Cumuli Structure at Various Stages of Development

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ABSTRACT

The results of simultaneous measurements of thermal structure (convective column temperature and dimensions), of the concentration of droplets of various sizes (diameters from 3–70 μm), and liquid water content in clouds, which during a period of a day undergo various development stages, are considered.

It is shown that maximum droplet concentrations of all dimensions are observed in the convective columns at points where temperature excess maxima relative to environmental cloud air occur. However, this relation between drop number and temperature excess exists only in growing clouds.

Approximate estimates are also obtained of the droplets of critical size, above which they are observed, as a rule, only in convective columns. It is found, in individual clouds at a relatively early stage of development, that droplets are found with diameters $\geqslant 70$ μm. The diameters of cloud droplets, which give the maximum contribution to cloud liquid water content as well as to the relative quantity of environmental cloudless air entrained, increase in developing clouds as the cloud thickness increases.

1. Introduction

It is known that convective updrafts are of importance for cumuli formation and development, and cause their inhomogeneous structure (Vulfson, 1961). The results of numerous measurements, in particular those carried out in the Institute of Applied Geophysics (Vulfson *et al.*, 1965, 1968; Huan-Mej-Yuan, 1963; Skatsky, 1969) have showed that convective columns in clouds differ from the environmental cloud air not only in temperature and velocity but also in the microstructure parameters. For further study of cumuli structure it would now be desirable to investigate separately those parameters which are involved in the macro- and microstructure of cloud development. The present paper is an attempt at such an investigation. The structure of convective plumes, the concentrations of droplets of various sizes, and liquid water contents in 57 cumuli in the initial (100–2100 m) and final dissipation stages (300–500 m) are considered on the basis of a single day's measurements.

2. Instrumentation and measurement conditions

Convective updrafts were studied using their temperature field, obtained from an airborne resistance thermometer having a sensitivity of 0.02C and a time constant of 0.03 sec (Vulfson, 1961; Skatsky and Shelokov, 1963). Convective columns were then identified as zones with temperatures higher than those of the environmental cloud air. These zones, as a rule, have a relatively thin boundary layer and are thus indicated on the temperature oscillograph tapes by characteristic pulses whose height and width permit us to determine convective column sizes (more correctly, the sizes of the sections traversed by an aircraft) and the temperature excess in these sections.

The cloud microstructure was determined by means of two air-stream photoelectric devices used to measure concentrations of various size cloud droplets with the help of pulse-height analyzers and intensiometers (Konishev and Laktionov, 1966; Laktionov and Tulupov, 1969) and a device to measure cloud liquid water content (Skatsky, 1969). The two photoelectric instruments allowed us to record (with a time constant of 0.1 sec) integral droplet concentrations with diameters greater than 3, 5, 10, 15, 27 μm, and 32, 38, 52, 57 and 70 μm, respectively. The liquid water concentration measuring device allowed us to make measurements in both warm and supercooled (to −15C) clouds in the range from 0.15–0.20 up to 5 gm^{-3} with a time constant of about 2 sec; liquid water content was also determined from the observed droplet size distribution.

Measured cloud parameters (and the aircraft flight pattern) were recorded with three loop oscillographs. The records on the oscillograph tapes were synchronized using a 0.5-sec time-marking intervalometer with special loops which enabled the flight chief to make simultaneous marks (for example, of flight duration in the cloud) on all three tapes. A sample record of all measured values (except for the aircraft flight pattern and its vertical accelerations) is given in Fig. 1.

The measuring apparatus was installed on board an IL–14 aircraft. The flights were conducted in the region of Syktyvkar (Komi, ASSR).

As stated above, all measurements were performed during one day, on 10 July 1970.

