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SOME CHARACTERISTICS OF RADAR FIRST ECHOES IN THE HIGH PLAINS

James R. Miller, Jr., and Paul L. Smith
Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
501 East St. Joseph Street
Rapid City, South Dakota 57701-3995

Abstract. Radar first echoes identified in northeast Colorado and southwestern North Dakota convective clouds are examined. The first-echo temperatures in Colorado appear related to thermodynamic energy in the sounding rather than to seeding effects, when compared to earlier South Dakota studies. Mean first-echo temperatures in North Dakota are related to model-predicted maximum updraft speeds. New echoes developing near existing radar echoes have lower temperatures than ones developing far away from existing echoes. These results suggest that cloud dynamics play an important role in the temperature and height of first-echo formation. About one-third of the first-echo temperatures are higher than -5°C, which suggests that collision-coalescence rain processes may be important in High Plains clouds.

1. INTRODUCTION

First radar echoes in convective clouds have been a subject of study throughout the history of weather radar. In the early 1950's, Reynolds and Braham (1952) discussed the significance of initial radar echoes. The temperature at which the first echoes appear is important since it likely reflects the primary precipitation formation mechanism working in a young convective cloud. Battan (1953, 1963) interpreted the observations in terms of precipitation processes and subsequently related first-echo heights with cloud-base heights. He found a significant relationship, but only 23% of the variance of first-echo heights was explained by the cloud-base height. Heights of vigorous convective first echoes were reported by Browning and Atlas (1965); they also summarized previous findings, including those of Ackerman (1960). More recently, Braham and Dungey (1978) and Ochs and Johnson (1980) noted again that first echoes in the central United States tend to occur mainly below or around the 0°C level in the atmosphere.

First echoes in the Dakotas were discussed by Dennis and Koscielski (1972) and Koscielski and Dennis (1976). In the Dakota studies, temperatures at which seeded and natural first echoes appeared were compared. These studies suggest that modified clouds produce first echoes earlier and at higher temperatures than untreated clouds. Examination of the North Dakota Pilot Project first-echo data indicates that the primary precipitation formation mechanism is an ice process, but a sizable fraction of the first echoes appeared at temperatures higher than -5°C. The time needed to grow sufficient numbers of ice particles large enough to be detected by typical weather radars is on the order of a few minutes. The updraft speeds and related vertical echo growth rates in typical High Plains convective storms suggest that first radar echoes detected at or below the -5°C level are not likely due to an ice-phase process unless some kind of particle recirculation mechanism is involved. Along with a lack of sufficient natural ice-nuclei active at high temperatures, the frequent presence of high temperature first echoes suggests that the condensation-coalescence or warm rain process may be active in many High Plains convective clouds This follows Battan's (1963) finding suggesting an active coalescence process in many cold or supercooled clouds.

The purpose of the present study was to examine first-echo data from convective clouds in northeast Colorado and North Dakota. This study continues the search for explanations for observed first-echo temperatures. First echoes were tabulated from radar scan data collected during the National Hail Research Experiment (NHRE) in Colorado and the North Dakota Cloud Modification Project (NDCMP).

2. NHRE FIRST ECHOES

An S-band, 10.7 cm radar with 1° beamwidth and associated processing equipment described by Foote et al. (1976) was used to collect and preprocess the northeast Colorado data. Representative sounding data were used to obtain environmental temperatures corresponding to observed first-echo heights. These sounding data were selected, analyzed, and tabulated by Fankhauser et al. (1976).

A total of 188 first echoes were identified and their heights tabulated using the 1973 and 1974 microfilm output of raster scan data: 41 in 1973, and 147 in 1974. To minimize the effects of beam spreading and radar sensitivity variations with range, only echoes within 80 km of the radar were tabulated. The threshold reflectivity contour of the microfilm output was 25 dBz. The NHRE first-echo data were discussed in Breed and Miller (1981). A mean first-echo height of 6.7 km MSL for this two-year NHRE data set resulted.

Histograms of the first-echo heights (FEH) and temperatures (FET) are shown in Fig. 1. Data in Fig. 1a and b summarize 41 first echoes within the primary NHRE target area during times when cloud seeding operations were being conducted (Sanborn et al., 1976). Data in Fig. 1c and d summarize 122 no-seed-day echoes and seed-day echoes which occurred prior to any release of seeding agent. All first echoes occurring following the seeding period were omitted from the no-seed category because of possible contamination, which explains why the total of 163 first echoes included in Fig. 1 is less than the total of 188 observed.

