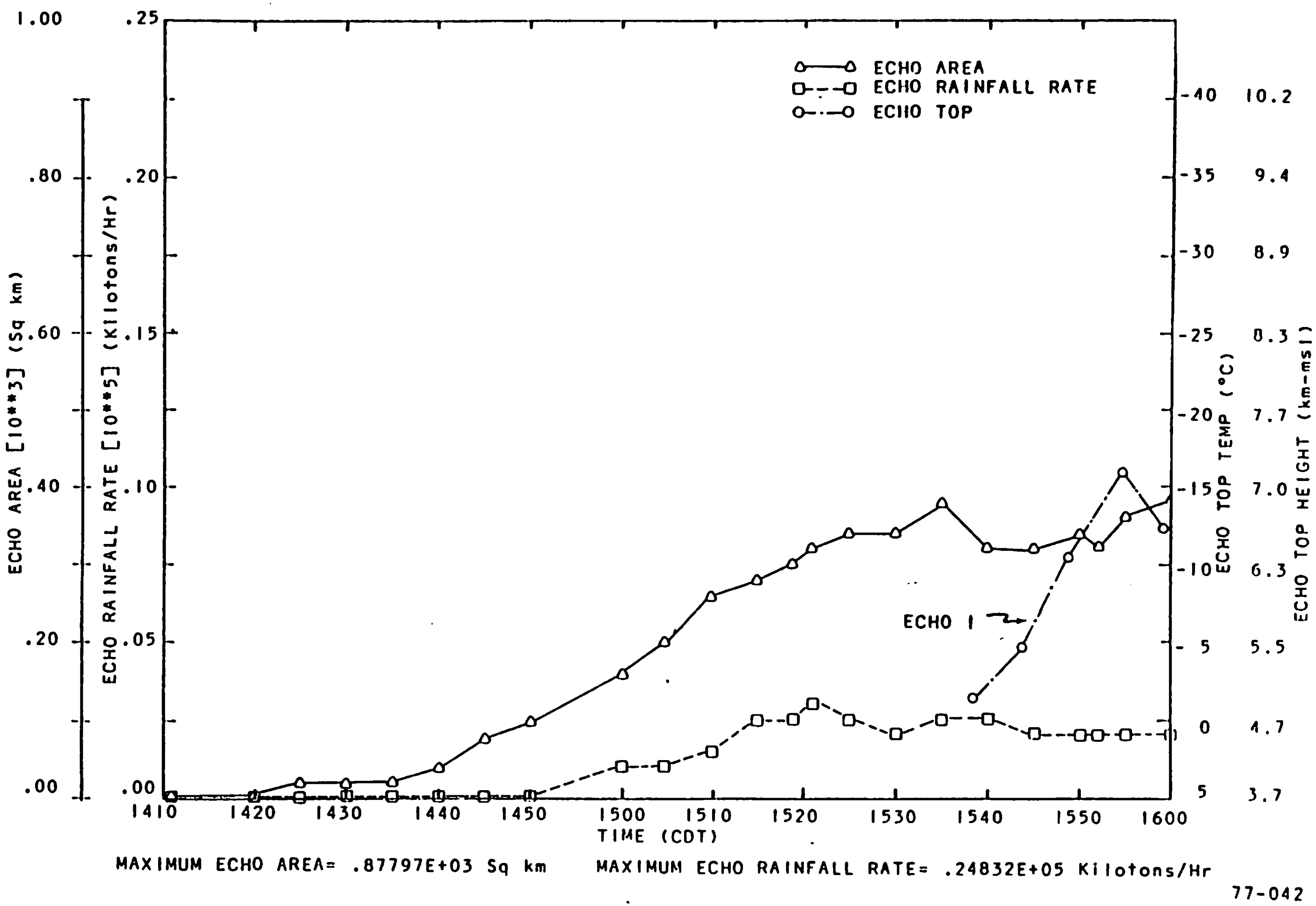


Figure 11a. Echo Time History - Snyder, Texas 7/19/75
Echo J, Seed

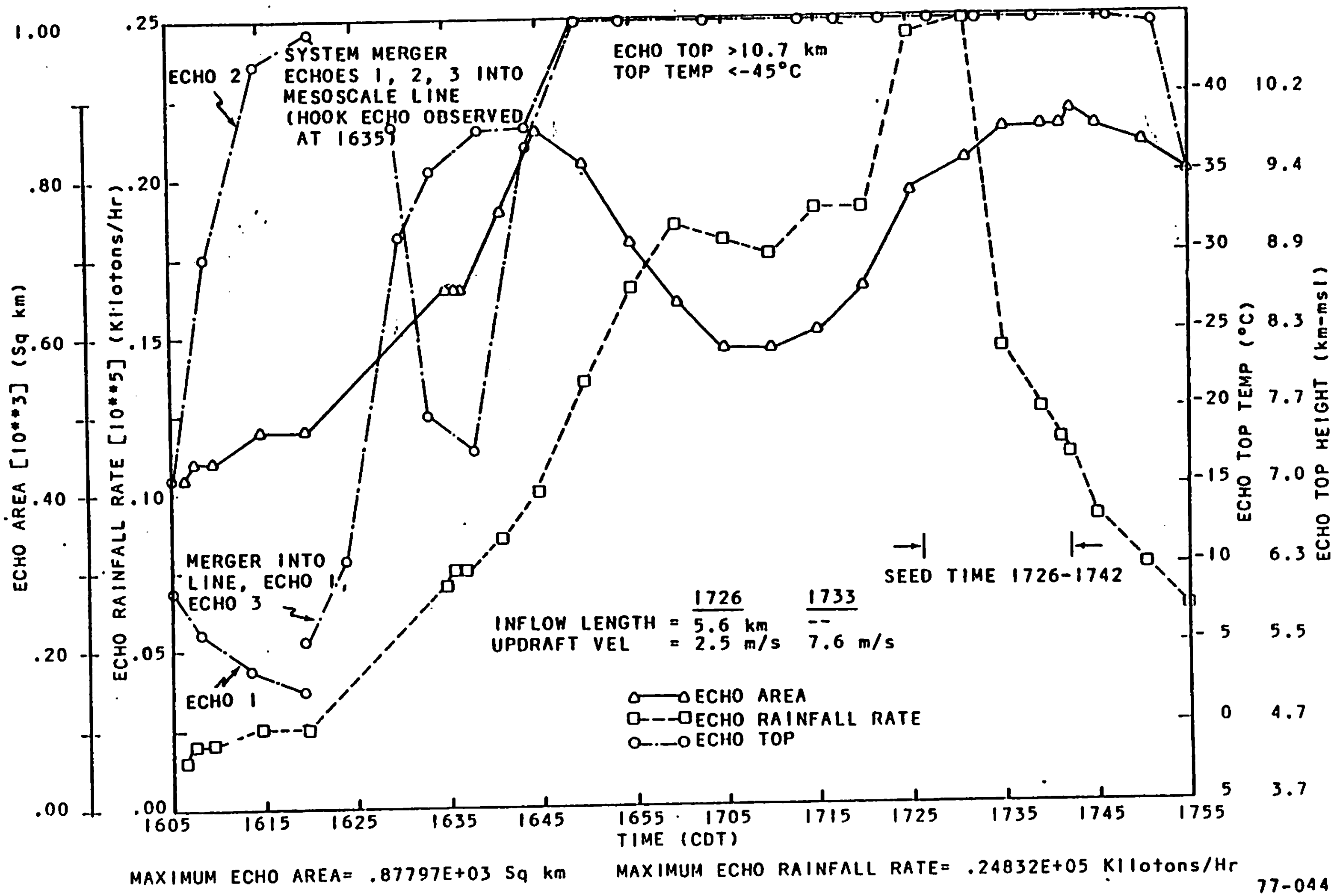
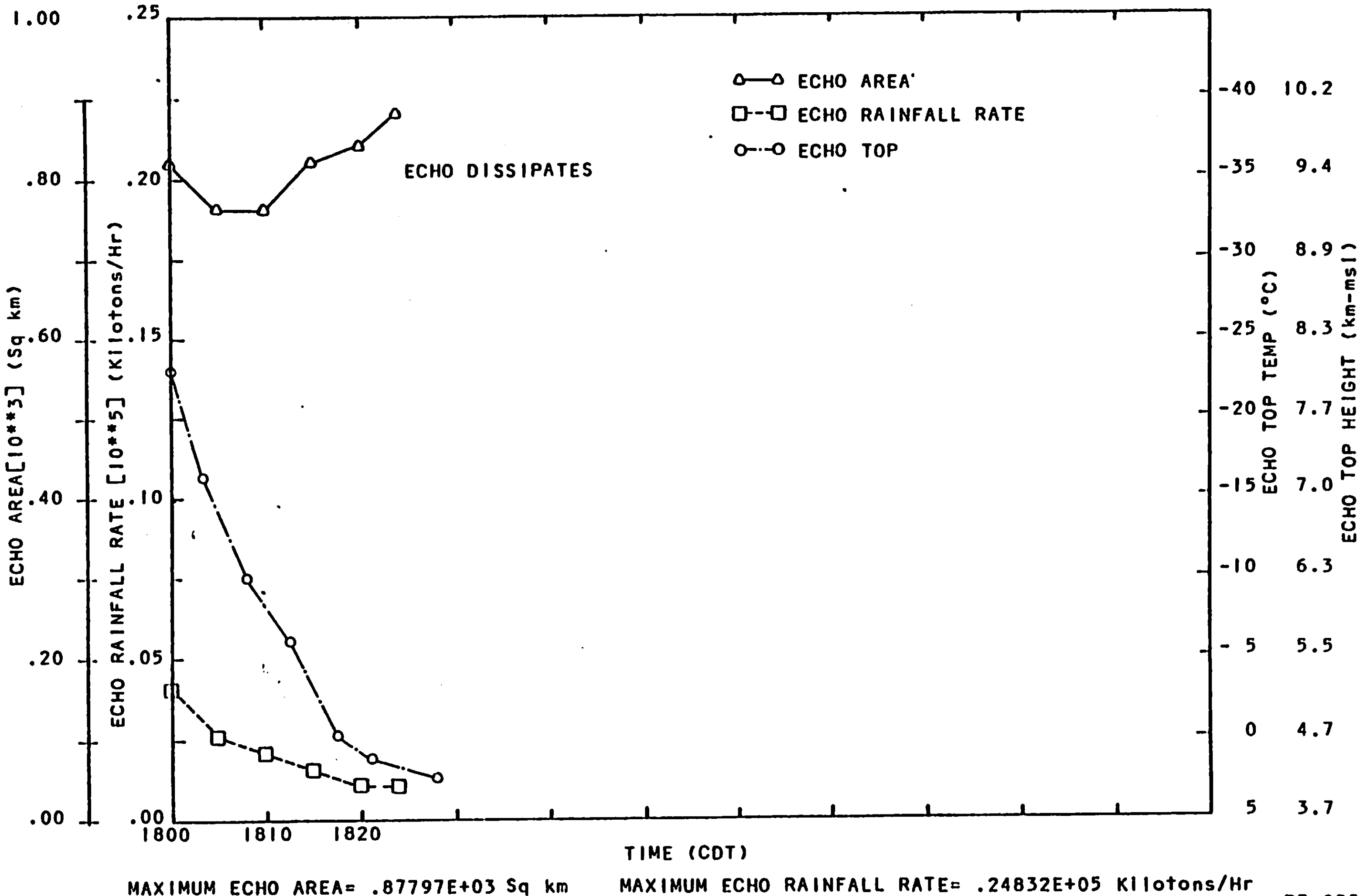


