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MIDWESTERN CONVECTIVE CLOUDS; A REVIEW

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ABSTRACT. Studies of midwestern convective clouds and precipitation spanning some 40 years have contributed information addressing many aspects of weather modification experimentation and operation. In this paper we have focussed on the studies which provide insight into the microphysical and dynamical characteristics of these clouds, with a view toward assessing the state of our current knowledge and providing the information base needed for the development of physical hypotheses for natural and modified cloud behavior and for design of future experimentation.

1. INTRODUCTION

Convective clouds are the prime producers of warm season precipitation in the United States Midwest and thus have significance for the regional economy. A number of research studies of midwestern convection and convective precipitation have been carried out since the late 1940's with objectives varying from description of surface rainfall to identification and understanding of precipitation processes. Publications stemming from these studies have been reviewed with a view toward establishing an information base pertinent to the development of physical hypotheses for natural convection and precipitation processes in this region and for their beneficial modification.

1.1 The Information Source

Our review covered reports stemming from 11 projects and other assorted studies. They have contributed information of interest for all aspects of weather modification experimentation and operation and are reviewed in detail elsewhere (Ackerman and Westcott, 1985; Westcott, 1985). In this paper we have focussed on the findings from aircraft and radar observations of the physical and dynamical characteristics of convective clouds. These have come primarily from six projects.

The **Thunderstorm Project (TSP)** was a study of convective weather in Florida in 1946 and in Ohio in 1947 (Byers and Braham, 1949, hereafter referred to as B & B). The midwestern field program included several instrumented airplanes, radar, and a dense surface network of meteorological sensors.

The **Artificial Cloud Nucleation (ACN) Project** (Braham, et al., 1957), was directed toward developing an understanding of the physical processes governing the formation of convective precipitation with a view toward testing the possibility of the modification of rainfall. Instrumented aircraft, including airborne radar, were used to study cumulus clouds in Illinois and Missouri during the summer of 1954, unfortunately a year of severe drought. Some randomized cloud seeding with dry ice and large water drops was included.

Whitetop was a multi-year randomized seeding experiment with a strong effort in basic cloud physics research (Braham, 1966). Aircraft, radar, and rainfall measurements were made in central Missouri in the summers of 1961-65.

METROMEX had as its overall objective the study of the inadvertent modification of the weather by urbanization (Changnon, 1981). Extensive measurements were made in and around St. Louis, MO during the summers of 1971-75, using aircraft, radar and surface networks.

The **Illinois Precipitation Enhancement Project (PEP)**; was a comprehensive program in weather modification, which included a field project (Changnon, 1973). Aircraft measurements were obtained around the freezing level in convective clouds over the rural areas around St. Louis during the summer of 1973. Supplementary data were provided by METROMEX.

PACE (Precipitation Augmentation for Crops Experiment) is a long term, comprehensive weather modification program (Changnon and Ackerman, 1979). Data were collected primarily at temperature levels around -10 C, in convective clouds by instrumented aircraft, on several flights in the Midwest in 1978. A second series of high level data collection in 1980 occurred during a period of weather generally unfavorable for deep, convective clouds.

There was considerable variety in the particular objectives of these projects which was reflected in the data collected and in the way in which they were analyzed. In addition integration of the reported findings was often complicated by the way in which they were presented and by diversity in measurement technique. We have attempted here to summarize those findings which provide a physically consistent description of convective clouds in the Midwest.

1.2 The "Building Block" of Midwestern Convective Storms

Byers and Braham (1948) proposed a conceptual model of convective clouds composed of "cells", i.e., dynamic units defined by a vertical velocity field that evolved with time. This generalized model has been confirmed in many subsequent studies. Moreover it has been found that the semi-organized cloud systems which produce most of the rain during the summer develop as these multicellular clouds merge into lines or clusters.

The dynamic forces which cause these larger systems to develop are complex and very poorly understood. However it is generally accepted that modification of precipitation at the current level of technology can come about only through manipulating the physical processes of the smaller elements in the hierarchy of convective clouds. Thus the discussion below focusses on the morphology of individual cells and multicellular clouds.

2. CLOUD BASE PROPERTIES

Most convective clouds have their "roots" in the atmospheric boundary layer, the lowest 1 to 2 km, or feed on the air from this layer. Thus the properties at cloud base, where condensation first occurs, influence cloud development.

The temperature at cloud base determines the maximum realizable amount of moisture in a rising thermal. and also the distance the condensate will travel as liquid before freezing can occur. In the Middle West warm season cloud bases can vary from about +2 to +24°C but are usually between 16 and 22°C (Johnson, 1982a). Temperatures at the bases of deep convective clouds during PEP ranged from 15.3 to 21.8°C, but were above 19.5°C on half the days (Ackerman et al., 1979).