Means and standard deviations of the first-echo heights and corresponding environmental temperatures are shown in the upper corner of each panel in the figure. A comparison of the mean first-echo temperatures and heights shows that those echoes within the seeding period were slightly higher and colder than first echoes on no-seed days and seed days prior to the commencement of seeding. The difference is opposite to what one would expect from glaciogenic seeding, and these results are diametrically opposed to the results of Dennis and Koscielski (1972) and Koscielski and Dennis (1976) using data from South and North Dakota, respectively.

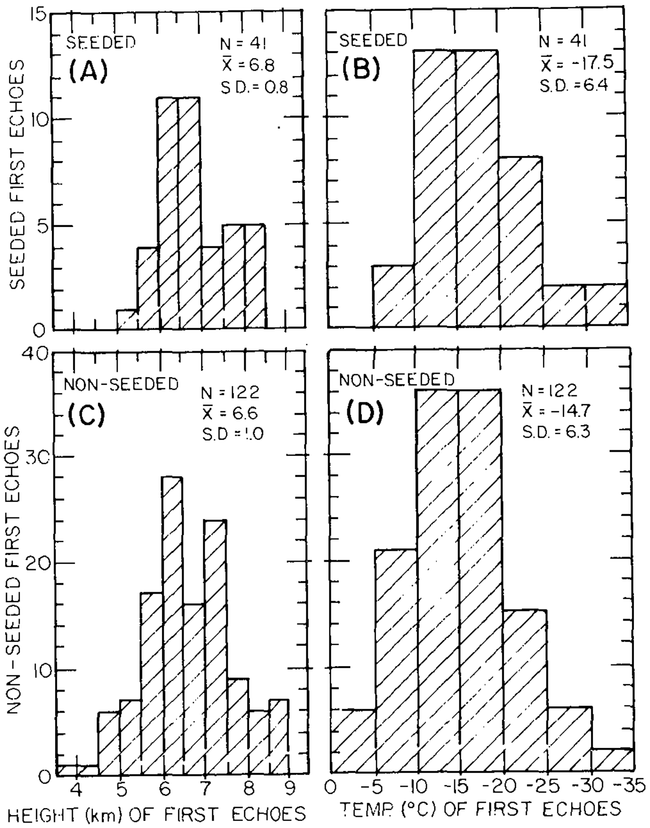

Fig. 1: Histograms showing distributions of:
a) First-echo heights for seeded NHRE storms;
b) First-echo temperatures for seeded NHRE storms
c) First-echo heights for non-seeded NHRE storms;
d) First-echo temperatures for non-seeded NHRE storms.

Table 1 shows the results of a t-test used to compare seed and no-seed, first-echo characteristics, with the probability of a larger difference in FET being only 0.01. There are several possible explanations for the observed seed/no-seed differences in first-echo heights and temperatures. Seeded convective elements might experience an increase in updraft speed and convective circulation as liquid water is changed to ice, releasing the heat of fusion earlier in the life of the updraft. A one-dimensional convective cloud model suggests such a possibility (Chang, 1976). That could carry the ice particles to higher altitudes before they grow to radar-detectable sizes. Orville and Chen (1982), using a 2-D, time-dependent cloud model, have also shown slight changes in updraft speeds and the heights of computed reflectivity values in "seed" model runs as compared to unseeded cases.

Another possible explanation is that a difference was found between sounding parameters on NHRE seed and no-seed days. More potential energy, greater instability, and greater low-level moisture were found on seed days compared to no-seed days (Crow et al., 1979). Table 1 also shows some comparisons between sounding parameters on the NHRE seed and no-seed days with first-echo data. They indicate differences similar to those found by Crow et al., but the only quantity showing a possibly statistically significant difference between seed and no-seed days was the mean thermodynamic potential energy (α = 0.09). However, our analysis of data from North Dakota (Sec. 3) suggests that updraft speed computed from a cloud model could be a more useful indicator of differences among soundings. All of these possibilities imply that dynamical as well as microphysical considerations may influence the occurrence of first radar echoes.