Figure 11b. Echo Time History - Snyder, Texas 7/19/75
Echo J, Seed (Continued)



77-038

Figure 11c. Echo Time History - Snyder, Texas 7/19/75
Echo J, Seed (Continued)

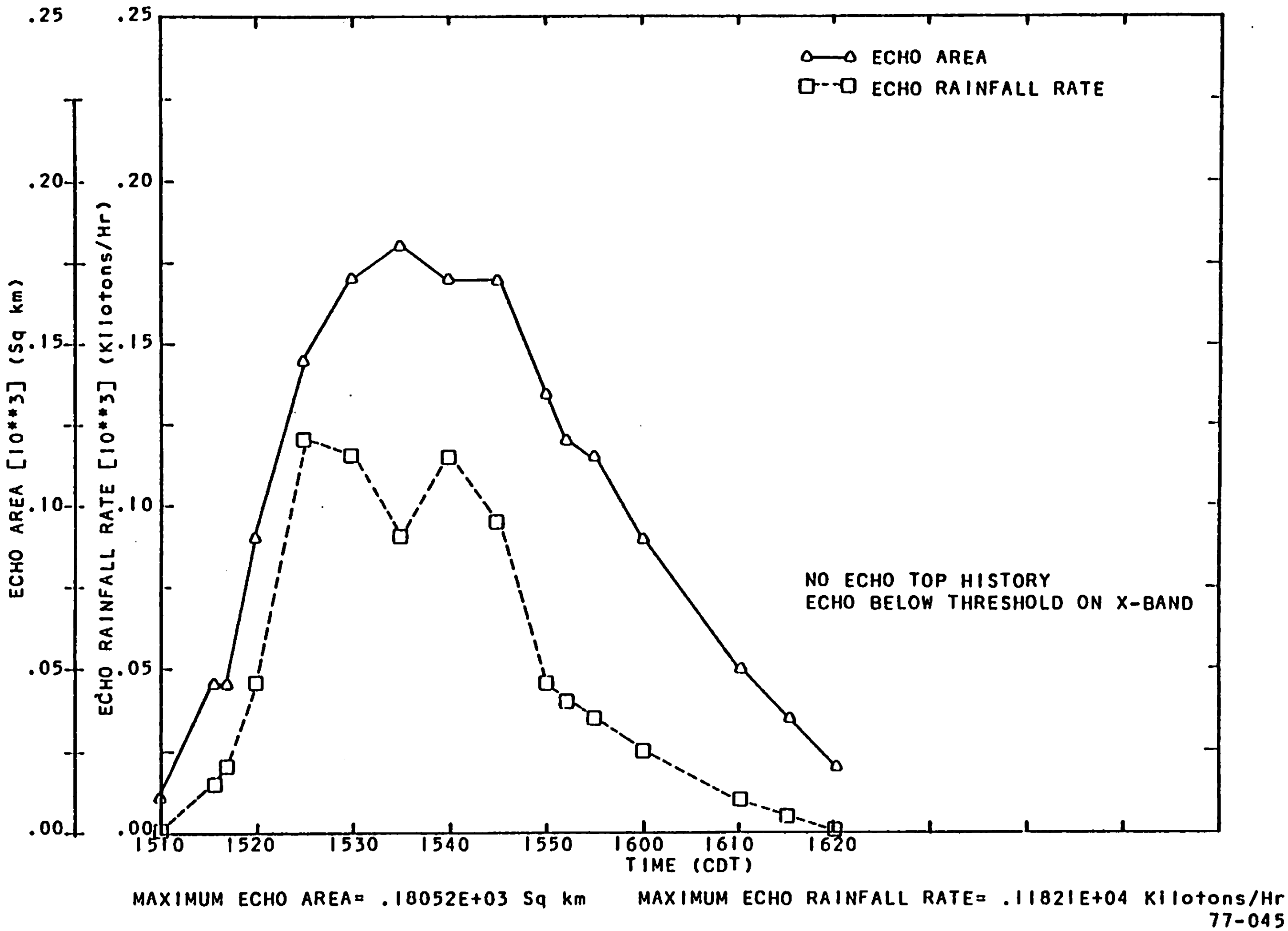


Figure 12. Echo Time History - Snyder, Texas 7/19/75
Echo K, No Seed

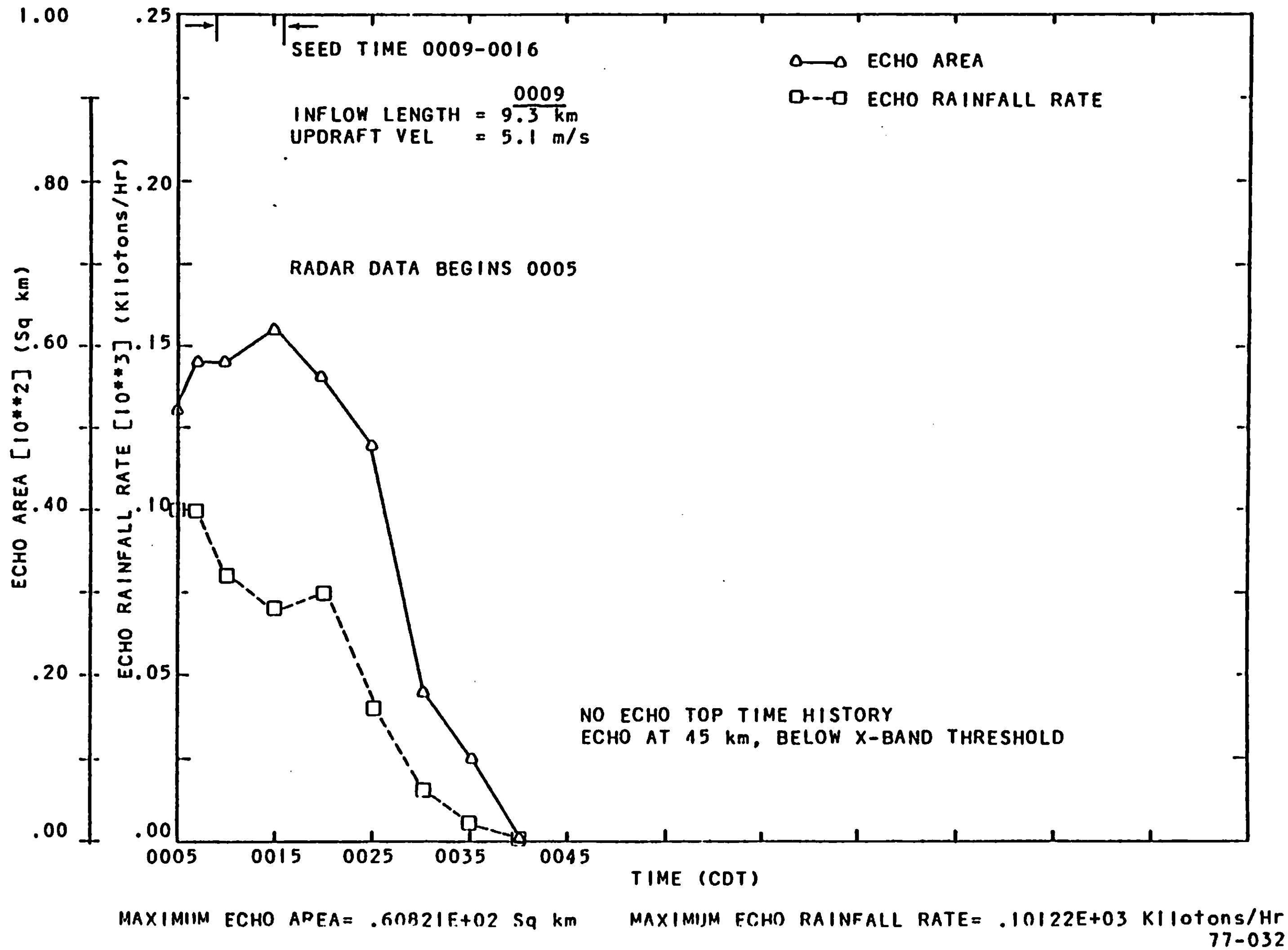