Below-base updrafts are most easily detected when the clouds are active congestus or thunderstorms. Inflow areas tended to be of small diameter and short duration except when the cloud complex was well organized. In a sample of 69 below-base updrafts measured on 13 days during METROMEX, the strongest was 7.1 ms^{-1} and half were greater than 2.5 ms^{-1} (Semonin, 1978). Consistent with theoretical expectation, in-cloud updraft velocities within a few hundred meters of the base measured during TSP were generally larger. The strongest draft was 9 ms^{-1}, with half the velocities greater than 4 ms^{-1} (B & B).

Daily average cloud-droplet concentrations within 600 meters of cloud base measured during METROMEX in clouds unaffected by the city, were between 350 and 550 cm^{-3} in cumulus congestus and between 280 and 666 cm^{-3} in small cumuli (Dytch, 1977). In individual small clouds (depths between 0.7 and 1.6 km), drop concentrations averaged from 280 to nearly 1000 cm^{-3}. Cloud droplet concentrations in small cumuli (depths of 1 km or less) during the ACN project tended to be lower, about 300 per cm^{3} (Battan and Reitan, 1957). This may be traceable to differences in measurement technique but also could reflect the influence of a particular weather regime.

The cloud droplet concentrations measured near cloud base during METROMEX are consistent with CCN concentrations in the same area, as measured with a technique which emphasizes small particles. However, Byers et al. (1957), also found large chloride particles (diameters greater than 10 µm) in concentrations of 10^{3} m^{-3} at about cloud base level when Gulf air was moving into the Midwest. Moreover Johnson (1976) found aerosol particles with diameters larger than 10 µm in concentrations of 7500 m^{-3} and of 200 m^{-3} for those larger than 30 µm. Both the chloride particles, which, because of their size and hygroscopicity can rapidly develop into large drops, and the giant particles found by Johnson, which serve effectively as "collectors" (Johnson, 1982b; Ochs and Semonin, 1979), can initiate the coalescence process early in cloud development.

3. DYNAMIC PROPERTIES

The vigor of a convective cloud can be estimated from the size and strength of its upward motions and from the acceleration arising from density differences. Both temperature (which provides an estimate of one component of the buoyancy acceleration) and vertical velocity were measured in most of the projects utilizing aircraft.

3.1. Updrafts

The velocities of updrafts measured at 5 levels during the TSP increased with height, but not monotonically (Fig. 1). The decrease in velocity between 4.5 km and 6 km and increase above is suggestive of re-invigoration, in some clouds, of the updraft due to the buoyancy acceleration caused by the latent heat release in freezing. However, given the decrease in sample size at 6 km, the break in monotonic increase in velocity expected from theory may merely be an artifact of sampling.

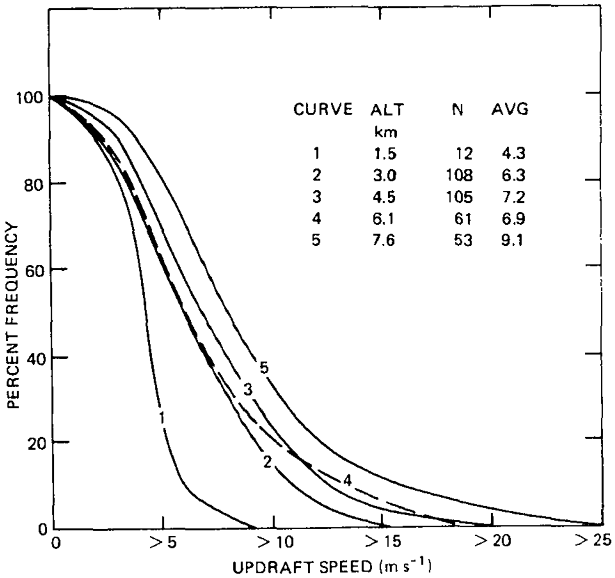

Figure 1. Cumulative frequency distributions of updraft speeds measured during the Thunderstorm Project. (From tabulations in Byers and Braham, 1949.)

The average velocities in updrafts at 6 km measured during PACE. (Johnson, 1980) agree with those found during the Thunderstorm Project at this level (Fig. 2a), for similar clouds. However updraft velocities measured at about 4.5-5 km during PEP (Ackerman et al., 1979) were generally less than those given in B & B for this altitude (Fig. 2b). Although disparity in measurement technique may be the cause, different parts of the cloud population may have been sampled in the two projects, since the PEP penetrations were near the tops of growing clouds, whereas many of the TSP updrafts at 4.5 km were deep within larger clouds.

