Some Observations of Vertical Velocities and Precipitation Sizes in a Thunderstorm[1]

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ABSTRACT

Observations were made of a thunderstorm which formed over a vertically-pointing X-band pulsed-doppler radar set. They show details of the vertical velocity field in the storm and yield information about the growth of the precipitation particles. It is inferred that a downdraft starts early in the life of the cloud and is accompanied by precipitation particles which break up and evaporate under the cloud base.

1. Introduction

Many fundamental cloud physics problems have remained unsolved because of the lack of adequate measurements of vertical air speeds and particle sizes in clouds. During the past few years, meteorologists have begun employing doppler radar for the measurement of air motion and drop-size distribution in an effort to fill two of the large voids in atmospheric measurements.

A pulsed-doppler radar set similar in many important respects to the one used by Probert-Jones and Harper (1961) was designed and constructed at the University of Arizona. The radar set was designed to sense vertical velocities ranging from -20 to $+20$ m sec^{-1}. But the recording system employed during the early operations did not cover the entire range. Instead only 10 contiguous filters centered at intervals of 2 m sec^{1-} (except near zero) could be recorded at any one time. The echo strength in these 10 channels was recorded digitally. The 10-channel restriction introduces some problems in the analysis of the data in thunderstorms because the range of vertical velocities is often greater than the range of velocities covered by the 10 channels, for example -11 to $+3$ m sec^{-1} or -7 to $+7$ m sec^{-1} (see Fig. 1).

Because of this problem, a number of aspects of the analysis to be discussed are speculative in nature. A new recording system has been designed to increase the range of recorded doppler velocities. These data are not yet available. It seems to be in order to present the initial results in a short note to acquaint the meteorological community with the potentialities of pulsed-doppler radar equipment. Furthermore, this analysis sheds some light on the properties of air motions and particle sizes in one small thunderstorm.

The 3.25 cm pulsed-doppler set used in this study was designed and built in large part through the efforts of Theiss (1963). It generates $\frac{1}{4}$ μsec pulses with a peak power of 40 kw at a frequency of 4000 per second and has a symmetrical beam 1.3 deg wide. Further details have been reported by Theiss and Kassander (1963).

2. Observations of a thunderstorm

On 17 August 1962, a shower developed over the radar set at about 1942 MST. The calculated cloud base was 12,800 msl (10,000 ft above the radar set), a not unusual value for convective clouds in southeastern Arizona. The cloud base temperature was about 8C. (See the temperature scale on Fig. 3.) As will be shown, the maximum altitude reached by the radar echo in this cloud was about 24,000 ft msl.

The radar set measures V, back-scattered signal voltage, as a function of W_r, velocity of the scatterers relative to the radar, which, in the case of a vertically pointing beam, is also the vertical velocity relative to the ground. If the vertical velocity of the air were negligible, W_r would depend only on the terminal speed of the particles and hence the particle diameter (at any particular altitude). However, this is not the case in an active convective cloud where the updrafts and downdrafts can be of the same order of magnitude as the terminal velocities of the large hydrometeors.

Since the radar discriminates the droplets by values of W_r, the signals received in the velocity channel corresponding to the maximum upward velocity are associated with the droplets having the smallest terminal velocities. The characteristics of this radar set are such that one can reasonably expect it to detect water droplets of the order of 300 microns in diameter at the small radar ranges involved. The terminal velocities of droplets of this diameter are about 1 m sec^{-1}. If there is a broad spectrum of particles ranging from cloud droplets