Figure 13. Echo Time History - Snyder, Texas 7/24/75
Echo L, Seed

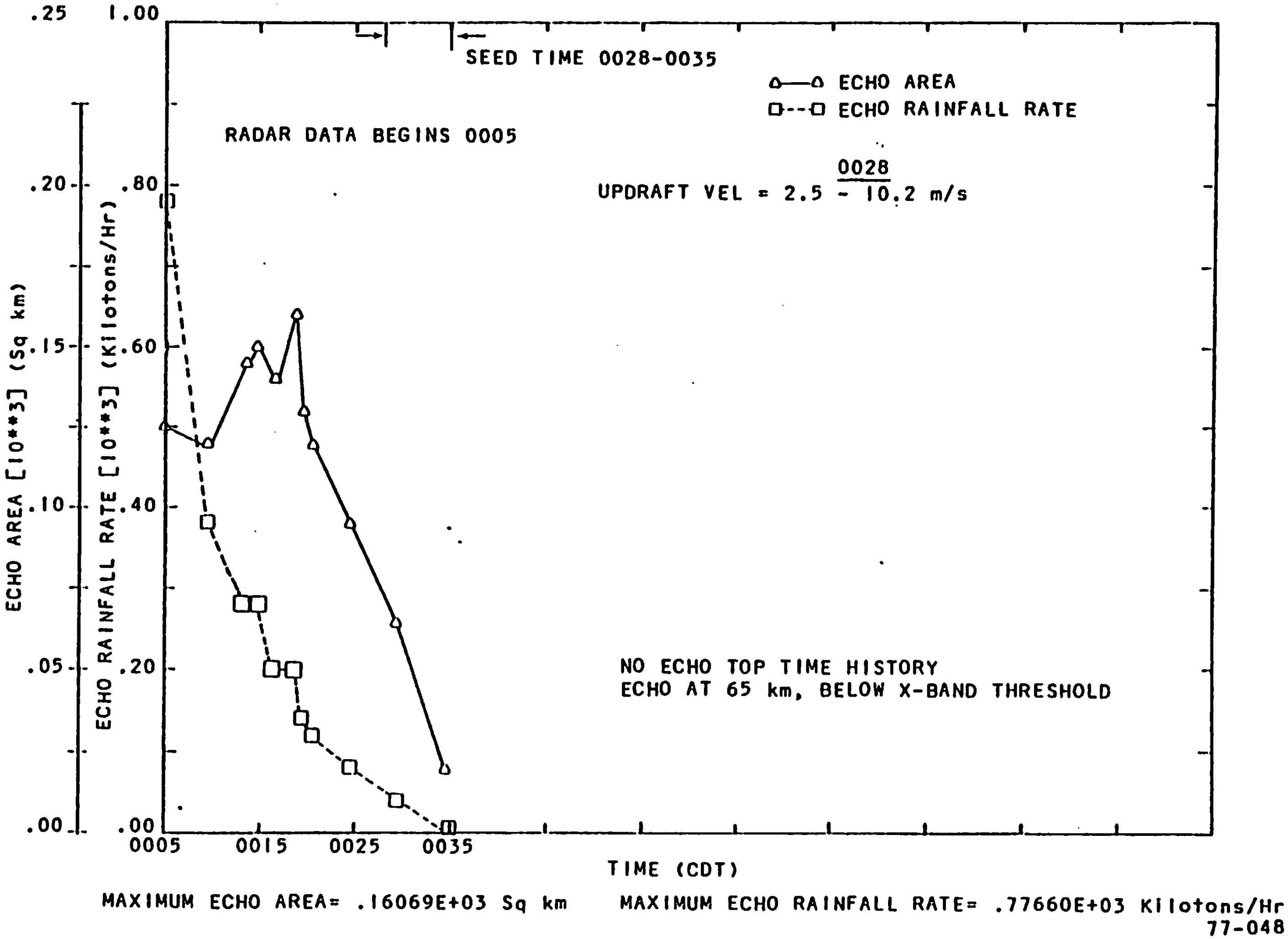


Figure 14. Echo Time History - Snyder, Texas 7/24/75
Echo M, Seed

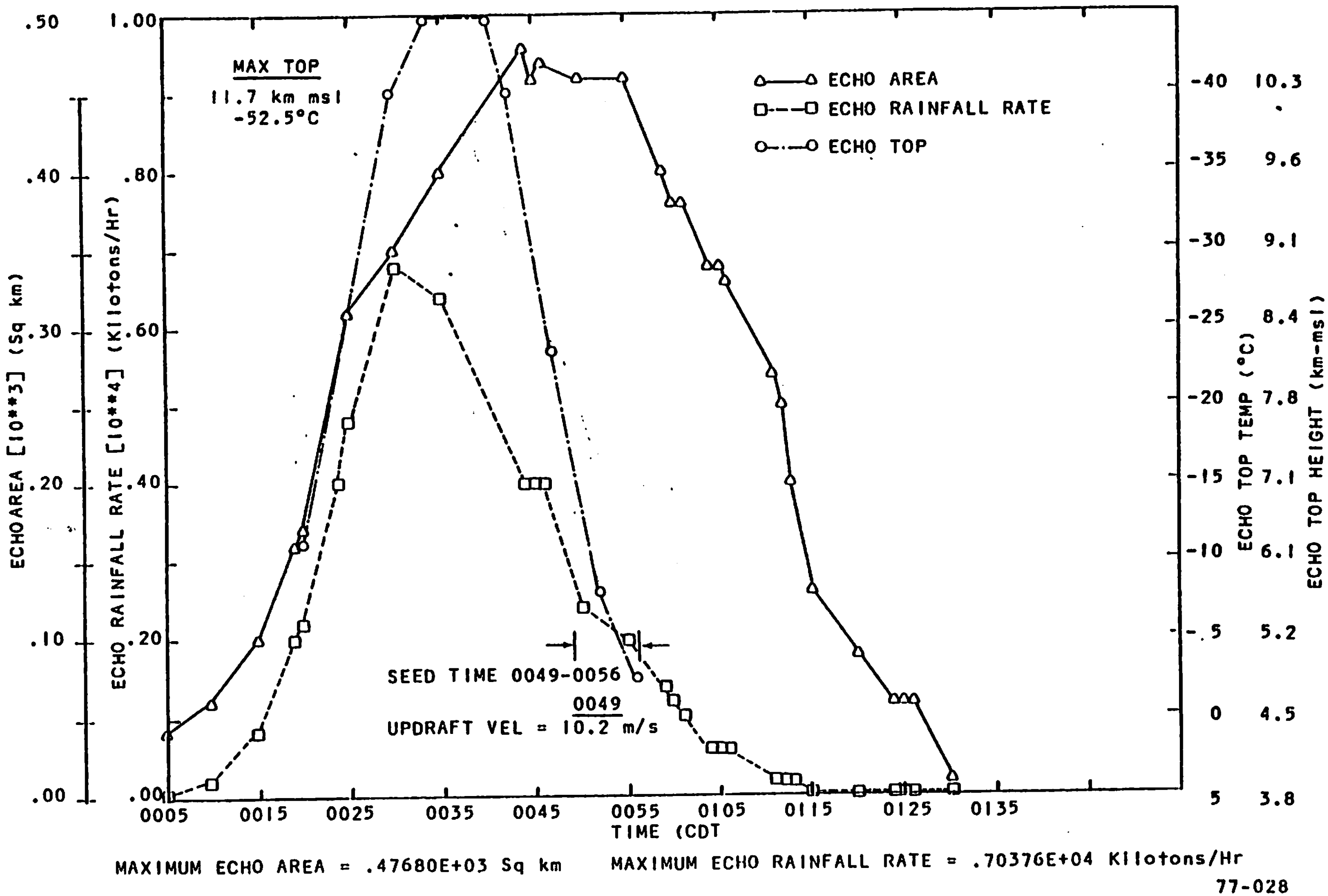


Figure 15. Echo Time History - Snyder, Texas 7/24/75
Echo N, Seed

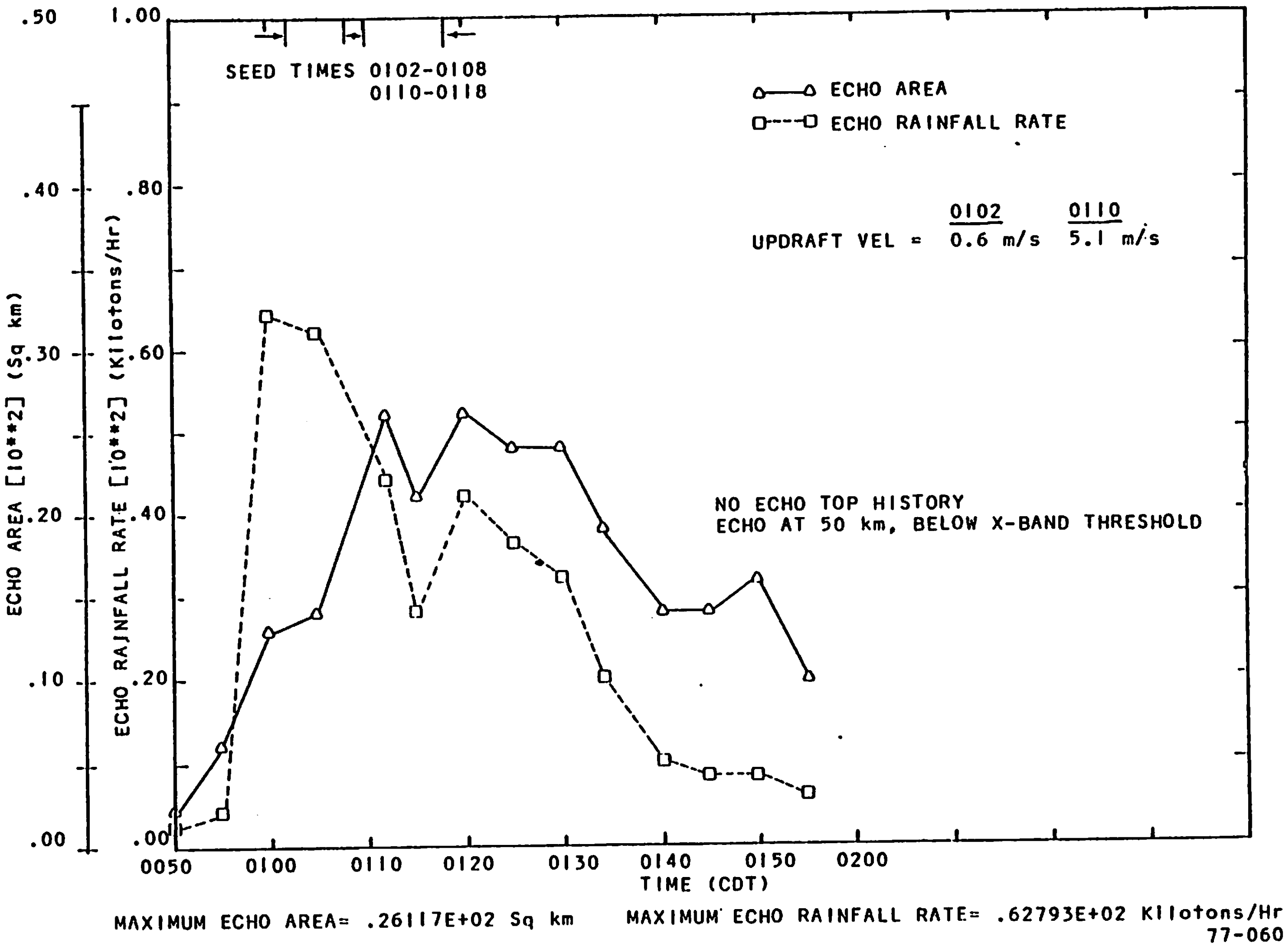
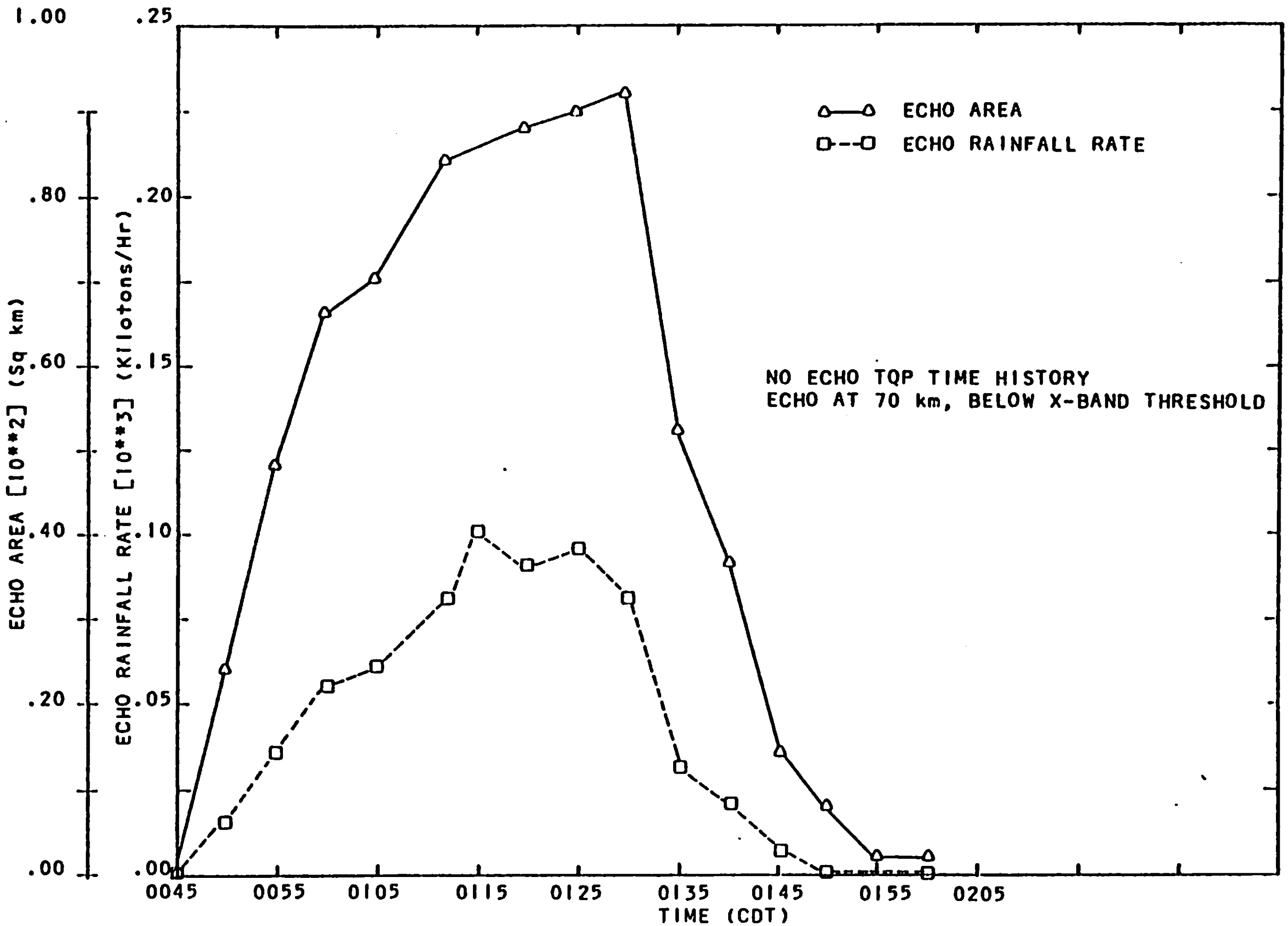