The dimensions of updrafts are estimated only crudely from traverse distance. They varied between 2 and 2.5 km with no consistent trend with height in the Thunderstorm data. They were narrower in PACE (average about 1.1 km), probably

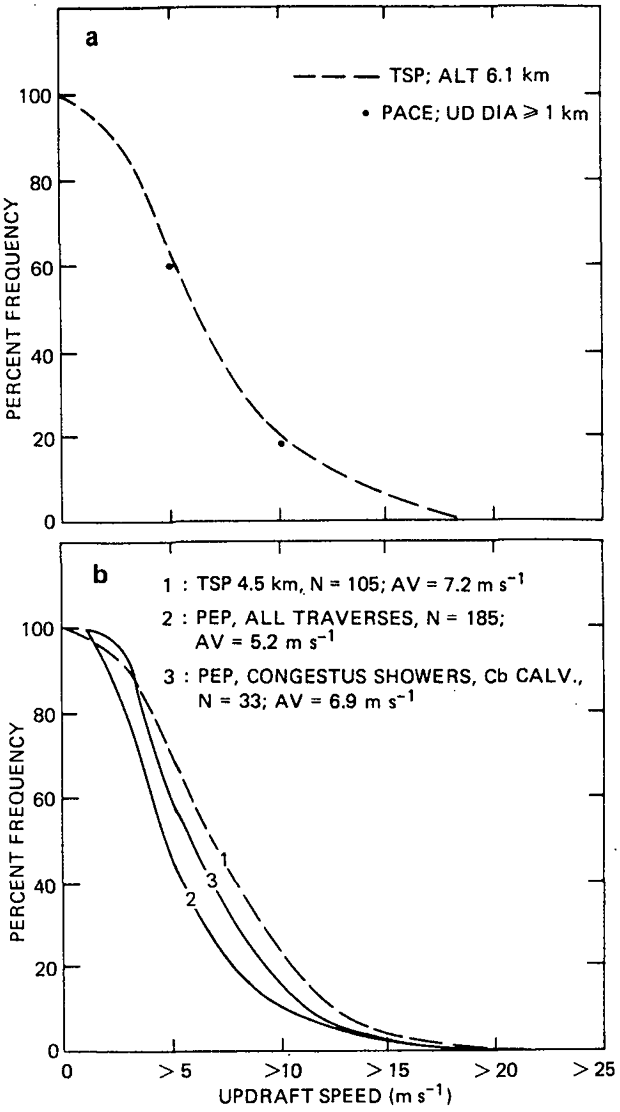

Figure 2. Cumulative frequency distributions of updraft speeds (a) at approximately -8 to -10^{o}C, and (b) around the freezing level. (From tabulations in Byers and Braham, 1949; Johnson, 1980; and Ackerman <u>*et al.*</u>*, 1979.)*

because higher spatial resolution available in the measurement permitted the breakdown of broad areas of upward motion into segments. The average dimensions of the cloud cells traversed at 4.5 km during PEP was about 2 km. This is an upper limit for updraft width since in some cases the updraft did not extend through the whole cell. In both PACE and PEP, peak updraft velocities tended to be larger in the larger updrafts (cells).

3.2 <u>Ascent Rate of Radar Echoes</u>

The top of a radar echo changes height due to morphological changes in the cloud particles as well as by advection of those particles. However the ascent rate does provide an indicator of cloud vigor. Moreover B & B reported relatively good correspondence between the daily means and maxima of updraft speeds measured by aircraft at 6 and 7.5 km and of the ascent rates of radar echoes passing through these levels, with the latter 1 to 2 m s^{-1} smaller. However only 38 to 68% of the echoes analyzed grew after detection, the percentage varying between studies (Battan, 1953; Braham, 1963, 1964; Braham and Dungey, 1978; Changnon, 1976). The largest percentage was for a sample of echoes with initial depth of less than 1 km.

B & B indicate a positive relationship between average echo ascent rate and the height of the echo top. Average ascent rates were 5.5 m s^{-1} for tops at 4.5-7.5 km, 6.5 m s^{-1} at 7.5-10.5 km, and 7.4 m s^{-1} at 10.5-16 km. This trend was indirectly confirmed by Battan (1953) who found average ascent rates of 3.8 m s^{-1} for echoes which grew a total of 1.5 to 3 km and 4.5 m s^{-1}, for those which grew more than 3 km. The latter tended to be the warmest when first detected. Battan's sample, with peak echo tops at 6 to 9 km, came primarily from the smaller clouds in the TSP data.