The seeding techniques and procedures used on the NHRE project were primarily aimed at existing echoes. It is likely that the first echoes called

TABLE 1

Mean Seed and No-Seed First-Echo Characteristics
and Mean Sounding Parameters on Days with
First Echoes (1973-74 NHRE Data)

	Seed	No-Seed	t-test Pr Level
No. Days with Observations	11	26	
No. First Echoes	41	122	
Mean F. E. Time (hr MDT)	16.2	15.6	0.08
Mean F. E. Height (km)	6.81	6.58	0.09
Mean F. E. Temperature (°C)	-17.5	-14.7	0.01
Max F.E.H. (km)	7.5	7.3	0.27
Min F.E.T. (°C)	-21.1	-19.2	0.25
500 mb Temp (°C)	-9.4	-8.8	0.35
L.I. (°C)	-2.8	-2.2	0.21
Therm. Energy (J/g)	0.72	0.54	0.09
Low-Level Moisture (g/kg)	8.3	7.6	0.13

"seeded" in this study may well have been, for the most part, natural first echoes. It is also possible that the seeding as practiced in NHRE was ineffective in inducing early glaciation in the clouds (e.g., Linkletter and Warburton, 1977; Stith et al., 1986). If either is the case, then the appearance of higher and colder first echoes in the small "seed" sample would most likely be due to the greater available potential energy (stronger vertical air motion) on those days. In any event, the "seeded" first echoes in northeast Colorado did not follow the same trend as those in the Dakotas.

In another study of NHRE first echoes in which no separation was made between seed and no-seed echoes, Breed and Miller (1981) found little relationship between FET's and various other cloud base or sounding parameters. They also found no correlation between the height of the first echo above cloud base and any of those quantities. "The comparisons of first echoes and cloud base/sounding parameters showed those data to have little or no value in predicting or explaining first-echo characteristics." Such a conclusion would be consistent with the dominance of ice processes in the development of precipitation.

A plot of mean first-echo height versus time of day (Fig. 2) shows that the first-echo height peaks in the late afternoon and begins to decline in the evening hours. This might be expected since the strength of convection is related to the daily radiation budget. There was a slight difference between the mean time of occurrence of seeded and non-seeded first echoes (Table 1), with the former tending to occur slightly later. This might favor lower first-echo temperatures in seeded clouds since storms tend to become more organized later in the afternoon and the near-storm environment results in stronger cloud dynamics (e.g., reflected in stronger vertical velocities).

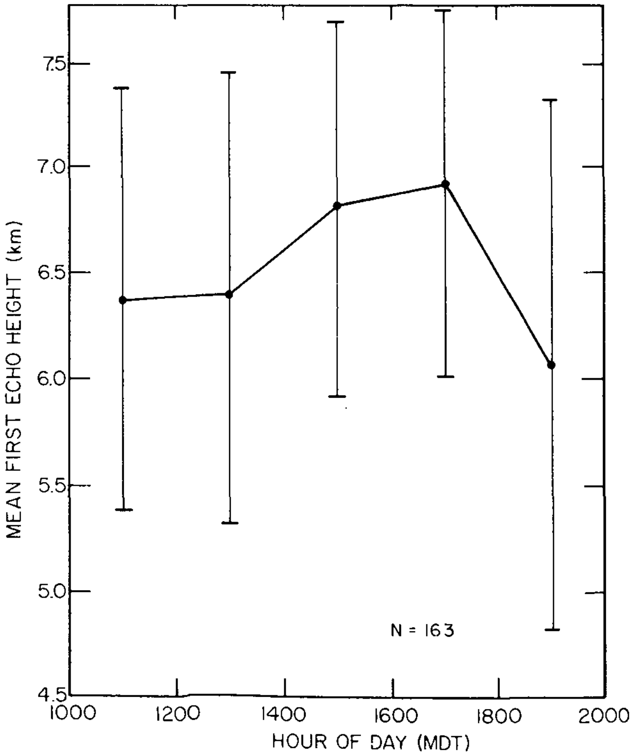

Fig. 2: Mean NHRE first-echo heights as a function of time of observations. The extended vertical lines indicate standard deviations.