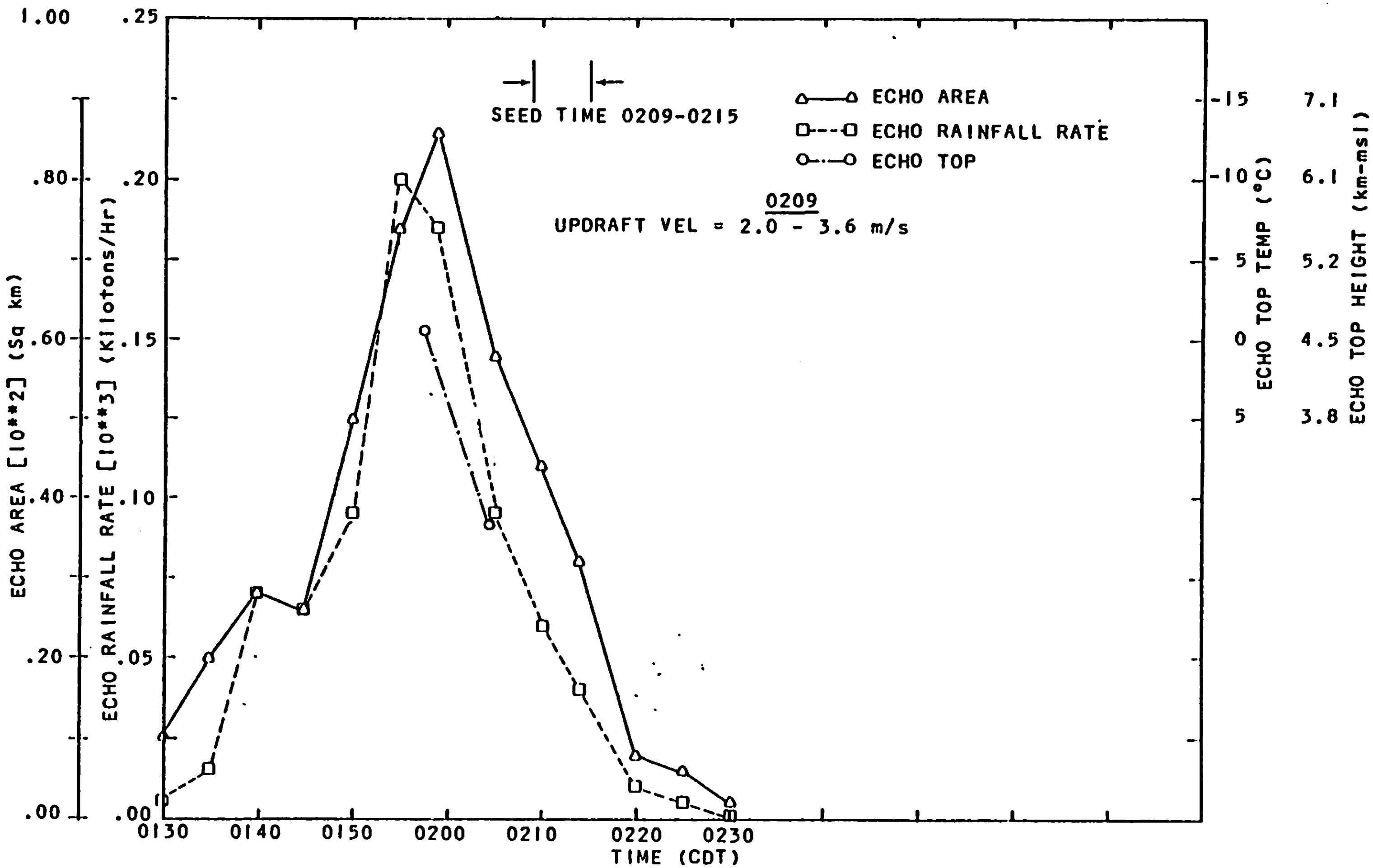
Figure 16. Echo Time History - Snyder, Texas 7/24/75
Echo P, Seed



MAXIMUM ECHO AREA = .91741E+02 Sq km   MAXIMUM ECHO RAINFALL RATE = .10013E+03 Kilotons/Hr

77-031

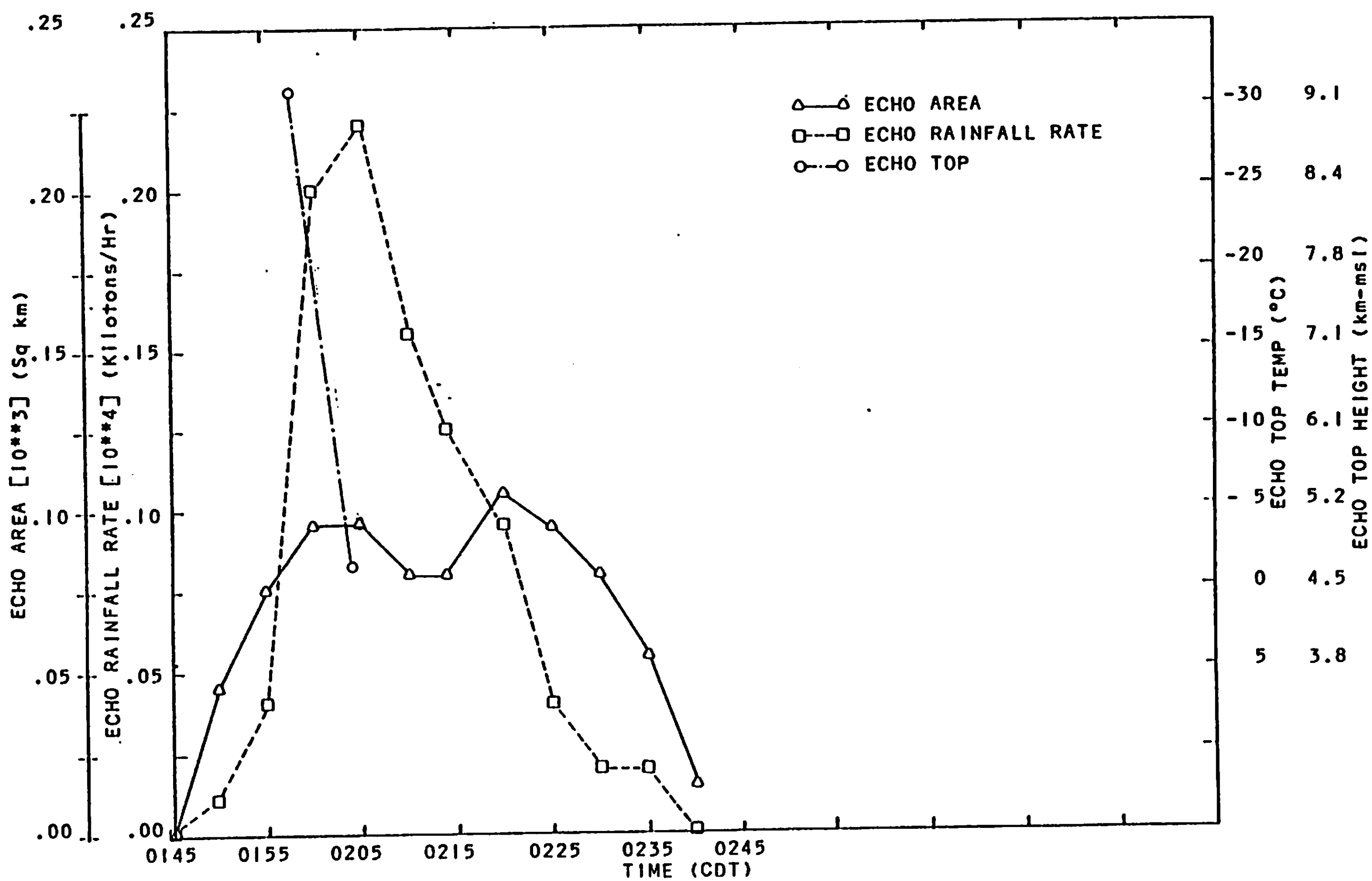
Figure 17. Echo Time History - Snyder, Texas 7/24/75
Echo Q, No Seed



MAXIMUM ECHO AREA = .85083E+02 Sq km   MAXIMUM ECHO RAINFALL RATE = 19959E+03 Kilotons/Hr

77-052

Figure 18. Echo Time History - Snyder, Texas 7/24/75
Echo R, Seed



MAXIMUM ECHO AREA= .10652E+03 Sq km MAXIMUM ECHO RAINFALL RATE= .21917E+04 Kilotons/Hr