It should be noted that the ascent rate of the echo is not necessarily that of the visual cloud. Changnon and Bigler (1957) reported average rates of 5.1 and 3.8 m s^{-1}, for echo and cloud tops, resp., for a small sample of four clouds. They also found that echo tops started to descend while clouds were still growing.

3.3 <u>Thermal Buoyancy</u>

The thermal buoyancy, which is a major component of the acceleration to which the updraft is subject, is given by the deviation (ΔT) of the in-cloud virtual temperature (T_c), a measure of air density, from the mean virtual temperature (T_e) in the surroundings.

Thermal buoyancy was positive at all levels over some part of the updrafts penetrated by TSP aircraft during the building and early mature stages of the thunderstorm cell, with 4 C the largest value reported (Table 1). Average values of maximum buoyancy (peak T_c-T_e), exceeded 1 C for both the ACN (unpublished) and PEP (Ackerman <u>et al</u>, 1979) traverses. About 11% of the <u>cells</u> on PEP penetrations were more dense than the surrounding environment throughout but not all contained updrafts. B & B also reported some instances in the later stages of the cell life cycle when updraft areas were entirely colder than the environment. A positive correlation (coefficient of 0.7) was found between thermal buoyancy and updraft velocity in the PEP data and both tended to increase with increasing cell size and deeper clouds.

Table 1. Average values, and ranges of maximum buoyancy, ΔT_x, (maximum T_c - mean T_e).

Project	$\overline{T}_e$ (^{o}C)	Aver.	Range	N	N (ΔT_x<0)
TSP(Updr.)	+17	+0.9	---	1	0
	+8	+0.8	0.1-1.7	4	0
	0	+1.9	0.3-3.6	2	0
	-8	+2.1	0.3-4.0	10	0
ACN(Trav.)	0	+1.2	0.2-2.9	20	0
PEP(Trav.)	0	+1.4	-0.5-5.1	140	5
PEP(Cells)	0	+1.1	-1.0-5.1	276	31

4. **CLOUD CONDENSATE**

Cloud condensate has been measured in midwestern clouds by both bulk means (i.e., those that provide only the amount) and by detailed microphysical means (i.e., those that provide detailed information of the size, concentration and/or phase of the condensed vapor). Although the latter is generally preferred, measurements by bulk methods have been more plentiful and have provided crucial information about cloud processes.

4.1 Liquid Water Contents

The reported liquid water contents fall into two categories, usually dictated by the project instrumentation.

1. Cloud water content (CW), the amount contained primarily in drops with diameters less than 50-70 microns, was measured using the Johnson-Williams liquid water content meter (JW) in both the PEP and PACE Projects.

2. Total liquid water content (TW) which includes all drop sizes, was measured during PEP using an evaporator and in the ACN Project using a conductive paper tape.

The measured water content is frequently compared to the adiabatic water content(AWC), i.e., the amount of vapor condensed in an undiluted parcel ascending from cloud base to the altitude at which the measurement was made, assuming a purely adiabatic process. In the discussion below, reference is made both to AWC and to a cloud water content of 1 g m^{-3} which is a criterion used in making the seeding decision during FACE.

The cloud water content at -8 to -10 C (PACE) was generally lower than that recorded in PEP around the freezing level (Fig. 3). However the CW exceeded 1 g m^{-3} frequently at both levels, not only in cells and updrafts, but on cloud penetrations as well (80% in PEP and 75% in PACE). At both levels, the probability of the cloud water content exceeding 1 g m^{-3} increased with the width of the cell or updraft (Table 2).

The CW never exceeded the adiabatic water content on the PEP penetrations but the TW reached values greater than the AWC in about half the cloud cells (Ackerman et al., 1979). During the ACN Project, peak TW equalled or exceeded the AWC on one third of the penetrations, (Figure 4; Draginis, 1958). In every case when this was true, the penetration was through a cloud which contained, or subsequently developed, a radar echo. In the remaining cases, only one cloud developed an echo before dissipating. For the non-echo clouds in Draginis' sample, the ratio TW/AWC decreased with height, as has been found elsewhere.

