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DEPARTMENT OF COMMERCE
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CONVECTIVE CLOUD MODIFICATION POTENTIAL IN ILLINOIS COMPARED WITH THAT FOR SOUTH FLORIDA AND DEDUCED FROM SOUNDINGS AND CLOUD PHYSICS MEASUREMENTS

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CONVECTIVE CLOUD MODIFICATION POTENTIAL IN ILLINOIS COMPARED WITH THAT FOR SOUTH FLORIDA AND DEDUCED FROM SOUNDINGS AND CLOUD PHYSICS MEASUREMENTS

Victor Wiggert, Robert I. Sax,* and Ronald L. Holle

ABSTRACT

The potential for enhancing rain output over central Illinois through modification of summertime convective clouds was investigated. Model predictions of cumulus growth, as well as direct, internal measurements of cloud physical characteristics, were used. Comparisons were made with similar studies for south Florida.

The growth of unseeded and seeded clouds was predicted numerically with a one-dimensional cumulus model. The predicted height increase from seeding is the "seedability" of the modeled cloud. In Florida, seedability is correlated with actual increases in vertical growth and enhanced rain output of individual clouds, following seeding. For the Illinois environment, a climatology of seedabilities, derived from radiosonde data regularly gathered during 10 summers at Rantoul and Peoria, was assembled. Principal characteristics of the Illinois seeding climatology were found to be the following:

1) Median maximum seedability was between 2 and 2.5 km.
2) Average maximum seedability was largest in July, second highest in August, and least in June.
3) The maximum seedability from nearly one-third of the soundings was zero, indicative (in Florida at least) of suppressed convection that had no potential for modification.
4) Seedability varied greatly, when averages were compared for (a) morning versus evening, (b) 1 month versus the 10-year average for that month, and (c) June versus August for the same year.
5) Disturbed weather, during summer 1957, occurred as frequently with zero seedability as with non-zero seedability.

Measurements were made during July 1977 in cumuli over central Illinois that bear upon the natural evolution of the ice-water budget and the life history of the updraft. Cloud water content characteristics near the -10°C level in Illinois, in convective clouds that were developing in moist air in advance of a weak cold front, were equivalent to those characteristics encountered at the same penetration level of Florida cumuli of similar size and depth. The updraft velocities were somewhat weaker in the Illinois sample than those typically found in Florida cumuli. The Illinois cumuli developing in advance of the cold front were characterized by high cloud water contents, moderate updrafts and, on initial penetration, low concentrations of graupel ice. In Florida, these characteristics are believed to be important

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contributors to the enhancement of cloud growth and rainfall following seeding. The few Illinois clouds that were penetrated in the dry air behind the cold front were struggling to grow and contained very weak updrafts, low concentrations of cloud water, and an abundance of ice in the form of graupel, even on initial penetration. The microstructure of the postfrontal clouds near the -10°C level appeared to differ greatly from that encountered in clouds developing in tropical maritime airmass conditions, and would probably not have responded to attempts at modification by seeding.

Cumuli have been found in the Illinois environment that were as amenable to artificial modification as those found in south Florida. However, such favorable occasions occurred less frequently in the Illinois environment, and unlike the situation in south Florida, they may be associated with intense, organized, rapidly moving convection induced by advancing fronts.

1. INTRODUCTION

Controlled enhancement of rainfall is often desirable. The purpose of this report is to evaluate the degree to which the summertime atmospheric conditions in Illinois present suitable opportunities for enhancement of convective rainfall, if we were to use dynamic seeding techniques that have been developed and tested in Florida. Predictions of cumulus growth enhancement for Illinois were compared with those from south Florida. A day-by-day comparison, for one of the Illinois summers, was made among observations of disturbed weather and two categories of predicted seedability--zero and nonzero. In-cloud measurements of ice, water and updraft microstructure were collected in Illinois cumuli and analyzed and compared with in-cloud observations obtained in Florida.

A randomized cumulus cloud seeding experiment that was begun 10 years ago in south Florida has established some quantification of the response of single isolated cumuli to silver iodide seeding (Woodley, 1970a,b; Woodley and Herndon, 1970; Simpson and Woodley, 1971; Simpson et al., 1971). Subsequently, the experimental program was expanded to determine the efficacy of seeding many cumuli to promote their merger over a large (13×10^3 km^2), fixed target area (Woodley and Williamson, 1970). The promotion of cumulus merger is believed desirable because rain budget studies (Woodley et al., 1971) show that merged shower complexes yield, by far, the major rain volume in south Florida. This research project is known as the Florida Area Cumulus Experiment (FACE), and the rationale, design, procedures, and some early results have been summarized by Woodley and Sax (1976).

The effectiveness of the dynamic seeding technique used in FACE is evaluated statistically by the ratio of seed-day rainfall to control-day rainfall. Rainfall is recorded in the target area by the National Hurricane Center's WSR-57 radar. The output of this S-band radar is digitally quantified, tape recorded, and adjusted by measurements from networks of rain gages (Woodley et al., 1974, 1975; Wiggert and Ostlund, 1975; Wiggert et al., 1976).

FACE rainfall data, derived from the Miami radar and adjusted by gage measurements, indicated that a statistically significant enhancement of target area rain volume has occurred on seed days compared with that measured on no-seed experimental days (Simpson and Woodley, 1975; Woodley et al., 1977, 1980). The ensemble of FACE hypotheses, technology and methods has shown promise for the enhancement of rainfall in the south Florida target area. A confirmatory experiment was initiated during the summer of 1978 (Woodley et al., 1978) to verify the effectiveness of the technology for a chosen, fixed experimental design.

One of the key components in the FACE daily operational procedures is an objective prediction of suitability for experimentation. The suitability is based, in part, upon predictions of top heights made by a one-dimensional Lagrangian model of a cumulus cloud tower. Development of the model was discussed by Simpson et al. (1965; 1967). Simpson and Wiggert (1969; 1971) described the incorporation of cloud physics parameterizations and discussed tests of a variety of models for simulating artificial seeding. The seeding model "EMB68P," defined in Appendix A, has been used in the daily FACE program calculations and has been the only seeding model used in preparing the Illinois seedabilities below. The cloud model, being one-dimensional, deals only with a point within the actively ascending phase of a single cumulus tower (Appendix B). Despite these unrealistic features, it has predictive skill, as demonstrated by Simpson and Wiggert (1971). They compared the model-predicted top heights of individual unmodified and individual seeded cumulus towers with photogrammetrically measured top heights and found good agreement. To make these single-cloud predictions, measurements of cloud base height, cumulus tower radius, and radiosonde data from a site and time that were near the observed clouds were used. For each cloud tower diameter, the difference between predicted seeded and unseeded cloud top heights was defined as the "seedability" (Appendix A) for that cloud diameter. A statistically significant positive correlation was found to exist in Florida between model-predicted seedability and the measured rain volume difference of seeded versus unseeded individual cumuli; for details see Simpson and Wiggert (1971) and Holle (1974). The model, however, makes no attempt to simulate the complex dynamics of several convective clouds that have merged, although such merging systems often are encountered and are believed to be crucial to rainfall enhancement in the area cumulus experiment.

During the FACE program, the model has been utilized as a predictor of days suitable for experimentation; this was based on the belief that a large value of single-cloud seedability is indicative of atmospheric structure conducive to large growth enhancement, to merger of many clouds and, hence, of rainfall enhancement over the FACE area, on days when silver iodide seeding actually occurs. However, for the prediction of experimental days, the requisite measurements of cloud base and tower radius are often unavailable. Instead, a matrix of assumed cloud base heights and assumed tower radii is used each day with the 1200 GMT radiosonde data (surface to 100 mb) from the nearest National Weather Service site. One calculation of seedability results from each of eight radii used by the model, and the maximum seedability of those calculated is then extracted. Even in this day-predictor mode, large maximum seedability is recognized as necessary, but insufficient, for the selection of an experiment day, as discussed by Woodley and Sax (1976) and as noted below. For the purposes of this report, the model was used with a different objective: to form a climatological assessment of the potential for rain augmentation in Illinois. However, as noted by Simpson (1975), when any one-dimensional cumulus model is applied in this manner, it is necessary, first, to determine an empirical relation between measured rain volume increase and model-predicted single cloud seedability and, second, to document with photogrammetric and/or radar techniques the frequency that cumulus cloud tops are observed to be in the seedable height range (-5°C to -10°C). There is no known empirical relationship for south Florida, or any other location, between the growth of many seeded clouds over a wide area and the potential enhancement of rainfall over that area. For single cumuli over Florida, the photographic and radar documentation of cumulus tops achieving heights suitable for seeding was accomplished by Holle (1974). Such documentation remains to be done in Illinois.

The one-dimensional cumulus model has been found to have some limitations in its basic concepts and mechanics of operation. These limitations, their causes, importance, and means of correcting for them are discussed in Appendix B. Section 2 provides a discussion of Florida seedability calculations contrasted with actual seeding opportunities. Section 3 compares the presence or absence of cumulus showers in central Illinois each day during the summer of 1957 with the presence or absence of null seedability, calculated from a Peoria sounding for that day. Section 4 contains the main thrust of this report: a seedability climatology for central Illinois based upon 10 summers of radiosonde sounding data from Rantoul and Peoria, Illinois. In Illinois, advective processes in the course of a summer day can alter the atmospheric structure much more profoundly than usually occurs in Florida. In turn, the changes in moisture and stability profiles result in changes in model-predicted cloud growth and seedability. In an attempt at assessing such changes from one day to the next, we compared average seedabilities from daytime with those from nighttime soundings. We also investigated the occurrence and length of multiday sequences of maximum seedabilities that exceeded a threshold value; that value has been found to be useful in the FACE program. Presented in section 5 are measurements of cloud microphysical properties that were obtained in central Illinois on 22 and 23 July 1977 with the NOAA WP-3D airborne cloud physics laboratory. Also in section 5 are model-predicted seedabilities that were derived from soundings taken on the same two days at Salem, Illinois. These soundings were the nearest in space and time to the aircraft flights. Conclusions are presented in section 6.

2. SEEDABILITY VERSUS SEEDING OPPORTUNITIES IN FLORIDA

The single-cloud as well as the multiple-cloud seeding programs carried out over south Florida have made use of daily model-predicted maximum seedabilities to aid in the decision to launch, postpone, or cancel the seeder aircraft flights. In the FACE program, the dates of the cloud seeding experiment varied slightly from year to year. The months for which radiosonde data (gathered at 1200 GMT at Miami) and seedability calculations were available are indicated in table 1. Experience has shown that for use in the model calculations, a limited range of tower radii is adequate to encompass the observed cloud sizes; the five radii used are listed in column 1 of table 2. The cloud model was run for each of these radii, for both unseeded and artificially seeded simulations for each of the 478 soundings. Cloud base was presumed to be at 915 m. The *seedability* (italicized terms are defined in Appendix A), the *maximum seedability* (S_{max}), and the radius associated with the S_{max} then were extracted and tabulated. For most soundings, there was only one radius that gave the maximum increment of growth (S_{max}). In the few cases where two radii gave the same seedability, and it was a maximum, the

*Table 1. Distribution of 478 Miami 1200 GMT Soundings With Month and Year**

Year	May	June	July	August	September
1968	17	2	-	-	-
1970	30	2	19	-	-
1971	30	30	23	-	-
1972	-	-	19	18	-
1973	-	29	30	31	12
1975	-	17	31	31	15
1976	-	30	31	31	-

Table 2. Average Maximum Seedability and Percentage Frequency as Functions of Modeled Cumulus Tower Radius for Soundings at Miami, Florida

Tower radius (m)	All years and months: Zeros included (km/%M)	All years and months: Zeros excluded (km/%N)	1975 only (km/%N)
1000	2.3/35.4	3.0/45.3	2.9/39.4
1250	2.1/18.9	3.6/18.2	3.4/18.1
1500	2.1/18.9	3.6/18.2	3.4/25.5
2000	1.5/13.4	3.6/09.2	3.8/11.7
2500	1.3/13.4	3.1/09.2	3.2/05.3
	M = 694*	N = 424	N = 94
		$\frac{N(0) = 54}{N_T = 478}$	$\frac{N(0) = 0}{N_T = 94}$
			$N(0) = .113\ N_T$

Cloud base = 915 m.
N = number of soundings with $S_{max} \geq 0$.
N(0) = number of soundings with $S_{max} = 0$.
N_T = total number of soundings.
M = number of calculations.
*M = 694 results from there being 424 soundings with $S_{max} > 0$ and 54 soundings with $S_{max} = 0$ calculated for each of the five radii.
Thus, 424 + (5) X 54 = 694.

smaller radius was chosen as the radius that gave S_{max}. For each of the radii, the *average* S_{max} was calculated. The average maximum seedabilities and occurrence frequencies as a function of tower radius are shown in table 2.

For each tower radius, the average maximum seedability calculated from soundings made in Florida was always the simple average of all maxima for that radius, even when S_{max} was zero. In the second column in table 2 are listed the average S_{max} (km) and the frequency of occurrence of S_{max} at each particular radius. However, when seedability calculations were based upon sets of sounding data from Illinois and from some stations in the Great Plains, a surprisingly large percentage of the S_{max} were found to be zero. As a result, the average S_{max} were much smaller than any derived from Florida data. In an attempt to objectively exclude soundings that (in Florida) would be associated with stunted convection, a new method of averaging was introduced. The new method excludes all cases of $S_{max} = 0$ and is the *zeros-excluded average* S_{max}. The third column of table 2 lists these values for the 478 Miami soundings. The zeros-excluded procedure is usually unnecessary when Miami soundings are processed. For example, seedabilities for FACE 1975 in column 4 of table 2 contain no instances of $S_{max} = 0$ for that summer.

Averages of seedabilities, calculated with zeros included, yield modification potentials (i.e., growth increments and occurrence frequencies) that are directly comparable with counterparts from any other radiosonde site. On the other hand, the zeros-excluded average S_{max} values can be deceptive, unless the reader always bears in mind that all cases of $S_{max} = 0$ are ignored, even though such cases may be very frequent. Radiosonde data from sites with atmospheric structures even more stable and drier than in Illinois have $S_{max} = 0$ from a majority of soundings. We believe that seedability results from both of the averaging procedures provide a truer picture of modification potential than would result from either one alone.

In table 2, the average maximum seedabilities for Miami reveal that the smallest tower radius (1000 m) was responsible for the largest average seedability (2.3 km) and was so most often (35.4% of 694 seedability calculations). By contrast, the largest tower radius submitted with these soundings to the model was responsible for the maximum seedability least often (13.4% of the calculations) and yielded the lowest average value (1.3 km). The calculations with "zeros excluded" also show that the smallest radius produced the maximum seedability most frequently. There were 54 soundings that had S = 0 for each of the five radii; therefore, 11.3% of the 478 soundings had $S_{max} = 0$. The zeros-excluded average maximum seedabilities are from 3 km to 3.6 km for these Miami soundings. In comparison with these Miami results, the 10 summers of Illinois seedabilities (discussed in Section 4) have the <u>largest</u> radius most frequently resulting in maximum seedability, have $S_{max} = 0$ from about 30% of the soundings and, from only a small percentage of the soundings, have zeros-excluded S_{max} exceeding 3 km.

Table 3 contains the frequency of occurrence of Miami S_{max} in increments of 500 m, regardless of tower radius. The median S_{max} is 3 km, and a majority of the soundings had 2 km $< S_{max} \leq$ 4 km. But S_{max} varies from day to day; furthermore, large seedability is only one link in the decision chain of a precipitation enhancement effort.

In the FACE program, the seeding aircraft can be launched only if satisfactory answers are obtained for a sequence of questions. FACE aircraft

Table 3. Percentage Frequency of Maximum Seedability (S_{max}) in 500-m Height Increments (Results are From 478 Miami 1200 GMT Soundings)

S_{max} (km)	Percentage frequency
$S_{max} = 0.0$	11.3
$0.0 < S_{max} \leq 0.5$	00.4
$0.5 < S_{max} \leq 1.0$	01.5
$1.0 < S_{max} \leq 1.5$	02.5
$1.5 < S_{max} \leq 2.0$	06.1
$2.0 < S_{max} \leq 2.5$	13.2
$2.5 < S_{max} \leq 3.0$	14.9
$3.0 < S_{max} \leq 3.5$	15.7
$3.5 < S_{max} \leq 4.0$	13.4
$4.0 < S_{max} \leq 4.5$	08.8
$4.5 < S_{max} \leq 5.0$	06.7
$5.0 < S_{max}$	05.6

launches ("GO" days) are determined by a procedure detailed by Woodley and Sax (1976), who point out that the maximum seedability is only one of the factors in the procedure. Another factor is introduced to bias the decision for experimentation against naturally rainy days. This factor, which is related to the late morning occurrence of convective showers in the target area, is called "N_e." It is the number of hourly observations, of the FACE target area at 0930, 1030 and 1130 local time, when radar rain showers that had VIP level 2 (30 dBZ) were observed by the WSR-57. N_e, thus, is an integer 0 or 1 or 2 or 3. It is a necessary condition for aircraft launch for the dimensionless quantity ($S_{max} - N_e$) to be 1.5 or larger (Woodley and Sax, 1976).

In the 92-day field program of FACE 1975,

1) S_{max} ranged from 1.4 to 5.05 km, with an average of 3.2 km.
2) $S_{max} = 0$ never occurred.
3) ($S_{max} - N_e$) ranged from -1.05 to 5.0.
4) ($S_{max} - N_e$) $\geq$ 1.5 occurred on 73 days, but only 54 of them were flight days.
5) Of the 54 flight days, 21 were rejected for experimental purposes after the scientists were airborne and observed poor or deteriorating convective conditions over the south Florida peninsula.
6) Of the remaining 33 days on which at least one flare was released, 24 were "B-type" GO days (i.e., days on which at least 60 flares were

released; see Woodley and Sax, 1976, for purpose of "B" day classification).

7) (S_{max} - N_e) was < 1.5 on each of the 5 days with N_e = 3.

The seedabilities in table 3 must be viewed in the foregoing context because seedability can be vitiated by a large value of N_e. Moreover, even when the seedability criterion for aircraft launch is satisfied, there remain causes for the rejection of days for experimental purposes. Cancellation has resulted from suppressed convective activity, which was caused by decreased insolation resulting from the presence of middle and high cloud decks. There were instances of weak, small-scale middle and upper tropospheric disturbances moving into the target area (more disturbed conditions); there were other instances of strengthening of low-level inversions accompanied by high concentrations of African dust (suppressed conditions). Together, these accounted for the rejection of many of the 21 days after aircraft launch. It is probable that regions outside of south Florida will have similar "unworkable" days that cannot be adequately rejected by a simple cumulus model that uses input data obtained several hours before the experiment is set to begin. Thus, although seedability is a useful tool, caution is urged in the use of seedability frequencies of arbitrary magnitude, or clouds of arbitrary size, as sufficient criteria for the performance of a seeding experiment. It also should be noted that in Florida, the predicted seedability, regardless of magnitude, has not been a predictor of the occurrence, strength or extent of cumulus rain showers. Shower activity was seen over land almost every afternoon within a 100-mile range of the Miami weather radar, regardless of the seedability of that morning. A similar situation was found to have occurred during one summer in Illinois.

3. SEEDABILITY AS A FUNCTION OF METEOROLOGICAL CONDITIONS DURING ONE SUMMER IN ILLINOIS

On the basis of soundings and weather observations from one summer, seedability each day in central Illinois tended to be uncorrelated with the convective activity that occurred during that calendar day.

Good radar data and four soundings per day existed during the summer of 1957, which was wetter than normal in June and changed to drier than normal in August. Seedability results calculated from the 1200 and 1800 GMT soundings at Peoria, for June, July and August 1957, are shown in table 4. Maximum seedability exceeded zero in about 70% of the calculations that were based on the 1200 GMT soundings, and about the same fraction of the calculations that were based on the 1800 GMT soundings.

The meteorological events cited were observed to occur at some time during a 24-hour observation period. The area of evaluation contained 18 cooperative observer stations, which were distributed over 11 counties of central Illinois, and which made daily reports. Many of the observations were for the day ending at 5 to 7 p.m. However, some other observers ended their data "day" at 7 or 8 a.m. When the prediction of seedability on a given day was compared with the observed weather, the afternoon records of the first group of observers and the following day's morning records of the second group of observers were used.

Table 4. Observed Meteorological Events, Summer 1957, Versus Maximum Seedability From Peoria Soundings

	Hail	Thunder	Rain	Radar echoes
$S_{max} = 0$	7% (4%)	41% (35%)	66% (69%)	54% (52%)
$S_{max} > 0$	3% (5%)	39% (42%)	66% (66%)	58% (60%)

Values are in percent of days with indicated S_{max}.
Observations for 1800 GMT soundings are followed by those for 1800 GMT in parentheses.

Radar data were obtained from the Illinois State Water Survey CPS-9 X-band radar at Champaign-Urbana. Coverage of the same 11 counties was attained by using only the northwest quadrant of the PPI display out to 100 statute miles.

Table 4 indicates that the days of $S_{max} = 0$ had observed weather quite similar to that associated with soundings yielding $S_{max} > 0$. At least one observer recorded hail on 7% of those days when the 1200 GMT sounding was found to yield $S_{max} = 0$. By comparison, on 3% of the days with $S_{max} > 0$, at least one observer recorded hail. When the 1800 GMT sounding was used as model input, 4% of the days with $S_{max} = 0$, but 5% of the days with $S_{max} > 0$, had at least one observer who recorded hail.

In this study of a single Illinois summer, seedability, whether or not it was zero, was found to be uncorrelated with weather events for the day as a whole, and was not a good predictor of precipitation or cumulonimbus activity. Semonin (1977) noted similar results from the same region, but used a different data set and cloud model.

4. CUMULUS MODEL RESULTS FROM 10 SUMMERS OF ILLINOIS SOUNDINGS

Radiosonde data from central Illinois for 1953 through 1962 were acquired from the Illinois State Water Survey (ISWS). According to Semonin (1977), that block of data was chosen by ISWS "because (1) the precipitation regime in Illinois varied from very dry in 1953-55 to very wet in 1957-58, and (2) the reported error in more recent radiosonde measurements of relative humidity was avoided." We selected only the June, July and August soundings for this study. Through the summer of 1956, the soundings were taken at Chanute Air Force Base (Rantoul) at 0300, 0900, 1500 and 2100 GMT. Beginning in September 1956, soundings were made by the U.S. Weather Bureau at Peoria, about 150 km west-northwest of Rantoul. In 1957 the launches were at 0000, 0600, 1200, and 1800 GMT, but, in all subsequent years, soundings were regularly made only at 0000 and 1200 GMT. The vertical interval of data separation was never more than 50 mb; all mandatory and significant levels were present. Only soundings that ascended at least to the 200-mb level were used as input for the FACE cumulus model. Altogether, 2751 soundings were processed with the FACE one-dimensional cumulus model and the EMB 68P seeding routine.

In an earlier study, Wiggert and Holle (1977) presented seedability results from the same data set for these 10 summers and also results for one subset based upon 1200 GMT soundings only. But in that subset, the 1953-56 data from Rantoul (never scheduled at 1200 GMT) were effectively disallowed. Here we ameliorate that difficulty as Semonin (1977) did in his study; all soundings with launch times between 1100 and 1500 GMT (0500 to 0900 CST) are considered representative of "morning" conditions. Similarly we have "evening" results extracted from all soundings with launch time between 2300 and 0300 GMT.

As noted, model calculations of seedability require not only the thermodynamic structure (sounding data), but also cloud base height(s) and cloud tower size(s). Wiggert and Holle (1977) presented seedabilities based upon five cloud tower radii and two cloud base heights. One cloud base height was fixed at 915 m (the same as used in FACE), whereas the other was a calculated convective condensation level (CCL, defined in Appendix A). The detailed results of the CCL's, as functions of month, year, and hour, are in Appendix C. The average CCL was about 2320 m in June, but was about 150 m lower in July and August. However, about 10% of the soundings had CCL's exceeding 3500 m. All June, July and August soundings were used by Wiggert and Holle (1977), and no constraints were placed upon CCL cloud base height. Their tabulations of Illinois seedabilities indicated that the largest of the five tower radii gave the maximum seedability in 23.9% of the calculations, and that about one-third of the zeros-excluded average S_{max} resulted from using the 2500-m tower radius. For that radius, these frequencies were much higher than those observed for Miami soundings; there was an indication that a broader range of tower sizes than found in Florida might occur as seeding opportunities in Illinois.

In view of the foregoing, we present and discuss Illinois seedabilities calculated with eight cloud tower radii (500, 750, 1000, 1250, 1500, 2000, 2500, and 3000 m) and with CCL cloud bases no higher than 3500 m. Table 5 presents average maximum seedabilities as functions of modeled cumulus tower radius for Rantoul/Peoria, Illinois, for the 30 months of data. When null values are included, the average maximum seedabilities were $\leq$ 1 km, regardless of radius. But when averages were formed for all maximum seedabilities that exceed zero, then S_{max} ranged from 2.6 to 3.7 km. These zeros-excluded averages are comparable to FACE results in table 2. Nevertheless, the largest of the eight radii used here gave the S_{max} for nearly one-fourth of 1779 soundings. Altogether, there were 2476 soundings that had CCL cloud bases within 3500 m of the ground. Of these 2476 soundings, 28.2% had S_{max} = 0. Tables of average seedabilities from various subsets of the Illinois sounding data set are presented in Appendix D for (a) morning or evening soundings from (b) June, July, or August for (c) eight tower radii (with CCL bases $\leq$ 3500 m) or five tower radii (with all CCL bases), and including (d) either S_{max} = 0, or zeros-excluded S_{max}. Results shown in those appended tabulations are

1) Morning seedabilities tended to be smaller than those from evening soundings.
2) June seedabilities were almost never larger than the 3-month average.

Table 5. Average Maximum Seedability and Percentage Frequency Versus Modeled Cumulus Tower Radius for Rantoul/Peoria, Illinois, Soundings of June, July, and August 1953 to 1962

Radius (m)	Zeros included (km/%M)	Zeros excluded (km/%N)
500	0.4/11.4	2.6/08.1
750	0.9/13.4	2.9/16.1
1000	0.9/12.9	3.3/14.3
1250	0.8/12.2	3.5/11.2
1500	0.7/12.0	3.5/10.3
2000	0.7/11.7	3.7/09.1
2500	0.5/11/3	3.4/07.5
3000	1.0/15.1	2.7/23.4
	M = 7355	N = 1779
		N(0) = 697 = soundings with S_{max} = 0
		$N_T = N + N(0) = 2476$
		$N(0) = .282\ N_T$

Cloud bases are CCL's ≤ 3500 m.
M = number of calculations.
N = number of soundings.

3) The largest tower radius was most frequently responsible for maximum seedability.
4) Between 28% and 33% of the soundings had S_{max} = 0.
5) Excluding the soundings with S_{max} = 0, the resulting average maximum seedabilities ranged from 2 to 4 km.