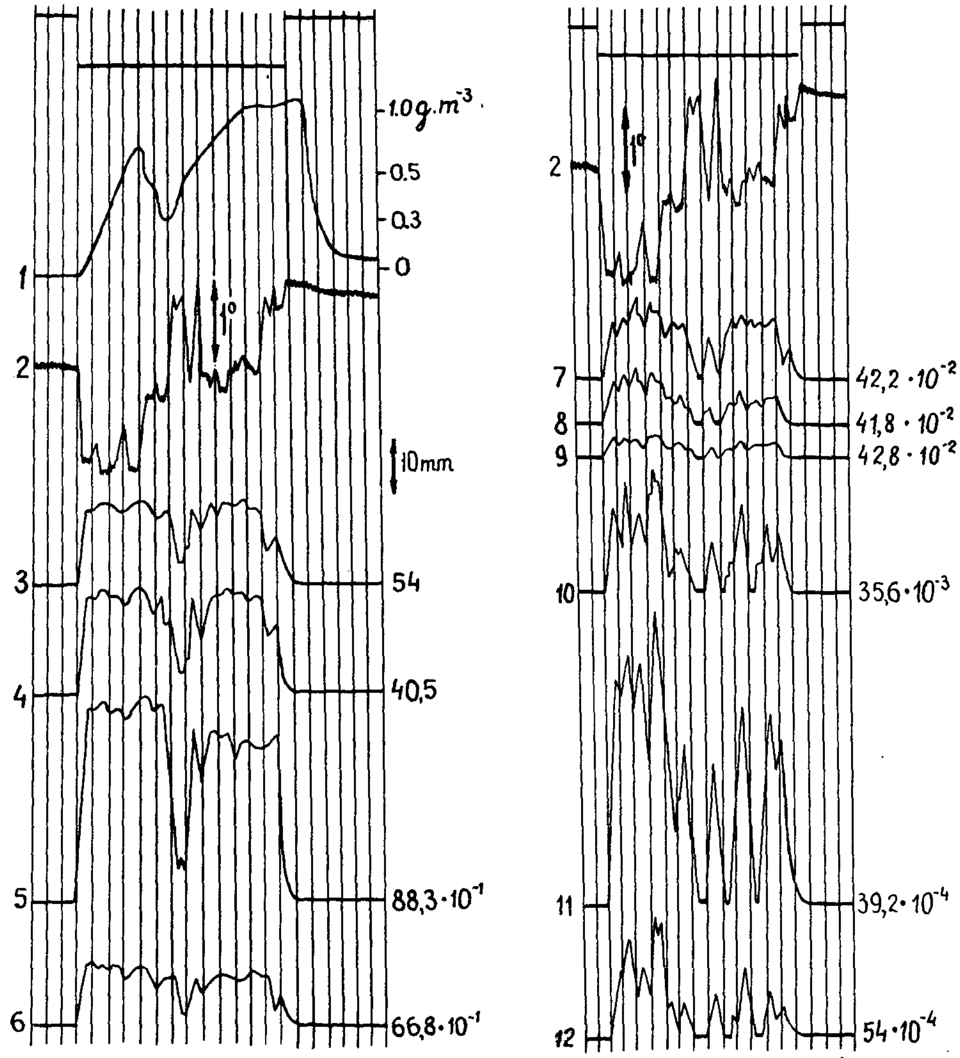

FIG. 1. Oscillogram patterns: 1, liquid water content; 2, temperature (increases downward); 3–12, integral concentration of droplets with diameters exceeding 3, 5, 10, 15, 27, 32, 52, 57 and 70 μm, respectively. Numbers on the right relate the ordinate change in millimeters to droplet concentration (cm^{-3}). Vertical lines are time marks at 1-sec intervals, and the horizontal lines at the top show the residence time of the aircraft in the cloud.

Early that morning the skies were cloudless; cumuli began to form at about 0830 (all times Moscow Standard) at an altitude of 1100–1200 m. Prior to 0930 the cloud thicknesses did not exceed 150 m. Clouds then began to develop quickly; by 1300 individual clouds reached the cumulonimbus stage and had thicknesses of the order of 5000–6000 m. The height of the cloud bases at the time was 1400–1500 m. The maximum cloud development was at 1500. At that time, approximately in the region of Syktyvkar, a thunderstorm with heavy rain was observed. After the thunderstorm there remained a field of cumuli and stratocumuli (7–8

TABLE 1. Measurement time, number and thickness of the clouds.