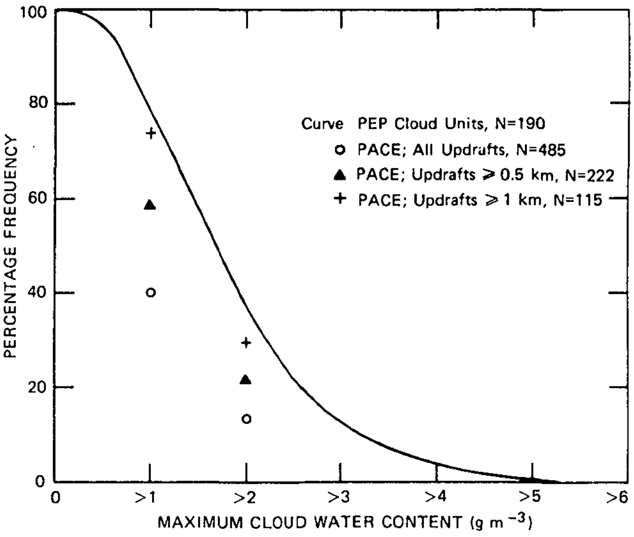

Figure 3. Cumulative frequency distribution of peak cloud water content measured during PEP and PACE. (From tabulations in Ackerman et al., 1979 and Johnson, 1980.)

Table 2. Peak cloud water content (CWX) as a function of updraft width (PACE) or cell size (PEP). N gives total sample size.

Size (km)	N	CWX (g m^{-3}) ≤ 1	1-2	> 2
		a. PACE Updrafts		
<0.5	263	80%	15%	5%
0.5-1	107	58%	29%	13%
>1	115	26%	44%	30%
		b. PEP Cells		
<1.5	153	34%	41%	26%
1.5-3	96	23%	30%	47%
>3	37	11%	24%	65%

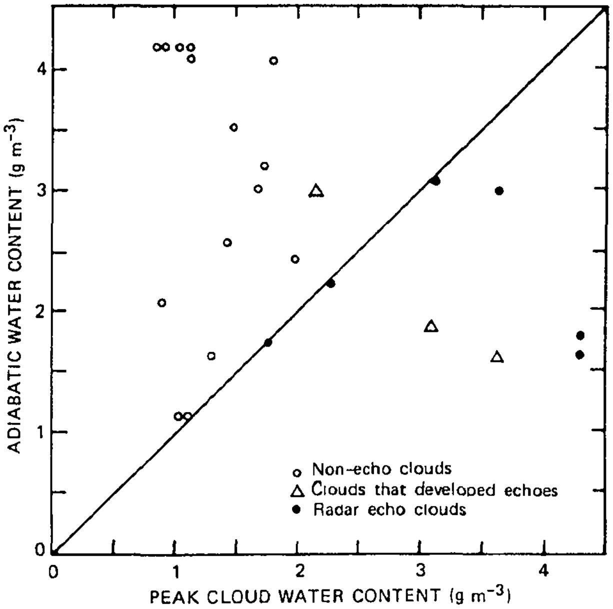

Figure 4. Peak liquid water content measured on a traverse plotted as a fraction of the adiabatic water content. (From Draginis, 1958.)

In both the ACN and the PEP data the peak TW exceeded 1 g m^{-3} on most of penetrations, and often reached several grams/meter^3. In PEP the TW exceeded the FACE criterion over more than half the cloud traverse 95% of the time and was greater than 2 g m^{-3} over this distance 85% of the time. However the CW exceeded 1 g m^{-3} over more than half the cloud traverse only 35% of the time (Fig. 5). In PACE, the CW exceeded 1 g m^{-3} over more than half the length in 45% of the updrafts longer than 0.5 km.

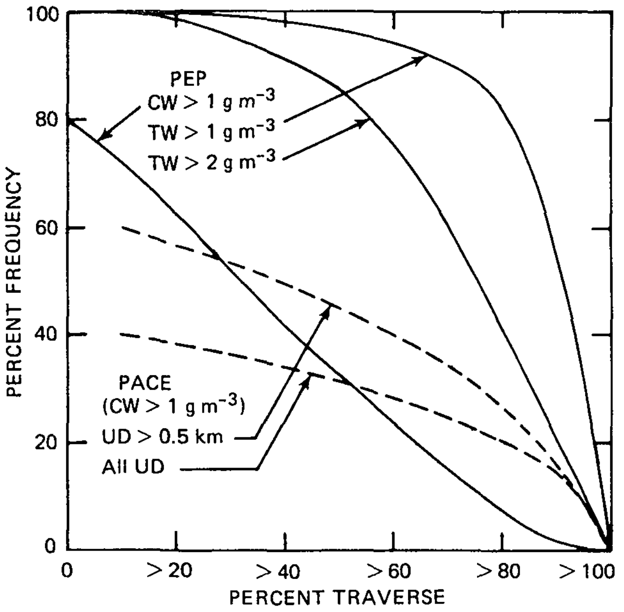

Figure 5. Cumulative frequency of cloud traverses (PEP) or updrafts (PACE) on which cloud and total liquid water content exceeded 1 or 2 g m^{-3} over indicated percentage of the penetration distance. (After Ackerman et al., 1979 and Johnson, 1980.)