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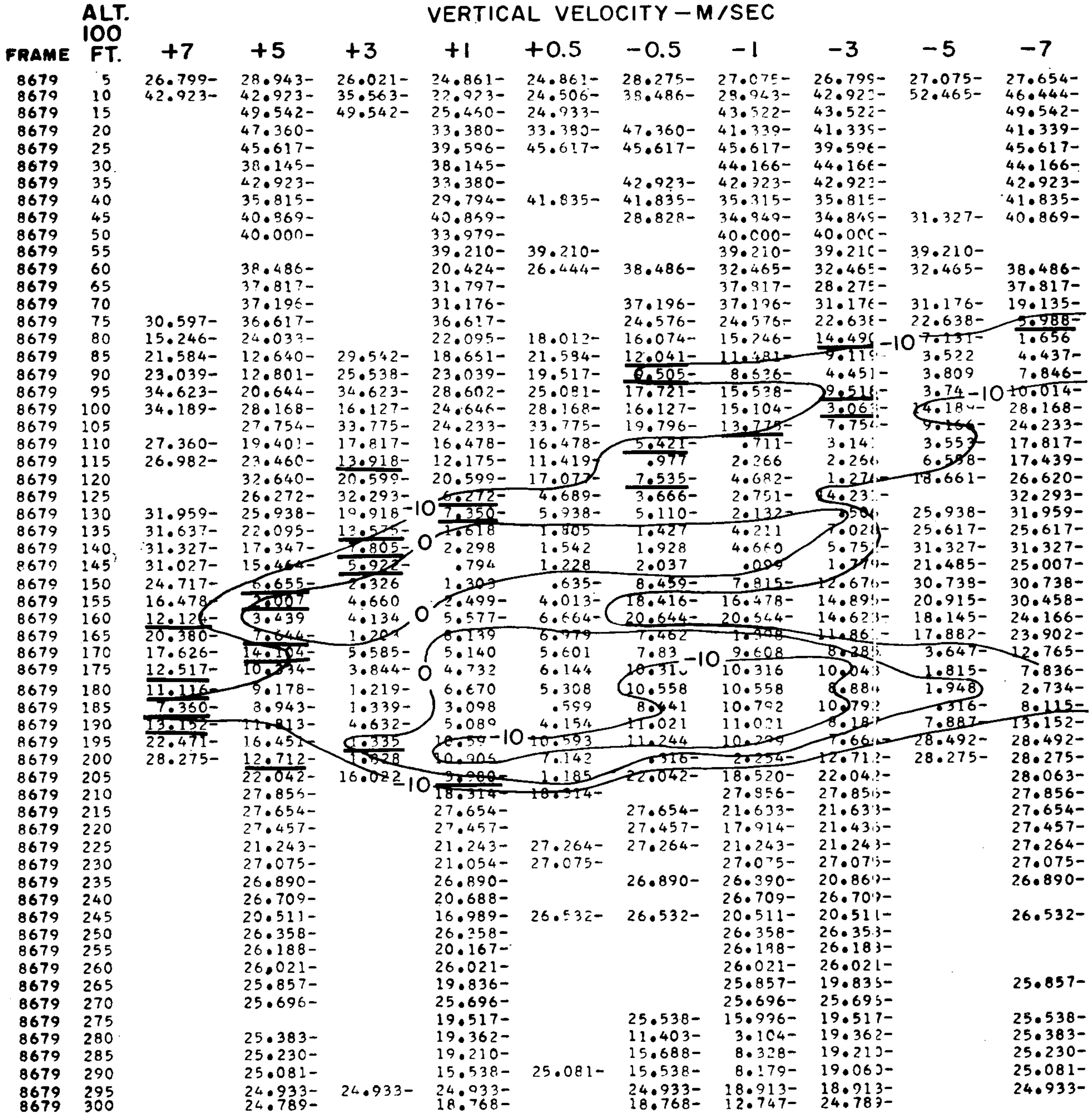