From this, we see that zeros-excluded average maximum seedabilities derived from these Illinois summer soundings have magnitudes that approximate those from south Florida, but the frequencies are much lower in Illinois than in Florida. The distribution with tower radius of the Illinois results seems to imply that larger cumulus towers will be seeding candidates more often there than in south Florida. About one summer day in three will have null seedability (S_{max} = 0) for even the largest of eight tower radii. In Florida, S_{max} = 0 is well correlated with clouds that are not worth seeding, either because of the formation of enormous, late afternoon cumulonimbi, or (as is most often the case) because of conditions where no clouds reach -4°C. Removal of these S_{max} = 0 cases, then, excludes a few very unstable and many very stable convective situations.

Now let us consider frequency of occurrence of maximum seedability > 1.5 km. These maximum seedabilities are depicted for June, July and August in figures 1a through 1c. No notice is taken of which tower radius produced the S_{max}. The threshold of 1.5 km is chosen because, in Florida, the FACE program uses an aircraft launch (GO-day) criterion of (S_{max} - N_e) $\geq$ 1.5. At best, N_e is zero, but we actually do not know the number of forenoon hours of radar rain showers for any of these soundings. If this same criterion is imposed on these Illinois data, and if we also presume a "best case" (N_e = 0) for each sounding, figures 1a through 1c reveal the frequency of satisfaction of the FACE criterion for morning and evening soundings in each of the 30 months of these Illinois data. Seedability, calculated from the evening soundings for the 30 months, exceeded the 1.5-km criterion more often than did that from morning soundings. Also, for the 10 Julys, the average frequencies of satisfaction of the FACE criterion (morning or evening) were > 64% and were larger than the frequencies for the counterpart averages of the 10 Junes or 10 Augusts. Furthermore, regardless of month, at least five evening soundings out of eight satisfied the criterion. However,

1) Half of the Junes had lower averages when evening rather than morning soundings were used.
2) Differences exceeding 10% between the morning and the evening results occurred in two out of three months in 1957, 1960, 1961, and 1962.
3) In 1959, the year when June had the lowest percentages, August had the highest percentages.
4) One of the best Junes (1953) was followed by the worst August.

Thus, in Illinois there was notable variability in the frequency of occurrence of "acceptable" seedability (i.e., that meeting the criterion used in FACE). This variability was seen when individual years were compared with the 10-year mean, when morning averages were compared with those from evening soundings for the same month, and when results for June were compared with those for August within a particular year. Presumably, similar variations in acceptable seedability in Illinois will be observed in the future, as was found during these 10 years, and will be observed elsewhere in the midcontinental United States as in Illinois.

The percentage frequencies of maximum seedability in 500-m increments are presented in figures 2a and 2b. Results from morning soundings are displayed in figure 2a; those from evening soundings are in figure 2b. In each figure, a quintet of bar graphs permits comparison of the seedabilities from 10 Augusts with those from 10 Julys, or 10 Junes, or with averages for the 30 months. The leftmost bar in each quintet in figure 2a is exactly the same as the leftmost in figure 2b. These pin-striped bars are results from all hours of soundings and, therefore, include seedabilities from soundings taken at 0600, 0900, 1800, and 2100 GMT that are excluded from both the morning (1100 to 1500 GMT) and the evening (2300 to 0300 GMT) averages. We conclude that

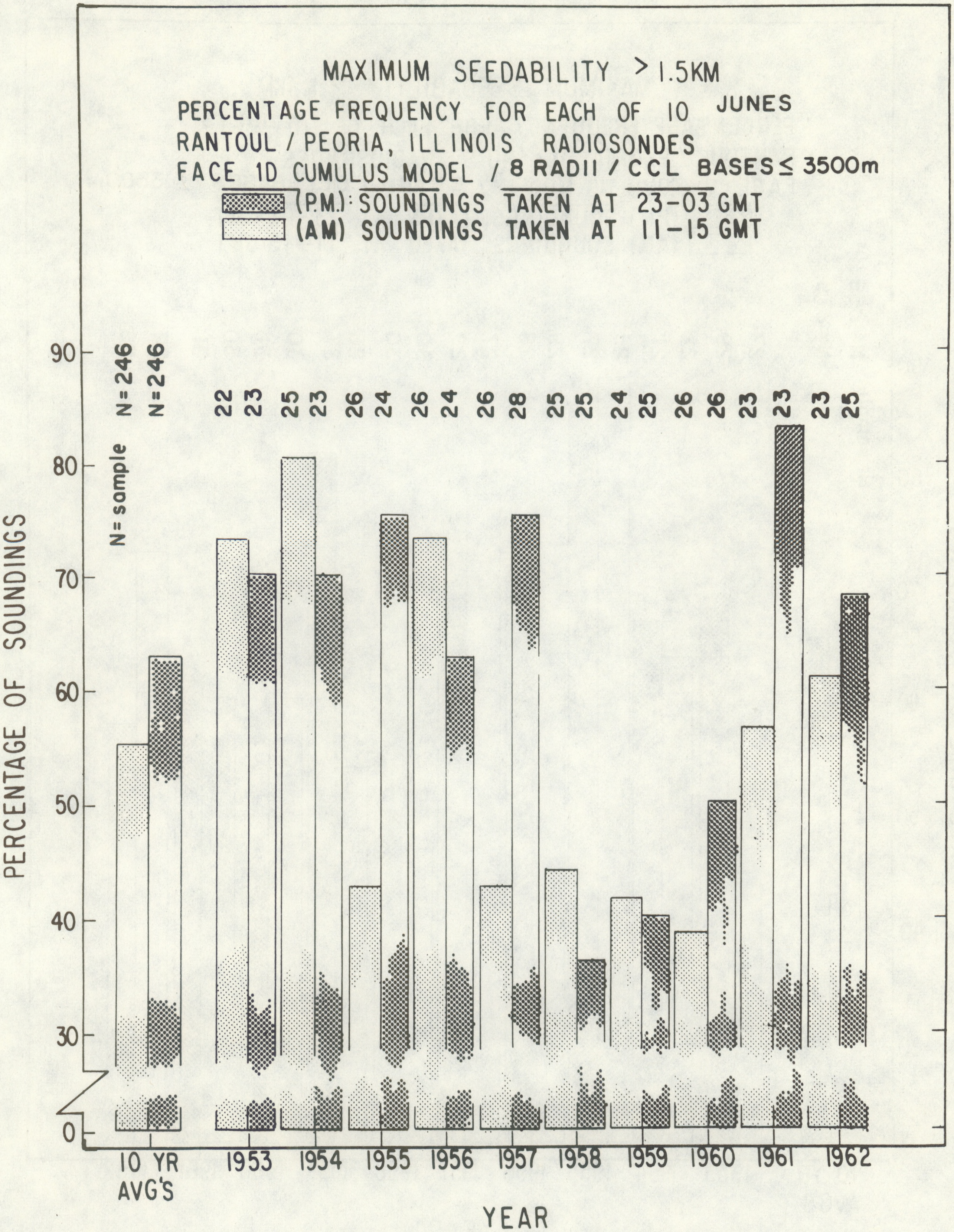


Figure 1a. Maximum seedability > 1.5 km. Percentage frequency for 10 Junes at Rantoul/Peoria, Illinois.

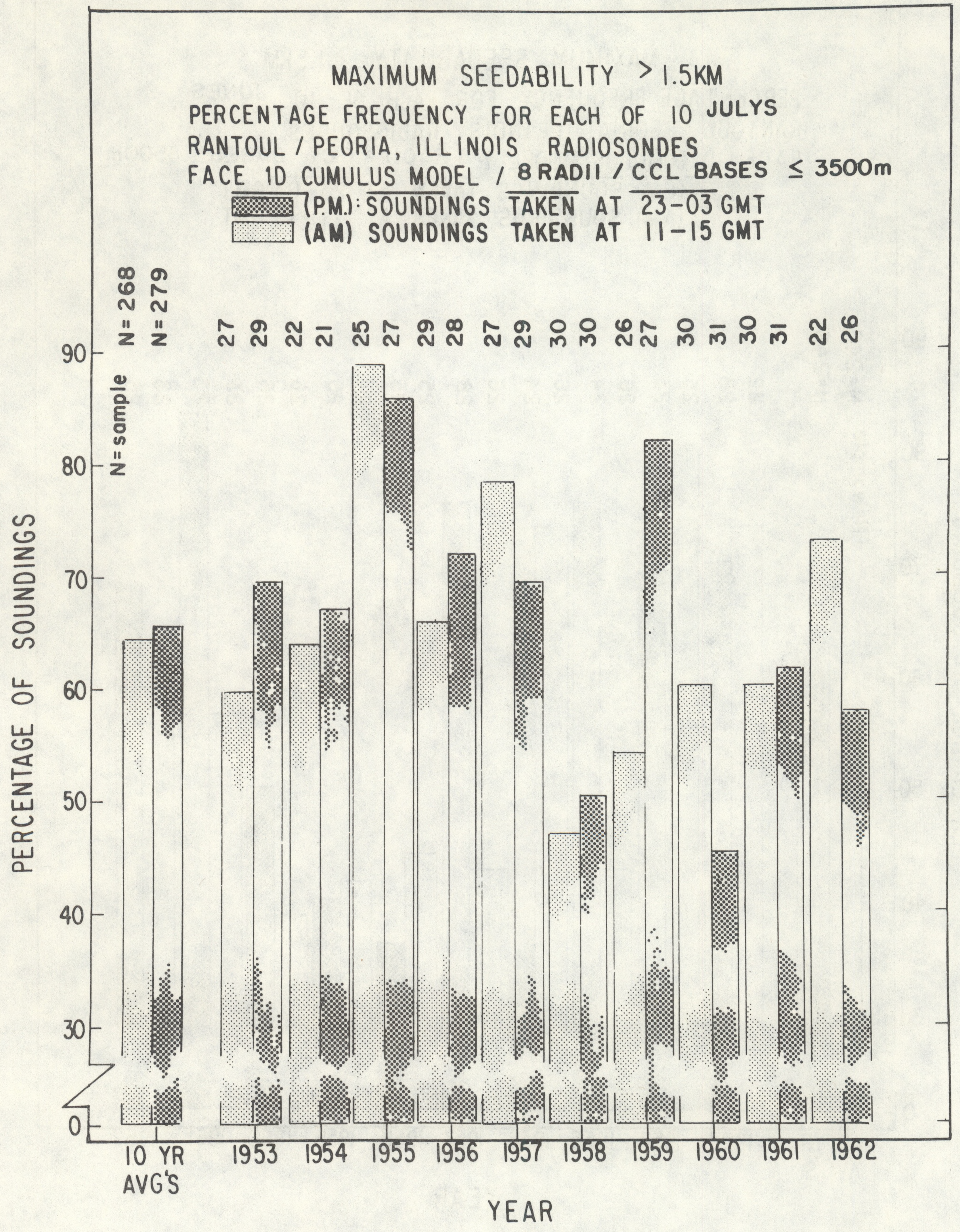


Figure 1b. Maximum seedability > 1.5 km. Percentage frequency for 10 Julys at Rantoul/Peoria, Illinois.

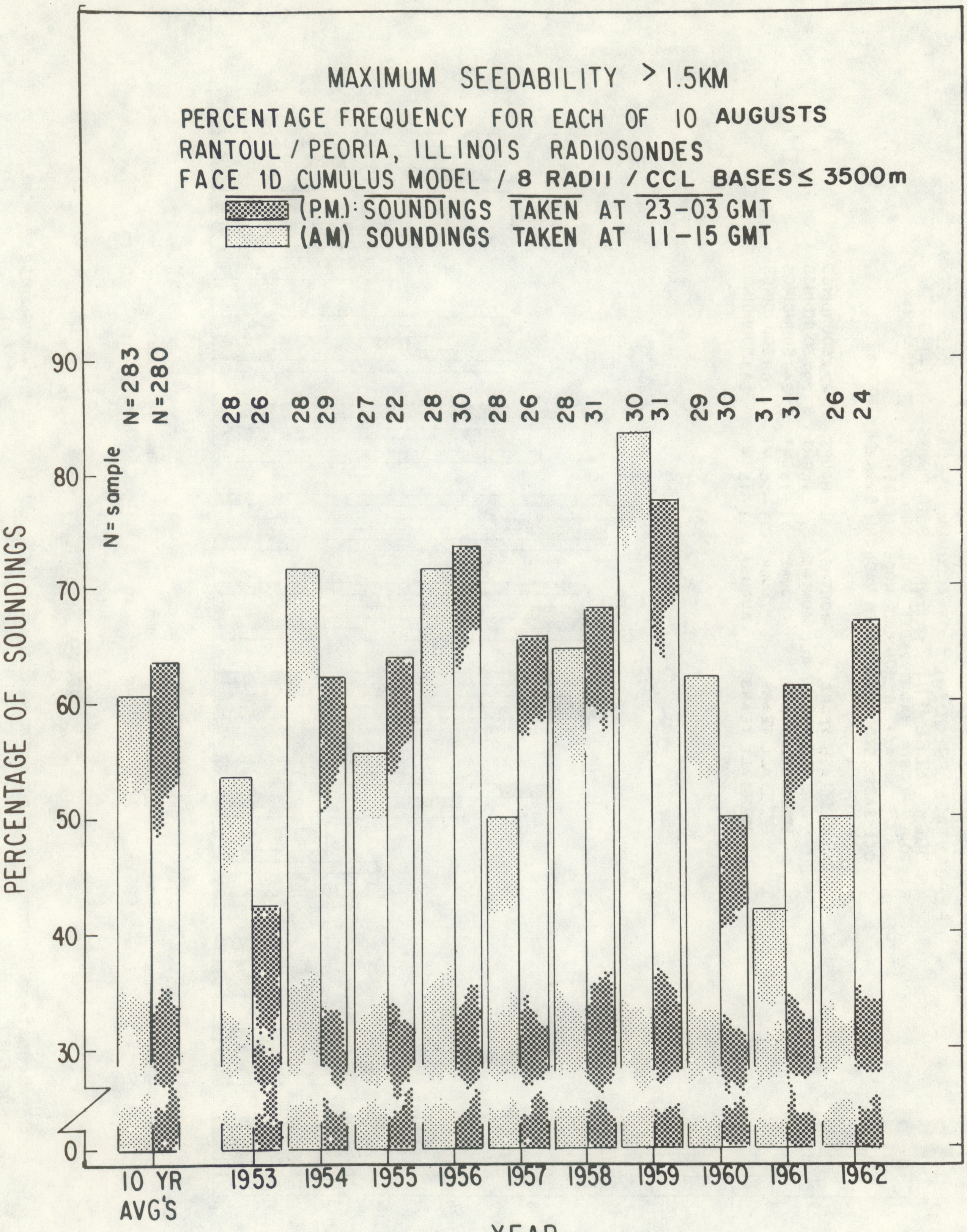


Figure 1c. Maximum seedability > 1.5 km. Percentage frequency for 10 Augusts at Rantoul/Peoria, Illinois

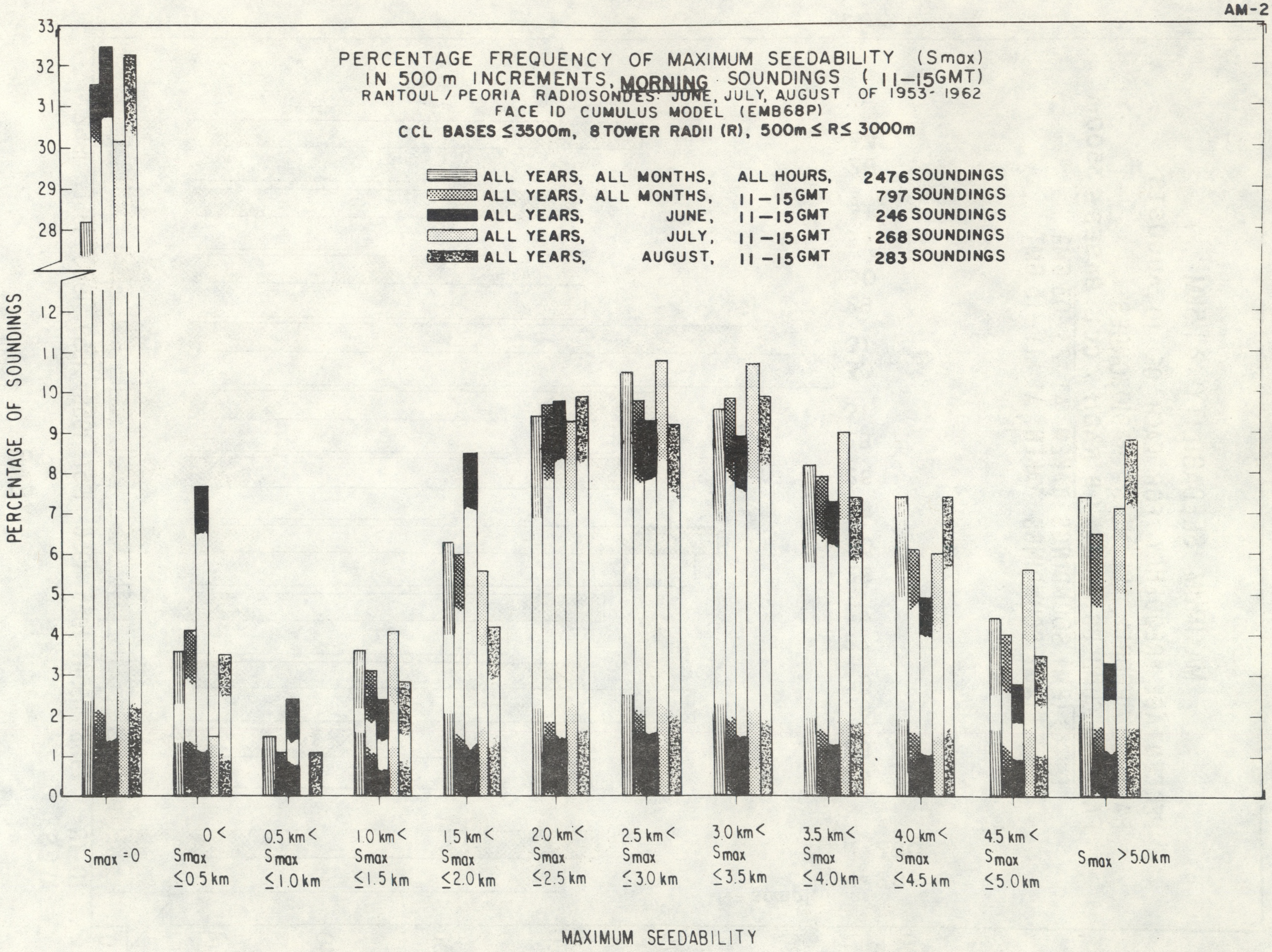


Figure 2a. Percentage frequency of maximum seedability (S_{max}) in 500-m increments for morning (1100 to 1500 GMT) soundings.

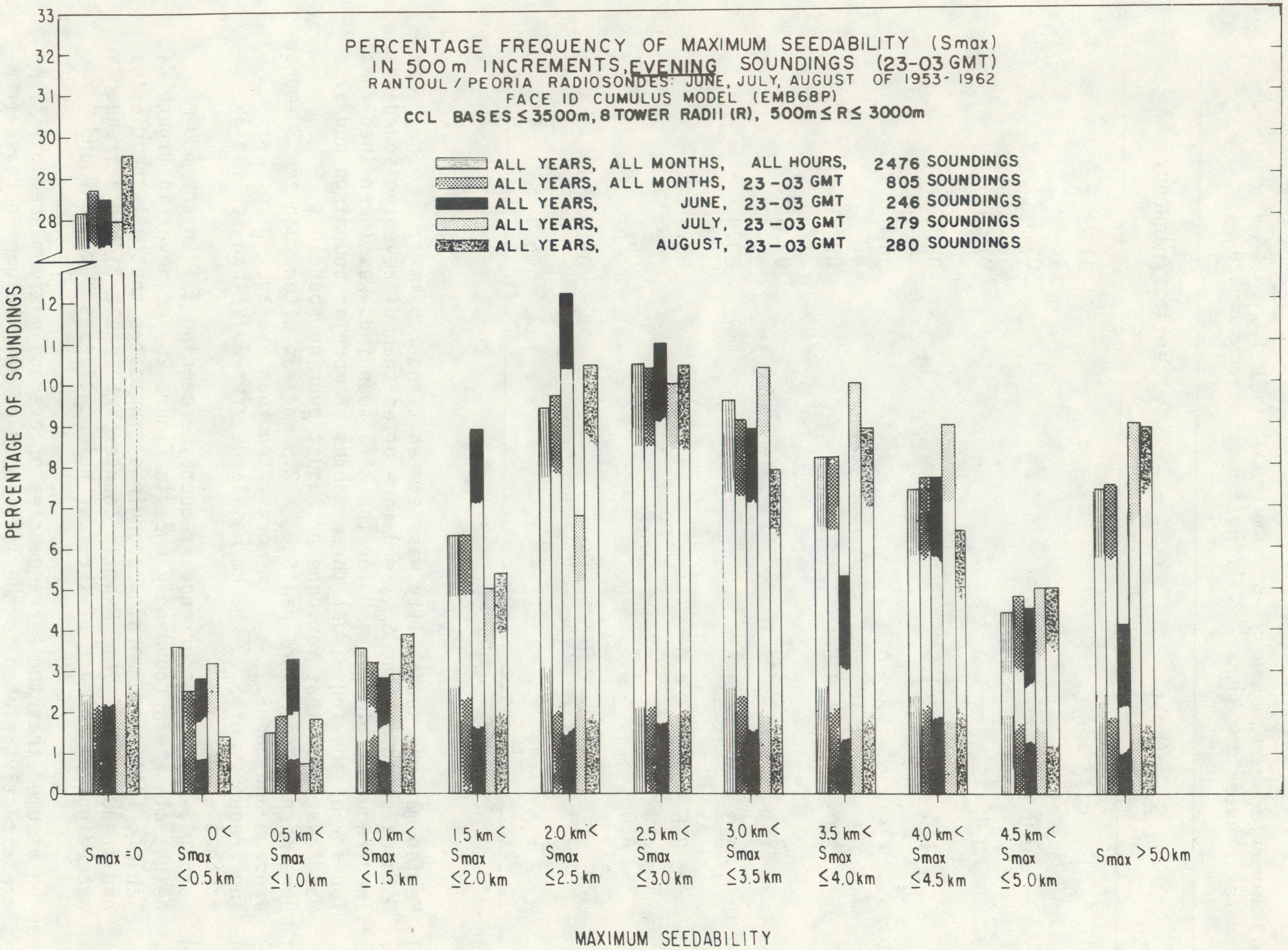


Figure 2b. Percentage frequency of maximum seedability (S_{max}) in 500-m increments for evening (2300 to 0300 GMT) soundings.

Table 6. Percentage Frequency of Maximum Seedability (S_{max}) in 500-m Height Increments (Results are from 797 Illinois morning soundings)

S_{max} (km)	Percentage frequency
$S_{max} = 0.0$	31.6
$0.0 < S_{max} \leq 0.5$	04.1
$0.5 < S_{max} \leq 1.0$	01.1
$1.0 < S_{max} \leq 1.5$	03.1
$1.5 < S_{max} \leq 2.0$	06.0
$2.0 < S_{max} \leq 2.5$	09.5
$2.5 < S_{max} \leq 3.0$	09.8
$3.0 < S_{max} \leq 3.5$	09.9
$3.5 < S_{max} \leq 4.0$	07.9
$4.0 < S_{max} \leq 4.5$	06.1
$4.5 < S_{max} \leq 5.0$	04.0
$5.0 < S_{max}$	06.5

1) Median maximum seedability was between 2 and 2.5 km.
2) Morning soundings had $S_{max} = 0$ more often than did evening soundings.
3) The frequency of $S_{max} = 0$ for the 2476 soundings was lower than that for any of the individual three months of morning soundings and also was lower than that for June or August evening soundings.
4) June morning soundings had $S_{max} > 2.5$ km less often than the 30-month average and had $S_{max} \leq 1$ km more often than average.
5) The frequency of $S_{max} > 3$ km was larger for July than for the 30-month average.
6) For $S_{max} > 0$, an occurrence frequency exceeding 12% in any 500-m height class was found only once in figure 2b and never in figure 2a. Table 6 (Illinois, morning soundings) indicates that all the classes had frequencies < 10%; Miami's counterpart (table 3) had a frequency exceeding 13% in each of the four height classes between 2 and 4 km.

If it can be assumed that these frequencies of average maximum seedability in Illinois are directly related to the likelihood of rain volume increase from seeding of cumuli, then June is the summer month with the smallest potential for modification; July is the best month, and about half of the days in an average summer have modification potential ≤ 1 km. (In south Florida, research based upon seeding of single cumuli seemed to show that on days when $S \leq 1$ km was predicted, rainfall decreases were observed (Holle, 1974)).

The day-to-day persistence of good seedability may offer a clue to the persistence of favorable conditions for precipitation enhancement. The number of occurrences when "n" days in sequence were found to have $S_{max} \geq 1.5$ km are plotted in figure 3. Only the morning soundings and CCL bases $\leq$ 3500 m were used; therefore, within each summer a sequence broke when a morning S_{max} was < 1.5 km or when the CCL cloud base was > 3500 m. Of course, when n equaled 1, there was no sequence; and in 10 summers there were 79 instances when n equaled 1. The search and tabulation procedure first sought the longest sequence in each 92-day summer. Once found, that sequence was tabulated and removed from further consideration. The next longest sequence was then sought and the process repeated. At least one sequence of 5 or more days having $S_{max} \geq 1.5$ km occurred in every 1 of the 10 summers. In 1956 there were 14 consecutive June mornings with $S_{max} \geq 1.5$ km; subsequently that summer, there was a 9-morning sequence. The strings of "unusable" days, when either S_{max} was < 1.5 km or CCL cloud bases exceeded 3500 m are also displayed in figure 3. There were four cases when more than a week of morning soundings had low seedabilities or high CCL cloud bases.

In south Florida, the FACE program has met with similar sequences of 5 or more days with $S_{max} \geq 1.5$ km, but, as noted, other factors besides satisfactory seedability must be considered for actual operations by seeder aircraft to take place. For example, the concentration of ice particles and the relationship between ice, water and updraft structure within the cloud envelope are important parameters affecting on-the-spot decisions of seeding opportunity. Knowledge of these parameters is gained through direct penetration of the cloud by specially instrumented aircraft, as was done in Illinois on two days in summer 1977.