77-050

Figure 19. Echo Time History - Snyder, Texas 7/24/75
Echo S, No Seed

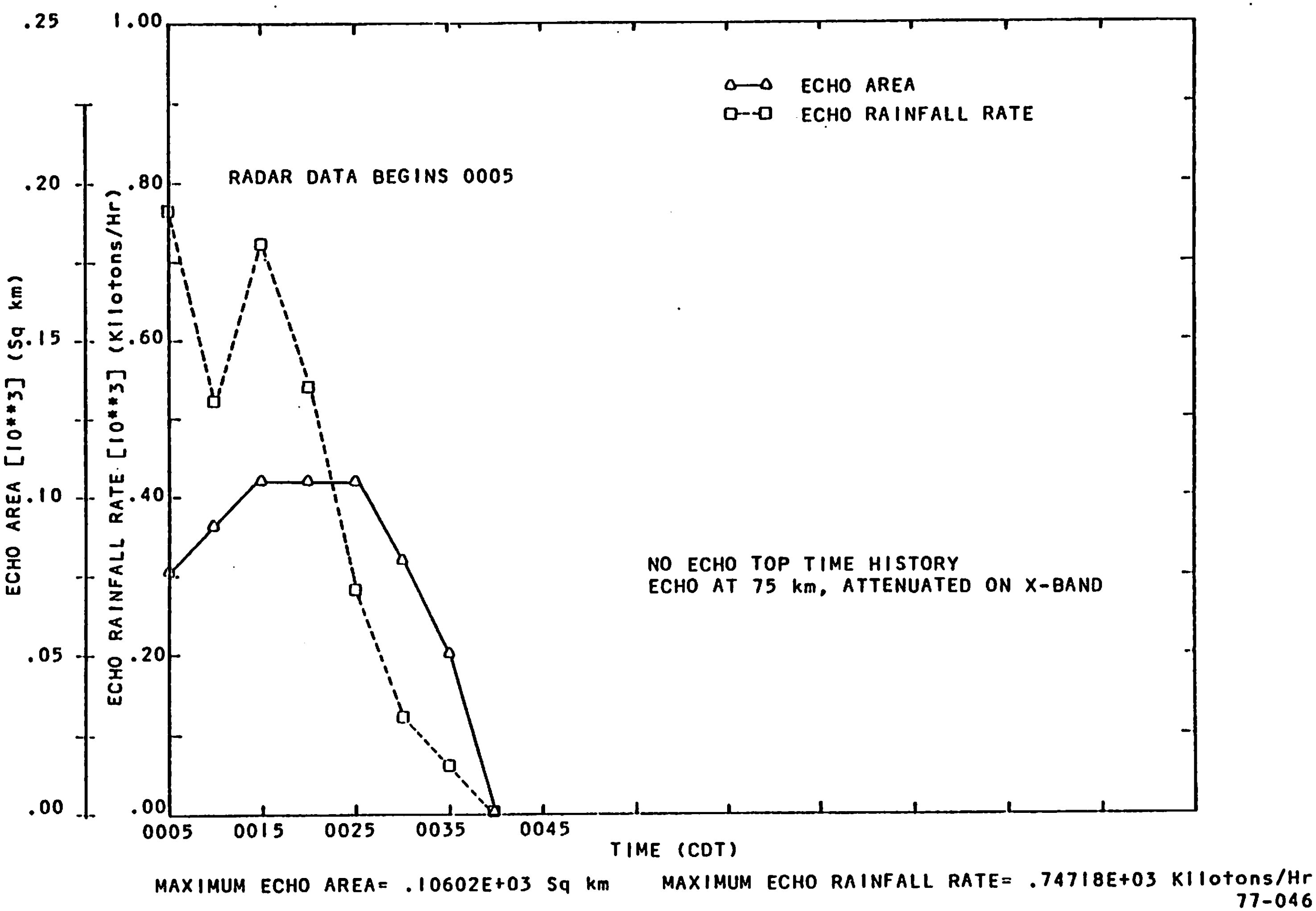
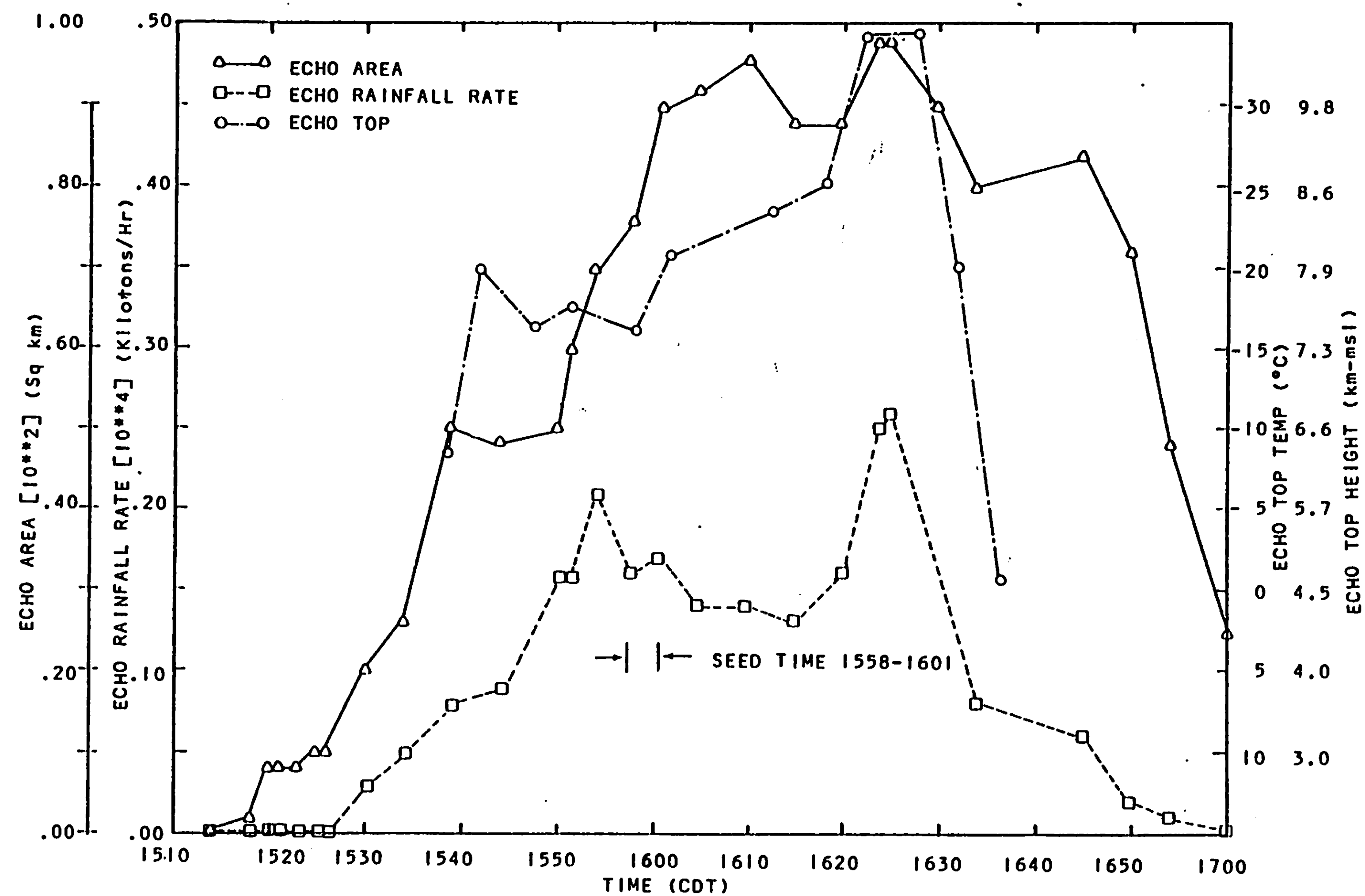


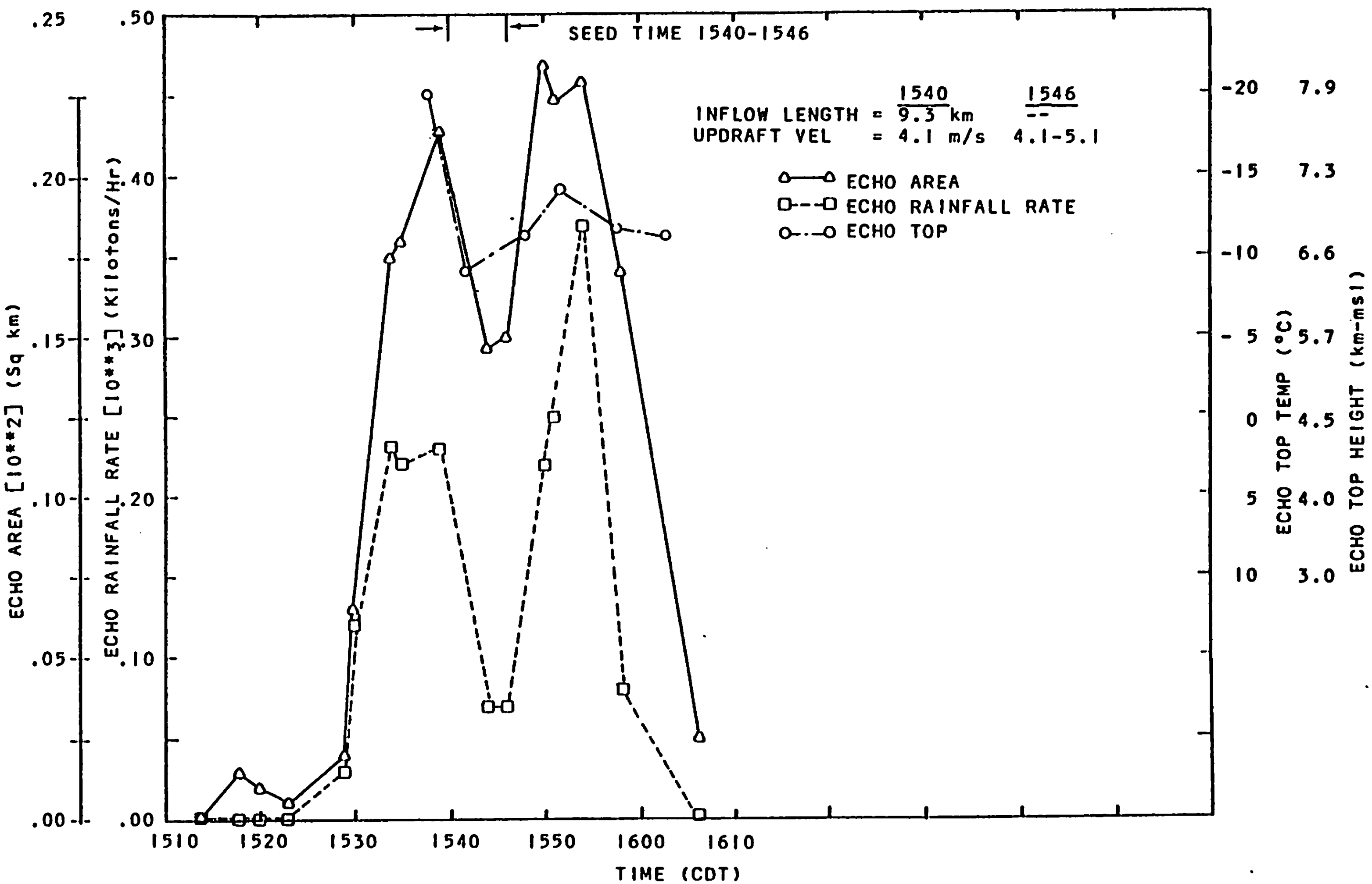
Figure 20. Echo Time History - Snyder, Texas 7/24/75
Echo T, No Seed