FRAME	ALT. 100 FT.	+7	+5	+3	+1	+0.5	−0.5	−1	−3	−5	−7
		VERTICAL VELOCITY—M/SEC									
8679	5	26.799-	28.943-	26.021-	24.861-	24.861-	28.275-	27.075-	26.799-	27.075-	27.654-
8679	10	42.923-	42.923-	35.563-	22.923-	24.506-	38.486-	28.943-	42.923-	52.465-	46.444-
8679	15		49.542-	49.542-	25.460-	24.933-		43.522-	43.522-		49.542-
8679	20		47.360-		33.380-	33.380-	47.360-	41.339-	41.339-		41.339-
8679	25		45.617-		39.596-	45.617-	45.617-	45.617-	39.596-		45.617-
8679	30		38.145-		38.145-			44.166-	44.166-		44.166-
8679	35		42.923-		33.380-		42.923-	42.923-	42.923-		42.923-
8679	40		35.815-		29.794-	41.835-	41.835-	35.315-	35.815-		41.835-
8679	45		40.869-		40.869-		28.828-	34.949-	34.849-	31.327-	40.869-
8679	50		40.000-		33.979-			40.000-	40.000-		
8679	55				39.210-	39.210-		39.210-	39.210-	39.210-	
8679	60		38.486-		20.424-	26.444-	38.486-	32.465-	32.465-	32.465-	38.486-
8679	65		37.817-		31.797-			37.817-	28.275-		37.817-
8679	70		37.196-		31.176-		37.196-	37.196-	31.176-	31.176-	19.135-
8679	75	30.597-	36.617-		36.617-		24.576-	24.576-	22.638-	22.638-	5.988-
8679	80	15.246-	24.033-		22.095-	18.012-	16.074-	15.246-	14.490	7.131-	1.656
8679	85	21.584-	12.640-	29.542-	18.651-	21.594-	12.041-	11.481-	9.119-	3.522	4.437-
8679	90	23.039-	12.801-	25.538-	23.039-	19.517-	6.505-	8.636-	4.451-	3.809	7.846-
8679	95	34.623-	20.644-	34.623-	28.602-	25.081-	17.721-	15.538-	9.518-	3.74	10.014-
8679	100	34.189-	28.168-	16.127-	24.646-	28.168-	16.127-	15.104-	3.063-	4.184-	28.168-
8679	105		27.754-	33.775-	24.233-	33.775-	19.796-	13.775-	7.754-	9.164-	24.233-
8679	110	27.360-	19.401-	17.817-	16.478-	16.478-	5.421-	.711-	3.141	3.553-	17.817-
8679	115	26.982-	23.460-	13.918-	12.175-	11.419-	.977	2.266	2.266	6.558-	17.439-
8679	120		32.640-	20.599-	20.599-	17.077-	7.535-	4.682-	1.274-	18.661-	26.620-
8679	125		26.272-	32.293-	6.272-	4.689-	3.666-	2.751-	4.231-		32.293-
8679	130	31.959-	25.938-	19.918	7.350-	5.938-	5.110-	2.132-	.504	25.938-	31.959-
8679	135	31.637-	22.095-	13.575-	1.618	1.805	1.427	4.211	7.028-	25.617-	25.617-
8679	140	31.327-	17.347-	7.805-	2.298	1.542	1.928	4.660	5.751-	31.327-	31.327-
8679	145	31.027-	15.464-	5.922-	.794	1.228	2.037	.099	1.770-	21.485-	25.007-
8679	150	24.717-	6.655-	2.326	1.303	.635-	8.459-	7.815-	12.676-	30.738-	30.738-
8679	155	16.478-	2.007	4.660	2.499-	4.013-	18.416-	16.478-	14.895-	20.915-	30.458-
8679	160	12.124-	3.439	4.134	5.577-	6.664-	20.644-	20.544-	14.623-	18.145-	24.166-
8679	165	20.380-	7.644-	1.204	6.139	6.979	7.462	1.398	11.861-	17.882-	23.902-
8679	170	17.626-	14.104-	5.585-	5.140	5.601	7.83	9.608	8.285	3.647-	12.765-
8679	175	12.517-	10.334-	3.844-	4.732	6.144	10.31	10.316	10.043	1.815-	7.836-
8679	180	11.116-	9.178-	1.219-	6.670	5.308	10.558	10.558	8.884	1.948	2.734-
8679	185	7.360-	8.943-	1.339-	3.098	.599	8.441	10.792	10.792	.316-	8.115-
8679	190	13.152-	11.813-	4.632-	5.089	4.154	11.021	11.021	8.187	7.887-	13.152-
8679	195	22.471-	16.451-	1.335	10.59	10.593	11.244	10.299	7.664-	28.492-	28.492-
8679	200	28.275-	12.712-	1.828	10.905	7.142	.316-	2.254-	12.712-	28.275-	28.275-
8679	205		22.042-	16.022	9.980-	1.185	22.042-	18.520-	22.042-		28.063-
8679	210		27.856-		18.314-	18.314-		27.856-	27.856-		27.856-
8679	215		27.654-		27.654-		27.654-	21.633-	21.633-		27.654-
8679	220		27.457-		27.457-		27.457-	17.914-	21.436-		27.457-
8679	225		21.243-		21.243-	27.264-	27.264-	21.243-	21.243-		27.264-
8679	230		27.075-		21.054-	27.075-		27.075-	27.075-		27.075-
8679	235		26.890-		26.890-		26.890-	26.390-	20.869-		26.890-
8679	240		26.709-		20.688-			26.709-	26.709-		
8679	245		20.511-		16.989-	26.532-	26.532-	20.511-	20.511-		26.532-
8679	250		26.358-		26.358-			26.358-	26.353-		
8679	255		26.188-		20.167-			26.188-	26.183-		
8679	260		26.021-		26.021-			26.021-	26.021-		
8679	265		25.857-		19.836-			25.857-	19.835-		25.857-
8679	270		25.696-		25.696-			25.696-	25.695-		
8679	275				19.517-		25.538-	15.996-	19.517-		25.538-
8679	280		25.383-		19.362-		11.403-	3.104-	19.362-		25.383-
8679	285		25.230-		19.210-		15.688-	8.328-	19.210-		25.230-
8679	290		25.081-		15.538-	25.081-	15.538-	8.179-	19.060-		25.081-
8679	295		24.933-	24.933-	24.933-		24.933-	18.913-	18.913-		24.933-
8679	300		24.789-		18.768-		18.768-	12.747-	24.789-		