5. MEASUREMENTS OF ILLINOIS CLOUD CHARACTERISTICS

5.1 Introduction

Our experience in Florida has shown that successful dynamical stimulation of cumuli depends not only upon the atmosphere's thermodynamic structure (as indicated by seedability), but also upon the internal microstructure of the cumulus cloud. Lamb et al. (1978) have shown the importance of both the cloud droplet and rain water contents on the rate of heat release as glaciation proceeds within the seeded cloud. Hallett et al. (1978) have shown that convective clouds with broad drop size distributions (such as those in Florida), which may be ideally suited for the effective inducement of warming through the introduction of an ice-phase nucleant, have exceedingly short time windows during which they remain microphysically suitable for artificial alteration. It has been observed that natural glaciation can occur very rapidly in such clouds, but not until the tower's updraft begins to weaken. It is postulated that a secondary ice generation process, dependent upon an initial concentration of graupel particles in the presence of both small ($d < 12$ μm) and large ($d > 24$ μm) cloud droplets within a critical temperature range (-3° to -8°C), is responsible for the efficient conversion of water to ice. Since dynamic seeding is expected to produce sudden and massive

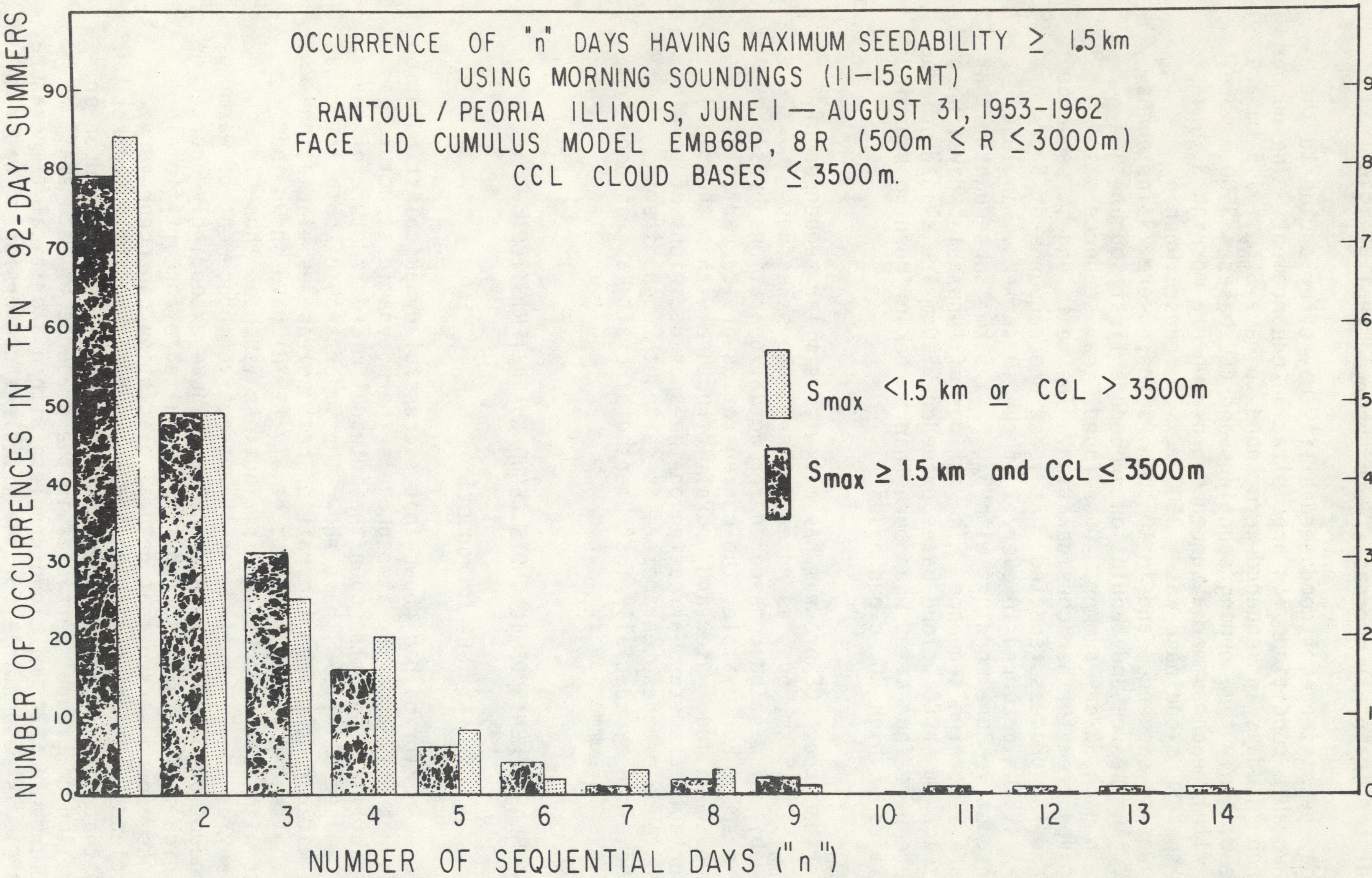


Figure 3. Occurrence of "n" days having maximum seedability ≥ 1.5 km when morning (1100 to 1500 GMT) soundings were used.

glaciation within the active updraft region of the cloud, it is very important to obtain measurements bearing on the natural evolution of the ice-water budget in relation to the life history of the updraft.

The NOAA WP-3D aircraft was dispatched to Illinois in mid-July 1977, as a first step in efforts to obtain a series of microphysical measurements of clouds developing in that environment. The objective of the measurement program was to determine if the microstructure of Illinois cumuli is sufficiently similar to that of cumuli developing in Florida to warrant further exploratory studies to determine the feasibility of applying dynamic seeding technology in that area. No cloud seeding was done. No photogrammetric measurements were made of top heights or diameters of the cumuli.

During the afternoons of 21 and 22 July 1977, the NOAA WP-3D penetrated, near the -10°C isotherm level, convective complexes that were developing in central and southern Illinois. Measurements of updraft profile, cloud water content, cloud drop size distributions and the concentrations of graupel, crystalline ice and raindrops were obtained for each cloud. A ground-based dual X-band and S-band digitized radar (CHILL) was operated by the ISWS in a tilt-sequence mode to obtain echo height population data for the sample of clouds developing in the area selected for the aircraft measurements. But larger scale events also played a role in some of the changes in cloud growth and behavior that were observed during the two days.

5.2 Meteorological Conditions - Synoptic and Radar Summary

As summarized by Sax et al. (1978), central Illinois experienced deep moist convection on 21 July as an upper level trough that was associated with a midtropospheric short wave crossed the state. Figure 4 shows the progressive positioning of the 700-mb trough axis and the surface cold front in relation to the location of the measurement area. The trough moved rapidly across Illinois during the day but became nearly stationary during the following night. Associated with the upper level trough was a diffuse surface cold front separating a shallow dome of cool air to the north from deep moist air to the south. The leading edge of the frontal zone, which was almost directly below the 700-mb trough, was definable mainly by a wind shift; the moisture gradient was 100 to 150 km wide, and several hours behind. Frontal movement was similar to that of the 700-mb trough.

The air over central and southern Illinois was moist and conditionally unstable through nearly the entire depth of the troposphere on 21 July. As the trough passed, replacement of moist air with dry occurred first at the upper levels during the night and then propagated downward. By late in the afternoon of 22 July the atmosphere over Illinois was relatively dry at all levels. The thermodynamic structure of the lower troposphere at Salem, Illinois, is shown in figures 5a through 5d for four observation times from 1200 GMT 21 July to 0000 GMT 23 July. The proximity of the surface front to Salem is particularly evident from the low-level inversions seen in figures 5b and 5c.

The presence of an extensive layer of moist, conditionally unstable air, and the probable presence of convergence, resulted in deep convection both ahead of and in the broad frontal zone over Illinois on 21 July (fig. 5a).

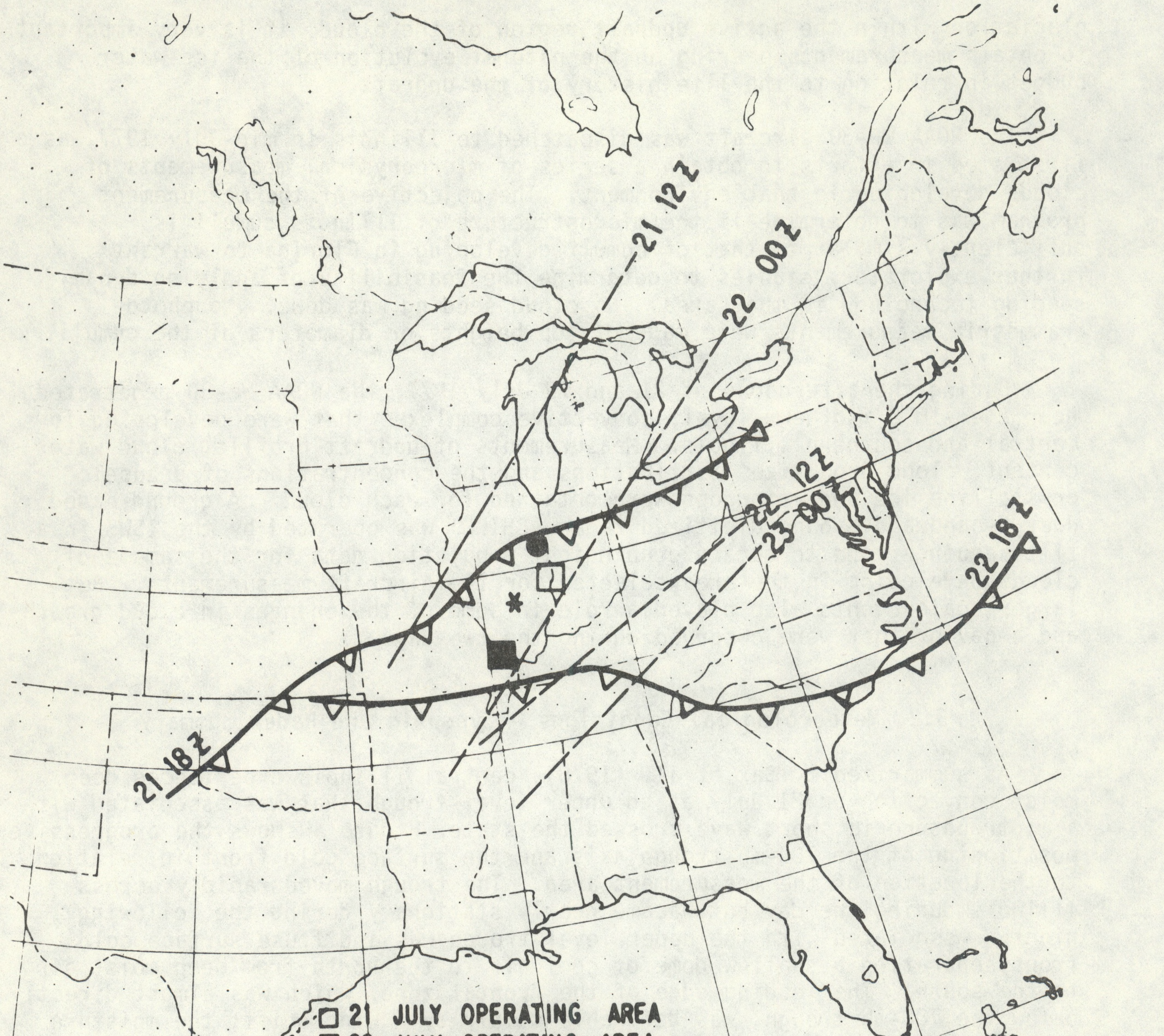


Figure 4. Surface front, 700-mb trough positions, and Illinois measurement area, 21 and 22 July 1977.

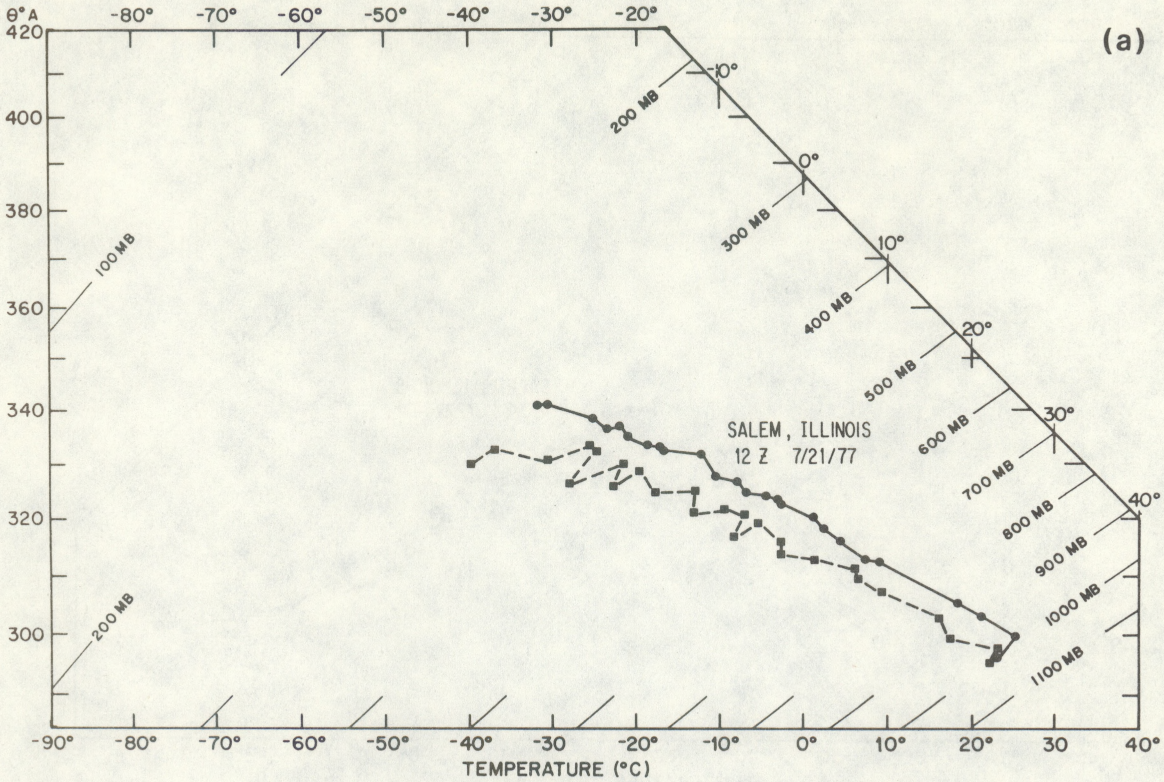


Figure 5a. Temperature (solid) and dew point (dashed) soundings at Salem, Illinois, for 1200 GMT, July 1977.

Convective clouds with low (about 0.8 km) bases started developing as soon as the surface heating was adequate to destroy the nocturnal stable layers. By 1300 CDT (noon solar time), there were large convective clouds with top heights reaching 12 km in central and southern Illinois. On 22 July (figs. 5c, 5d), however, cumuli developing in the dry air behind the front were struggling to reach 6 km. Even this small degree of activity was confined to a region of extreme southern Illinois (fig. 4) well beyond the range of the CHILL radar at Champaign.

On 21 July, a volumetric radar surveillance by the ISWS within a 110-km radius of Champaign indicated widespread echo coverage throughout the afternoon. In figure 6 are shown the average frequency distributions of cloud echo tops representative of three 2-hour periods between 1300 and 1900 CDT, and of the whole 6-hour period. Each average is based on six volume scans, one every 20 min. There is similarity in the shapes of the frequency distributions, although the number of individual summits decreased systematically as the afternoon passed. There is also evidence of an increase in both the modal and mean summit heights with time. A very noticeable feature of the frequency distributions is the bimodality, with peak frequencies at 5 to 7 km and at 9 to 10 km. This suggests that the population of echo summits may be the result of two modes of cloud development, one in which maximum heights were primarily below 8 or 9 km and the other in which the maximum clouds reached the tropopause.

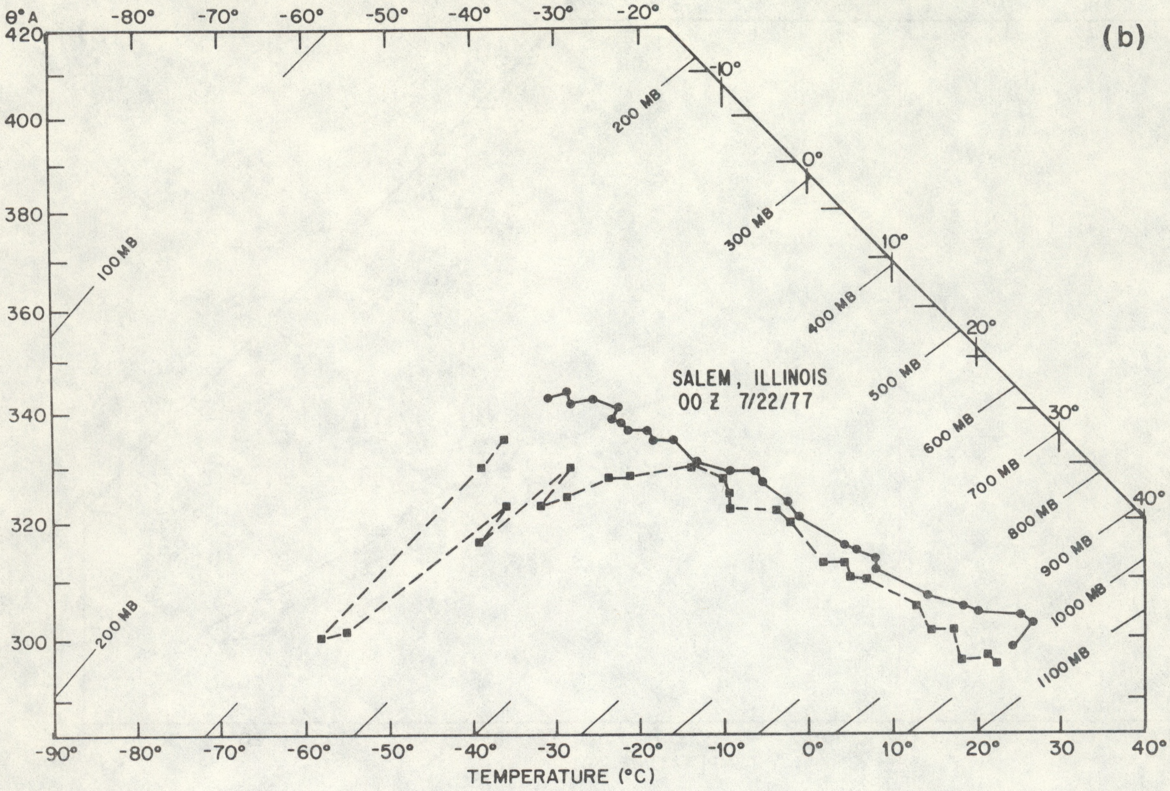


Figure 5b. Temperature (solid) and dew point (dashed) soundings at Salem, Illinois, for 0000 GMT, 22 July 1977.

The radar echoes occurred in the southeast, spreading rapidly throughout the 110-km circle within an hour. To determine whether the distribution of echo heights differed as a function of location relative to the front, the area was divided into three "bands" oriented roughly ENE-WSW. It is difficult to determine the exact time of the passage of the leading edge of the frontal zone from the hourly surface observations because of showers, but one may assume the most southern of the three cloud regions (Area I) was most distant from the dry air and the northern one (Area III) was closest.

The average frequency distribution of echo height for the individual cloud regions, normalized by area of radar coverage, is shown in figure 7. The frequency distribution of a fourth region (Area IV) is also shown. The clouds in this group developed around 1630 CDT in the northwest corner of the radar coverage and may have been postfrontal, although the late hour of their development certainly would also have had an important effect on their intensity. The other three cloud regions existed throughout the 6-hour period, drifting slowly southward with time. The distributions of the three main cloud regions are very similar, all showing the bimodal characteristic of the combined data.

With the exception of the late-forming clouds of Region IV, the average echo summit heights in the cloud regions are very similar. On the average, the echo tops were between 7 and 8 km, but this value must be interpreted in light of the skewness and bimodality of the distributions.

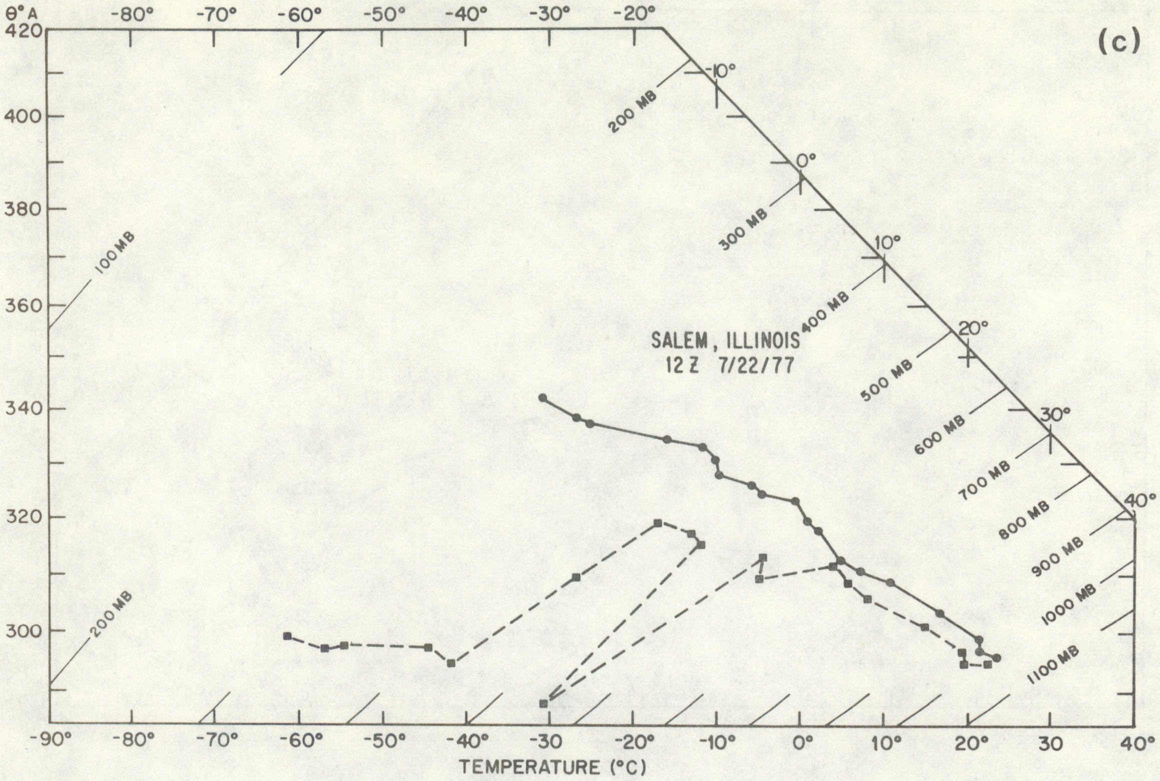


Figure 5c. Temperature (solid) and dew point (dashed) soundings at Salem, Illinois, for 1200 GMT, 22 July 1977.

The frequency that individual echo summits were in the higher of the two modes was about 30% to 35% greater in Areas I and III than in Area II. The poor spatial and temporal resolution of the upper air network makes it difficult to place these mesoscale cloud regions relative to the trough line exactly. However, Area I was probably in the leading part of the trough and Area II closer to the center of the trough. In this case, one may speculate that the frequency, rather than the depth, of convective development is more sensitive to location in the trough.

5.3 Microphysical Characteristics - Cloud Water and Updraft Structure

A series of 14 clouds in Band I was penetrated at flight level 6100 m (-9°C) during the afternoon of 21 July. Four of these clouds were penetrated a second time and, of those, two were penetrated a third time. Three clouds were penetrated at least twice each at about the same flight level during the afternoon of 22 July. Although the temperature at penetration altitude was similar on both days, the dew point spread ($T-T_d$) was a factor of 4 greater on the 22nd.

Table 7 gives the cloud water and vertical velocity statistics obtained from initial penetrations of convective towers on both days. For each cloud, the maximum, minimum, mean, median, and standard deviation values of both Johnson-Williams cloud water content ($g\ m^{-3}$) and draft-scale vertical velocity

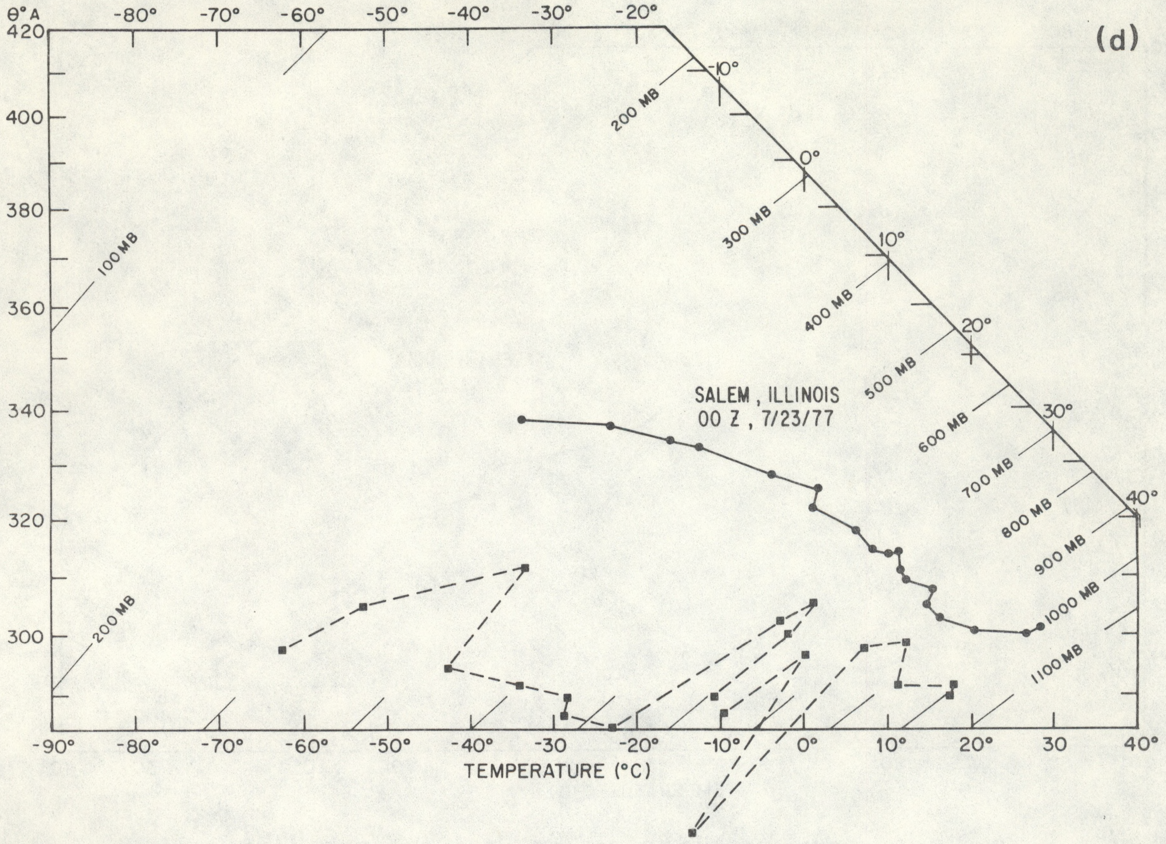


Figure 5d. Temperature (solid) and dew point (dashed) soundings at Salem, Illinois, for 0000 GMT, 23 July 1977.