3. NDCMP FIRST ECHOES

During the summer of 1982 an Enterprise WR-100 5-cm radar with 2° beamwidth was used to collect data on convective storms in southwestern North Dakota. Volume scans were made in 1° elevation steps from 1° to 12° with a typical scan cycle requiring about 5 to 6 min. Data between ranges 40 and 140 km on twelve days resulted in identification of 333 first echoes. Those first echoes were studied to gain some further insight about the microphysical mechanisms at work in North Dakota convective clouds.

First-echo heights were determined by taking the height at the strongest portion of a first-observed radar echo. For the most part, this was just at or above the middle level of the echo. Temperatures corresponding to the observed first radar echo heights were taken from the closest (in time) rawinsonde data for Bismarck, North Dakota. Following the usual practice in such studies, no correction was made for possible higher in-cloud temperatures. Histograms of the first-echo temperatures are shown in Fig. 3. Seeding was conducted in the NDCMP, but no separation of seeded and unseeded echoes was made in the data because only a few echoes could be identified as having been seeded prior to appearance.

Examination of the 1982 NDCMP first-echo data in Fig. 3 shows considerable scatter in the temperatures. Approximately 38% of the first echoes form at temperatures ⩾ -5°C. These results are in agreement with the study of first echoes by Koscielski and Dennis (1976) using unseeded 1972 North Dakota data. There is very little chance that ice-forming nuclei are the direct cause of first echoes at temperatures ⩾ -5°C. It is more likely that giant condensation nuclei or other warm precipitation formation processes are

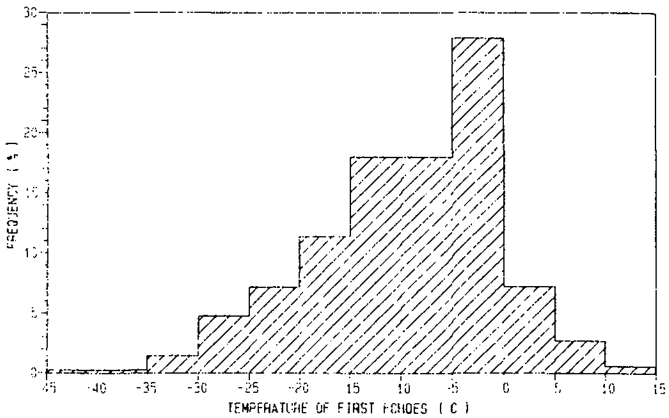

Fig. 3: Percentage frequency distribution of NDCMP first echoes vs. temperature. The median first echo temperature was -8.2°C.

responsible for these first radar echoes. Another possibility is that recirculating ice particles grow to detectable sizes in subsequent updrafts; this possibility would be supported if higher-temperature first echoes were found in new growth regions close to existing echoes.

Table 2 shows a day-by-day summary of the mean FEH's and FET's, including the number of first echoes identified on each day. The overall mean FET is about 6° higher than that found in the NHRE data (Fig. 1), but the NHRE observations were only from days declared to be potential hail days. Examination of these data suggests considerable variability among days and within days. One day (6 July) stands out as having conspicuously high first-echo temperatures together with low standard deviation. First-echo temperatures vary from +13°C to -43°C, and individual case studies would likely show evidence for recirculation, warm-rain processes, ice-phase processes, and mixed-phase microphysical processes all at work. Such variations suggest that investigating relationships to other meteorological variables should point toward further understanding of the first-echo observations.

An earlier attempt using the NHRE data (Breed and Miller, 1981) failed to identify any definitive FEH/FET predictors, but an effort was made to continue the search using other quantities as possible predictors. First, scatter plots were generated showing observed first-echo temperatures as a function of the distance to the nearest existing radar echo. These revealed a tendency for lower first-echo temperatures when the first echo was nearer to an existing radar echo. Day-to-day correlation coefficients (r) varied from -0.19 to +0.42 with a mean of 0.18. Though weak, this suggests that first-echo temperatures are lower if the echo is developing in close proximity to existing echoes. When all days' data were combined, the correlation coefficient was only 0.13.