FIG. 1. Tabulation of range-normalized radar echo intensity as a function of height and doppler velocity channel in decibels relative to an arbitrary power level.

to precipitation particles exceeding a millimeter in diameter, the lowest value of W_r is a measure of W_a, the air velocity, within an accuracy of about a meter per second. If the slowest falling particles are snow particles, the estimated terminal velocity of 1 m sec^{-1} is still appropriate. This scheme of obtaining a measure of the air motion was first proposed by Probert-Jones and Harper (1961). The technique is satisfactory providing the spectrum of particle sizes is such that the smallest detectable ones have fall velocities of the order of 1 m sec^{-1} or less. In certain rain showers, where large drops have been sorted out by wind shear effects, this may not be true.

An example of the type of record used to obtain the vertical profile of vertical velocity is shown in Fig. 1. It can be seen that the recorded signals go "off-scale" at both sides of the chart. Calculations were made of the normalized signal power in decibels relative to an arbitrary unit (full-scale deflection at 5250 ft). A signal of −15 db was just above the noise level, and this has been taken as the threshold of detection. The selection of −15 db was also somewhat arbitrary. An examination of the records shows this value is probably within 2 or 3 db of the actual threshold. With the new recording system, it should be possible to determine the threshold of detection with greater certainty. The underlined values show the signals corresponding to the channel having the smallest downward velocities.

From data such as those illustrated in Fig. 1, obtained at intervals of about 1.5 min, it was possible to derive the pattern of vertical motion (Fig. 2). In the light of earlier discussion, a more correct value of vertical speeds would be obtained if $+1$ m sec^{-1} were added, particularly in regions where the velocities are greater than 1 or 2 m sec^{-1}.

It seems reasonable to suppose that, in the cloud itself, there is a broad spectrum of particle sizes, so that the assumptions used to infer air velocity are valid. It is possible that, below the cloud base, the smaller rain drops evaporated while the larger drops fell faster and were sorted out.

Let us assume initially that there were sufficient drops with diameters smaller than about 300 μ so that the velocities of the slowest falling detectable particles represent the air velocity. In this event, the heavy lines in Fig. 2 represent updrafts (the solid lines) and downdrafts (the dashed lines). When the first echo appeared, the drafts were upward but weak. As the cloud developed, updraft speeds increased to a maximum of more than 7 m sec^{-1}. Within 3 min after the initial echo, a downdraft appeared in the lower part of the cloud. As the updraft strengthened, so did the downdraft. It can be seen that the updraft was composed of a broad rising current of air with several maxima whose magnitudes increased with height. The validity of the indicated downdraft speeds at the leading edge of the rainfall streamer is subject to serious question. This point is discussed in more detail in the next section.