(m s^{-1}) are provided. For the 13 clouds on 21 July (and again for the 3 clouds on 22 July), the ensemble maximum, ensemble minimum, etc., are listed, as well as the whole-day means and standard deviations. Table 7 indicates that the clouds penetrated on 21 July as a group were much wetter and contained much stronger updrafts than those penetrated on 22 July. Maximum cloud water contents > 1 g m^{-3} occurred on initial penetration of all but 2 of the 13 clouds sampled on 21 July, and maximum cloud water contents < .75 g m^{-3} were found in the three clouds sampled on 22 July. The strongest updraft encountered in the 22 July clouds was found to be < 5 m s^{-1} in contrast to 21 July, when the mean maximum updraft for all clouds was > 7 m s^{-1}.

One of the wettest clouds observed on 21 July was pass 13/1 penetrated at 204025 GMT. The duration of the pass was 11 seconds, which, at WP-3D airspeed (140 m s^{-1}), was equivalent to a tower diameter of a little more than 1.5 km. The profiles of water content and vertical velocity are shown in figure 8a. The cloud boundaries are clearly defined by the water content profile. The water content exceeded 1.5 g m^{-3} for about 75% of the traverse. However, the vertical velocity was very peaked and, for most of the cloud pass, was < 2 m s^{-1}. The cloud was penetrated about .3 km below its visible top.

Figure 8b shows the water and updraft profiles for two new cloud towers (considered together as penetration 14/1 in table 7) sampled about 4 min after the pass shown in figure 8a. A growing turret, penetrated just as its top moved upwards through flight altitude, contained moderate (1.3 g m^{-3}) water content but only a very weak (3 m s^{-1}) peak updraft. The second tower, when penetrated several seconds later, however, already had grown well above the sampling altitude and had a substantial (20 m s^{-1}) updraft along with its moderate (1.4 g m^{-3}) value of cloud water content. Similar profiles have been commonly observed in convective towers penetrated in south Florida, with the updraft/water ratio depending, at least partially, upon how far below cloud top the penetration was made. On some occasions in Florida, high water contents have been found to be coincident with only weak updrafts, as in the cases so far presented here, whereas, on other occasions, very strong updrafts without much cloud water have been observed.

The evolution of cloud water and updraft structure in a tower penetrated twice on 21 July is shown in figure 9. The cloud was sampled very close to its visible top on the initial pass, but about .3 km below the top on the second pass 3.5 min later. It can be seen that the tower retained its cloud

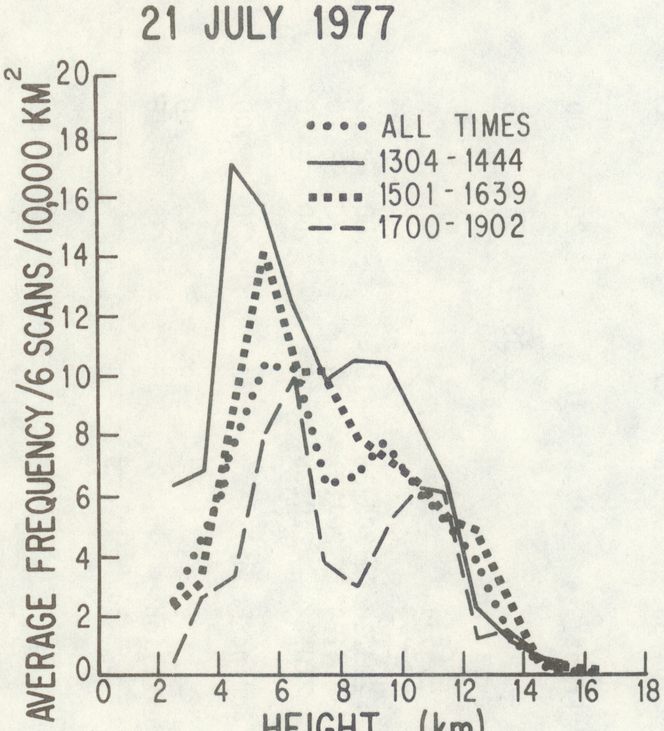


Figure 6. Cloud echo tops, 1300 to 1900 CDT, in three successive 2-h periods within 100 km of Champaign, Illinois, 21 July 1977.

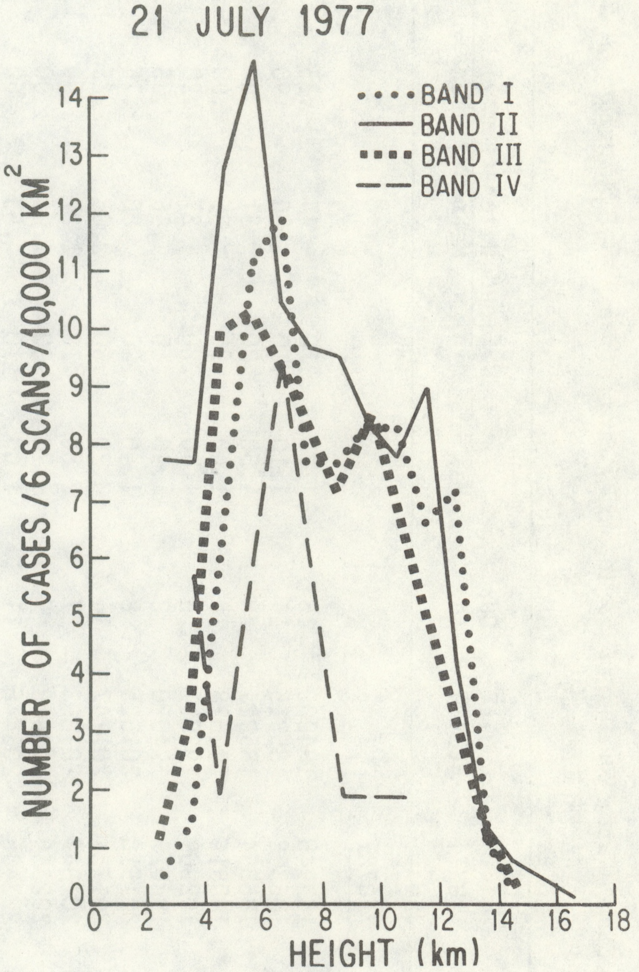


Figure 7. Cloud echo height, relative to distance from frontal zone, within 100 km of Champaign, Illinois, 21 July 1977.

Table 7. Cloud Water and Vertical Velocity Statistics for Population of Illinois Cumuli Penetrated on 21 and 22 July 1977 (First Pass Data Only)

Cloud	In (GMT)	Out (GMT)	Dur (s)	JW Cloud Water ($g\ m^{-3}$) Max	Min	Mean	Med	σ	Vertical Velocity ($m\ s^{-1}$) Max	Min	Mean	Med	σ
770721													
1-1	183945	184000	16	1.20	.10	.44	.35	.00	11.3	-4.1	3.4	2.8	4.6
2-1	185302	185315	14	1.10	.10	.80	.90	.30	13.9	-3.6	5.3	4.2	6.1
3-1	185854	185921	28	1.50	.20	.81	.80	.38	8.6	-4.8	.5	0.0	3.8
4-1	190815	190828	14	1.40	.30	.86	.90	.36	4.5	-2.5	.9	.6	1.7
5-1	192809	192811	3	.40	.20	.27	.20	.12	1.3	0.0	.4	.1	.7
6-1	194013	194020	8	.90	.10	.46	.35	.30	1.5	-3.7	-.8	-.5	1.6
7-1	201518	201525	8	1.40	.20	.80	.75	.45	2.7	-4.5	-.5	.1	2.3
8-1	201734	201747	14	3.20	.30	2.03	2.25	1.00	7.0	-1.0	2.4	1.8	2.6
9-1	201847	201853	7	2.50	.10	1.27	1.60	1.04	11.8	-1.2	4.3	3.2	4.4
10-1	202359	202403	5	1.70	.30	1.04	1.00	.54	2.8	-4.7	.0	.3	2.9
12-1	203436	203446	11	1.00	.10	.53	.60	.34	.4	-7.8	-3.3	-3.2	2.4
13-1	204025	204035	11	2.60	.10	1.64	1.90	.84	7.6	-4.4	1.2	1.0	3.2
14-1	204456	204502	22	1.40	.00	.77	.95	.53	20.5	-3.7	3.0	.1	6.2
13 Clouds (Ahead of Front)			161	3.20	.00	.91	.80	.70	20.5	-7.8	1.6	.4	4.5
Means			12.38	1.56	.16	.90	.97		7.2	-3.5	1.3	.8	
Standard Deviations			6.90	.77	.10	.50	.61		5.9	2.0	2.3	1.8	
770722													
1-1	203226	203235	10	.00	.00	.00	.00	.00	2.0	-4.4	-1.3	-1.4	1.8
2-1	204129	204131	3	.70	.20	.47	.50	.25	1.4	.0	.5	.1	.7
3-1	210122	210135	14	.60	.10	.44	.50	.17	4.8	-7.5	.4	.3	2.7
3 Clouds (Behind Front)			27	.70	.00	.28	.30	.26	4.8	-7.5	-.2	0.0	2.3
Means			9	.43	.10	.30	.33		2.7	4.0	-.1	-.3	
Standard Deviations			5.57	.38	.10	.26	.29		1.8	3.8	1.0	1.0	

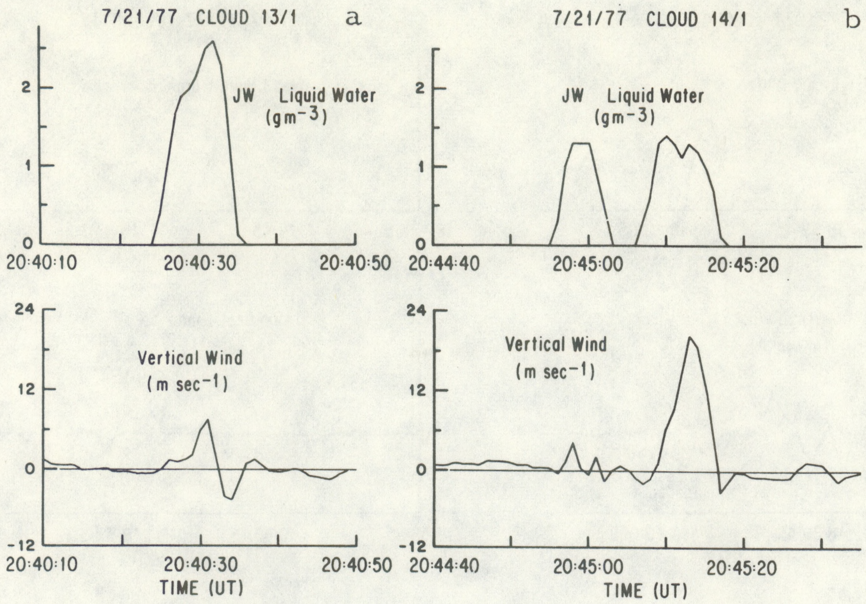


Figure 8. Illinois cloud liquid water and vertical wind profiles during 21 July 1977 penetration of (left) cloud 13, pass 1, and (right) cloud 14, pass 1.

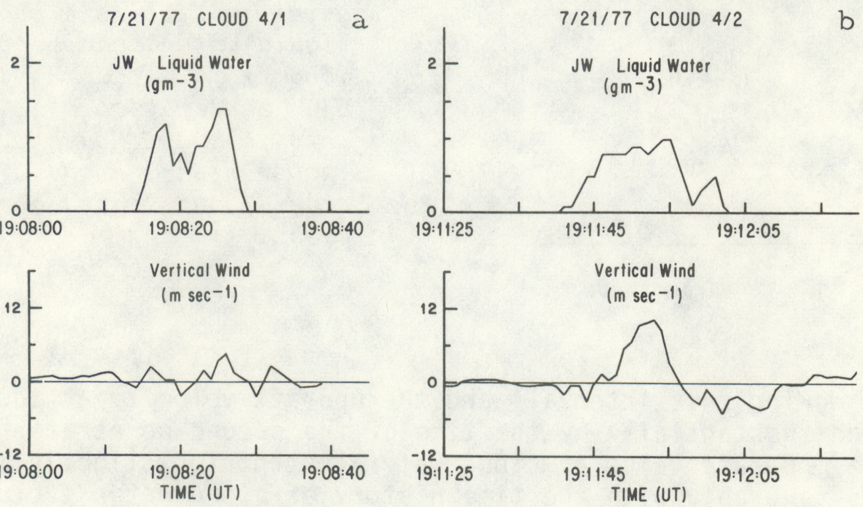
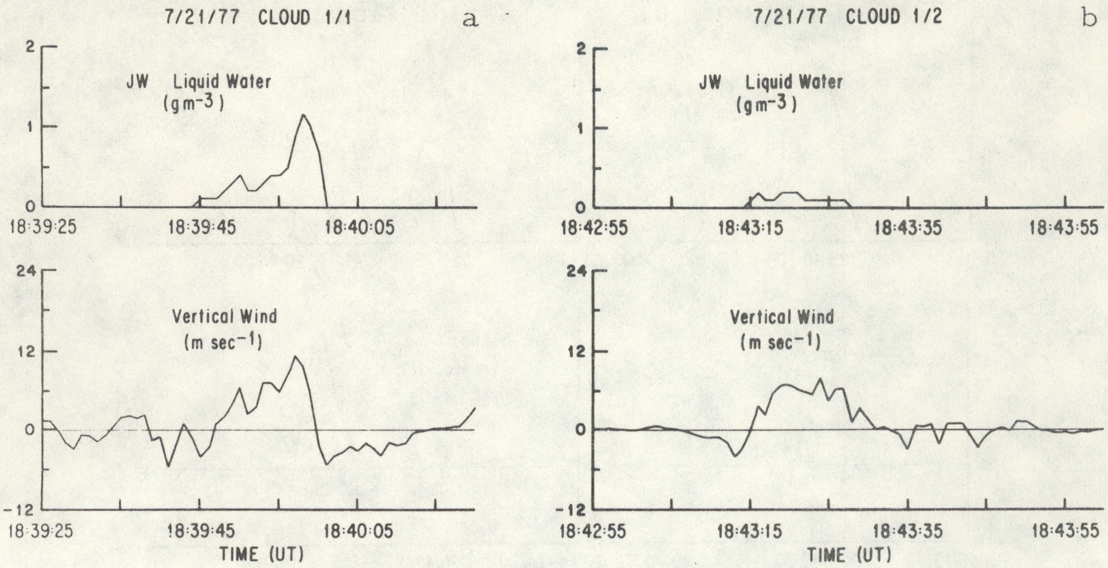


Figure 9. Illinois cloud liquid water and vertical wind profiles during 21 July 1977 penetration of (left) cloud 4, pass 1, and (right) cloud 4, pass 2.



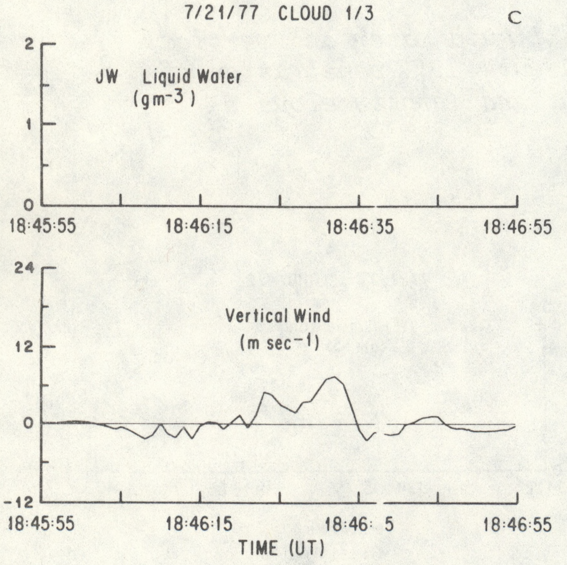


Figure 10. Illinois cloud liquid water and vertical wind profiles during 21 July 1977 penetration of (upper left) cloud 1, pass 1, (upper right) cloud 1, pass 2, and (left) cloud 1, pass 3.

water content during this interval, and the updraft velocity at the sampling level increased substantially by the time of the second penetration. The retention of a moderate value of cloud water content for slightly more than 3 min compares favorably with the time history of cloud water evolution observed in Florida cumuli (Sax and Keller, 1980).

A tower that was penetrated three times, early in the afternoon of the 21st is shown in figure 10. The cloud top was close to the -9°C level on the three passes, although, by the time of the final penetration, the cloud had considerably "softened" in its appearance. It can be seen that moderate values of updraft and cloud water existed in a narrow portion of the tower at the time of the initial penetration, but the cloud water content decreased markedly by the time of the second penetration 3.5 min later. No cloud water content was found during the third pass (3 min after the second), although a weak updraft still was evident. The cycling of cloud water from moderate quantities to zero within 6 min frequently is found to occur in Florida cumuli as well, although the retention of a detectable updraft during the period of cloud water disappearance is somewhat unusual.

Figure 11 illustrates how critical the time and location (relative to cloud top) of sampling is to the impression one has of cloud suitability for seeding. When the cloud was sampled initially, it had just grown through the penetration altitude and sampling occurred within about 100 m of cloud top. At that level no updraft was detectable and the peak value of cloud water was < 1 g m^{-3}. When a repeat penetration was carried out 2 min later, the cloud top was about 500 m above the sampling altitude. A moderate (10 m s^{-1}) updraft was found coincident with a large (3 g m^{-3}) quantity of cloud water. As far as water content and updraft are concerned, this cloud clearly was suitable for dynamic seeding, although the measurements of these parameters initially did not indicate that this was the case.

In contrast to the clouds penetrated on 21 July, the updraft strength and cloud water content near the -9°C sampling level were minimal in towers penetrated on 22 July. Figures 12a and 12b show the velocity and cloud water profiles from the two initial tower penetrations on 22 July. Figure 12a (cloud 2/1 in table 7) shows a narrow tower (.5 km diameter) with almost no updraft and a peak cloud water content of slightly more than .5 g m^{-3}. This cloud, though struggling to reach the sampling altitude, managed to remain an entity for two more penetrations for nearly 8 min. However, no increase in either cloud water or updraft velocity was observed as the cloud progressed through its life history. Figure 12b shows a water/updraft profile for a cloud which in breadth (diameter about 2 km) resembled many of those penetrated the day before. Again, however, almost no updraft was observed at the sampling level and the maximum water content was only slightly more than .5 g m^{-3}. When this cloud was penetrated a second time, decreases in both parameters were observed.

Figure 13 shows the size distribution of cloud droplets for two towers (4/1 and 13/1) penetrated on 21 July and one tower (3/1) penetrated on 22 July. The drop size distributions were derived from an analysis of data obtained by a Desert Research Institute (DRI) formvar replicator. It can be seen that the general shape of the distribution is similar for all clouds, with an appreciable percentage (> 20%) of the total drop concentration contained in sizes > 20 μm diameter. This is true even for the cloud sampled on 22 July.

Additional cloud penetrations were carried out on 22 July in the moist tropical air ahead of the trough line while the WP-3D aircraft was enroute to Miami. The air mass characteristics were similar to those encountered in Illinois the day before, and a field of vigorously growing cumuli was found to be developing over northern Georgia in advance of the position of the surface cold front. Figures 14a and 14b show the cloud water content and updraft profile from two adjoining towers growing together on the same convective base. Both clouds were very sharply defined (hard in appearance) and tower 5/1 was draped in pileus (indicative of vigorous growth) just before its penetration by the sampling aircraft. The JW instrument saturated at 3 g m^{-3} during both cloud passes, and peak updrafts > 10 m s^{-1} were encountered. The Georgia penetrations help to emphasize the overriding importance of air mass characteristics on convective cloud development and

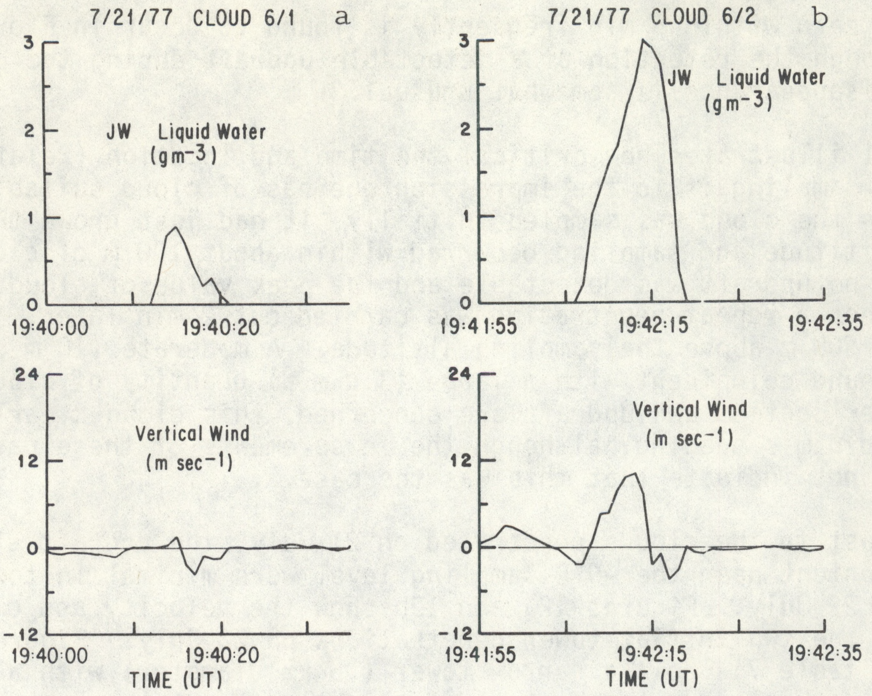


Figure 11. Illinois cloud liquid water and vertical wind profiles during 21 July 1977 penetration of (left) cloud 6, pass 1, and (right) cloud 6, pass 2.

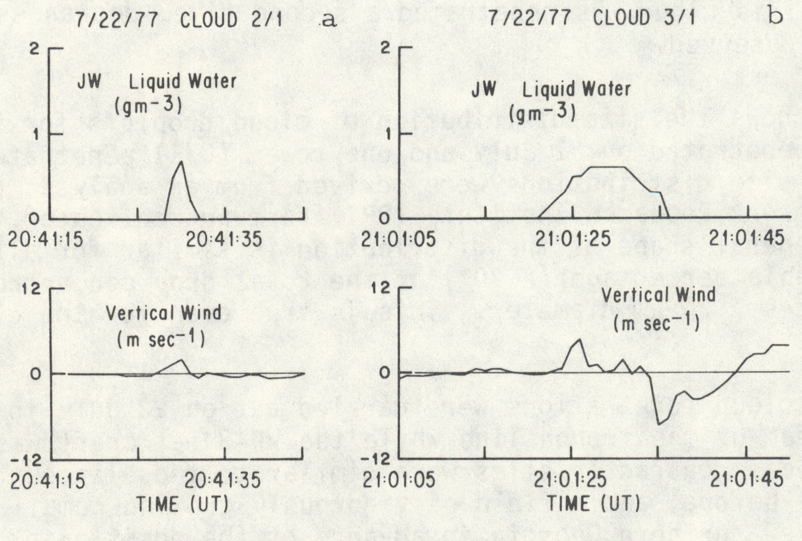


Figure 12. Illinois cloud liquid water and vertical wind profiles during 22 July 1977 penetration of (left) cloud 2, pass 1, and (right) cloud 3, pass 1.

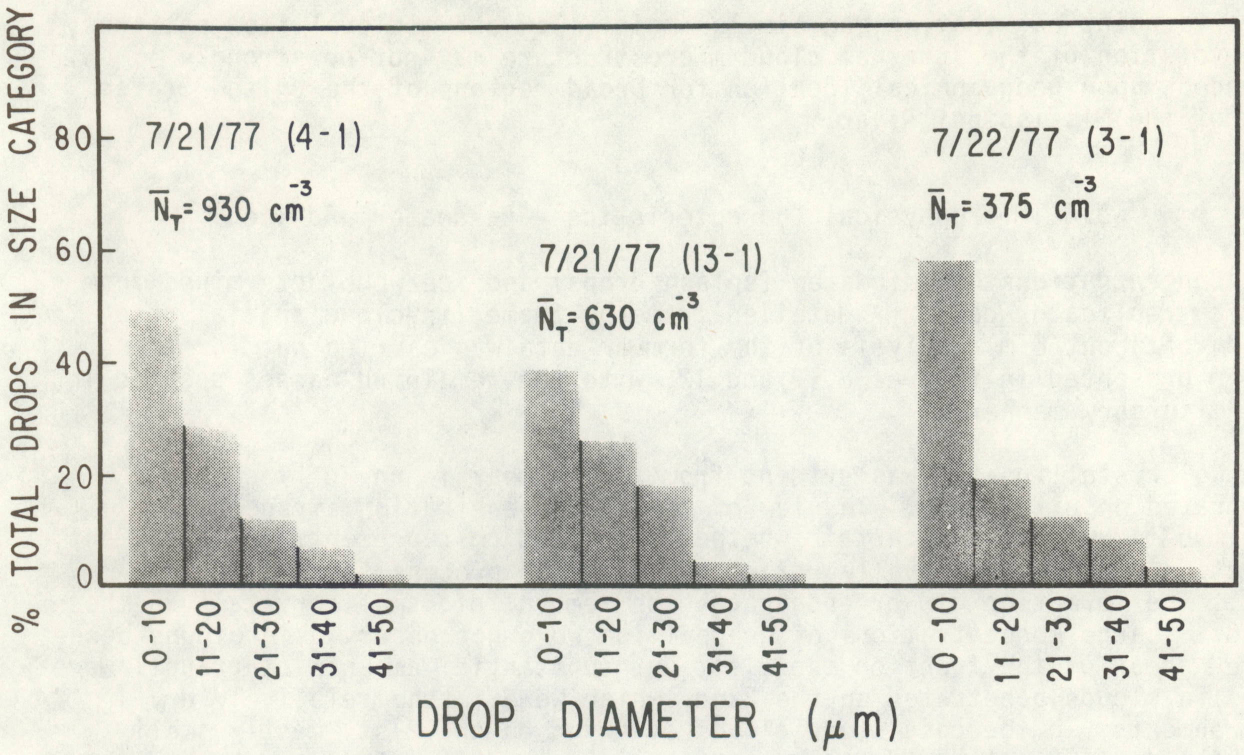


Figure 13. Distribution of cloud droplets for cloud 4, pass 1, and cloud 13, pass 1, on 21 July 1977, and cloud 3, pass 1, on 22 July 1977.