MAXIMUM ECHO AREA = .96930E+02 Sq km MAXIMUM ECHO RAINFALL RATE = .25678E+04 Kilotons/Hr

77-057

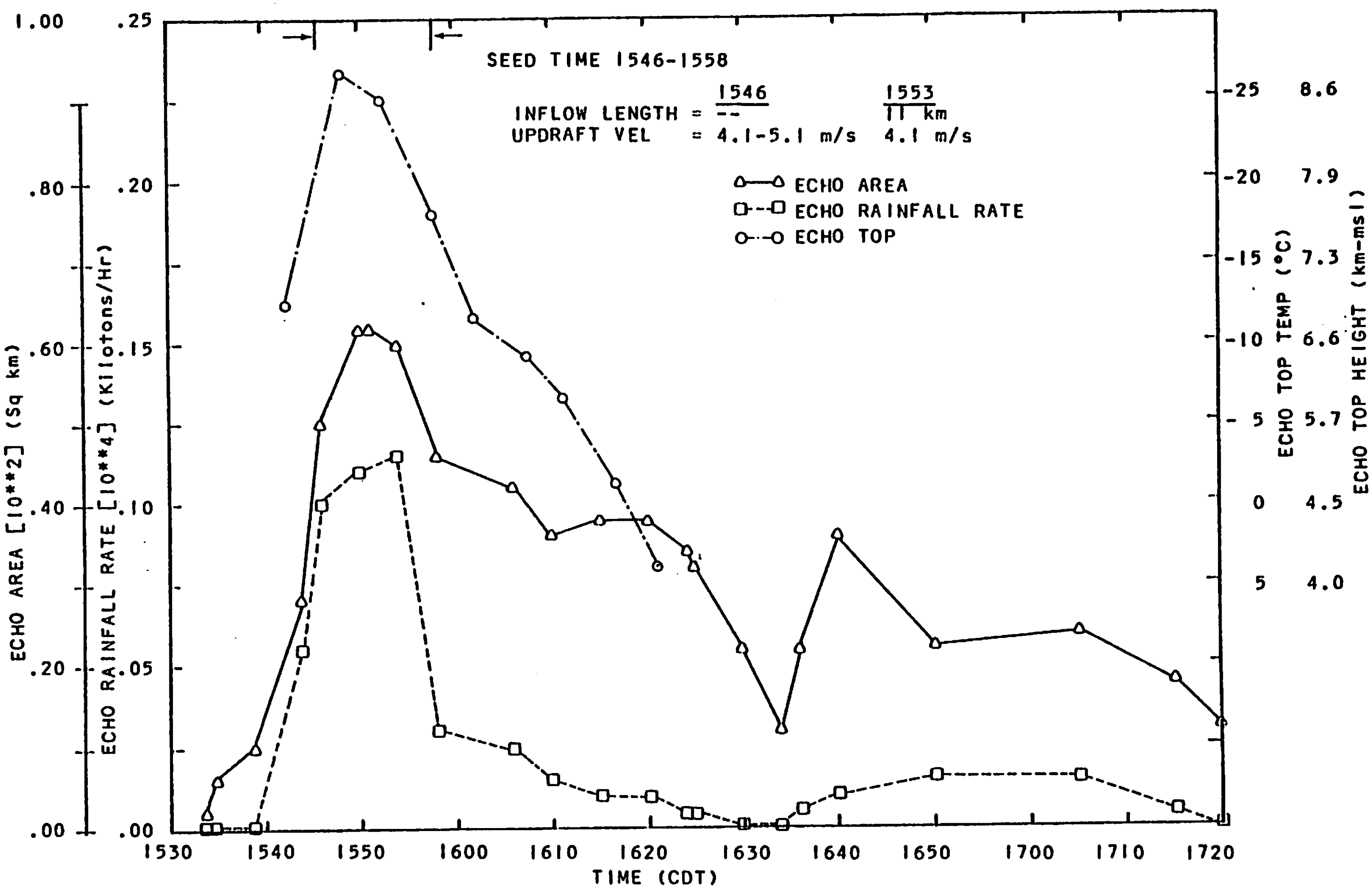
Figure 21. Echo Time History - Snyder, Texas 8/2/75
Echo U, Seed



MAXIMUM ECHO AREA = .23243E+02 Sq km MAXIMUM ECHO RAINFALL RATE = .37116E+03 Kilotons/Hr

77-058

Figure 22. Echo Time History - Snyder, Texas 8/2/75
Echo V, Seed



MAXIMUM ECHO AREA = .62423E+02 Sq km MAXIMUM ECHO RAINFALL RATE = .15200E+04 Kilotons/Hr