Also plotted on Fig. 2 in the form of dotted lines is the pattern of average returned power, $\bar{V}^2$, in decibels above an arbitrary level. The level was adjusted to make the values approximately decibels relative to a milliwatt. The average is taken over a time period of about 0.66 sec. At each level and time, a weighted average of the signals was obtained by weighting the signal power in each velocity channel by the width of the channel in meters per second. An analysis of A-scope presentation showing both the video and a test-set signal gave a similar pattern of echo intensity.

In the downdraft regions, two major tongues of precipitation can be seen. Even in such a short-lived shower as this one, precipitation was released from the cloud in several bursts rather than a single one. As the precipitation approached the ground, its rate, R, de-

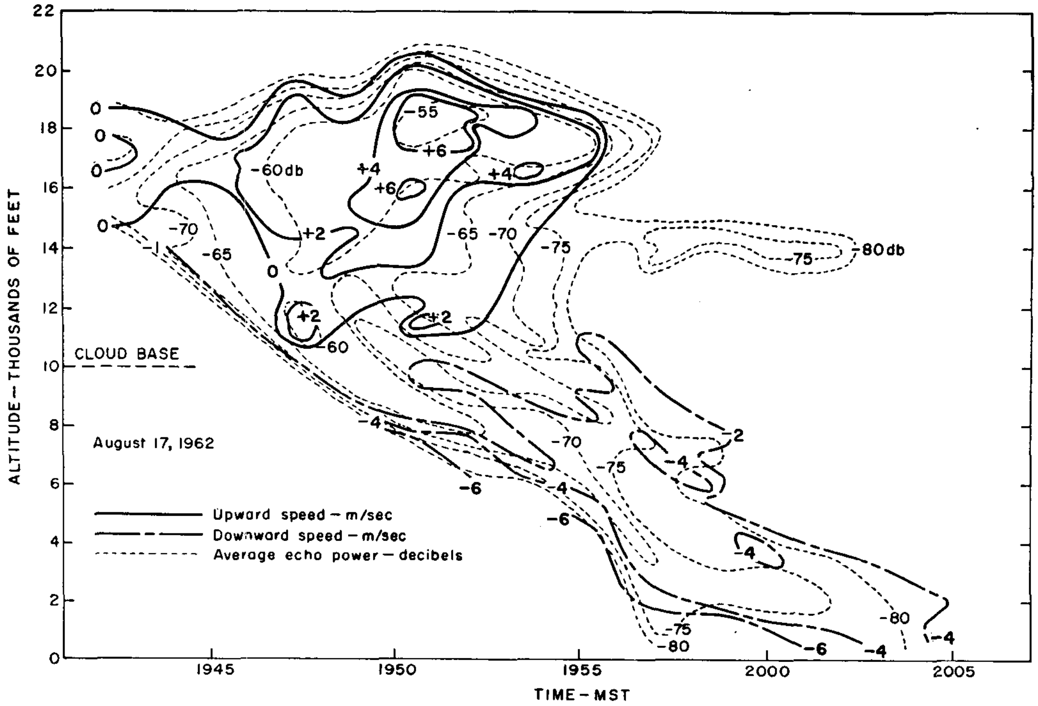

Fig. 2. Height-time cross section through a thunderstorm. The heavy, solid lines represent updrafts, the heavy, dashed-dot lines represent downdrafts. Lines are labeled in meters per second. The light, dotted lines represent average echo intensity in decibels relative to an arbitrary power level.