There is strong evidence from these projects, that the liquid water content is very frequently greater than the 1 g m^{-3} criterion in midwestern convective clouds. However the PEP measurements also indicate that the cloud water content represents only a fraction of the condensate around the freezing level. The cloud water fraction, CW/TW, (ratio of the average CW to average TW) was less than 0.25 in half the cloud cells, and less than 0.5 in 94% of the cells. Moreover, the findings from PACE and PEP suggest that the cloud water content decreases with height above the freezing level.

5. MICROPHYSICAL MEASUREMENTS

Measurements of the detailed microphysics in midwestern clouds have been fragmentary. They generally have been limited to a particular size range.

Cloud droplet concentrations measured 1.6 to 2.1 km above the bases of small cumulus congestus varied cloud-to-cloud, and day-to-day, during METROMEX (Dytch, 1977). Daily averages were between 355 and 549 cm^{-3}. The cloud droplet concentrations reported by Battan and Reitan (1957) in small cumulus congestus (measurement level unknown) were somewhat less; 250 cm^{-3} for clouds that did not develop echoes and 188 cm^{-3} for those that did.

On the basis of data from 133 traverses through 58 deep cumulus congestus and small cumulonimbus during Whitetop, Brown and Braham (1963) concluded that nearly every cloud of this type contains large particles (d > 250 μm) in the upper levels at some point in their evolution. Over 40% of their sample developed large particle concentrations of at least 100 m^{-3} and 20% developed concentrations of 1000 m^{-3} or more. There was also significant horizontal variability in concentration, particularly for very large particles.

Koenig (1962, 1963), examined the Whitetop data from 226 traverses at 0 to -4 C through 84 clouds with summits between 4.6 and 6 km. He detected no precipitation-size particles on 42% of the initial penetrations (32% of the clouds). Liquid precipitation-size drops were found in most of the 57 remaining clouds and 60% of these (34 clouds) contained solid hydrometeors at some time and place during their lifetime. In over half of the latter, ice developed subsequent to traverses on which only liquid precipitation particles were observed, and 30% contained mixed-phase hydrometeors on the first penetration. From 7 case studies, and the large sample statistics, Koenig deduced that rapid glaciation was characteristic of relatively small cumulus congestus and small Cb Calvus clouds in the Midwest, with liquid to solid phase transition spreading through the cloud volume within 10 or 15 minutes. When large concentrations of ice developed in a comparatively short time, it was preceded by precipitation-size liquid drops (diameters up to 1 mm) in concentrations of 50 m^{-3}. Moreover he found that in mixed phase volumes of small cumulonimbi, the largest liquid and solid hydrometeors were similar in size, suggesting that the solid phase built on the size structure achieved by the liquid phase prior to glaciation. In addition Koenig found evidence of secondary-ice production which he proposed was a by-product of the freezing of water drops.

Many of Koenig's case-study clouds were small (though all extended above the freezing level) and developed rain showers before the ice phase was present at -4 C. In an eighth case study of a vigorous cloud which grew from 5.7 to 9 km in 10 minutes, Koenig (1962), found large numbers of supercooled water drops in the interior of the cloud throughout its active life while small, dry solid particles were found on the edges. When the cloud started to decay, the mixed phase spread to the interior.

The PACE microphysical observations, obtained with the PMS probes, (Johnson, 1980) lend support to the general pattern deduced by Koenig although they were from larger and more vigorous cloud systems and at slightly colder temperature. The presence of significant amounts of supercooled water inferred from "streamers" (associated with shedding of liquid water from the probe tips) was frequently noted. The onset of glaciation, usually as frozen drops or graupel, was most often found to occur in the later passes through a cloud, as the updraft began to weaken. On occasion, as the updraft died, a "shower" of millimeter-sized ice pellets in concentrations of over 1000 m^{-3} were detected with little or no evidence of supercooled liquid water.

The evolution of glaciation appeared to be different in convective elements embedded in stratiform layers which were observed on two PACE flights. Between active cells there were large numbers of millimeter-sized crystals and/or aggregates which appeared to mix into the convective cores growing up through the stratiform layers. In the convective cores, the crystals showed evidence of riming, eventually producing large pellets, with no serious depletion of the cloud liquid water content. Koenig (1962) found similar hydrometeors in embedded convection, with some of the cores containing no ice while they remained above the general layer. Solid hydrometeors were a mix of small pellets and flake-like solids which, Koenig hypothesized, were loose aggregates of rimed crystals.

