Cumulus Cloud Characteristics over Western South Dakota

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ABSTRACT

Meteorological information from aircraft penetrations of cumulus clouds over western South Dakota has been analyzed to yield distributions of liquid water content, vertical motion and temperature. Ice particles are encountered in only 26% of the penetrations. Medium size clouds (diameters between 0.5 and 2 mi) tend to have higher mean liquid water contents than either small or large clouds; however, large clouds have the highest *maximum* liquid water contents. Peak values of both up- and downdrafts occur in the larger clouds but mean vertical motions tend to decrease with increasing cloud size. Cross correlations among various parameters show that the locations of wet and dry areas within clouds are not necessarily correlated with vertical air movement.

1. Introduction

Several statistical studies of cumulus clouds have been made in the last decade. These investigations have dealt with precipitating clouds in Missouri (Braham, 1964) and the liquid water content of clouds in the Caribbean and central United States (Draginis, 1958). None of these investigations have attempted to completely describe all the significant parameters in a cumulus cloud. Auer (1967) observed clouds in an environment similar to western South Dakota, but his measurements were made near cloud base and were largely concerned with nuclei and cloud droplet spectra.

In order to build a source of information regarding clouds in the relatively dry environment of the high plains, research flights were made through clouds over western South Dakota. Clouds within 60 n mi of Rapid City and Lemmon, S. Dak., were penetrated near the −5C isotherm (between −2 and −10C). Two airborne meteorological systems were used to gather cloud data during the 1965 and 1966 summer seasons (Hirsch and Booker, 1966). The data from these two years were combined, and a statistical summary of the cloud data was made.

2. Operational methods

Meteorological information was gathered by two twin-engine aircraft in 1965 and 1966. Both aircraft were equipped to measure and record several meteorological parameters on strip chart recorders. Eight to ten parameters were recorded (Fig. 1); however, only air temperature, rate of climb, cloud liquid water content, wet-bulb depression, and temperature departure from ambient air were used in the analysis.

Penetration flights were planned before clouds began to grow above the −5C level and usually lasted ~3 hr. Almost all of the flights were made in an environment where some cumulus congestus clouds eventually grew to the mature cumulonimbus stage. Clouds were chosen for penetration only if they presented a general appearance of potential showers and their tops reached or exceeded the −5C level (Hirsch and Booker, 1966). Several penetrations were made on some clouds at intervals of 5–10 min. However, the data recorded on successive passes showed little evidence for persistence, so all penetrations were given equal weight in the analysis.

Because most cumulus clouds are roughly symmetrical about the wind shear vector at −5C, penetrations were made either with or against the shear vector whenever possible. The purpose of this mode of penetration was to gather data in such a way that one cloud or group of clouds could readily be compared with another.

3. Cloud classification

Clouds were classified by their mean vertical motion and size. The mean vertical motion was determined by the mean rate of climb in the cloud as measured by a sensitive variometer. If the mean rate of climb was positive, i.e., upward, the cloud was considered to be building. A cloud with a negative mean rate of climb was labeled as subsiding.

The criterion used for size classification was the cloud diameter at the level of penetration. A cloud with a diameter $\leqslant 0.5$ mi was considered small; a cloud with a diameter from 0.5–2.0 mi was considered medium; and a cloud with a diameter $\geqslant 2$ mi was considered large.

4. Statistical summary

Ice particles. Ice particles in and around the cloud were observed by two methods. First, the meteorological observer in the rear seat used one hand to operate