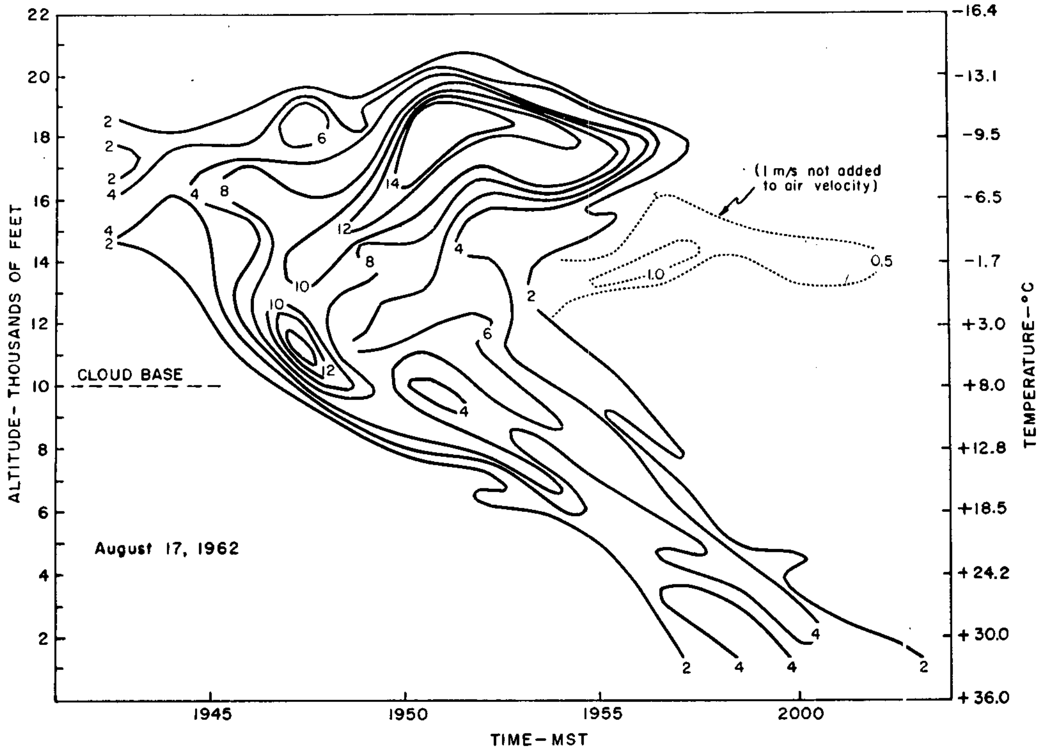

FIG. 3. Height-time cross section showing the inferred terminal velocities of the particles with the largest velocities. They are taken to be the largest particles at the indicated times and altitudes. In obtaining this diagram, 1 m sec^{-1} was first added to the vertical air speeds shown in Fig. 2.

creased markedly. For example, in the center of the first tongue of precipitation, the back-scattered power decreased from about -62 db at 1949 MST at the cloud base to -75 db at 1000 ft at 1957 MST. Assuming that at both altitudes $P_r = C\,R^{1.4}$, it is found that a 13 db decrease corresponds to a reduction of the rainfall intensity, R, by a factor of 0.12. It is likely that the relationships between P_r and R may not be exactly 1.4, but it seems reasonable to expect it to be between about 1.3 and 1.6 (Marshall and Gordon, 1957). Although C may also vary, it is not likely to change by more than a factor of 2 or 3. This calculation merely shows a substantial decrease in rainfall rate. An important factor must have been evaporation, particularly of the smaller water drops. The 1600 MST radiosonde observation showed that relative humidities decreased from 52 per cent near the cloud base to about 20 per cent near the ground where the temperature was about 88F.

The sequence of precipitation at the ground was the following. At 1957 MST, a few "large" drops were observed. By 1958 MST, there was light rain with only "small" drops. At 2002 MST, the light rain was still falling, and the upper part of the cloud could be seen. By 2006 MST, the rain had stopped, and the sky was clear overhead. A recording rain gage about 20 m from the radar set showed only a trace of precipitation (i.e., less than 0.01 inches).

By 1958 MST, about 15 min after the initial echo, what appears to be a well-formed bright band is evident. According to the 1600 MST sounding, the 0C level was located at 13,400 ft above the radar set. However, the top of the band is at about 14,500 ft. The discrepancies in altitude may be an indication that the atmosphere over the radar set was somewhat warmer than was measured by the radiosonde.