6. PRECIPITATION INITIATION: RADAR FIRST ECHOES

The aircraft measurements indicate that precipitation may be initiated in Midwestern convective clouds by an all-water coalescence mechanism. This is supported by radar studies of first echoes (FE), i.e., initial detection of clouds by radar. In a landmark paper, Battan (1953) reported that the majority (56%) of FE's detected during TSP were at heights totally warmer than 0 C, a third straddled the freezing level, and only a few percent were totally colder than 0 C. Results from a number of subsequent studies have been in general agreement with these findings, although not necessarily in detail (Table 3).

Table 3. Location of first echo formation. (Taken from information in Battan, 1953; Braham, 1964; and Braham and Dungey, 1978). MMX (R) and MMX (S) refer to subsamples composed only of rural echoes (R) and only of FEs less than 1 km in depth (S).

a. Percent of First Echoes

Project	N	Totally Warm	Totally Cold	Straddles 0°C
TSP	112	56	11	33
WTP	2000[1]	50	10	40
MMX	4553	40	7	53
MMX (S)	486	69		

b. Average Temperatures

Project	N	Top °C	Base °C	Depth km
TSP	97	0.4	10.0	1.7
MMX	4553	-2.0	11.0	2.2
MMX (R)	3413	-2.3	10.8	2.2
MMX (S)	486	+2.0[2]	6.4	0.7

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[1] Sample size not given, estimated from other information.

[2] Value of -2°C in paper is believed to be an error in sign.

Temperatures at the tops of FEs detected in the TSP, Whitetop, and METROMEX averaged between 0.4 C and -2.3 C and those at the bases were between 10 and 11 C. However, the temperature range for both tops and bases were very large: 24 to 26 C in the Thunderstorm data (Battan,1953) and, in a very large sample, about 45 C in the METROMEX data (Braham and Dungey, 1978). This variability is due in part to the scan rate (time between observations), customarily around 3-4 minutes. In most cases, a cloud will still be developing and expanding when first reaching radar detectability, so top and base temperatures will depend in part on when during the scan interval the FE was observed. Battan's data had scan rates which varied between 15 sec and 3.25 min. His FEs tended to be warmer and shallower than the METROMEX FE which had scan rates of 3-4 min (Table 3). Braham and Dungey also found that the shallow FEs in their sample were totally warmer than 0 C more frequently than were the deeper ones.

However, there is also evidence that meteorological factors may be responsible for some of the variability in FE heights and temperatures. Changnon (1978) reported that FE bases and tops in organized storms in METROMEX were markedly higher, and thus colder, than those in isolated systems. Evidence of meso- and macro-scale influences is also found in day-to-day differences in FEs. Johnson and Dungey (1978) found that the daily average top heights of Whitetop and METROMEX FEs varied between 10,000 and 22,000 ft (3-6.7 km; Fig. 6). They also found that colder first echoes occurred on days with more echoes, which is most likely to occur with convective organization. Similarly the daily average temperatures of FE tops reported by Battan varied between -5.1 and +6.9 C, and of bases between +4 and +14.7 C (Fig. 7). The variations in the daily mean FE temperatures reflected shifts in the sample distributions and were not due to rare events. However days with the warmest first echoes had the narrowest distributions, with almost all of the FEs originating entirely below the freezing level.

Numerical simulations of warm cloud processes also have indicated that dynamic influences are important in determining the level at which

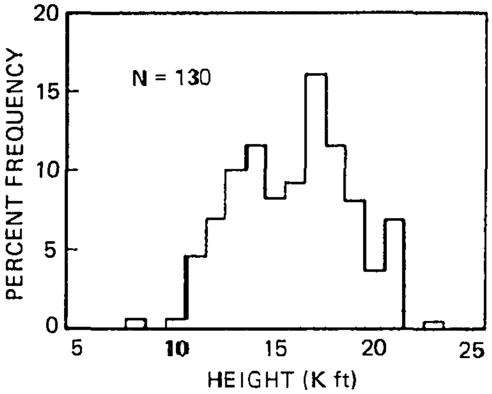

Figure 6. Frequency distribution of daily average echo top heights for days with more than 20 echoes during Whitetop and METROMEX. (Johnson and Dungey, 1978.)