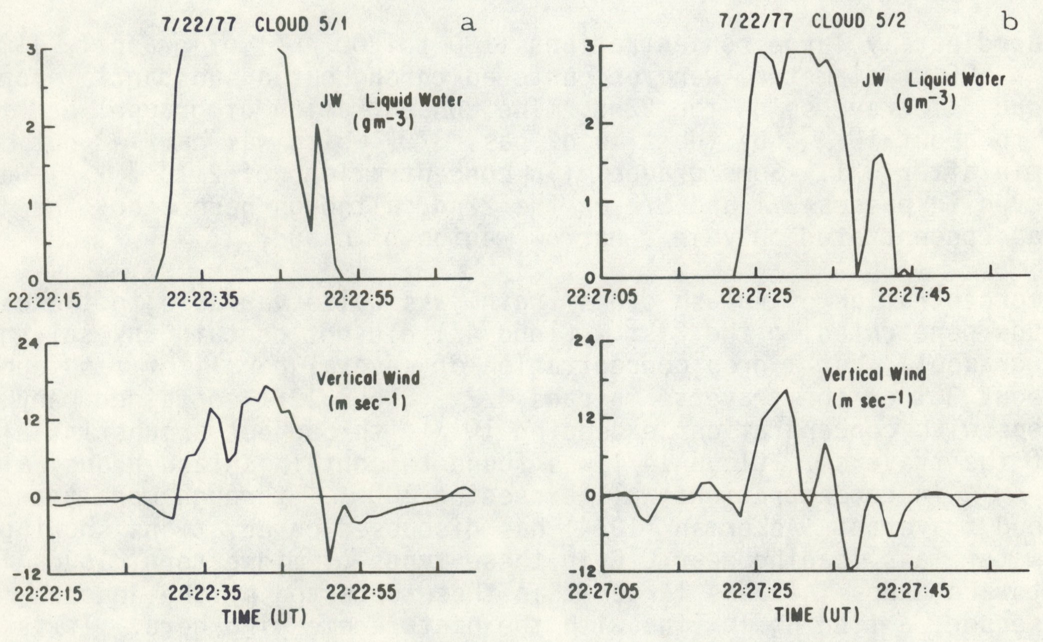


Figure 14. Georgia cloud liquid water and vertical wind profiles during 22 July 1977 penetration of (left) cloud 5, pass 1, and (right) cloud 5, pass 2.

serve to point out that, given similar moist, low and midlevel flow patterns, the evolution of the internal cloud microstructure may not be strongly dependent upon geographical location for broad regions of the United States east of the Mississippi River.

5.4 Microphysical Characteristics - Rainwater and Ice

Concentrations of rainwater (splash drops) and ice were determined from formvar replicator data. A detailed frame-by-frame (in-cloud spatial resolution of about 6 m) analysis of the formvar data was carried out for the passes presented in figures 8, 9 and 12, with the remaining passes scanned in a more cursory manner.

No crystalline ice was evident from the formvar in any of the clouds penetrated on either day. In view of the WP-3D penetration airspeed (140 m s^{-1}), we are not certain whether this finding represents an instrument detection problem or actually reflects a physical process that either prohibits the formation of, or encourages the removal of, small crystals in these clouds. Large concentrations of graupel ice were not observed in clouds penetrated ahead of the front on the 21st, but substantial amounts of graupel were found in clouds penetrated on the 22nd, which were in the relatively dry environment. In the case study clouds observed on the 21st, mostly small graupel (d < 500 μm) was found concentrated in very isolated pockets and, even then, did not exceed a concentration of about 2 ℓ^{-1}. No graupel was found throughout the major portion of the traverses through the four case study clouds. Moderate amounts (10 to 20 ℓ^{-1}) of graupel, almost all < 500 μm diameter, were found in the near vicinity of cloud 13/1 on the 21st, but only an occasional particle was encountered within the cloud boundary itself.

Extraordinarily large concentrations (100 to 200 ℓ^{-1}) of graupel, almost all of it < 500 μm diameter, were encountered throughout a substantial portion of the cloud 3/1 traverse on the 22nd. The concentration of graupel had decreased to about 10 ℓ^{-1} by the time of pass 3/2, which was carried out nearly 3 min after 3/1. Some graupel (in concentrations of 2 to 5 ℓ^{-1}) was also observed in passes 2/1 and 2/2 on the 22nd, although here, too, the graupel was concentrated only in a narrow region of cloud.

The concentration of splash drops (rain) was quite variable in the case study clouds penetrated on the 21st. Cloud 4/1 did not contain any splash drops (or graupel), but a drop concentration of several per liter was found through about 30% of the traverse in pass 4/2. Cloud 13/1 contained many more splash drops with concentrations exceeding 10 ℓ^{-1} throughout a substantial portion of the traverse. Cloud 14/1 was found to contain splash drops, almost all < 500 μm , in concentrations well exceeding 100 ℓ^{-1} through more than half of the cloud traverse. Ackerman (1974) has discussed observations showing that the water mass loading near 0°C in these types of midwestern clouds is weighted toward drops in sizes larger than those detected by the Johnson-Williams sensor, a finding in line with the picture emerging here. It is interesting to observe that the maximum splash drop concentration in pass 14/1 is of the same order as the maximum graupel concentration appearing in pass 3/1 on the 22nd. The concentration of small splash drops found in the case study clouds on the 22nd was about 10 ℓ^{-1} .

5.5 Model-Predicted Seedabilities

The FACE one-dimensional cumulus model was used to calculate potential seedability from the four soundings shown in figure 5. The principal results are displayed in tables 8 through 11 and figures 15 through 18. In table 8, the column labeled "S" contains seedability, which is the difference between height predictions in column B ("artificial seeding") and column A ("unseeded"). The maximum seedability is 3.2 km and is the result of calculations that presumed the cloud tower to be 2000 m in radius. Figure 15 then displays predictions of cumulus tower properties for that one radius. On the left are seen cloud water and the sum of cloud plus suspended rain water, as the vortex ascended. In the center are displayed temperature anomalies, cloud minus environment. On the right are the rise rates of the center of the circulating vortices. Rise rate is not updraft as such, as discussed in Appendix B.

When tables 8 through 11 are compared, it can be seen that the maximum seedability within the range of tower radius of 750 to 2500 m increased from 3.2 km for the 21/1200 GMT sounding (table 8) to 5.6 km for the 22/1200 GMT sounding (table 10) before decreasing markedly to 0 km at the time of the final sounding (table 11). The somewhat lower maximum seedabilities initially were caused by the large natural growth even at small radii (nearly 10-km growth for a 1-km radius with the first two soundings). The model results in figure 15 are similar in many ways to those in figure 16. Nearly the same CCL cloud base was calculated, and the same tower radius yielded similar modeled enhancements of cloud top heights from seeding. Cloud water, suspended rain water, and the variation of these with height were similar. But the seeded top heights differed because of decreased stability and a deeper region of positive temperature anomaly in the 150- to 400-mb layer on the evening sounding (fig. 16). By the next morning (fig. 17) the CCL cloud base was calculated to be about 400 m lower, which indicated increased low-level moistening. As drying began to progress downward to midlevels on the 22nd, the natural growth potential decreased considerably (< 6-km growth from a 1-km radius for the final two soundings). The dry stable region at about 450 mb seen in figure 5c, along with only small positive temperature anomalies below that altitude, fostered shallow unseeded cloud growth. Seeding, as seen in figure 17, would have resulted in a modeled temperature anomaly of only 1° to 2°C. However, this would have occurred through about 6-km depth; as a result, the tower ascent rate, though only half that of the previous day, would have been sustained through that 6-km depth and would have yielded the largest of the S_{max} calculated for any of these soundings for these five radii. Only clouds with radii > 1.5 km were calculated to grow appreciably past the -10°C isotherm level naturally at the time of the 1200 GMT sounding on the 22nd (table 10). After the frontal passage, even the largest unseeded cumulus, modeled from the sounding in figure 5d, was so stunted (fig. 18) that it failed to reach the -4°C altitude where seeding-induced fusion heat release would commence.

From the viewpoint of model-calculated seedability, the temperature-humidity structure of the atmosphere was ideally suited for dynamic seeding early in the morning of the 22nd. At that time, natural growth was not overwhelmingly large, yet clouds with radii of ≥ 1.5 km could grow at least to the seeding level. This type of seedability condition is similar to that observed in south Florida on many occasions during the summer. It is

Table 8. Model-Predicted Cloud Growth and Seedability From 1200 GMT Sounding of 21 July 1977, Salem, Illinois (Assumed Cloud Base at 1326.2 m)

Radius (m)	A Unseeded	B Seeded (-4° to -8°C)	S B - A	Natural glaciation (-15° to -40°C)	(-04° to -15°C)	(-10° to -15°C)
500.0 m	6676.2 m (5.3 g/kg)	9226.2 m (8.6 g/kg)	2.55 km	0.0 m (0.0 g/kg)	7376.2 m (6.0 g/kg)	0.0 m (0.0 g/kg)
750.0 m	8576.2 m (8.5 g/kg)	10976.2 m (10.7 g/kg)	2.40 km	8726.2 m (8.6 g/kg)	10826.2 m (10.5 g/kg)	10826.2 m (10.6 g/kg)
1000.0 m	9926.2 m (10.0 g/kg)	11576.2 m (11.7 g/kg)	1.65 km	10276.2 m (10.4 g/kg)	11376.2 m (11.4 g/kg)	11376.2 m (11.4 g/kg)
1250.0 m	10976.2 m (11.1 g/kg)	13276.2 m (12.7 g/kg)	2.30 km	11426.2 m (11.5 g/kg)	12876.2 m (12.5 g/kg)	12976.2 m (12.6 g/kg)
1500.0 m	11676.2 m (11.7 g/kg)	13976.2 m (13.2 g/kg)	2.30 km	11876.2 m (12.0 g/kg)	13626.2 m (13.0 g/kg)	13676.2 m (13.0 g/kg)
2000.0 m	12426.2 m (12.3 g/kg)	15626.2 m (13.9 g/kg)	3.20 km	13976.2 m (13.3 g/kg)	14826.2 m (13.6 g/kg)	14976.2 m (13.7 g/kg)
2500.0 m	14126.2 m (13.4 g/kg)	16776.2 m (14.3 g/kg)	2.65 km	14926.2 m (13.7 g/kg)	16226.2 m (14.1 g/kg)	16376.2 m (14.2 g/kg)
3000.0 m	14976.2 m (13.7 g/kg)	17676.2 m (14.6 g/kg)	2.70 km	15876.2 m (14.0 g/kg)	17126.2 m (14.4 g/kg)	17276.2 m (14.5 g/kg)

Table 9. Model-Predicted Cloud Growth and Seedability From 0000 GMT Sounding of 22 July 1977, Salem, Illinois (Assumed Cloud Base at 1453.7 m)

Radius (m)	A Unseeded	B Seeded (-4° to -8°C)	S B - A	Natural glaciation (-15° to -40°C)	(-04° to -15°C)	(-10° to -15°C)
500.0 m	6103.7 m (4.3 g/kg)	6103.7 m (4.3 g/kg)	0.00 km	0.0 m (0.0 g/kg)	6103.7 m (4.3 g/kg)	0.0 m (0.0 g/kg)
750.0 m	8703.7 m (8.4 g/kg)	10803.7 m (10.9 g/kg)	2.10 km	8803.7 m (8.6 g/kg)	10453.7 m (10.5 g/kg)	10053.7 m (10.2 g/kg)
1000.0 m	9703.7 m (9.9 g/kg)	12503.7 m (12.2 g/kg)	2.80 km	9803.7 m (10.1 g/kg)	11903.7 m (11.9 g/kg)	11803.7 m (11.9 g/kg)
1250.0 m	10303.7 m (10.7 g/kg)	14003.7 m (13.0 g/kg)	3.70 km	10653.7 m (11.2 g/kg)	13203.7 m (12.7 g/kg)	13303.7 m (12.7 g/kg)
1500.0 m	11053.7 m (11.5 g/kg)	15303.7 m (13.5 g/kg)	4.25 km	11903.7 m (12.3 g/kg)	14403.7 m (13.2 g/kg)	14653.7 m (13.3 g/kg)
2000.0 m	12453.7 m (12.6 g/kg)	16803.7 m (15.0 g/kg)	4.35 km	14553.7 m (13.4 g/kg)	16253.7 m (13.8 g/kg)	16453.7 m (13.9 g/kg)
2500.0 m	14003.7 m (13.5 g/kg)	17753.7 m (14.5 g/kg)	3.75 km	16203.7 m (13.9 g/kg)	17353.7 m (14.2 g/kg)	17503.7 m (14.3 g/kg)
3000.0 m	15253.7 m (13.9 g/kg)	18553.7 m (14.8 g/kg)	3.30 km	17353.7 m (14.2 g/kg)	18203.7 m (14.5 g/kg)	18303.7 m (14.6 g/kg)

Table 10. Model-Predicted Cloud Growth and Seedability from 1200 GMT Sounding of 22 July 1977, Salem, Illinois (Assumed Cloud Base at 1065.8 m)

Radius (m)	A Unseeded	B Seeded (-4° to -8°C)	S B - A	Natural glaciation (-15° to -40°C)	(-04° to -15°C)	(-10° to -15°C)
500.0 m	4715.8 m (2.5 g/kg)	0.0 m (0.0 g/kg)	0.00 km	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)
750.0 m	5365.8 m (4.1 g/kg)	0.0 m (0.0 g/kg)	0.00 km	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)
1000.0 m	5965.8 m (5.4 g/kg)	0.0 m (0.0 g/kg)	0.00 km	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)
1250.0 m	6515.8 m (6.3 g/kg)	0.0 m (0.0 g/kg)	0.00 km	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)
1500.0 m	7115.8 m (7.3 g/kg)	7215.8 m (7.6 g/kg)	.10 km	0.0 m (0.0 g/kg)	7165.8 m (7.4 g/kg)	0.0 m (0.0 g/kg)
2000.0 m	8065.8 m (8.4 g/kg)	12865.8 m (12.6 g/kg)	4.80 km	0.0 m (0.0 g/kg)	8915.8 m (9.7 g/kg)	0.0 m (0.0 g/kg)
2500.0 m	9115.8 m (9.4 g/kg)	14715.8 m (13.2 g/kg)	5.60 km	0.0 m (0.0 g/kg)	9665.8 m (10.3 g/kg)	9115.8 m (9.4 g/kg)
3000.0 m	9765.8 m (9.7 g/kg)	16165.8 m (13.7 g/kg)	6.40 km	0.0 m (0.0 g/kg)	14915.8 m (13.3 g/kg)	9815.8 m (9.9 g/kg)

Table 11. Model-Predicted Cloud Growth and Seedability From 0000 GMT Sounding of 23 July 1977, Salem, Illinois (Assumed Cloud Base at 3436.2 m)

Radius (m)	A Unseeded	B Seeded (-4° to -8°C)	S B - A	Natural glaciation (-15° to -40°C)	(-04° to -15°C)	(-10° to -15°C)
500.0 m	4836.2 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.00 km	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)
750.0 m	5436.2 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.00 km	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)
1000.0 m	5886.2 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.00 km	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)
1250.0 m	6236.2 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.00 km	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)
1500.0 m	6536.2 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.00 km	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)
2000.0 m	7186.2 m (.1 g/kg)	0.0 m (0.0 g/kg)	0.00 km	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)
2500.0 m	7786.2 m (.1 g/kg)	0.0 m (0.0 g/kg)	0.00 km	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)
3000.0 m	8336.2 m (.1 g/kg)	0.0 m (0.0 g/kg)	0.00 km	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)	0.0 m (0.0 g/kg)

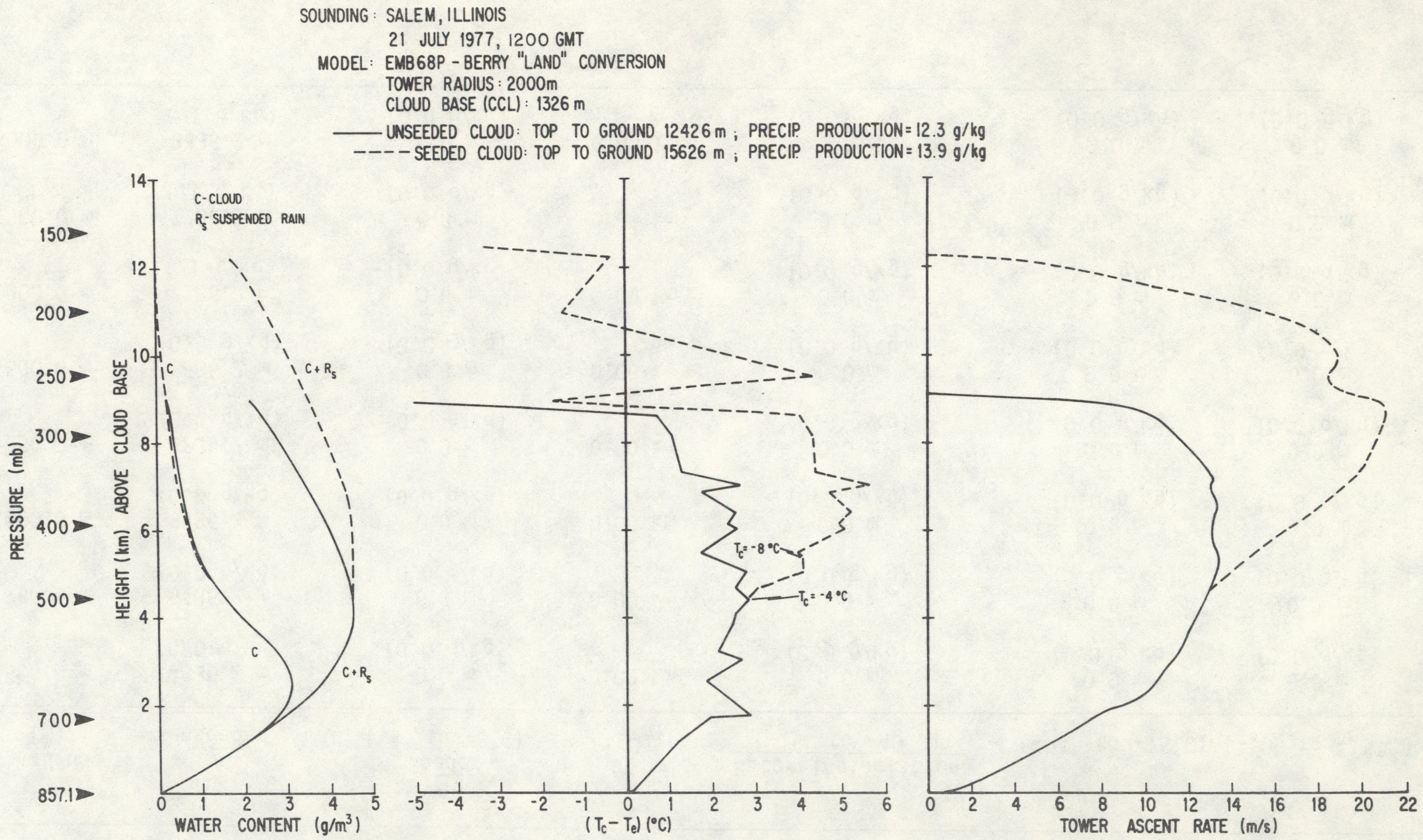


Figure 15. Predictions of properties of unseeded and seeded cumulus towers for radius of maximum seedability at Salem, Illinois, from 1200 GMT sounding on 21 July 1977.

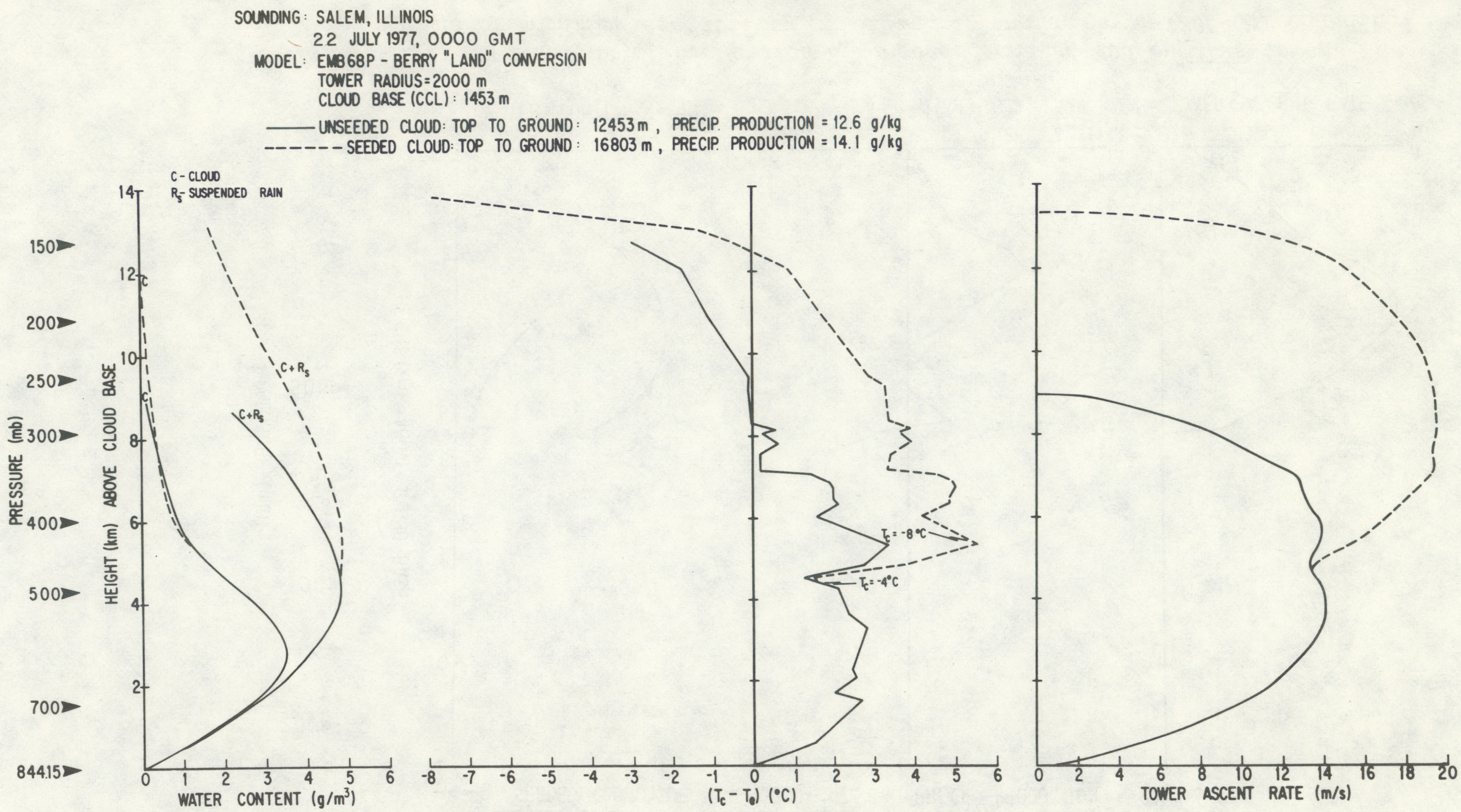


Figure 16. Prediction of properties of unseeded and seeded cumulus towers for radius of maximum seedability at Salem, Illinois, from 0000 GMT sounding on 22 July 1977.

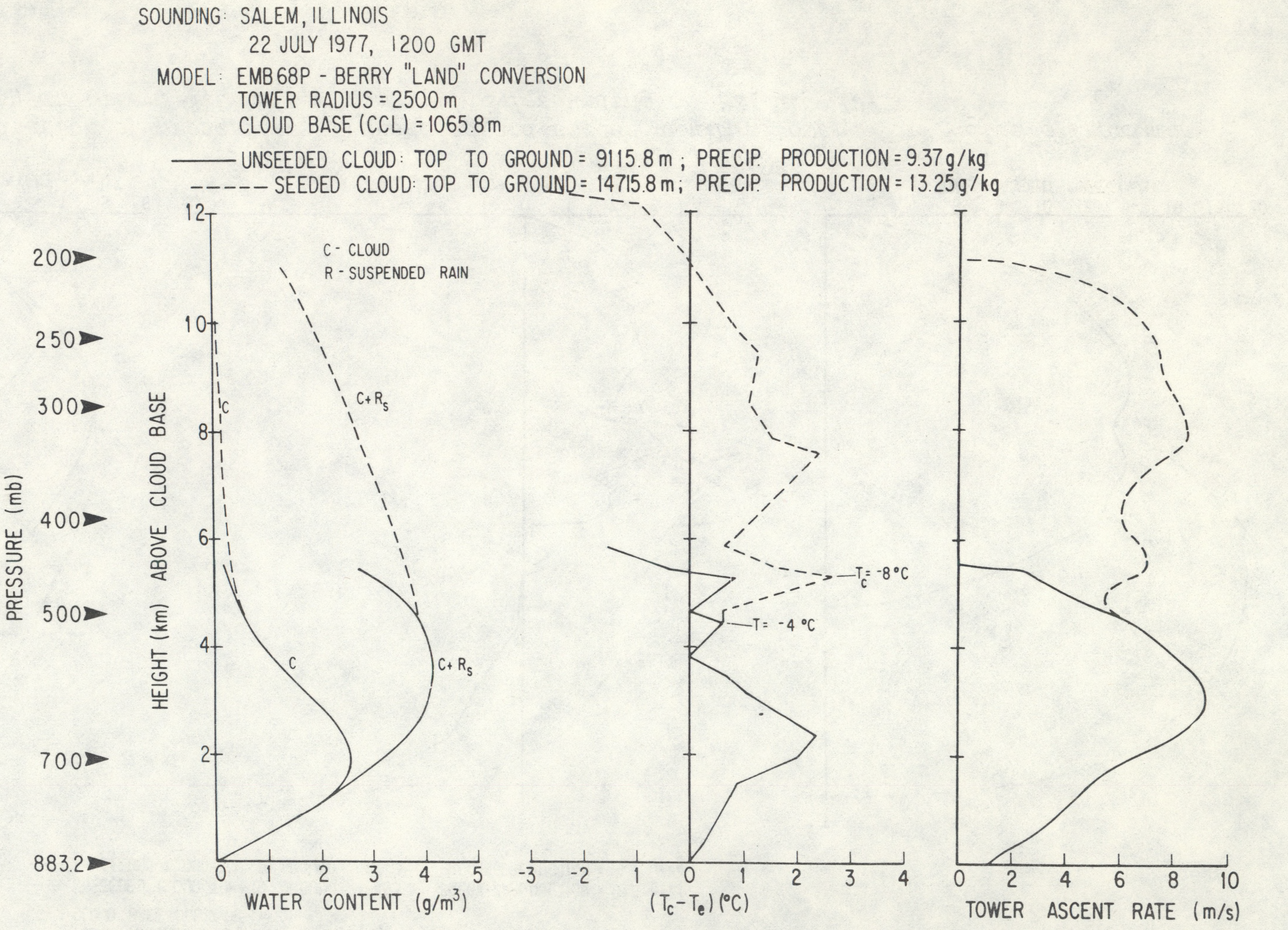


Figure 17. Predictions of properties of unseeded and seeded cumulus towers for radius of maximum seedability at Salem, Illinois, from 1200 GMT sounding on 22 July 1977.