Maximum particle sizes. As shown in Fig. 1, at any one altitude, there was often a range of particle velocities. The signals corresponding to the maximum negative velocities, W_n, must have been associated with the largest particles. Since the vertical velocity of the air, W_a, has already been estimated, the terminal velocities of the largest particles can be inferred from $W_n - W_a$. This quantity was derived for each altitude and time, plotted, and the pattern shown in Fig. 3 was obtained. It should be noted that, because of the limitation on the range of velocity recording, the maximum terminal velocities could have been greater than the indicated maxima.

The validity of this analysis depends on the validity of the inferred vertical velocities of the air. This, in turn, depends on the existence of a sufficient number of particles with terminal velocity less than about 1 m sec^{-1}. Above the cloud base, it seems safe to assume that this was the case. At greater and greater distance below the cloud base, particle sorting makes it less likely that this was true, particularly at the lower edge of the rain shaft. An examination of the range of doppler velocities shows that, in the lowest 500 to 1500 ft of the rain shaft, the range of velocities was small; velocities extended from -5 to -7 m sec^{-1}. Since -7 m sec^{-1} represented the lower limit of measurement, the range of velocities may have been larger. However, lacking further measurements, it must be inferred that, at the lower edge of the rain shaft, there was a narrow range of drop sizes. It is not possible to specify to what extent the observed velocities are a measure of downdraft speeds or terminal velocities. Furthermore, it is also not possible to estimate the diameters of the particles involved.

Gunn and Kinzer (1949) published accurate measurements of the terminal velocities of water drops. Their observations were made at a pressure of 1013 mb, a temperature of 20C, and a relative humidity of 50 per cent. The deformation of drops from sphericity leading to an increase of the drag coefficient is likely to vary with altitude and, therefore, one cannot calculate precisely the terminal velocities of water particles as a function of altitude. It is necessary to make some reasonable estimates.

Following the procedure proposed by McDonald (1960), calculations were made of the terminal velocities of hypothetical, rigid water spheres at four pressure levels, 1013, 700, 500 and 400 mb. For various drop diameters between 0.2 and 6.0 mm, the ratios of velocities at the 700-mb to 1013-mb level were computed. They were employed to adjust the original Gunn and Kinzer data to 700 mb. The same procedure was applied to the 500- and 400-mb levels. The results of the calculations are shown in Fig. 4. It is essential that further studies be made of drop deformations and terminal velocities as a function of pressure and temperature in order to check these values.

By employing the appropriate curve on Fig. 4, one can estimate the sizes of water drops corresponding to the terminal velocities shown in Fig. 3. Early in the life of the echo, the largest particles, if they were water drops, were less than about 1 mm in diameter. They grew rapidly in both the downdraft and the updraft. At 1948 MST, at about 11,000 ft, a small region of large particles was observed. In order to have terminal velocities of 15 m sec^{-1} or more, the particles could not have been water drops. If they were "mushy" graupel with a density of 0.9 g cm^{-3}, the diameters corresponding to 15 m sec^{-1} would have been about 6.4 mm. After these particles fell out of the cloud, they apparently continued melting and broke up. It can be seen from the terminal velocities that at lower elevations near the middle of the rain shaft small drops predominated.