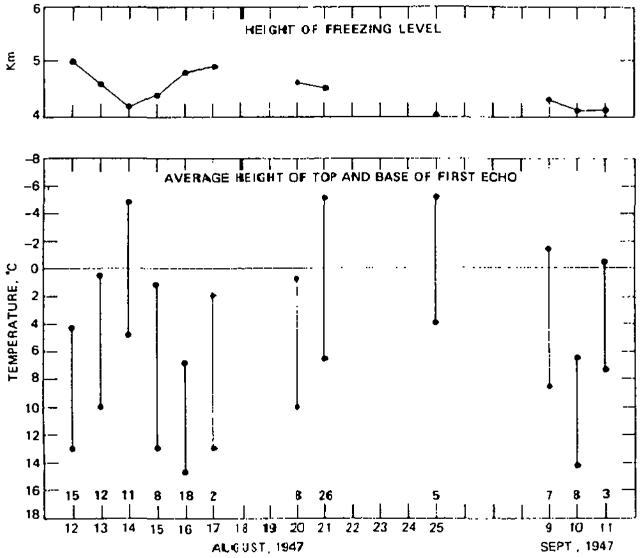

Figure 7. The daily average temperatures at the tops and bases of first echoes and the heights of the freezing level, for 12 summer days in Ohio. The daily sample size is given above the date. (Based on tabulations in Battan, 1953.)

precipitation-sized drops will first develop (Johnson and Dungey, 1978; Ochs and Semonin, 1979; Johnson, 1982b). These model results indicate that, with a stronger updraft, not only is the echo top height increased, but the bases also occur at greater heights, both because of the time required for development of precipitation sized drops through coalescence and because of a decrease in "sedimentation" of larger drops.

7. SUMMARY

Review and distillation of the findings from many studies of midwestern convective clouds have led to a physically consistent picture of some of the dominant features. These are summarized below. There remain many unknowns and many of the deduced characteristics need confirmation. Nevertheless we believe that, in most instances, there is sufficient evidence for the development of conceptual models and/or experimental designs based on these features.

Most of the significant rain in the Midwest comes from semi-organized lines or clusters of energetic, non-severe, convective clouds. These are composed of cells which undergo dynamic evolution from growth to dissipation in approximately 30 minutes. They grow in depth and breadth as new cells develop adjacent to, or join with, preceding ones. Individual clouds may last 1 to 2 hours or more as new cells develop and undergo their life cycles.

During the stages when there is visual evidence of active growth, well defined midwestern convective clouds have the following internal characteristics.

- Cloud bases usually are at altitudes of 1 to 2 km and temperatures usually between 16 and 22 C.
- Vigorous, buoyant, updrafts have dimensions generally between 1.5 and 4-5 km. Velocities average about 2 m s^{-1} at cloud base increasing with height to 9 m s^{-1} at 7.5 km. They may reach 15 to 20 m s^{-1} in some instances. Peak thermal buoyancy ranges up to 5 C with population average of 1 to 1.5 C. Updraft velocities and thermal buoyancy tend to be larger in more extensive updrafts.
- Cloud water content is close to adiabatic near cloud base but tends toward a decreasing fraction of this theoretical value with height as it is converted into larger drops and depleted by entrainment. At about 5 km it represents only a relatively small fraction of the total condensate (25% on average) which frequently exceeds adiabatic. At 5 to 6 km (0 to -10 C) the total water content usually (and cloud water frequently) exceeds the 1 g m^{-3} criterion used as a seeding criterion in Florida over significant fractions of the cloud diameter.
- Large chloride particles and non-hydrophobic aerosols are common at cloud base heights during weather favorable for deep convection. Cloud droplet concentrations are moderate, with daily averages of 300 to 600 cm^{-3}. Large cloud particles (incipient precipitation and drizzle drops) always occur in the upper reaches of deep cumulus congestus and cumulonimbus. Glaciation occurs, apparently as large water drops freeze into graupel particles, at temperatures of -5 to -10 C within 10 to 15 minutes, proceeding very rapidly once initiated. Riming and secondary ice particle production are also features of glaciation.
- Radar commonly receives precipitation echoes initially below the freezing altitude with day-to-day variations indicating the influence of mesoscale, or larger, influences on cloud dynamics and microphysics.

The evidence cited above indicates that coalescence is an important precipitation mechanism in midwestern convective clouds, resulting in the development of large water drops relatively low in the cloud and without the involvement of ice. This has been confirmed by theoretical calculations. Moreover the large drops thus produced influence cloud glaciation, playing a dominant role in cloud glaciation at relatively warm temperatures and apparently also determining, or at least strongly influencing, the characteristic of the early ice particles.

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