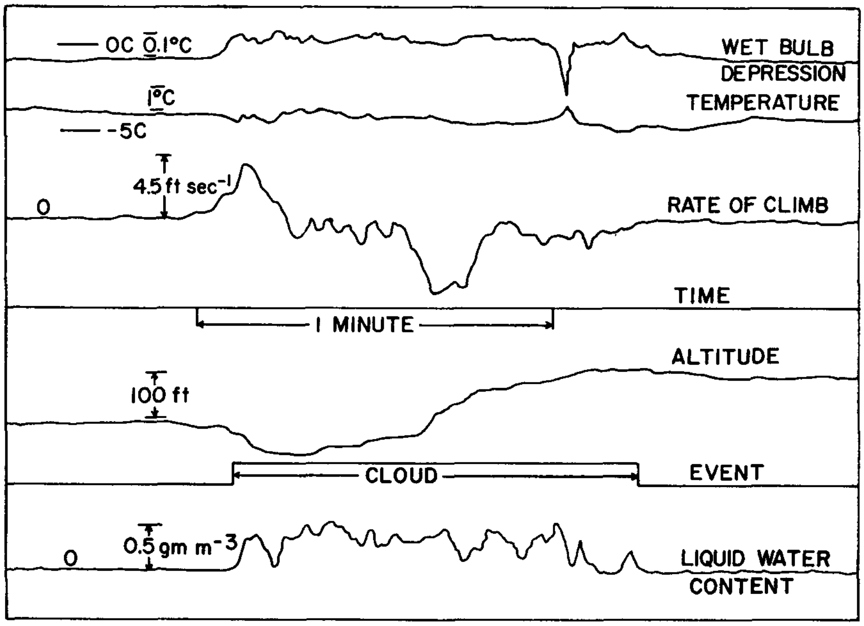

Fig. 1. Flight record through a cumulus cloud.

event buttons while observing the ice particles striking a black-gloved hand held out the window. The second method used a straight 2-inch copper tube which protruded through the nose of the aircraft to conduct particles into the co-pilot's position. The particles were viewed by the aircraft observer against a black velvet cloth.

At a mean temperature of -5C, 62.5% of all large clouds had ice in one form or another, 21% of all medium clouds had ice, and only 3% of all small clouds had ice. If one were to consider all clouds as one population, the percentage of cumulus in the high plains region with ice is less than 26%, a figure much lower than that quoted by Braham (1964) for clouds in south central Missouri.

Liquid water. A hot-wire liquid water content indicator was used. During multiple penetrations on a particular cloud, the probe would eventually gather enough ice to make measurements of liquid water meaningless. Usable data were obtained on 55 penetrations, with readings as high as 6.5 gm m^{-3} recorded.

The records of liquid water content show many inhomogeneities. Small wet regions or pockets occur with dry "holes ' interspersed between them (Fig. 1). Others report similar findings (Draginis, 1958; Warner, 1955).

A statistical summary is given in Table 1.

The "wettest" clouds, in terms of mean liquid water content, are the building-medium, with an average of 0.53 gm m^{-3}.

A more important measure of a cloud's "wetness" is its maximum liquid water content. As shown in Table 1, maximum liquid water contents increase with cloud size, which is as expected, but decrease when going from building to subsiding stages in the medium and large clouds. Two possible explanations for the decrease are 1) a combination of turbulence, which would tend to mix areas that were very wet with those that were dry, and entrainment of dry air around the edges of the subsiding cloud, and 2) coalescence of small droplets into larger drops that could not be measured by the hot-wire indicator. However, only the former explanation is consistent with the increase in *mean* liquid water content in going from building-large to subsiding-large clouds. In large clouds the effects of entrainment of dry air upon mean liquid water content would be smaller.

Draginis (1958) compared maritime clouds in the Caribbean area to continental clouds of central United States and found in both areas that some correlation existed between maximum liquid water content and cloud diameter. Maximum liquid water contents ranged from 0.7–4.0 gm m^{-3} for maritime clouds and from 0.7–4.5 gm m^{-3} for the continental clouds. These values are in agreement with the clouds found in South Dakota.

Rate of climb. The aircraft rate of climb, as measured by a variometer, was used to indicate the updrafts and

Table 1. Averages by category of mean and maximum liquid water contents (gm m^{-3}).

	Small		Medium		Large	
	Building	Subsiding	Building	Subsiding	Building	Subsiding
Average mean	0.26	0.31	0.53	0.34	0.36	0.39
Average maximum	0.46	0.58	1.13	0.67	1.28	0.86
No. of penetrations	6	3	19	9	11	7

TABLE 2. Averages by category of mean, maximum and minimum rate of climb (m sec^{-1}).

	Small		Medium		Large	
	Building	Subsiding	Building	Subsiding	Building	Subsiding
Average mean	1.08	−0.52	1.00	−0.56	0.54	−0.41
Average maximum	1.84	0.06	2.93	1.59	2.92	2.31
Average minimum	0.39	−1.11	−1.07	−2.21	−1.52	−3.23
No. of penetrations	10	5	47	26	27	16

downdrafts in clouds. Table 2 shows the results for the various categories.

Individual readings of rate of climb ranged from −5 m sec^{-1} in a large-subsiding cloud to +14 m sec^{-1} in a medium subsiding cloud. The strongest vertical motions occur in the larger clouds. However, because a single large cloud usually contains both updrafts and downdrafts, *mean* vertical motions tend to decrease with increasing cloud size.