Figure 4 shows the distribution of the number of observed first radar echoes as a function of the distance to a previously existing echo. Most first echoes appear close to existing echoes, where the atmosphere is already supporting mature convection. This suggests that supporting mesoscale or local-scale forcing functions (i.e., established convergence patterns) are more conducive to new convective growth and development than the surrounding atmosphere. The first echoes were then classified as close (<10 km) to a nearby echo or far away (≥10 km) from the nearest echo, a division that split the sample roughly in half. Cumulative frequency distributions of FET's were then generated and are shown in Fig. 5. Median FET's were -10.3°C for 150 "nearby" echoes and -6.5°C for 179 more distant echoes. This behavior is counter to that expected if recirculation processes were important. These data again suggest a dynamic effect on FET, and indicate that the updraft velocities of convective activity developing close to existing convection may be much stronger than those in convection developing some distance from established radar echoes.

The lowest-temperature first echoes, those below -30°C, occurred close to existing echoes (within 10 km) and during the time of peak surface

TABLE 2

Summary of Dickinson 1982 First Echoes by Day

DATE	N	$\overline{FEH}$ (km)	SD* (km)	$\overline{FET}$ (°C)	SD* (C°)
June 10	31	4.3	1.1	- 9.8	7.3
June 11	49	4.3	1.1	- 9.7	7.3
June 13	28	5.5	1.1	-13.0	7.7
June 14	36	4.7	1.4	- 8.5	8.7
June 15	21	5.4	1.4	-13.2	8.6
June 22	8	5.5	1.6	-10.2	9.9
June 23	26	5.5	1.6	- 9.5	10.1
June 26	36	4.9	1.2	- 7.0	7.0
June 28	25	5.3	1.5	- 8.4	9.5
July 5	20	5.8	2.0	- 9.1	14.9
July 6	19	3.5	0.7	- 0.4	4.4
July 8	34	5.9	1.7	-12.9	11.3
TOTAL/MEAN	333	4.99	1.50	- 9.3	9.4

*SD = Standard Deviation

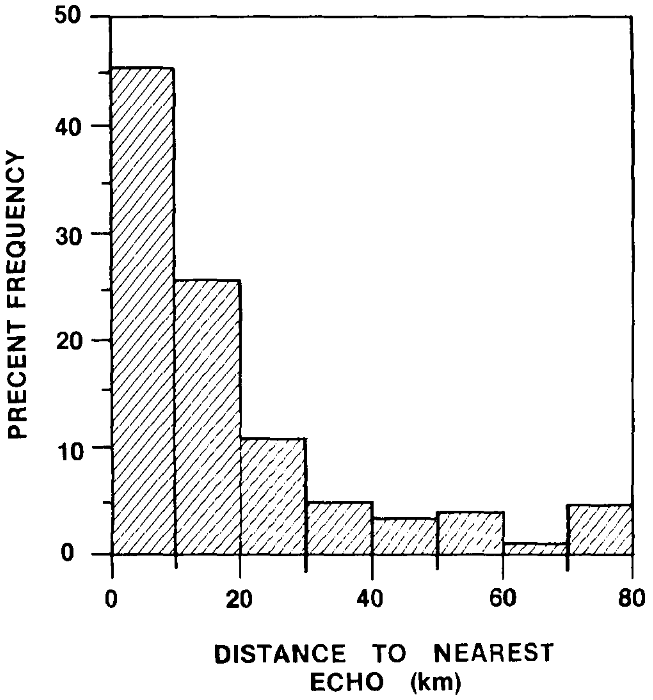

Fig. 4: Frequency distribution of NDCMP first radar echoes vs. distance to nearest existing echo.

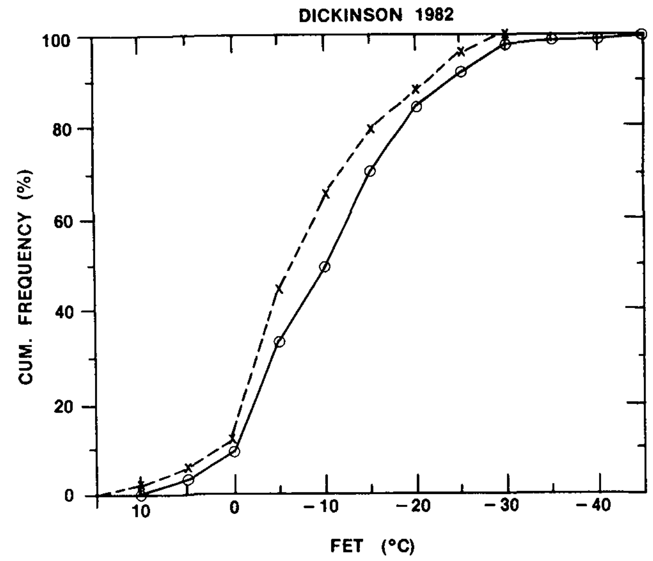

Fig. 5: Cumulative frequency distributions of NDCMP first-echo temperatures for "nearby" echoes (distance to nearest echo (≤10 km, solid line) and more distant echoes (distance (>10 km, dashed line). Median FET was -10.3°C for nearby echoes and -6.5°C for more distant echoes.