	Cloud group			
	I	II	III	IV
Measurement time	0923–0930	0953–1057	1104–1254	1626–1810
Number of clouds penetrated	5	17	15	20
Cloud thickness (m)	100–150	500–1000	1000–2100	300–500

TABLE 2. Sizes (m) and number (in parentheses) of convective columns and droplet zones in clouds.

Cloud group	Convective columns	Droplet zones with droplet diameters (μm) exceeding 3	5	10	15	27	32	38	52	57	70
I	86 (13)	334	323	210							
II	137 (53)	587 (17)	357 (27)	287 (33)	202 (40)	146 (50)	122 (49)	117 (43)	114 (38)	112 (36)	107 (28)
III	163 (61)	950 (15)	584 (24)	490 (28)	295 (42)	234 (46)	174 (44)	171 (42)	150 (42)	143 (41)	125 (40)
IV	147 (68)	886 (20)	636 (27)	510 (33)	222 (60)	171 (63)	128 (49)	91 (28)	90 (12)	72 (11)	36 (8)
Average values	146 (195)	766 (57)	511 (83)	411 (101)	238 (142)	181 (159)	140 (142)	131 (113)	127 (92)	121 (88)	109 (76)

tenths) with a thickness of 300–500 m and a cloud base height of about 1700 m.[1]

The measurements were made over the periods 0923–1254, and 1626–1810 from horizontal cross sections taken through the upper parts of the clouds when their thickness did not exceed approximately 2000 m. Since no thicker clouds were observed prior to 1200 and after 1600 the observational data are representative sufficiently to reflect some of the particular features of the cloud structure at their various development stages for the given time periods.

For convenient analysis the data are divided into four groups according to the time of measurement and the cloud thickness where the measurements were made (Table 1). The first three groups refer to the cloud growth stage, the last to the dissipating stage.

3. Data processing and analyses

Data processing was performed as following: The existence and number of convective columns in the cloud, their horizontal extent, and the magnitude and location of the maximum temperature excess (the location being the distance from the cloud edge to the convective column center, or more exactly, to the point of maximum temperature excess) were determined from the temperature record (curve 2 in Fig. 1). Zones with various size droplets, their horizontal extent, the maximum values of the droplet concentrations, and the location of such zones in the cloud (as in the case of the convective column) were determined from the integral droplet concentration record (curves 3–12).

Furthermore, temperature excess values over cloudless environmental air, liquid water contents, and integral droplet concentrations were obtained for the cloud as a whole as well as for the convective columns and droplet zones within the clouds. These values were calculated from corresponding oscillogram traces (Fig. 1) as arithmetic means of all the values observed every second along the entire cloud cross section, or only inside the convective columns or the droplet zones.

It is worth noting that the sizes of the convective columns or droplet zones taken from the oscillograms as well as the maximum temperatures and droplet concentrations refer to random crossings of these columns or zones by the aircraft (Fig. 1). Given a sufficient number of such crossings, theory (Vulfson, 1961) permits one to calculate the real diameter distribution of convective columns or droplet zones, the values of the center temperatures or concentrations, as well as the concentration of the convective columns or the droplet zones themselves. However, since there were insufficient data to obtain statistically significant variations of droplet concentrations inside droplet zones, no such analysis was made and the data were considered simply as they were taken from the oscillogram. However, the relative horizontal extent of the linear traces of the convective columns or droplet zones was interpreted, in accordance with Vulfson (1961), as the relative areas of the columns or zones in the cloud at the flight level.

The measured results for each of the cloud groups are given in Tables 2–4. Sizes and the number of convective columns and droplet zones are given in Table 2; their extent (area) in Table 3; and temperature excess values (ΔT), liquid water content (w), and droplet concentration (N) in Table 4. Four values are given for each parameter A: the average for all measurements (average for the cloud, $\bar{A}$), the average for measurements only inside convective updrafts ($\bar{A}_c$) or inside droplet zones ($\bar{A}_d$), the average maximum values in the columns or zone ($\bar{A}_m$), and the absolute maxima (A_m).