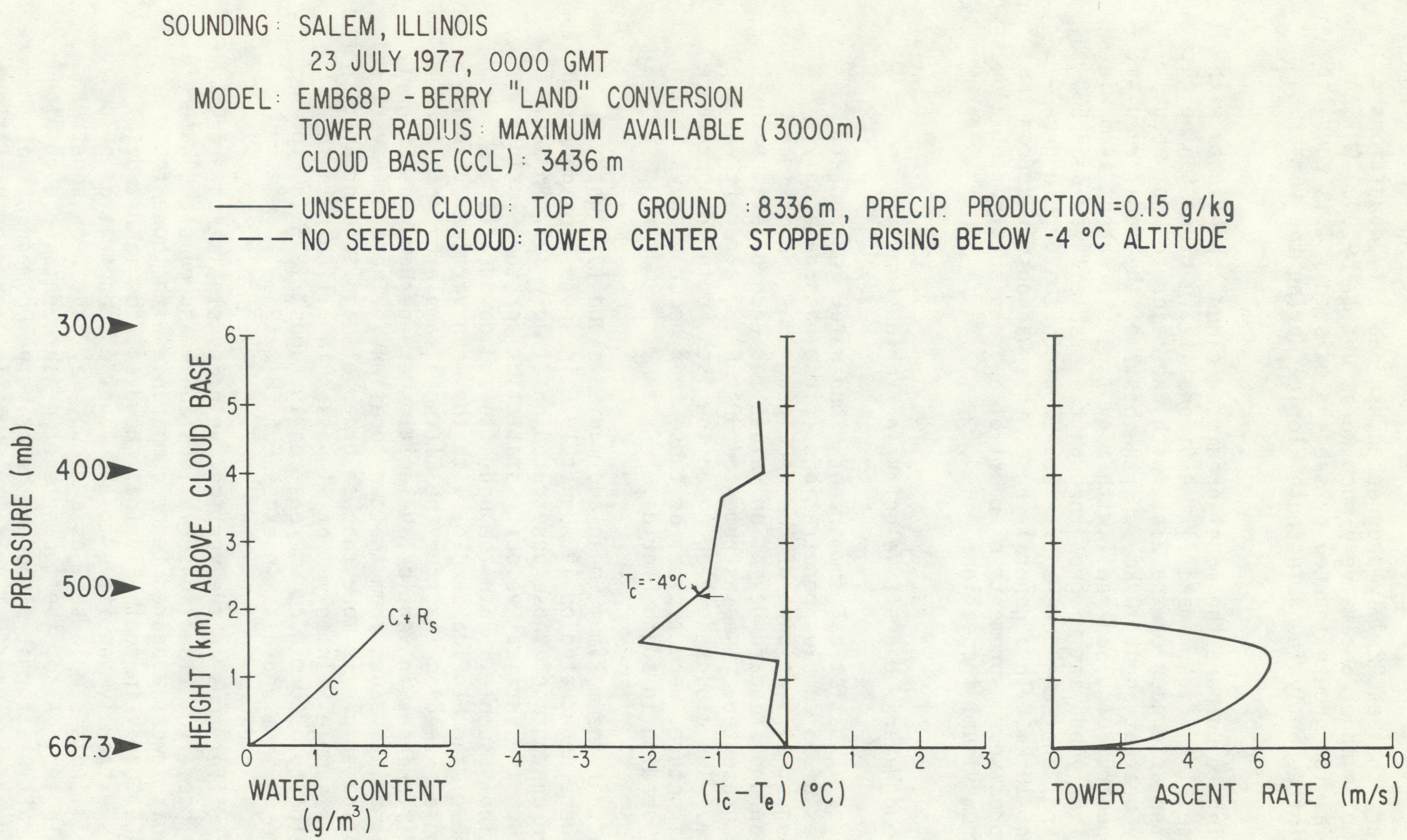


Figure 18. Predictions of properties of unseeded and seeded cumulus towers for radius of maximum seedability at Salem, Illinois, from 0000 GMT sounding on 23 July 1977.

reemphasized, however, that as 22 July progressed, seedability conditions as reflected by the cumulus model became very much worse until, by 0000 GMT on the 23rd, no potential for growth induced by seeding existed. This condition (S_{max} = 0) is only infrequently found in south Florida during the summer, as noted above.

It is interesting to compare the model-predicted cloud top heights with those observed on the 21st (figs. 6 and 7). A bimodality in cloud top heights is observed during the afternoon of the 21st, with the major peak at about 6 km and a secondary peak at about 10 km. On the basis of the model results, one would infer a spectrum of cloud radii with many towers of about 1-km width that are not sufficiently buoyant to grow through the stable layer near 500 mb (see 1200 GMT sounding) and some towers of $\geq$ 2.5-km width that could grow beyond an altitude of 10 km. In a general sense, this was observed from the aircraft, although precise measurements of radii of a broad spectrum of clouds were not possible from visual inspection.

5.6 Cloud Water - Updraft Velocity in Florida Cumuli

Table 12 provides a statistical summary of cloud water and updraft strength for a series of 35 cumulus penetrations (first-pass data only) carried out on 19 August 1975 as part of the FACE program. The maximum, minimum, mean, median and standard deviation values for each parameter for each cloud pass are presented. The instrumented NOAA C-130 aircraft was the measurement platform. The clouds developing on the 19th, both in appearance and internal microstructure, were typical of those that occur on days that qualify for dynamic seeding in south Florida.

It can be seen that the maximum, mean and median cloud (JW) water contents for the towers penetrated on 19 August 1975 in south Florida appear similar to the water contents of those penetrated on 21 July 1977 in east-central Illinois. But the vertical velocity statistics for the Florida sample differ from the Illinois sample. Both the updrafts and downdrafts are stronger in the case of the Florida sample, with the mean vertical velocity for the Florida sample exceeding that for the Illinois sample by more than a factor of 4. The differences in vertical velocities are perhaps most clearly demonstrated in the median values from the two locations. The median vertical velocity in the Florida sample is more than an order of magnitude greater than that for the Illinois sample. In only 1 of 14 passes in Illinois is the maximum vertical velocity > 20 m s^{-1}, whereas, on 19 August 1975 in Florida, 12 of 35 passes have maximum updrafts in excess of 20 m s^{-1}.

The systematic differences in the vertical velocity statistics are somewhat puzzling since, from visual observations and measured cloud water contents, the Illinois towers appeared to be comparable with those found during a typical FACE GO day in south Florida. However, the magnitude of vertical velocity is extremely sensitive to the level of penetration below cloud top, and the Illinois sample set, as a group, may have been penetrated closer to the visible top. Also, the two sets of measurements were obtained with different aircraft platforms, although the principal components of the instrumentation to determine vertical velocity were similar on both platforms.

Table 12. Cloud Water and Vertical Velocity Statistics for a Population of Florida Cumuli Penetrated on 19 August 1975 (First Pass Data Only)

	C-130			JW Cloud Water (g m^{-3})					Vertical Velocity (m s^{-1})				
Cloud	In (GMT)	Out (GMT)	Dur (s)	Max	Min	Mean	Med	σ	Max	Min	Mean	Med	σ
1-1	173902	173906	5	1.18	.30	.71	.63	.34	6.2	.10	3.2	3.4	2.2
2-1	174154	174208	15	1.39	.23	1.05	1.19	.35	19.5	-2.6	3.6	2.3	6.3
2-2	174540	174552	13	1.55	.25	.98	1.00	.34	15.5	-3.0	4.1	3.9	4.8
2-3	174838	174859	21	1.99	.30	.97	.86	.52	27.3	-12.0	11.9	13.3	11.1
2-4 a&b	175555	175603	5	1.71	.41	1.09	1.07	.61	11.8	3.9	8.2	10.2	3.8
2-4 c	175610	175618	9	1.46	.50	1.14	1.20	.35	8.2	-3.7	3.2	4.1	4.3
2-5	180036	180103	28	1.82	.30	.98	.90	.34	21.8	-11.6	6.9	6.2	7.4
3-1	180320	180322	3	1.61	.30	.98	.99	.63	8.7	-.7	3.2	1.7	4.9
2-8	181402	181407	6	1.21	.54	.98	1.06	.26	12.1	-20.7	2.8	6.7	12.3
4-1	184115	184128	14	1.15	.30	.75	.81	.29	13.6	-7.8	-1.2	-2.1	5.9
4-2	184426	184430	5	.38	.22	.30	.27	.07	.2	-5.4	-2.7	-2.7	2.5
7-1	185025	185034	10	1.10	.22	.77	.79	.23	9.4	-20.7	2.2	4.3	8.5
8-1	185515	185528	12	1.93	.20	1.32	1.47	.58	22.8	-12.3	9.9	12.3	12.4
7-2	185646	185704	19	3.17	.30	1.71	1.64	1.03	31.5	-8.6	13.9	14.8	9.2
7/8-1	185907	185916	10	3.35	.30	1.67	1.10	1.12	16.0	.6	9.1	9.0	5.8
7/8-2	190208	190227	18	1.08	.20	.59	.58	.24	15.4	-19.1	5.8	8.5	9.0
7/8-3	191254	191315	20	1.09	.20	.63	.53	.29	11.1	-10.6	1.9	2.1	5.4
7/8-4	191532	191559	27	3.36	.18	1.60	1.44	1.11	29.7	-23.5	7.7	9.2	11.8
7/8-6	192213	192226	13	.87	.25	.63	.64	.16	13.5	-5.4	7.6	8.7	5.4
7/8-7	192526	192537	12	3.30	.80	2.10	2.22	.91	21.9	-.1	12.8	14.3	7.6
7/8-8	192642	192645	4	.75	.25	.46	.44	.27	7.8	-4.9	2.1	2.7	5.6
7/8-9	192946	193023	28	1.69	.20	.97	1.03	.37	20.7	-4.4	5.8	5.2	6.6
7/8-10	193434	193437	4	.40	.25	.33	.32	.06	12.4	10.7	11.2	10.8	.8
9-1	195417	195430	12	3.05	.32	1.42	1.32	.84	33.1	-.2	14.6	16.1	10.8
10-1	195532	195540	9	1.50	.50	1.18	1.25	.30	11.7	-.1	7.1	9.2	4.2
9-2	195820	195848	26	.76	.30	.49	.49	.12	29.7	-5.9	11.4	11.9	9.4
10-2	200408	200423	14	1.41	.40	.80	.72	.39	21.4	-8.1	3.9	3.0	8.2
9-3	200915	200935	21	1.01	.20	.66	.72	.24	13.7	-13.4	3.5	5.5	8.4
9/10-1	201252	201302	10	1.60	.20	1.00	1.12	.44	20.1	-2.5	8.9	8.8	7.5
12-1	201807	201825	15	1.64	.30	1.23	1.35	.46	18.2	-8.0	10.4	12.4	7.8
11-2	202827	202848	22	1.38	.30	1.02	1.11	.30	21.8	-6.2	7.2	6.5	7.9
11-3	203058	203125	25	1.83	.30	.99	.95	.47	16.1	-18.1	5.2	5.9	8.2
9/10-3	203550	203604	15	2.29	.20	1.58	1.88	.67	17.0	-4.4	8.5	12.0	7.8
13-1	203703	203716	14	1.54	.40	.95	1.00	.36	16.4	-3.7	3.1	3.0	5.4
14-1	203954	204016	23	1.99	.50	1.36	1.41	.38	10.2	-7.3	4.0	5.4	4.6
35 cloud passes			507	3.36	.18	1.04	.93	.64	33.1	-23.5	6.7	6.3	8.6
Means			14.49	1.64	.31	1.01	1.01		16.8	-6.8	6.3	7.1	
Standard Deviation			7.44	.79	.13	.41	.43		7.6	7.4	4.1	4.7	

6. SUMMARY AND CONCLUSIONS

Characteristics of cumulus clouds in Illinois were studied and compared with counterpart predictions and observations of Florida clouds. Cumulus model predictions of seeding-induced growth enhancement, based upon 10 summers of central Illinois radiosonde data, have been presented, discussed, and compared with predictions from Miami soundings. If the model is as relevant and skillful in Illinois as in south Florida, then it has been shown that zeros-excluded S_{max} ranged from 2 to 4 km, which are values that offer good prospects for potential rainfall enhancement. But, in Illinois, large cloud sizes are more often responsible for these S_{max} values than in Florida. Also, about one sounding in three yielded maximum seedability that was zero. This would indicate that natural convection in Illinois would be stunted and would die before reaching the seeding level more often than is observed in Florida in summer. Large variability in Illinois seedability was also revealed--month to month within a summer, from one year to the next, and morning versus evening within a given month. In Illinois and Florida, null seedability was not found to be correlated with a lack of weather events.

Therefore, it seems that more rapid and significant changes in atmospheric structure occur during summer in Illinois than in south Florida. Average seedabilities were lowest in June and highest in July of the three summer months. According to Semonin (1977) it is during June, July and August that the preponderance of deep cumulus convection occurs in Illinois; the remainder of the year has even fewer workable clouds, as well as much less need for precipitation enhancement.

Observed characteristics of cloud water content near the -10°C level were not greatly different from those of similar-sized clouds penetrated in Florida, based upon a limited data sample of summertime convective clouds that were developing in Illinois in the moist air in advance of a weak cold front. The updraft velocities encountered in the Illinois sample were systematically lower than those found in similar 1-day samples obtained in Florida cumuli during FACE. The Illinois towers were characterized microphysically by high cloud water contents, moderate updrafts, and, on initial penetration, low concentrations of graupel ice. Clouds struggling to develop in the dry air behind the front, on the other hand, were found to contain very weak updrafts, low concentrations of cloud water, and an abundance of ice in the form of graupel, even on initial penetration. The microstructure of these post-frontal clouds near the -10°C level appeared to be very different from that encountered in clouds developing in tropical maritime airmass conditions.

Both model-predicted seedabilities and measurements of cloud microphysics indicate that cumuli over Illinois should exist, and do occur, which are as amenable to artificial modification as those over south Florida. But the suitable Illinois cumuli are predicted to occur less frequently. The rapidity with which seedability and observed cumulus growth changed in just 2 days, from moderately good, to excellent, to absolutely none at all, indicates that only a small time window may be available for seeding, and it may not be during daylight. Such a situation has not been encountered in the FACE program.

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APPENDIX A

Definitions

FACE one-dimensional cumulus model: Model that presumes a cumulus cloud to be a single, ascending, entraining spherical vortex, whose processes are defined only at the vortex center and only while the center ascends.

Seeding: Procedure in the FACE cumulus model for emulating the glaciation of supercooled liquid water. Unseeded cloud is presumed to retain water substance as a liquid for all cloud temperatures (T_c) > -40°C.

Model EMB 68P: Seeding procedure in the FACE cumulus model that restricts water saturation to $T_c \geq -4°C$. For all $T_c < -8°C$, saturation is assumed with respect to ice. In the "slush region" between these two temperatures, 60% of the fusion heat (released by freezing the total liquid water at -4°C) is linearly apportioned through the region. The terminal velocity of ice equals 70% that of an equal mass of water, and N_0 (the number of droplets with diameter of zero in the presumed inverse exponential droplet distribution) changes in value from 10^7 in the liquid phase to 10^8 in the all-ice phase.

Seedability (S): Difference in height between modeled seeded and modeled unseeded cumulus tops from calculations made from one sounding and one tower radius. S = 0 usually means that the cloud tower center has stopped rising before reaching the -4°C isotherm. In rare instances, S = 0 results from unseeded growth being so high that no height increase from seeding is predicted for that sounding and tower radius.

Maximum seedability (S_{max}): Largest S of those obtained (one per radius) for each sounding. $S_{max} = 0$ usually means that regardless of the tower radius used, no unseeded tower rose as far as the -4°C isotherm.

Average maximum seedability: Value derived by combining the S_{max} values from all soundings in a subsample and forming an average. A subsample might be based upon radiosonde release time, and/or month, and/or radius, etc.

Zeros-excluded average maximum seedability: Value that removes all occurrences of $S_{max} = 0$ from the subsample before computing an average.

Convective condensation level: The convective condensation level (CCL) is calculated with the assumption of complete mixing in the lowest 1000 m of the atmosphere and the result is the average mixing ratio ($\overline{q}$) for the entire layer. On the ambient thermodynamic sounding, the altitude is sought where the observed saturation mixing ratio is equal to $\overline{q}$. That altitude is then the CCL, and cloud base is presumed to be there.

APPENDIX B

Comments on the One-Dimensional Cumulus Model

B.1 Summary of Model Limitations

The one-dimensional model used here and in the FACE program is detailed in Simpson and Wiggert (1971), Simpson and Wiggert (1969), and Simpson et al. (1965). The model's development, testing, and refinement are treated in those publications and are not restated here or amplified, except for the following comments:

1) The model deals not with a cloud as such, but with the properties at the center point of an ascending, spherical vortex, which entrains air laterally through its sides in the manner postulated by Stommel (1947).

2) The model excludes effects of ambient wind, or its shear, and it also excludes the effects (external to the ascending vortex) of water loading, changing droplet spectra, or evaporative cooling.

3) The calculations for unmodified (i.e., "unseeded") vortices are performed with the presumption that saturation with respect to water applies for all cloud temperatures warmer than -40°C.

4) The entrainment calculations are performed at the levels supplied in the original radiosonde data; the ambient sounding and the in-cloud sounding resulting from the entrainment calculations are then linearly interpolated at fixed-height increments (e.g., 50 m). At those fixed-height increments, the calculations of the buoyancy, hydrometeors, and fallout are performed.

5) Dilution of cloud water by entrainment is ignored.

6) Pulsating growth behavior is not treated.

B.2 Discussion of Limitations

1) *The model deals not with a cloud, as such, but with the properties at the center point of an ascending, spherical vortex, which entrains air laterally through its sides in the manner postulated by Stommel (1947).* A cumulus tower is postulated as having a toroidal spherical vortex internal circulation, which then is idealized in a one-dimensional parameterized model (Simpson et al., 1965). The differential equation of the rise rate of the tower applies only to the center of the vortex in a quasi-Lagrangian coordinate system that follows the circulation system. That is, no attempt is made to calculate properties (1) elsewhere in the vortex, (2) at any level once the vortex has ascended past it, (3) outside the vortex, or (4) after the single vortex has stopped ascending. Moreover, it is recognized that the vortex is only a small fraction of the total bulk of an entire cumulus cloud.

2) *The model excludes effects of ambient wind or its shear; and it also excludes the effects (external to the ascending vortex) of water loading, changing droplet spectra, or evaporative cooling.* The model ignores modifications of surrounding, or subcloud, air resulting from compensatory air

motions, rainfall, or evaporative cooling. Also ignored are the changes in hydrometeor spectrum and concentration within the cloud body, but below the vortex, caused by precipitation fallout and droplet capture and collection. However, even with these and other conceptual simplifications, and even with no incorporation of wind shear, this model of a single cumulus tower has demonstrated some predictive skill in use. This skill is partly a consequence of the actual weather in the summer subtropics and south Florida. There, strong solar heating, rather than orographic or baroclinic uplift, initially forces convection. High humidity below cloud base reduces the cooling ordinarily resulting from reevaporation of rain. The resulting downdrafts and outflow, which elsewhere can yield dynamically complex convergence and convection lines, in Florida are relegated to the role of "second generation" producers of cumulus growth. The convection that does occur usually has simple causal agents, unlike that found by Zipser (1969; 1977) and by researchers studying convective storms in the middle latitudes (e.g., Ludlam, 1963). In Florida in summer, there usually is only small vertical shear of the horizontal wind. Hence, formation of a broad spectrum of smaller separated cumuli is not automatically disallowed. On the other hand, there is not the mass evacuation mechanism that strong vertical shear can provide, which can sustain massive quasi-steady-state squall systems as are observed (e.g., in midwestern United States) to thrive embedded in such shear long after solar heating has ended for the day. Thus, the model has been used in Florida under conditions dominated by low shear and simple thermal forcing, and such conditions help to mask its weaknesses. This (or any other) one-dimensional cumulus model would be functioning beyond the limits of applicability when it is attempting to emulate cumulus growth where high shear, strong, broad-scale low-level convergence and/or baroclinity are prevalent; for example, within frontal zones.

Taken together, comments (1) and (2) indicate that care must be exercised when comparisons are made between model predictions and cumulus observations. During the past decade there have been some strong criticisms of one-dimensional cumulus models. For example, the validity of the use of entrainment as postulated by Stommel (1947) and as used in this model was questioned by Warner (1970). He stated that "...such models cannot simultaneously predict values of liquid water content and cloud depth, which are in agreement with observations. If sufficient entrainment is postulated to get agreement with observations of cloud water content, the model cloud does not grow as high as those observed in the given environment, while entrainment appropriate to the observed height yields liquid water contents that are too high...." There ensued a public interchange of correspondence on this crucial topic between Warner (1972) and others, particularly Simpson (1971, 1972). An underlying premise in the comparisons made by Warner (1970) was that "...to compare observations with model predictions, we must concern ourselves with the average water content, not its maximum value." But it is our belief that any observational procedure that involves the averaging of cloud liquid water data can mask important space and time variations. In Florida, as noted by Sax and Keller (1980), summertime cumulus towers rapidly advance through their life cycles, changing from vigorously growing cloud elements with an abundance of cloud liquid water to collapsing, wispy, diffuse precipitating masses, essentially devoid of cloud droplets, within 3 to 5 min. Sax and Keller (1980) also observed that cloud water measurements obtained during second and third aircraft traverses of the same cumulus tower gave generally quite low amounts, relative to the total sample set. Because studies have shown that vertical velocity measurements on subsequent passes are not consistently lower than those found during initial tower penetration, the authors offer the view that temporal pulsations in updraft structure may be contributing to the lack of good correlation between upward velocity and cloud water. Thus, in Florida, rapid and profound changes occur in cloud water concentration in small time and space scales. Since the cumulus model performs calculations of properties (e.g., total liquid water) at the center of the entraining vortex, it would seem that observational data most relevant for any intercomparison with model predictions should be those acquired at the center of cumulus towers undergoing their first ascent--and should consist of maxima, not averages.

The inverse dependence of entrainment upon cloud tower diameter, as postulated by Stommel (1947), and as used in this cloud model, seems to have been verified 27 years later by McCarthy (1974). He made 231 traverses of small summertime cumuli in an instrumented aircraft and applied a set of six objective acceptability criteria. These required that cloud data, to be considered usable, must be from cumuli (1) with actively ascending towers, (2) having no precipitation measured within cloud or observed to be emanating from cloud base, (3) with no attachment to large congestus/cumulonimbus complexes, (4) with no multiple turrets, (5) with top temperatures warmer than 0°C, and (6) penetrated through the center of the cap region, with no instrumentation failures therein. All but 23 cloud passes (within 16 clouds) failed three or more of these reasonable, but crucial, criteria and only 6 cloud passes failed none of them. McCarthy (1974), after carefully investigating the data gathered in 23 cloud passes through active, isolated, relatively small cumuli, verified a basic postulate of the FACE one-dimensional cumulus model, namely that there is a strong inverse dependence between entrainment rate and cloud diameter. Cloud data, especially simple averages of data gathered on traverses through towers that are in various stages of their growth cycle, do not satisfy criteria such as those stipulated and utilized by McCarthy (1974); thus, they should not be used in comparisons with cloud models that emulate only very particular places and times in the genesis and growth cycle of cumuli.

3) *The calculations for unmodified (i.e., "unseeded") vortices are performed with the presumption that saturation with respect to water applies for all cloud temperatures warmer than -40°C.* The physical basis for this is simple: the model is of the vortex center during the first time it ascends. As such, the data most crucial for choosing the temperature of complete glaciation are those derived from laboratory experiments. In this context, we note Fletcher (1962, p.207), who indicated that freezing of pure water drops through homogeneous nucleation occurs in the range of -33° to -41°C. Also, Simpson (1963) has noted observations of liquid water at temperatures as cold as -40°C in squall lines and hurricanes in protected cores of exceedingly strong convective clouds. It is in view of such evidence that, in this cumulus model, we presume saturation of liquid water should be retained for all cloud temperatures warmer than -40°C. As a result, modeled unseeded clouds will almost always be water clouds through their entire depth. In turn, this will maximize the difference in heights predicted for seeded versus unseeded cumulus towers. Cotton and Boulanger (1975), in comparing results from the FACE EMB 68P model with those from another one-dimensional cumulus model (PSU 71) felt that higher seedabilities in the case of the EMB 68P were caused by failure to begin the ice phase change at temperatures near -15°C.

Although the presence of large concentrations of ice has been observed frequently in Florida cumuli at temperatures even warmer than -15°C (Hallett et al., 1978), there is little evidence to suggest that significant quantities of ice occur in the initial actively ascending convective bubble. Theoretically, it is such a bubble that the FACE cumulus model comes closest to simulating. FACE model tests that assume linear glaciation between -15° and -40°C show, in most cases, only small differences in seedability compared with results that assume an instantaneous phase change at -40°C.

4) *The entrainment calculations are performed at the levels supplied in the original radiosonde data; the ambient sounding and the in-cloud sounding resulting from the entrainment calculation are then linearly interpolated at fixed-height increments (e.g., 50 m). At those fixed-height increments, the calculations of buoyancy, hydrometeors, and fallout are performed.* Because the entrainment calculations are performed at the levels supplied by the radiosonde data (also noted by McCarthy, 1972), the computation is performed in finite difference steps wherein all the air mixed into the tower comes from the next higher sounding point. As long as sounding points are not too far apart (e.g., about 500 to 1000 m) this is a reasonable approach. In contrast, vertical separation of sounding data levels by 1500 m or more, especially at low levels, has been demonstrated (e.g., McCarthy, 1972) to result in miscalculations by the model.

5) *Dilution of cloud water by entrainment is ignored.* Simpson (1972) discussed detailed comparisons of the FACE EMB 68P cumulus model and the PSU 71 cloud model (Cotton, 1972). She indicated that a sounding interpolation procedure using height steps of about 200 m, and also a term in the governing equations for the mixing of cloud water, would be desirable and should be incorporated into the EMB 68P model as they are in the PSU 71 model. In fact, however, neither of these alterations has been incorporated in the FACE model, nor has the degree to which they alter the computations been calculated.

6) *Pulsating growth behavior is not treated.* Cloud growth through a series of pulsations, as discussed by Mason and Jonas (1974), or as modeled by Lopez (1973), cannot be addressed by the FACE model, since only the initial bubble behavior is simulated. Modification of the localized temperature and humidity fields by growth of a series of convective elements undoubtedly takes place and most certainly will have an important effect in furthering the development of convective systems.