Existing information concerning cross correlations of in-cloud parameters is scanty. Telford and Warner (1962) report strong correlation between liquid water content and virtual temperature at 250 m below tops of cumuli, and weak correlations of vertical velocities and buoyancy. The clouds in their data sample were of maritime origin and wholly warmer than freezing. The size of their data sample is not known.

Correlation coefficients were computed for each cloud penetration for six pairs of in-cloud parameters:

1) Temperature excess (temperature difference between in-cloud and ambient temperature, T EXC) vs liquid water content (LWC).
2) Temperature excess vs wet-bulb depression (TW).
3) Temperature excess vs rate of climb (R/C).
4) Liquid water content vs rate of climb.
5) Liquid water content vs wet-bulb depression.
6) Rate of climb vs wet-bulb depression.

For each pair of parameters, the hypothesis that the correlation coefficients for all penetrations were drawn from a single population was tested: it was rejected for every pair. The same hypothesis was then tested for the penetrations in each of the six cloud categories. The hypothesis was rejected at the 5% confidence level for all medium and large cloud categories but accepted for some parameters in the small cloud categories. For these cases, population correlation coefficients have been estimated. The population estimates and the ranges of correlation coefficients for the other cases are shown in Table 3.

Although the correlation coefficients for the small clouds are generally low, the differences between building and subsiding clouds are revealing. Building clouds are characterized by regions of warm, wet, rising air;

TABLE 3. Range of correlation coefficients or estimate of population correlation coefficient, by category, for various cloud parameters (number of penetrations in category indicated in parentheses).*

		T EXC	LWC	R/C
Small-building clouds				
	LWC	0.29 (5)	1	—
	R/C	0.31 (8)	0.45 (5)	1
	TW	0.02 (7)	−0.7 to +0.8 (5)	−0.6 to +0.8 (7)
Small-subsiding clouds				
	LWC	−0.15 (3)	1	—
	R/C	−0.08 (4)	0.11 (3)	1
	TW	−0.03 (3)	−0.17 (2)	0.30 (3)
Medium-building clouds				
	LWC	−0.1 to +0.9 (18)	1	—
	R/C	−0.5 to +0.7 (46)	−0.4 to +0.8 (18)	1
	TW	−0.8 to +0.8 (44)	−0.8 to +0.7 (17)	−0.8 to +0.7 (44)
Medium-subsiding clouds				
	LWC	−0.2 to +0.8 (9)	1	—
	R/C	−0.4 to +0.7 (24)	−0.6 to +0.8 (9)	1
	TW	−0.8 to +0.8 (22)	−0.9 to +0.7 (9)	−0.7 to +0.9 (22)
Large-building clouds				
	LWC	−0.4 to +0.8 (15)	1	—
	R/C	−0.2 to +0.8 (27)	−0.4 to +0.8 (15)	1
	TW	−0.9 to +0.9 (27)	−0.8 to +0.6 (15)	−0.8 to +0.6 (27)
Large-subsiding clouds				
	LWC	−0.2 to +0.8 (9)	1	—
	R/C	−0.8 to +0.7 (16)	−0.1 to +0.6 (9)	1
	TW	−0.9 to +0.7 (16)	−0.8 to +0.7 (9)	−0.6 to +0.8 (16)

* T EXC, temperature excess; LWC, liquid water content; R/C rate of climb; TW, wet-bulb depression.

subsiding clouds are less organized and their strongest updrafts tend to be cooler than the rest of the cloud. This might be related to overshooting.

Within each category of the medium and large clouds, significant differences occur in each of the correlation coefficient groups. For example, the correlation coefficient for rate of climb vs liquid water content ranged from −0.4 to +0.8 in large building clouds with a similar range (−0.2 to +0.7) for temperature excess vs rate of climb.

The lack of consistently positive correlations between parameters such as vertical motion and liquid water content is slightly surprising. Apparently, the interior of most high plains cumuli is a disorganized region of wet and dry pockets that are often not closely correlated with vertical air motions or the temperature field.

Experience during Project Cloud Cooler (Dennis *et al.*, 1967) in the vicinity of Rapid City showed that most of the test clouds dissipated within 10–30 min from the time of selection. The clouds that were selected were towering cumulus, which appeared to be actively growing, but the lifetime of these clouds was short. The short lifetime of these clouds could be due to the lack of positive correlation between in-cloud parameters such as buoyancy and liquid water content, or buoyancy and upward motion. If indeed this was the case, one might raise a question concerning modification of these clouds: Can regions that are disorganized within a cloud be changed through modification techniques (e.g., seeding) to cause positive correlation among the above parameters and, in turn, lengthen nature's life cycle of these clouds?

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