77-059

Figure 23. Echo Time History - Snyder, Texas 8/2/75
Echo W, Seed

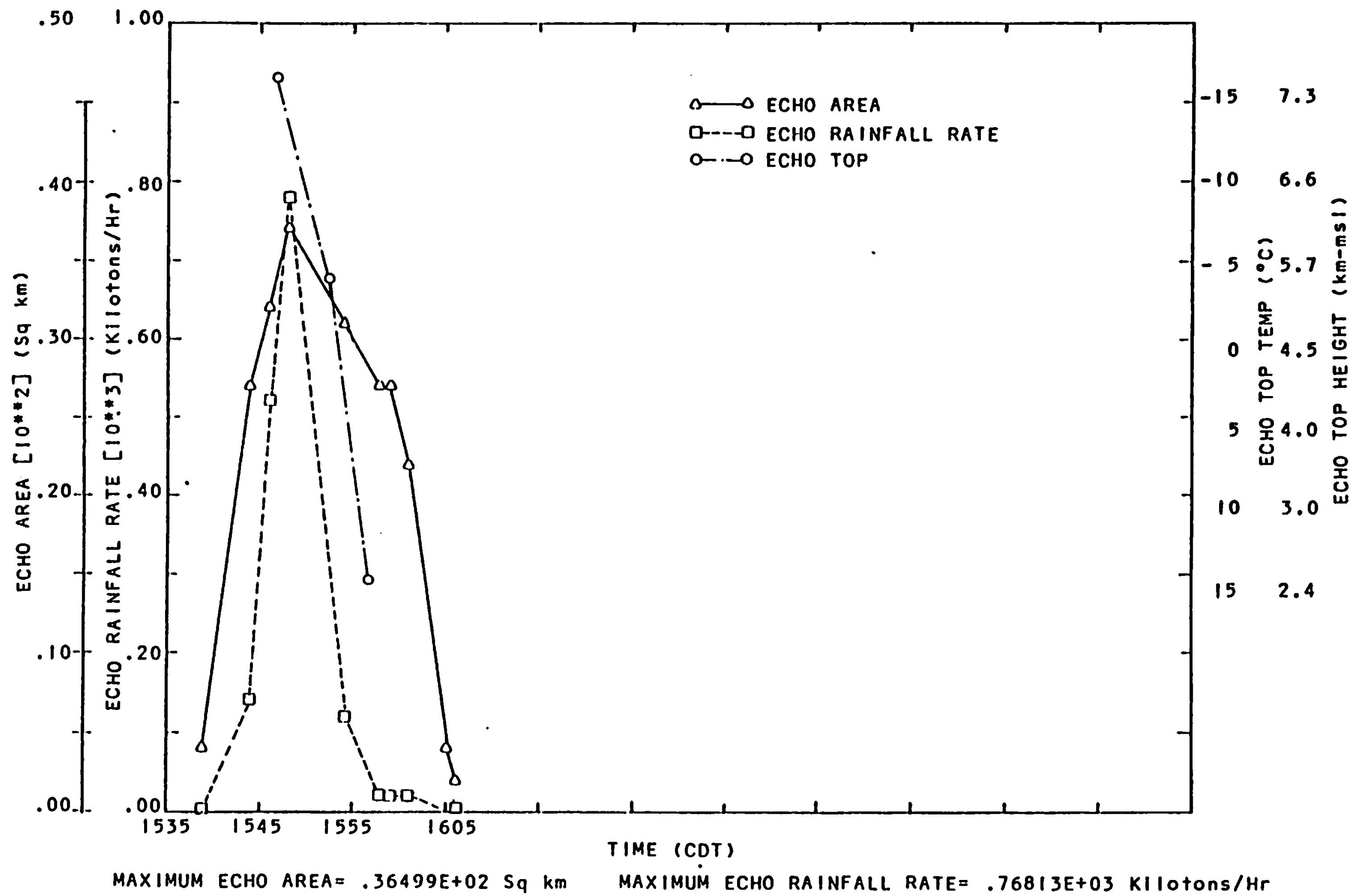


Figure 24. Echo Time History - Snyder, Texas 8/2/75
Echo X, No Seed

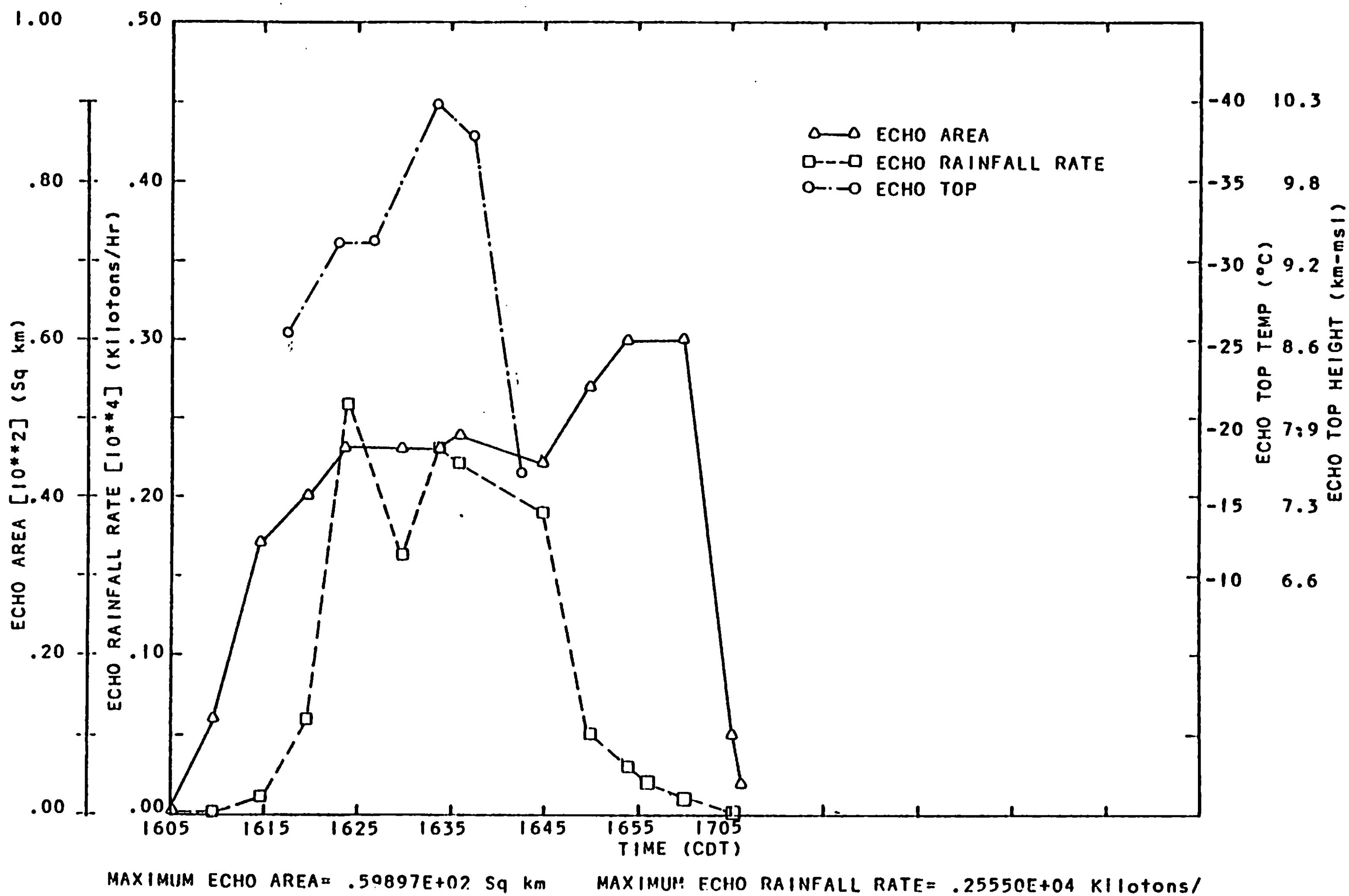
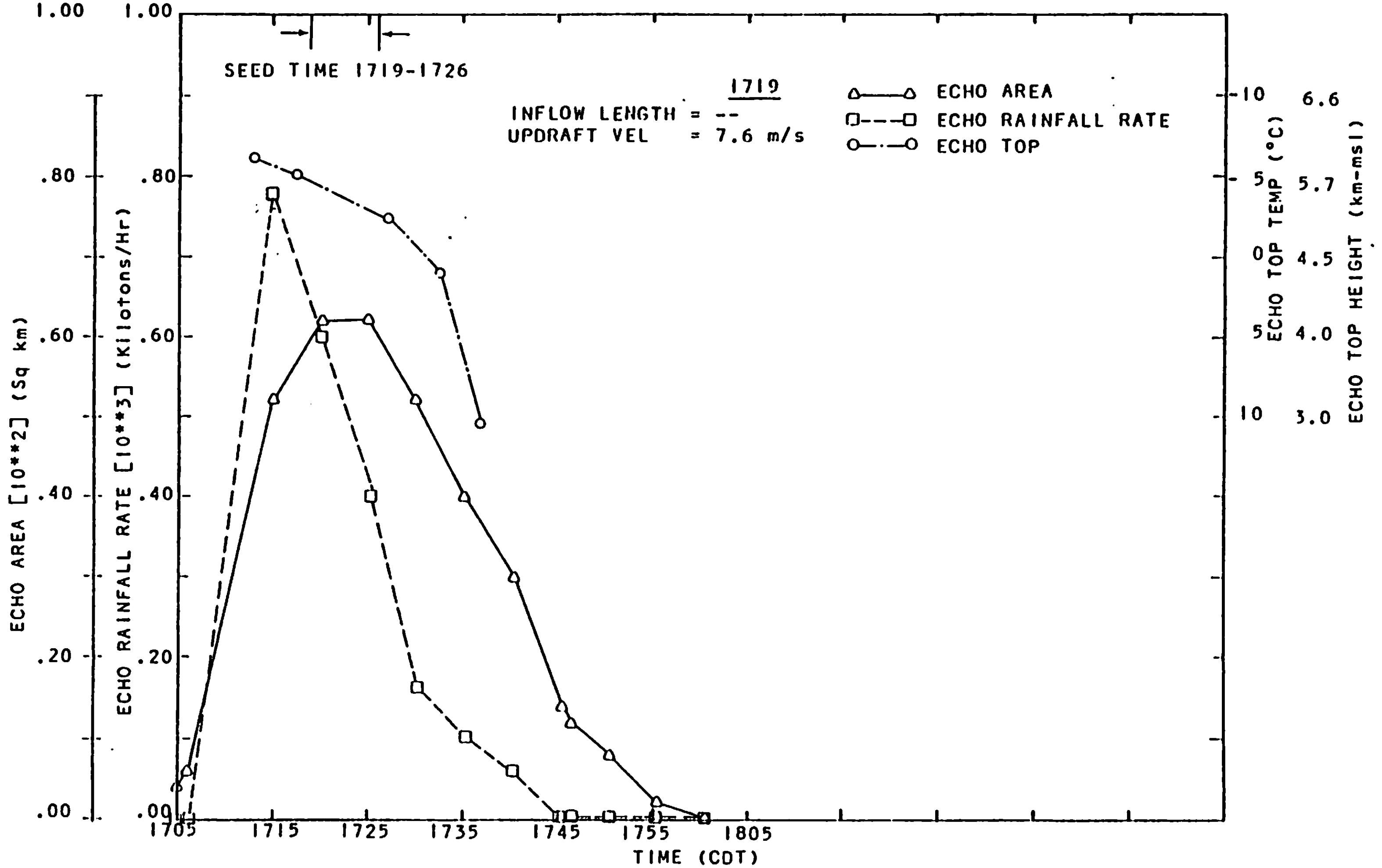


Figure 25. Echo Time History - Snyder, Texas 8/2/75
Echo Y, No Seed



MAXIMUM ECHO AREA= .61553E+02 Sq km MAXIMUM ECHO RAINFALL RATE= .76576E+03 Kilotons/Hr

77-056

Figure 26. Echo Time History - Snyder, Texas 8/2/75
Echo Z, Seed

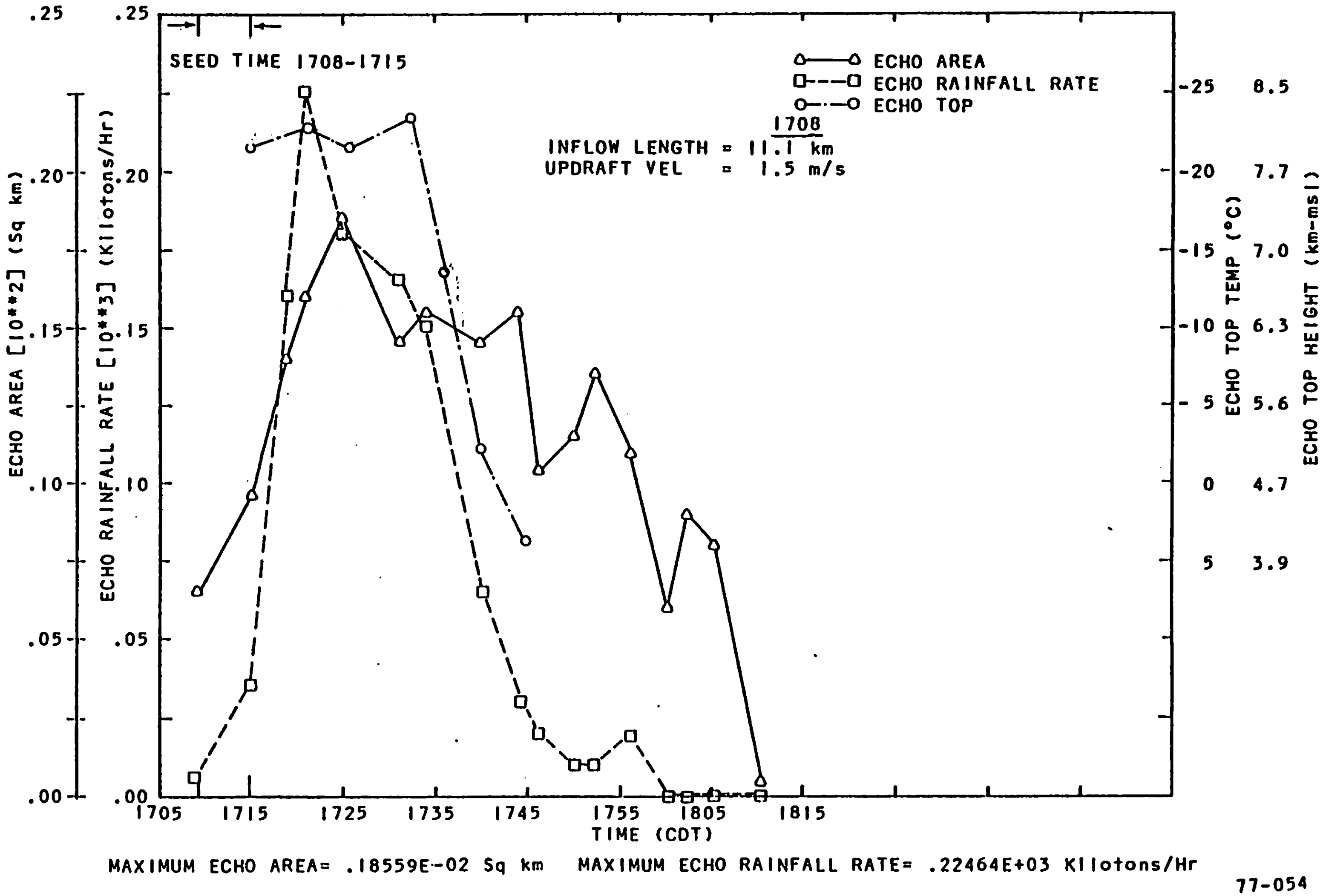
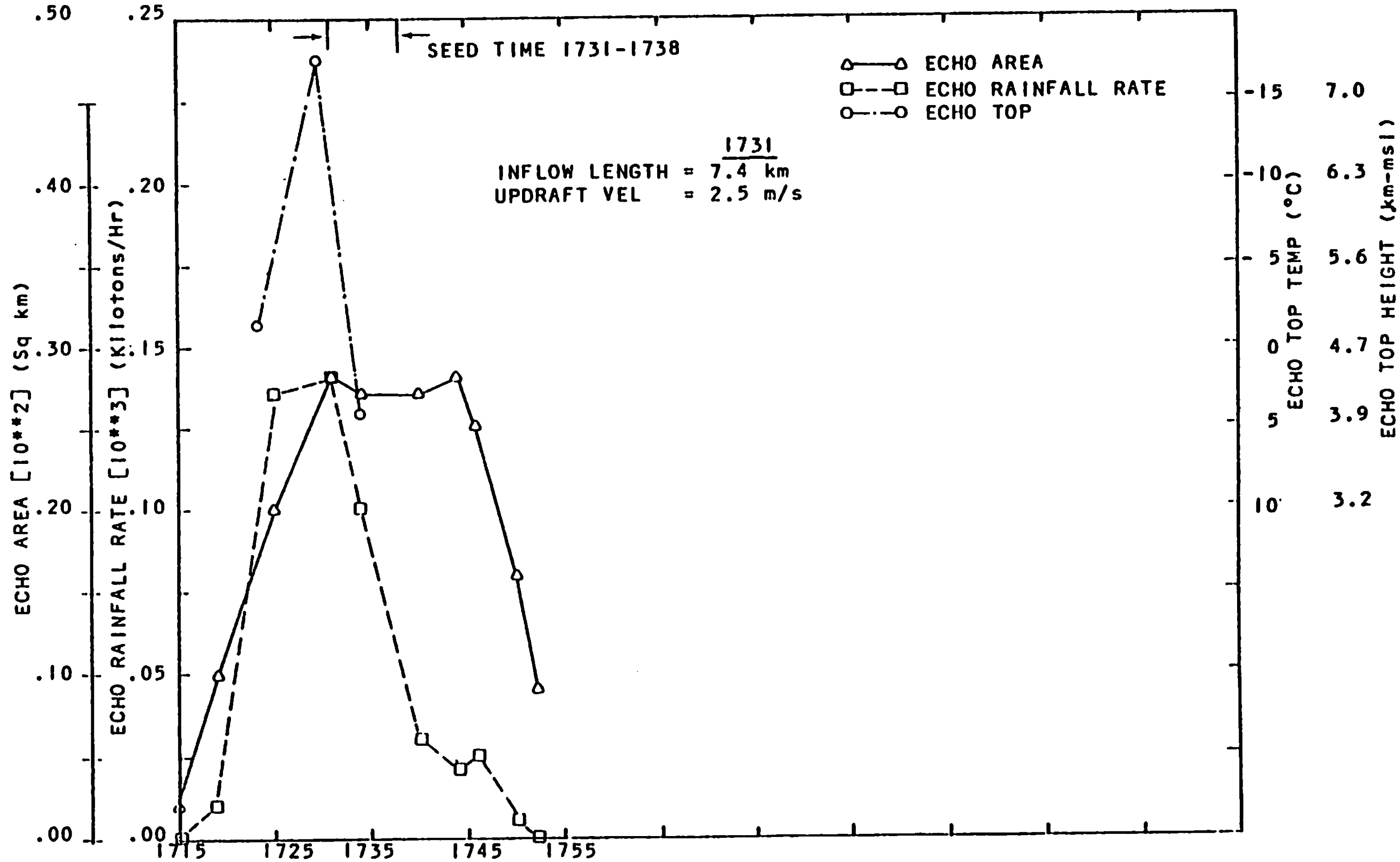