APPENDIX C

Calculated Convective Condensation Level (CCL) Cloud Bases in Illinois

Average convective cloud base heights are shown in figures C.1a through C.1f for mornings and evenings of June, July and August, respectively. Those for all CCL bases are shown as solid lines, whereas those for CCL $\leq$ 3500 m are shown dashed. Some surprisingly large differences are found between the average CCL for morning compared with those for evening soundings for a given year. For example, in July 1962, the average CCL for evening soundings (fig. C.1d) was 1810 m, whereas for morning soundings (fig. C.1c) it was 350 m higher. Differences of 250 m were found in August 1954 and 1955 between the morning (fig. C.1e) and the evening CCL (fig. C.1f). On the other hand, some of the more extreme values in the morning average are echoed, if not reproduced, by those respective evening average CCL values; for example, June 1960-62, July 1953-54 and 1960-61, and August 1961-62. The respective 10-year average CCL values also appear in each figure. Those for August, besides being at the lowest altitude, also have a morning average that is essentially equal to the evening average. By contrast, those for June are at greatest altitude and morning versus evening soundings are most dissimilar. Even so, June's year-to-year results show smaller deviations from the 10-year averages than are found for July or August. The average of cloud bases having CCL $\leq$ 3500 m is about 10% lower than average cloud base calculated from all CCL values. But the differences between the morning and evening CCL $\leq$ 3500 m (dashed lines) are larger (and always in the sense of morning lower than evening) than the differences, morning versus evening, when all CCL values (solid lines) are used. Thus, the morning soundings have a larger share of CCL > 3500 m than the evening soundings do.

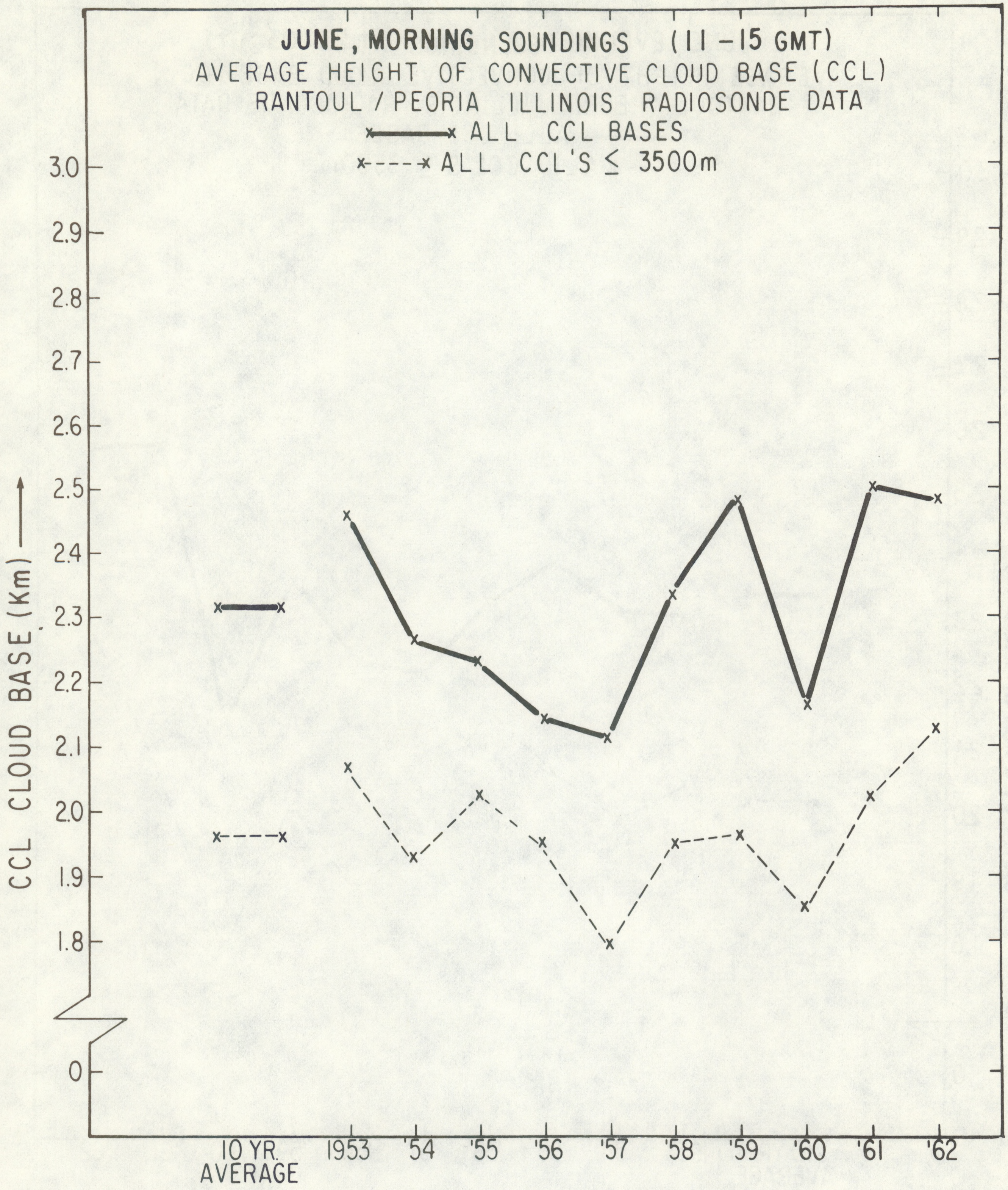

Figure C1a. Average height of convective cloud base, Rantoul/Peoria, Illinois, for 10 years of June mornings.

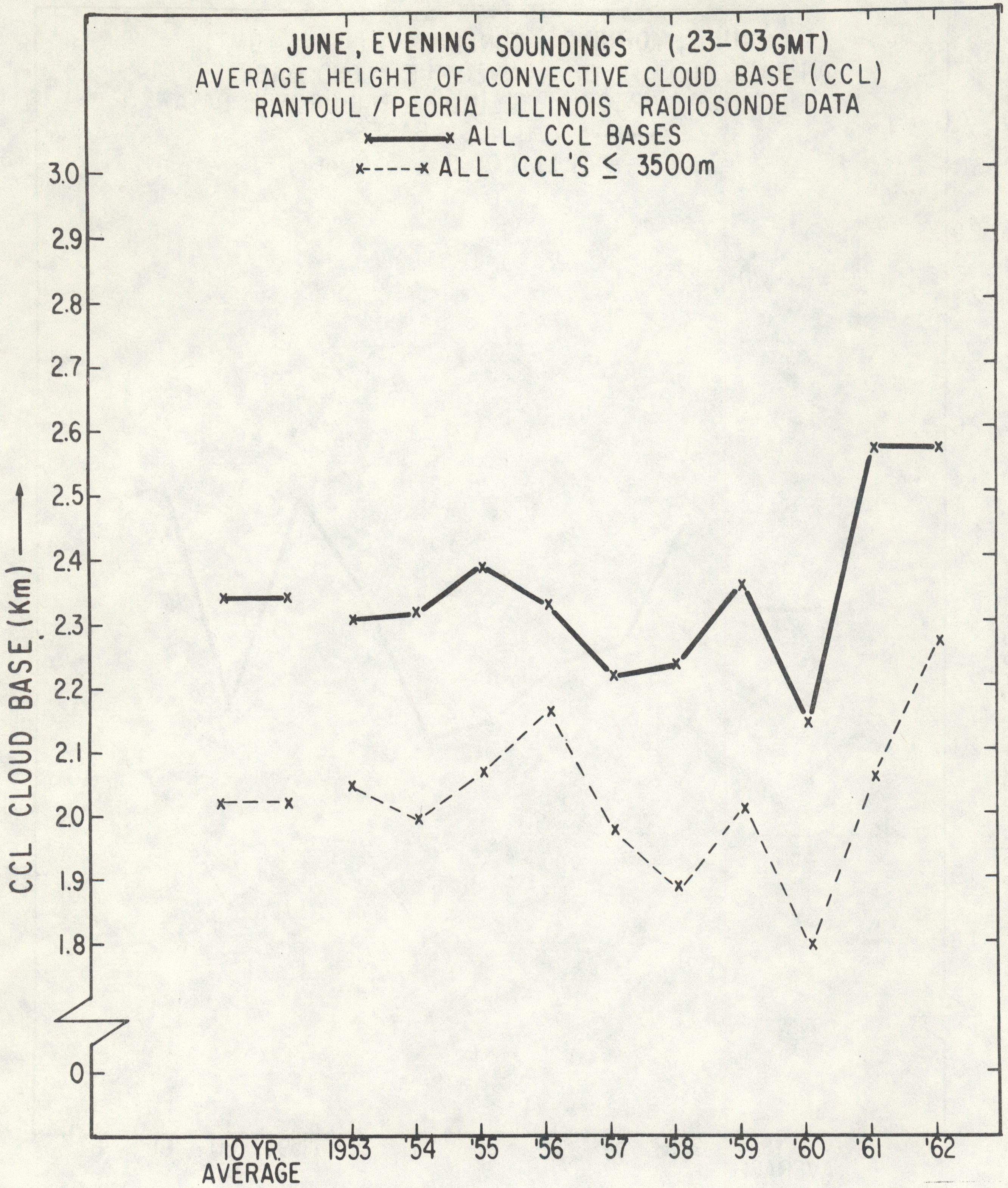

Figure C1b. Average height of convective cloud base, Rantoul/Peoria, Illinois for 10 years of June evenings.

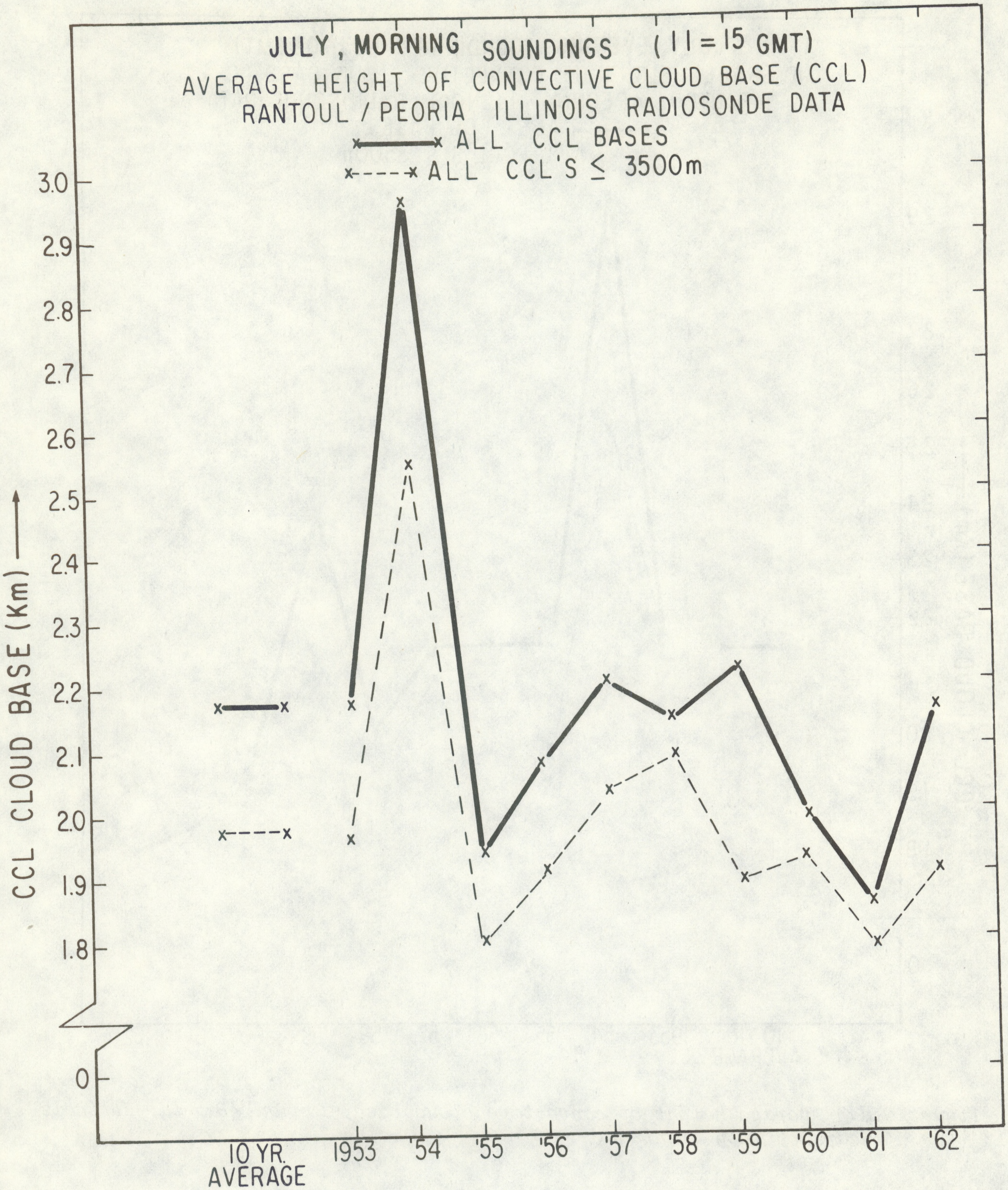

Figure C1c. Average height of convective cloud base, Rantoul/Peoria, Illinois for 10 years of July mornings.

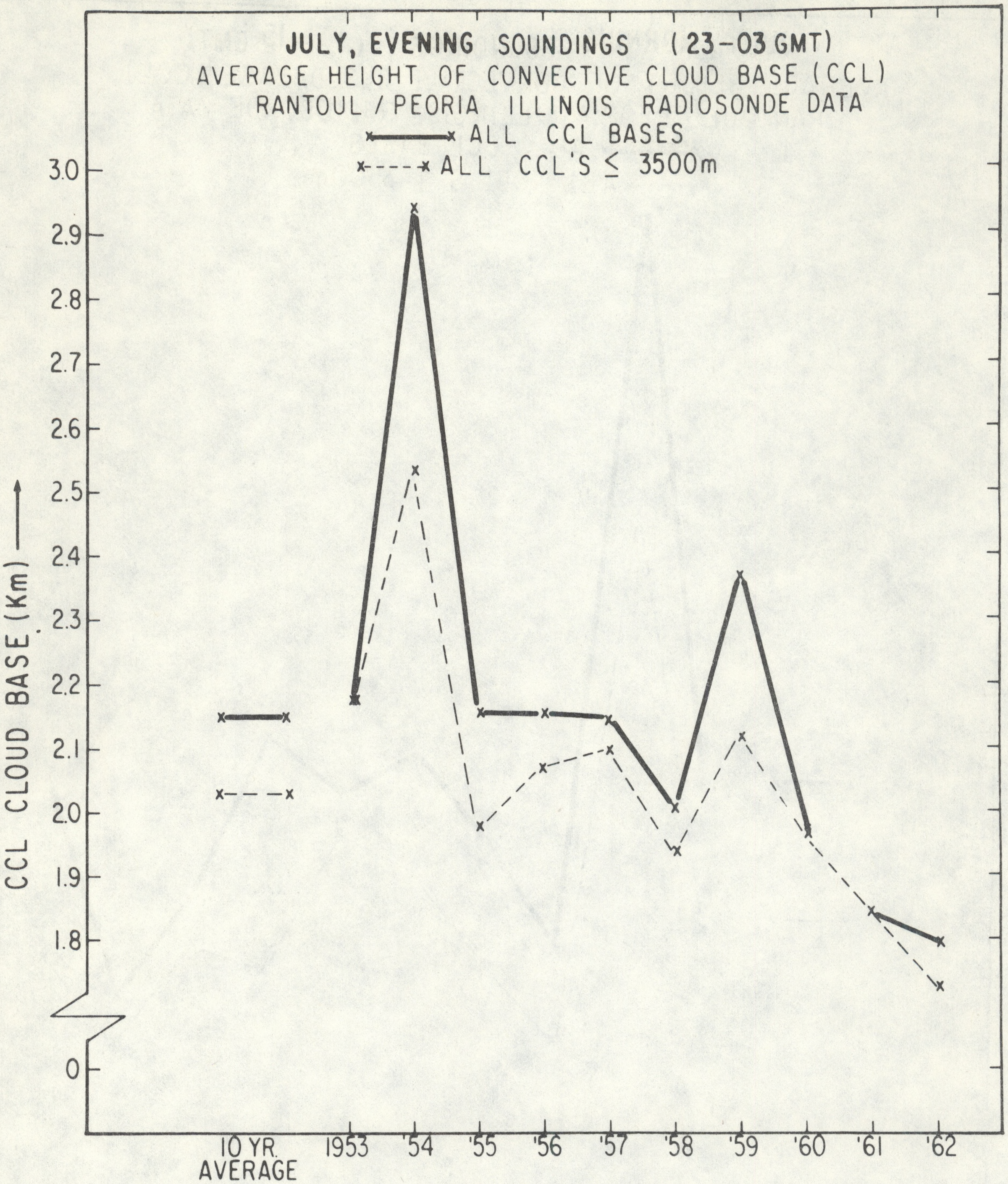

Figure C1d. Average height of convective cloud base, Rantoul/Peoria, Illinois for 10 years of July evenings.

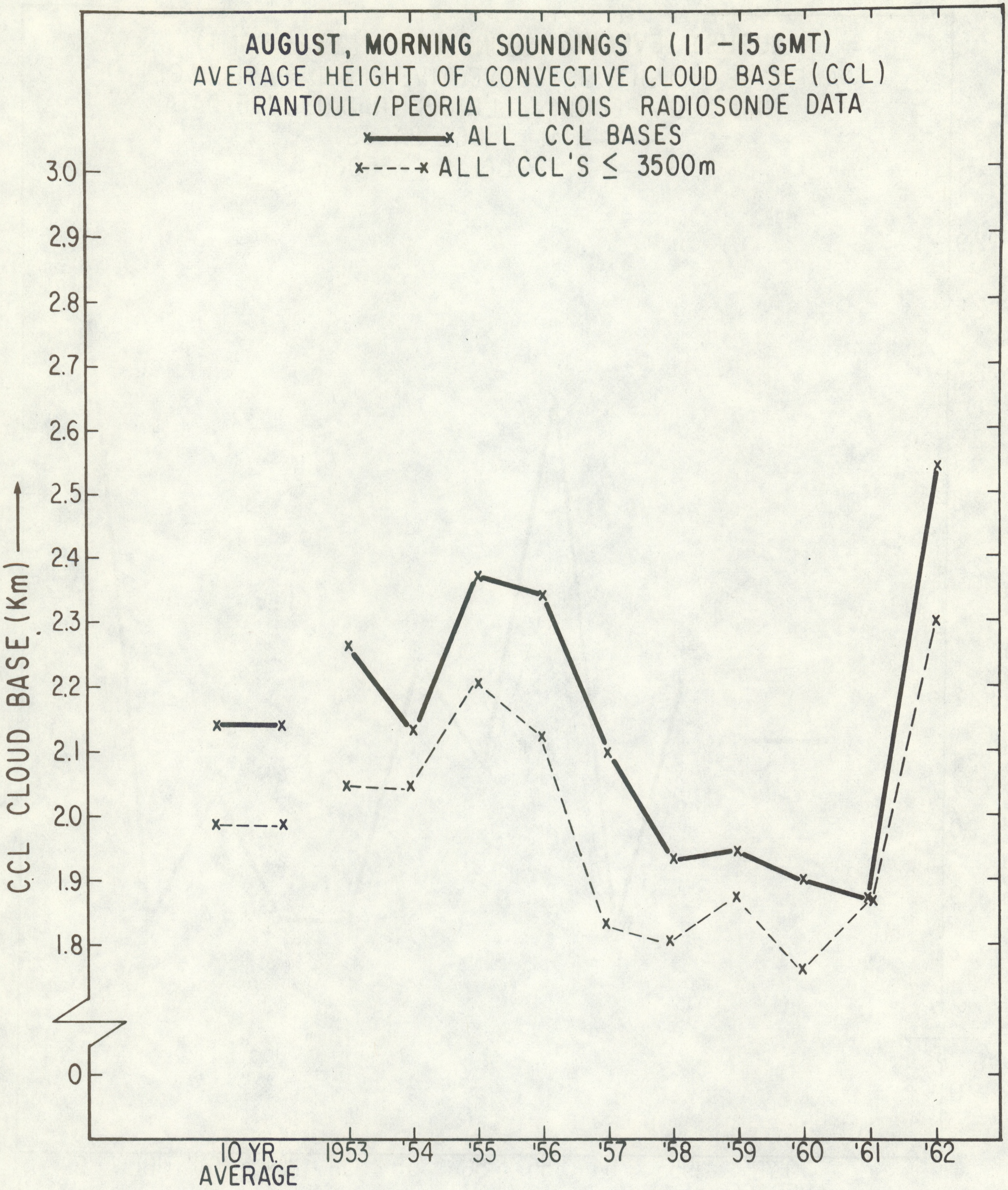

Figure C1e. Average height of convective cloud base, Rantoul/Peoria, Illinois for 10 years of August mornings.

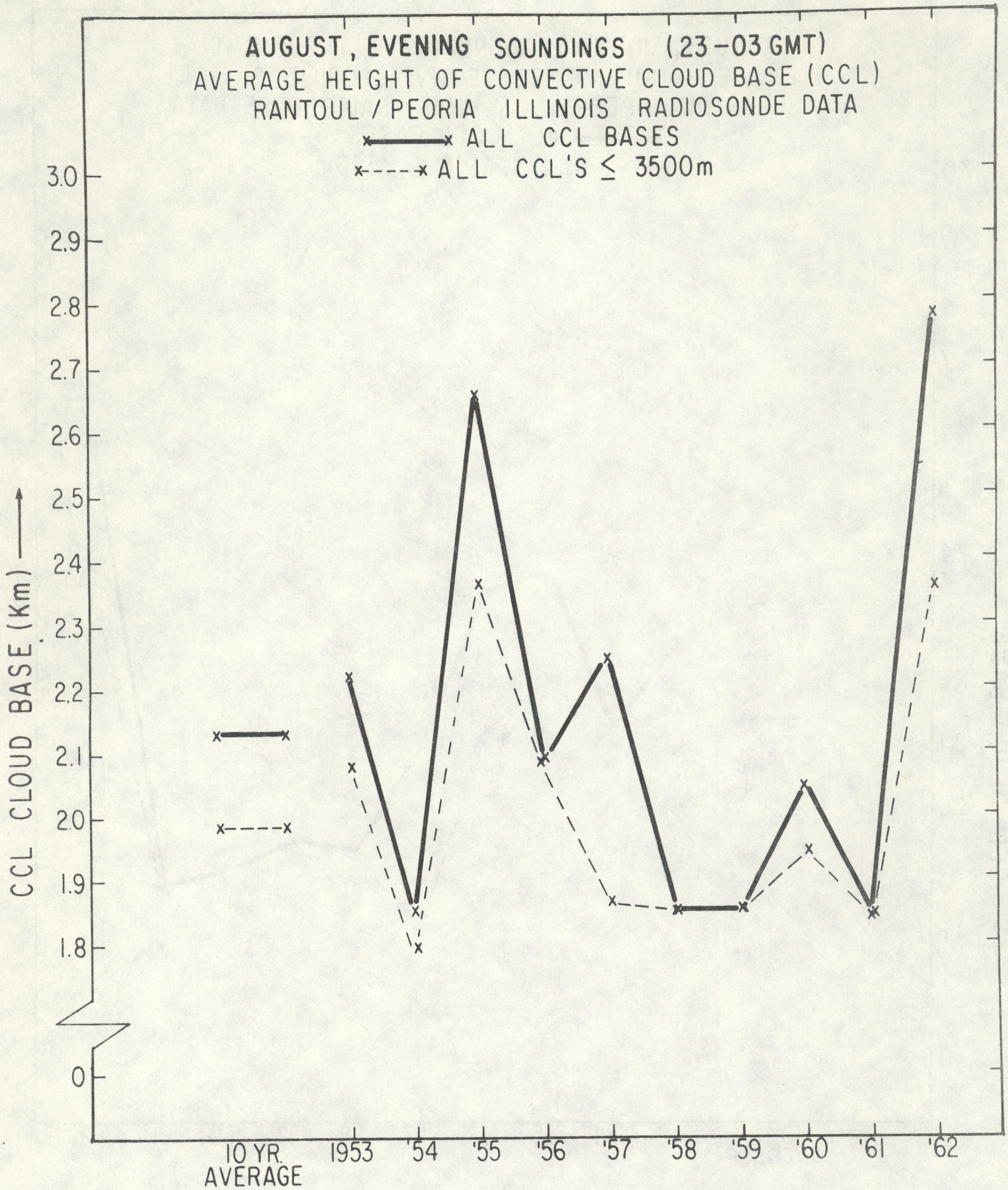

Figure C1f. Average height of convective cloud base, Rantoul/Peoria, Illinois for 10 years of August evenings.

APPENDIX D

Seedability Versus Cloud Tower Radius
Rantoul/Peoria 1953 through 1962, summer

Table D.1. Average Maximum Seedability Versus Modeled Cumulus Tower Radius for June, July, and August 1953-1962, Rantoul/Peoria

Radius (m)	Five radii, all CCL Evening (km/%M)	Five radii, all CCL Morning (km/%M)	Eight radii, CCL < 3500 m Evening (km/%M)	Eight radii, CCL < 3500 m Morning (km/%M)
500	*	*	0.4/11.5	0.3/11.3
750	*	*	0.9/13.6	0.6/12.2
1000	1.1/24.0	1.0/22.5	0.8/12.5	0.8/13.0
1250	0.7/17.3	0.7/18.4	0.7/11.9	0.7/12.6
1500	0.8/17.2	0.6/17.3	0.8/12.1	0.7/12.3
2000	0.7/17.6	0.6/17.5	0.8/11.9	0.6/11.9
2500	1.2/23.8	1.1/24.2	0.5/11.3	0.5/11.8
3000	*	*	1.1/15.2	0.9/14.9
	M = 1919	M = 2030	M = 2422	M = 2561

* These radii not used.
M = number of calculations.

Table D.2. Average Maximum Seedability Versus Modeled Cumulus Tower Radius for June 1953-1962, Rantoul/Peoria

Radius (m)	Five radii, all CCL Evening (km/%M)	Morning (km/%M)	Eight radii, CCL < 3500 m Evening (km/%M)	Morning (km/%M)
500	*	*	0.5/11.7	0.3/11.4
750	*	*	0.9/13.7	0.4/12.0
1000	1.0/24.5	0.8/22.4	0.7/12.2	0.7/12.9
1250	0.7/17.3	0.7/19.2	0.6/11.5	0.7/13.0
1500	0.7/17.1	0.6/17.4	0.7/12.2	0.7/12.5
2000	0.6/16.8	0.4/17.1	0.6/11.7	0.4/11.8
2500	1.2/24.3	0.8/23.9	0.6/11.3	0.4/11.7
3000	*	*	0.9/15.6	0.7/14.6
	M = 608	M = 673	M = 736	M = 806

* These radii not used.
M = number of calculations.