temperature (1400-1600 MDT). This is in agreement with other studies of first echoes in strong convective situations (Changnon and Stout, 1964; Browning and Atlas, 1965). These and some other first echo studies are summarized in Table 3. First echoes in severe storm environments are often found to occur at very low temperatures, < -30°C.

A plot of mean FET versus the distance between the first echo and the nearest existing radar echo is shown in Fig. 6. Although the scatter about the means is large (standard deviations are about 10C°), the data further support the indications that the near-cloud environment is very important in explaining FET's. The curve in Fig. 6 suggests that the strength of convection in the 20 to 50 km distance from existing echoes may be somewhat suppressed, and there is just a hint that convection is slightly stimulated in the 50 to 80 km range. In a future study, mesoscale factors should be considered to refine these suggestions.

The search for predictors for FET's continued. Rawinsonde data taken at Dickinson were used as input to a one-dimensional, steady-state cloud model (Hirsch, 1971). Soundings in 1982 were typically run at 0900 MDT (1500 GMT) each day and subsequently at 3-hourly intervals until 1800 MDT if convection was likely or in progress. Cloud-model predictions of maximum updraft velocities

TABLE 3

Summary of First-Echo Studies in Convective Clouds

Location	No. of First Echoes	$\overline{\text{FET}}$ (°C)	$\overline{\text{FEH}}$ (km)	Source
New Mexico	12	-10*(-13 top)	6.7	Workman and Reynolds (1949)
Massachusetts	2	MISG	4.3	Hilst and McDowell (1950)
Ohio	123	+5(+11.7 botton, +2.1 top)	3.7	Battan (1953)
Arizona	357	-1(+4.4 bottom, -7.2 top)	5.2	Braham (1958)
Arizona	294 bottoms, 289 tops	-3.7(+4.1 bottom, -11.6 top)	MISG	Ackerman (1960)
Illinois†	1	<-40	10.7	Changnon and Stout (1964)
Oklahoma†	3	-30	8.7	Browning and Atlas (1965)
South Dakota				Dennis and Koscielski (1972)
Natural	78	-14.8	6.2	
AgI Seeded	34	- 7.4	5.4	
Salt Seeded	60	- 3.1	4.9	
North Dakota				Koscielski and Dennis (1976)
Natural	40	-10.8	5.2	
Seed Days	93	- 5.3	4.4	
NE Colorado (NHRE)				(1973-74 data)
Natural	122	-14.7	6.6	
Seed Days	41	-17.6	6.8	
North Dakota				(1982 data)
All Data	333	- 9.3	5.0	

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*-10°C value is from "extrapolation of radiosonde data for the base of the cloud to the point in question, using pseudo-adiabatic lapse rates" (Workman and Reynolds, 1949, p. 142).

†These data from severe-storm convection.

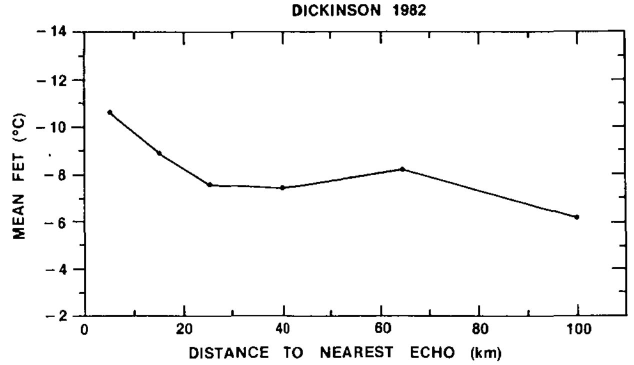

Fig. 6: Plot of mean first-echo temperatures vs. distance between the first echo and the nearest existing radar echo.

were generated and compared with those FET observations relatively near in time to the sounding time. Table 4 shows the dates and times of available sounding data, the numbers of corresponding FET observations, the mean FET for each sounding period, and the model-predicted maximum updraft velocity (W_{max}, m s^{-1}). (A 2-km diameter updraft was assumed for the model calculations.)