Figure 27. Echo Time History - Snyder, Texas 8/14/75
Echo AA, Seed



MAXIMUM ECHO AREA= .28023E+02 Sq km MAXIMUM ECHO RAINFALL RATE= .14167E+03 Kilotons/Hr

77-049

Figure 28. Echo Time History - Snyder, Texas 8/14/75
Echo BB, Seed

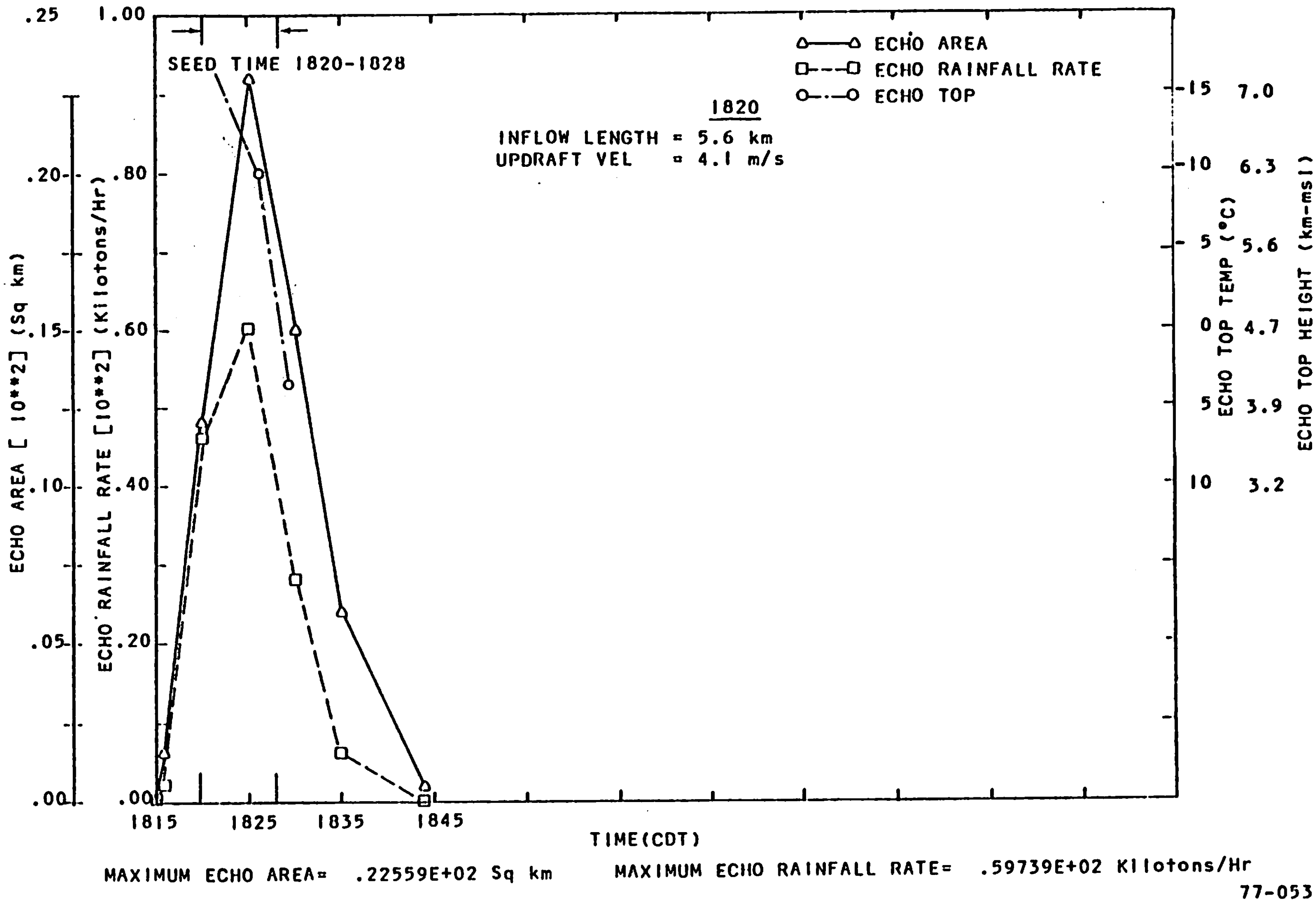
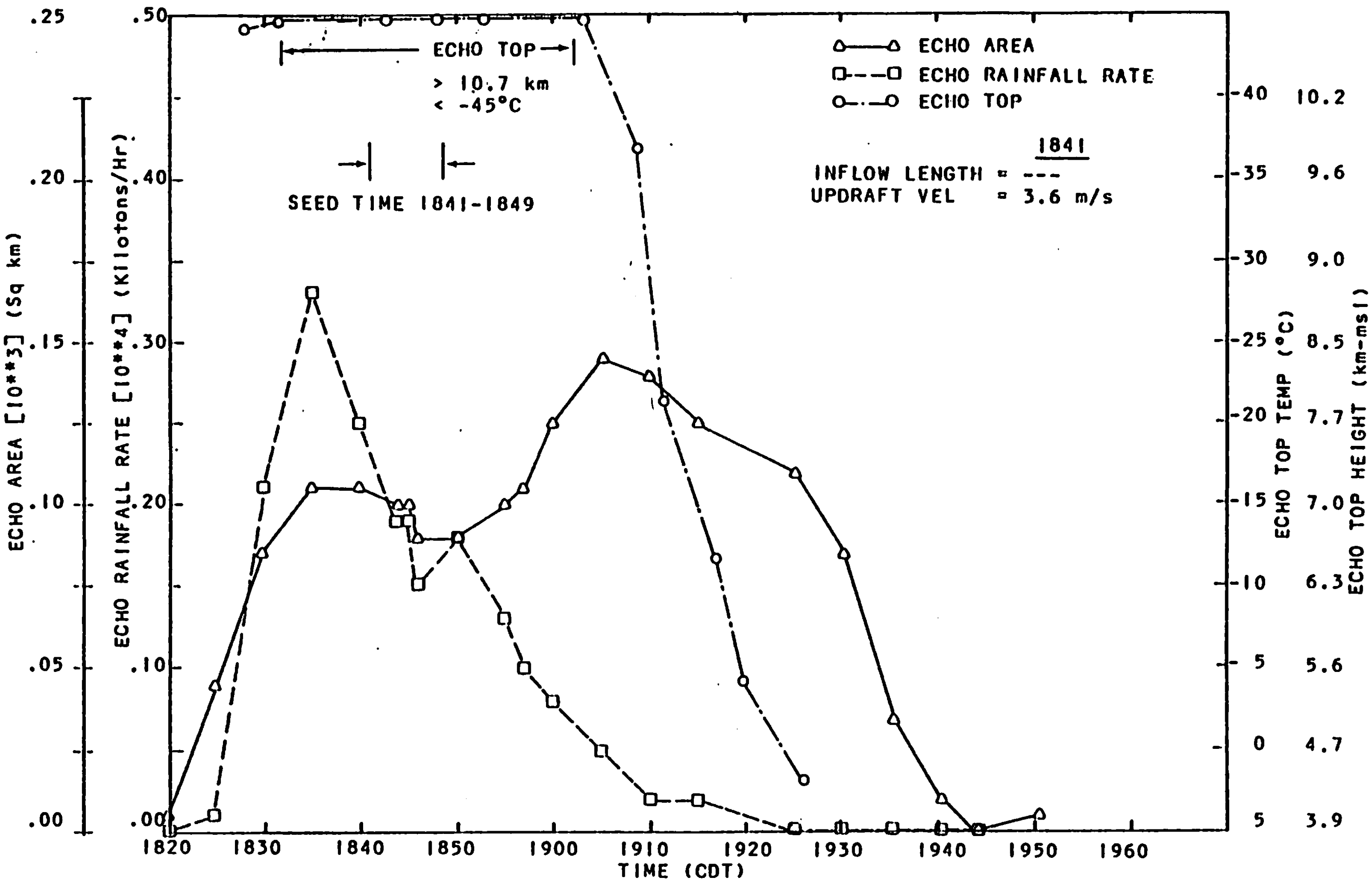


Figure 29. Echo Time History - Snyder, Texas 8/14/75
Echo CC, Seed



MAXIMUM ECHO AREA= .14293E+03 Sq km MAXIMUM ECHO RAINFALL RATE= .33135E+04 Kilotons/Hr

77-029

Figure 30. Echo Time History - Snyder, Texas 8/14/75
Echo DD, Seed