Table D.3 Average Maximum Seedability Versus Modeled Cumulus Tower Radius for July 1953-1962, Rantoul/Peoria

Radius (m)	Five radii, all CCL		Eight radii, CCL < 3500 m	
	Evening (km/%M)	Morning (km/%M)	Evening (km/%M)	Morning (km/%M)
500	*	*	0.4/11.0	0.4/11.3
750	*	*	0.7/12.2	0.6/12.1
1000	0.9/21.1	0.9/20.8	0.7/12.1	0.7/12.1
1250	0.9/17.9	0.7/18.0	0.9/12.4	0.6/12.3
1500	0.9/17.9	0.7/16.8	0.9/12.5	0.7/12.0
2000	0.7/17.8	0.8/17.7	0.8/11.9	0.7/11.9
2500	1.3/25.3	1.4/26.8	0.6/11.5	0.8/12.2
3000	*	*	1.4/16.4	1.2/16.2
	M = 653	M = 650	M = 825	M = 835

* These radii not used.
M = number of calculations.

Table D.4. Average Maximum Seedability Versus Modeled Cumulus Tower Radius for August 1953-1962, Rantoul/Peoria

Radius (m)	Five radii, all CCL		Eight radii, CCL ≤ 3500 m	
	Evening (km/%M)	Morning (km/%M)	Evening (km/%M)	Morning (km/%M)
500	*	*	0.5/11.7	0.2/11.0
750	*	*	1.0/14.9	0.7/12.5
1000	1.2/26.4	1.1/24.2	0.9/13.0	1.0/14.0
1250	0.7/16.7	0.8/18.0	0.7/11.8	0.7/12.5
1500	0.8/16.7	0.7/17.8	0.7/11.6	0.7/12.4
2000	0.8/18.2	0.7/17.8	0.8/12.2	0.7/12.2
2500	1.0/21.9	0.9/22.2	0.4/11.1	0.4/11.4
3000	*	*	0.9/13.6	0.8/14.0
	M = 658	M = 707	M = 861	M = 920

* These radii not used.
M = number of calculations.

Table D.5. Zeros-Excluded Average Maximum Seedability Versus Modeled Cumulus Tower Radius for June, July, and August 1953-1962, Rantoul/Peoria

Radius (m)	Five radii, all CCL		Eight radii, CCL < 3500 m	
	Evening (km/%N)	Morning (km/%N)	Evening (km/%N)	Morning (km/%N)
500	*	*	2.6/08.2	2.4/0.4
750	*	*	2.9/17.2	3.0/11.2
1000	2.4/32.3	2.5/28.3	3.3/12.4	3.3/15.0
1250	3.3/11.8	3.0/14.6	3.7/10.1	3.2/13.0
1500	3.6/11.6	3.3/11.2	3.6/10.8	3.4/11.6
2000	3.1/12.7	3.0/11.9	3.8/10.1	3.5/09.9
2500	2.6/31.6	2.5/34.0	3.2/07.5	3.3/09.0
3000	*	*	2.9/23.7	2.6/23.9
	N = 629	N = 615	N = 574	N = 545
	N(0) = 258	N(0) = 283	N(0) = 231	N(0) = 252
	N_T = 887	N_T = 898	N_T = 805	N_T = 797
	N(0) = .291N_T	N(0) = .315N_T	N(0) = .287 N_T	N(0) = .316N_T

* These radii not used.
N = number of soundings.
N(0) = soundings having S_{max} = 0.

Table D.6. Zeros-Excluded Average Maximum Seedability Versus Modeled Cumulus Tower Radius for June 1953-1962, Rantoul/Peoria

	Five radii, all CCL		Eight radii, CCL ≤ 3500 m	
Radius (m)	Evening (km/%N)	Morning (km/%N)	Evening (km/%N)	Morning (km/%N)
500	*	*	2.4/09.1	2.1/07.2
750	*	*	2.8/17.6	2.4/10.2
1000	2.2/33.2	2.3/28.3	3.2/11.4	3.2/14.5
1250	2.7/12.0	2.8/17.2	3.1/08.5	3.1/15.1
1500	3.2/11.5	3.2/11.1	3.2/11.4	3.3/12.7
2000	2.8/10.6	2.1/10.1	3.5/09.1	2.5/09.0
2500	2.6/32.7	2.0/33.3	3.5/07.4	2.4/08.4
3000	*	*	2.4/25.6	2.1/22.9
	N = 208	N = 198	N = 176	N = 166
	N(0) = 80	N(0) = 95	N(0) = 70	N(0) = 80
	N_T = 288	N_T = 293	N_T = 246	N_T = 246
	N(0) = .278N_T	N(0) = .324N_T	N(0) = .285N_T	N(0) = .325N_T

* These radii not used.
N = number of soundings.
N(0) = soundings have S_{max} = 0.

Table D.7. Zeros-Excluded Average Maximum Seedability Versus Modeled Cumulus Tower Radius for July 1953-1962, Rantoul/Peoria

Radius (m)	Five radii, all CCL		Eight radii, CCL < 3500 m	
	Evening (km/%N)	Morning (km/%N)	Evening (km/%N)	Morning (km/%N)
500	*	*	2.7/06.5	2.7/07.0
750	*	*	2.9/11.4	3.2/10.7
1000	2.5/23.6	2.5/22.4	3.2/10.9	3.3/10.7
1250	3.7/13.5	2.8/13.8	4.0/11.9	3.0/11.8
1500	3.6/13.5	3.4/10.0	3.7/12.4	3.6/10.2
2000	3.2/13.0	3.5/12.9	3.8/10.0	3.9/09.6
2500	2.8/36.5	2.8/41.0	3.1/08.5	3.9/11.2
3000	*	*	3.3/28.4	3.0/28.9
	N = 208	N = 210	N = 201	N = 187
	N(0) = 89	N(0) = 88	N(0) = 78	N(0) = 81
	N_T = 297	N_T = 298	N_T = 279	N_T = 268
	N(0) = .300N_T	N(0) = .295N_T	N(0) = .280N_T	N(0) = .302N_T

* These radii not used.
N = number of soundings.
N(0) = soundings having S_{max} = 0.

Table D.8. Zeros-Excluded Average Maximum Seedability Versus Modeled Cumulus Tower Radius for August 1953-1962, Rantoul/Peoria

Radius (m)	Five radii, all CCL Evening (km/%N)	Five radii, all CCL Morning (km/%N)	Eight radii, CCL ≤ 3500 m Evening (km/%N)	Eight radii, CCL ≤ 3500 m Morning (km/%N)
500	*	*	2.8/09.1	2.3/05.2
750	*	*	2.9/22.8	3.2/12.5
1000	2.5/39.9	2.7/34.3	3.5/14.7	3.4/19.8
1250	3.5/09.9	3.5/13.0	3.7/09.6	3.6/12.5
1500	4.0/09.9	3.2/12.6	3.8/08.6	3.5/12.0
2000	3.2/14.6	3.2/12.6	3.9/11.2	3.8/10.9
2500	2.5/25.8	2.6/27.5	2.9/06.6	3.3/07.3
3000	*	*	3.1/17.3	2.6/19.8
	N = 213	N = 207	N = 197	N = 192
	N(0) = 89	N(0) = 100	N(0) = 83	N(0) = 91
	N_T = 302	N_T = 307	N_T = 280	N_T = 283
	N(0) = .295 N_T	N(0) = .326N_T	N(0) = .296N_T	N(0) =.322N_T

* These radii not used.
N = number of soundings.
N(0) = soundings having S_{max} = 0.

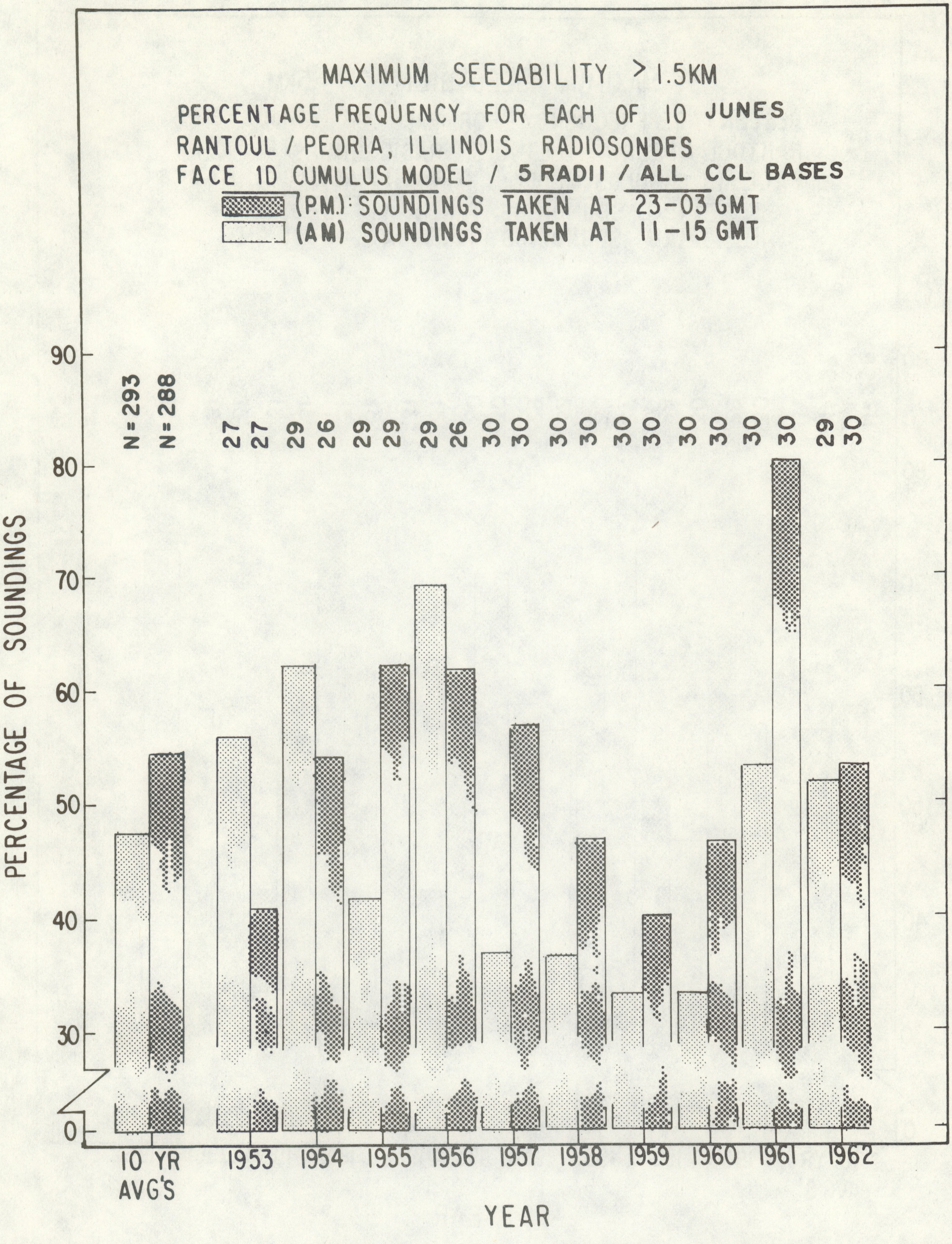

Figure D1a. Maximum seedability > 1.5 km. Percentage frequency for 10 Junes.

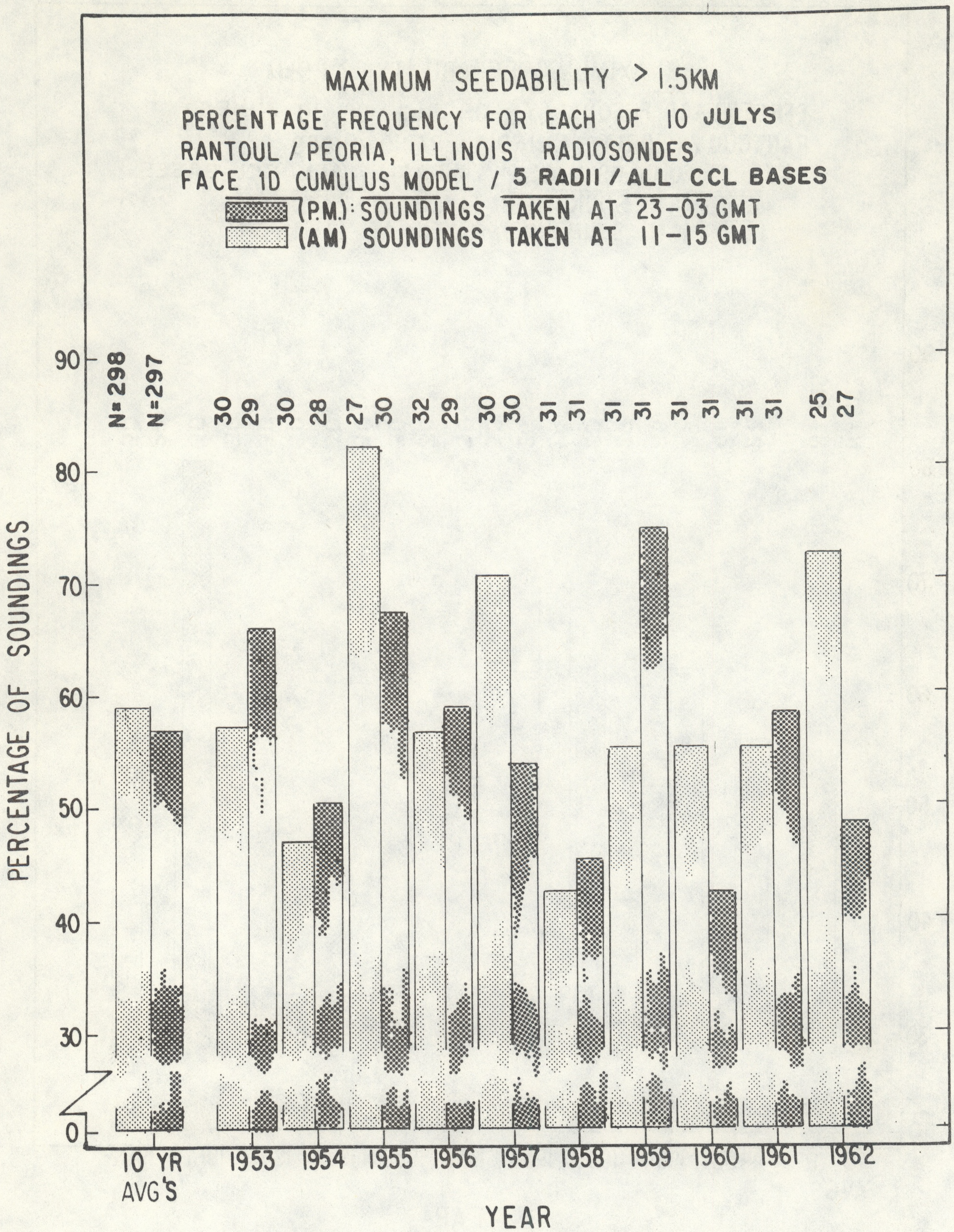

Figure D1b. Maximum seedability > 1.5 km. Percentage frequency for 10 Julys.

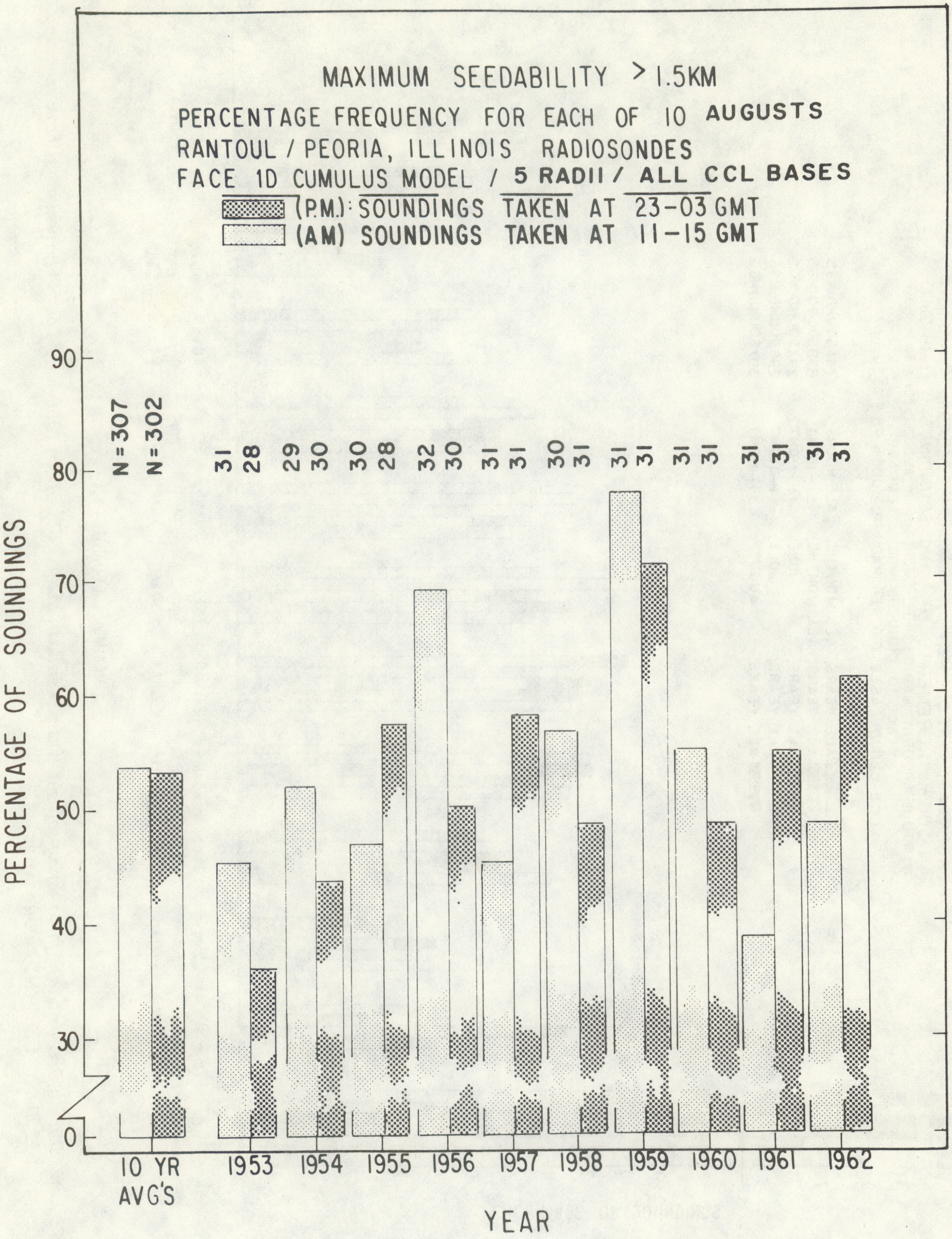

Figure D1c. Maximum seedability > 1.5 km. Percentage frequency for 10 Augusts.

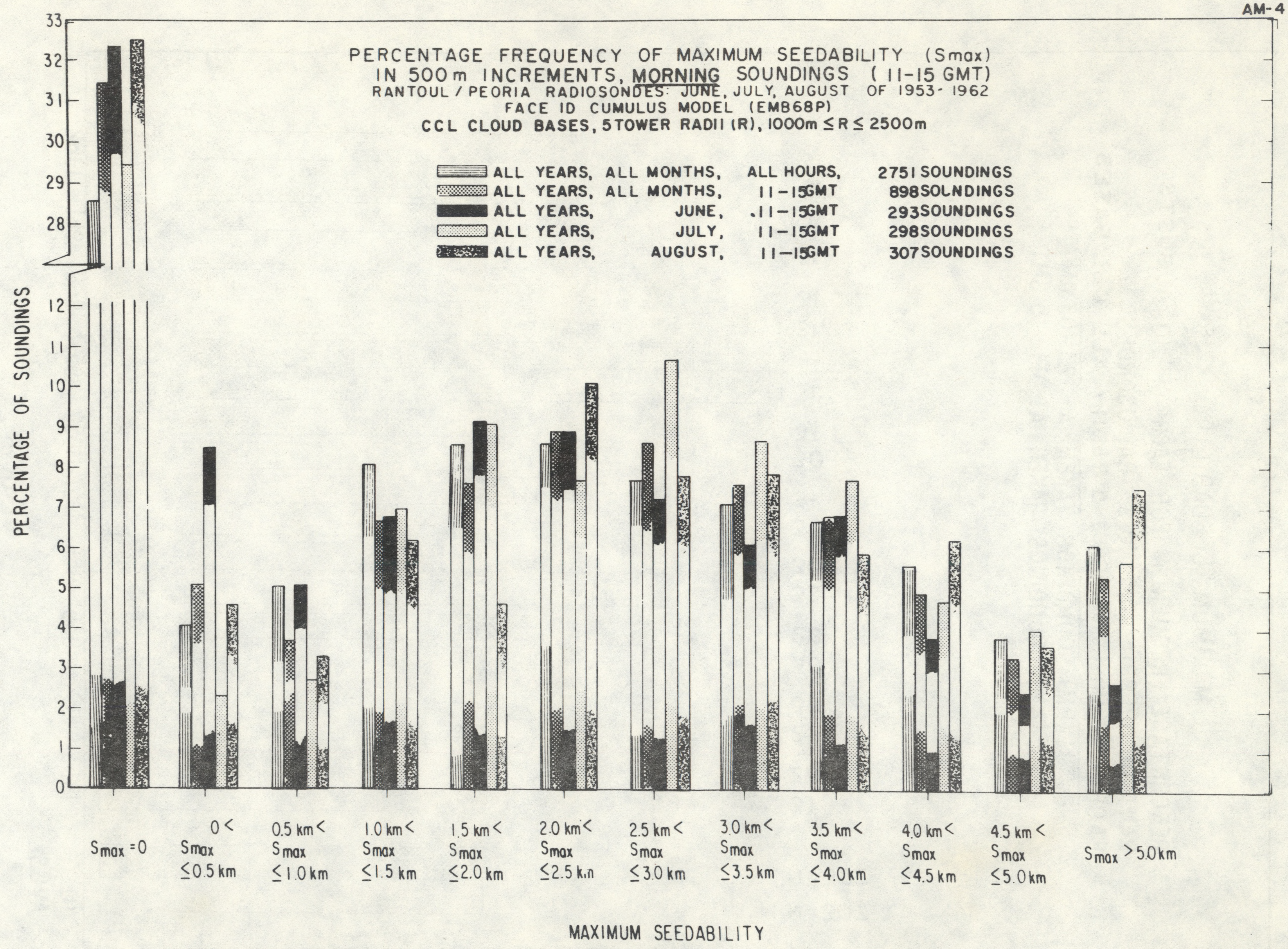

Figure D2a. Percentage frequency of maximum seedability (S_{max}) in 500-m height increments for morning (1100 to 1500 GMT) soundings.

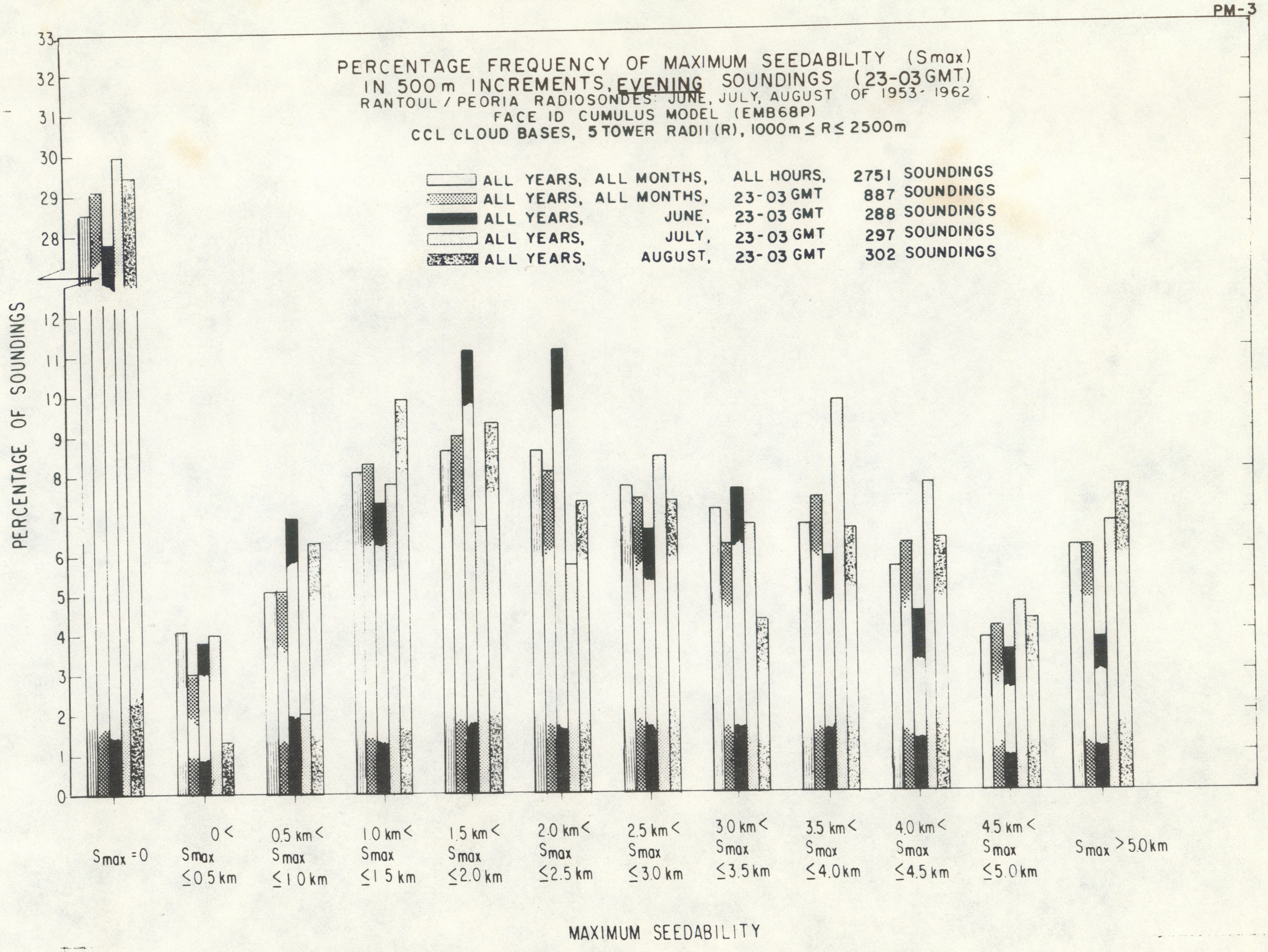

Figure D2b. Percentage frequency of maximum seedability (S_{max}) in 500-m height increments for morning (2300 to 0300 GMT) soundings.