Figure 7 shows a plot of model-predicted W_{max} versus mean FET. The correlation coefficient of 0.82 suggests that such cloud-model output statistics may well prove to have stronger predictive potential than other traditional meteorological quantities. It also provides a further indication that a supposedly "microphysical" quantity, first-echo temperature, is strongly influenced by dynamical factors.

TABLE 4

Summary of First-Echo Temperatures and Model Maximum Updraft Speeds

Date (1982)	Sonde Time (MDT)	No. Echoes	Mean FET (°C)	Times of FE's (MDT)	Cloud Model W_{max} (m s^{-1})
22 June	1800	8	-10.1	1544-1725	26.4
23 June	0900	1	-12.5	1549	21.5
23 June	1200	12	-11.2	1154-1428	14.9
23 June	1500	7	- 8.0	1447-1548	12.3
23 June	1800	6	- 4.7	1633-1830	5.6
26 June	1500	36	- 6.0	1414-2051	9.5
28 June	1200	3	- 5.1	1922-2021	7.5
29 June	1100	22	- 7.6	2047-0424	13.7
4 July	1800	11	-16.8	2350-0118	24.9
5 July	0900	9	- 3.9	0244-0327	10.9
6 July	0900	19	- 0.6	1538-1713	8.1
8 July	1500	24	-13.5	1446-1629	26.7
8 July	1800	10	-12.2	1641-1942	14.3
TOTAL		168			

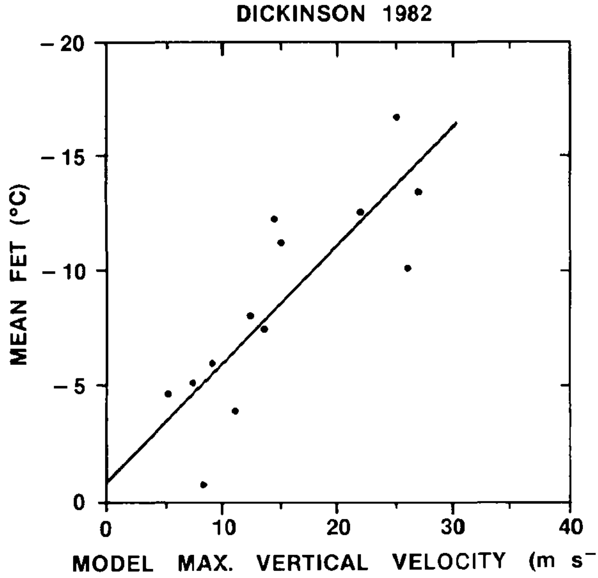

Fig. 7: Plot of model-predicted maximum updraft velocity vs. mean observed first-echo temperature.

4. DISCUSSION

Examination of the data in Table 3 shows that, in most cases, the first-echo temperatures indicate a preponderance of evidence for ice-phase processes to be working in continental convective clouds. However, sufficient data exist, in the Ohio and Arizona studies at least, to indicate that warm-rain processes are also important, in agreement with Reynolds and Braham (1952), and must not be neglected in the study of microphysical cloud/precipitation processes. Additional evidence in the distributions of FEH's and FET's reveals that from 25% to near 40% of northern High Plains first echoes (in South Dakota and North Dakota studies) suggest the possible importance of warm-rain processes as well.

This study of first echoes suggests that:

a) Early precipitation formation zones are higher in clouds which form in the near vicinity of existing convective storms.

b) Cloud dynamics set the stage for subsequent microphysical processes, and may well frustrate attempts to follow such processes using simple first-echo observations or periodic aircraft penetration measurement techniques. Development of improved radar and other remote sensing equipment and techniques that will be able to distinguish among particle types may be necessary to give more definitive answers.

c) One-dimensional, cloud-model-predicted updraft speeds show potential for use as predictors in helping to explain observed early echo development in Northern Plains convective storms.

d) Weather modification research and operations should take account of the nearly one in three clouds whose first-echo temperatures suggest warm-rain processes at work.

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