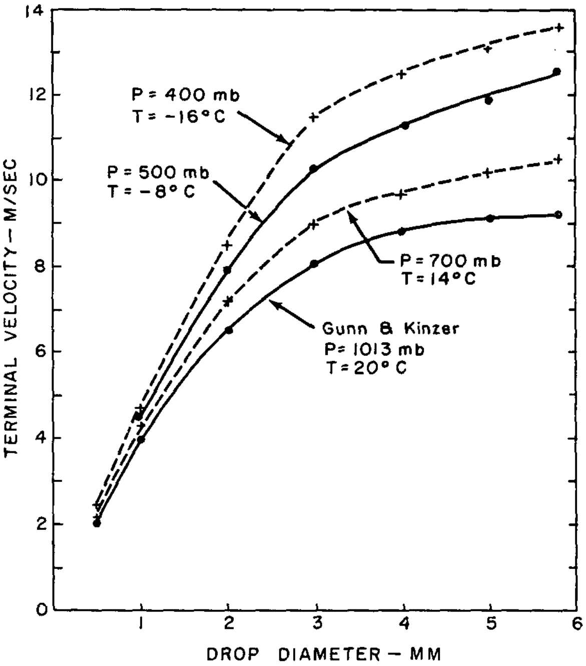

Fig. 4. Terminal velocities of water drops of various sizes as a function of pressure and temperature. The Gunn-Kinzer curve is based on measurements. The other curves are calculated.

Large particles were found in the updraft at the time that it reached maximum speed. From the curves of Fig. 4, it appears that these particles could not have been water drops. It is likely that the 15 m sec^{-1} velocities were associated with snow pellets or small hail. Assuming that they were spherical, the diameters were calculated to be either 4.8 mm or 8.7 mm, depending on whether the density of the ice was taken to be 0.9 or 0.5 g cm^{-3}, respectively. Flight observations made in the subfreezing part of precipitating convective clouds in southeastern Arizona have often revealed snow pellets with diameters of 5 to 7 mm.

Lightning and thunder. At 1955 MST, lightning was seen overhead and thunder was heard. No other lightning occurred. The observed sequence of events, rainfall just preceded by lightning, is common. The observations of this thunderstorm should firmly put to rest the old idea that the reason for the frequent occurrence of rain just following lightning is that electrostatic forces hold up the drops until the field is discharged. This idea already has been rejected on theoretical grounds. It can be seen from Fig. 2 that the precipitation particles were on their way towards the ground some 10 min before the lightning occurred.

If our previous inferences about size and composition of particles is correct, conditions were ripe for thunderstorm electrification by a mechanism involving ice pellets such as the ones proposed by Reynolds *et al.* (1957) and Latham and Mason (1961). The presence of ice pellets 0.5 to 1.0 cm in diameter at the 18,000-ft level where temperatures were about -10C would allow the rapid charge separation.

On the other hand, the occurrence of the lightning in the terminal part of the updraft history still makes it possible that the charging process occurred by an ionic process such as the one proposed by Vonnegut[1]. Further analysis of this and other thunderstorms may help to clarify the relative importance of air motion and precipitation to thunderstorm electrification.

3. Concluding remarks

This analysis has involved a number of assumptions and speculations. One of the possible difficulties which has not been mentioned earlier has to do with the interpretation of the measurements as time variations rather than space variations. The rawinsonde observations taken at 1600 MST showed that in the cloud layer, the winds were from the southeast at 5 to 12 knots. In the layer below the cloud, the winds were from the northwest at 4 to 12 knots. Thus there were only small components of wind across the northwest-southeast plane in which the cloud would be expected to move. If the cloud were an equal mixture of air from below the cloud layer and the air in the cloud layer, the average cloud velocity would be close to zero during the 15 min of interest. On this basis, one is led to conclude that the cloud movement was small. This leads to the assumption, implicit in the entire analysis, that the observed variations are mostly a function of time. On the other hand, there is one aspect of the analysis indicating some movement of the cloud relative to the radar set.

By comparing Figs. 2 and 3, it is seen that the larger particles in the upper part of the cloud were falling relative to the ground at a speed of about 7 m sec^{-1}. In order to explain their presence at the higher altitude, it appears to be necessary to assume that they were carried upwards in a region of still higher updraft speeds and then fell into the vertical plane observed by the radar set.

This analysis represents the beginning of a program aimed at studying the pattern of vertical motions and precipitation growth in clouds. The original recording system which permitted only 10 velocity-channel recording restricted the range of velocities observed at any one altitude. A new recording system has been developed. It involves the use of magnetic tape and should allow the study of the entire range of upward and downward velocities at velocity intervals of 1 m sec^{-1}. With these new observations, it is hoped that it will be possible to calculate rain drop spectra as a function of altitude and time.

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