4. Droplet zone relationship to convective columns

Oscillograms with droplet concentration records showed that droplet zones, especially those with droplet diameters $>$10–15 μm, do not fill the cloud completely. It is often observed that considerable portions of the cloud along the flight path have practically no droplets of these sizes (Table 3).

As the droplet sizes increase, the droplet zones be-

[1] According to the Syktyvkar radiosonde data the rapid decrease in cloud thickness is probably connected with a rather remarkable decrease of the upper boundary of the unstable layer and the subsequent development of an inversion at an altitude of about 2500 m.

TABLE 3. Relative extent (area) of convective columns and droplet zones in clouds (as a percentage of total cloud extent).

Cloud group	Convective columns extent	Extent of zones with droplet diameters (μm) exceeding 3	5	10	15	27	32	38	52	57	70
I	75	100	97	88							
II	73	100	97	95	81	73	60	50	43	40	30
III	70	100	99	96	87	76	54	50	44	41	35
IV	57	100	97	95	75	61	35	14	6	4	2
Average values	67	100	98	95	80	69	49	36	29	26	21

have as if they were separated or divided. An example of such a division can be seen in Fig. 1. The zones with droplet diameters larger than 3, 5, 10 and 15 μm (curves 3–6) fill practically the whole cloud, although the droplets concentrate mainly in two parts of the zone (the zones have two distinct maxima). In the zones with larger droplets the second maximum is first divided into two, and then three distinctly separate zones, which do not fill the cloud completely. The relative extent of the droplet zones for various size droplets, is presented in Table 3.

It is worth noting that in the same cloud the droplet concentrations in adjacent zones can significantly differ from each other; such differences are observed in all droplet measurement ranges.

The noted inhomogeneity of droplet concentration distributions in clouds correlate well with the thermal inhomogeneity of the clouds.

As is seen from the oscillogram patterns shown in Fig. 1, the main droplet concentration maxima with sizes exceeding 3, 5, 10 and 15 μm correspond to the two large thermal inhomogeneities or convective columns (curve 2). Furthermore, secondary maxima at the beginning and at the end of the second principal sections of the droplet zones correspond as well to two narrower convective columns. The above correspondence is better followed in the zones with larger size droplets. However, there is no complete correspondence between the numbers of convective columns and droplet zones; the oscillograms showed that in some convective columns, especially those of large extent, the zones with large size droplets can divide into a number of smaller zones, and in some cases they can completely disappear.

To estimate quantitatively the relation between droplet zones and convective columns in clouds, with allowance for the fact that droplet zone dimensions also depend on the given droplet size, the correlations between locations of maximum droplet concentration in

TABLE 4. Temperature excess, liquid water content,* and droplet concentration in clouds.

Cloud group	Temperature excess	Liquid water content	Droplet concentration (cm^{-3}) with diameter (μm) exceeding 3	5	10	15	27	32	38	52	57	70
I	$\bar{T}$ 0.13	$\bar{W}$ 0.23(0.14)	$\bar{N}$ 506	460	49							
	$\bar{T}_c$ 0.17	$\bar{W}_c$ 0.25(0.15)	N_d 506	460	54							
	$\bar{T}_m$ 0.23	$\bar{W}_m$ 0.26(0.21)	$\bar{N}_m$ 680	644	76							
	T_m 0.31	W_m 0.33	N_m 783	729	119							
II	$\bar{T}$ 0.34	$\bar{W}$ 0.37(0.38)	$\bar{N}$ 502	473	186	23	2.1	0.9	0.4	0.10	0.02	0.007
	$\bar{T}_c$ 0.45	$\bar{W}_c$ 0.43(0.45)	N_d 502	490	209	29	3.0	1.3	0.8	0.18	0.04	0.020
	$\bar{T}_m$ 0.64	$\bar{W}_m$ 0.59(0.67)	$\bar{N}_m$ 734	693	282	48	4.5	2.4	1.2	0.34	0.07	0.035
	T_m 1.18	W_m 1.27	N_m 837	810	318	74	6.8	4.6	3.2	1.21	0.21	0.135
III	$\bar{T}$ 0.36	$\bar{W}$ 0.55(0.61)	$\bar{N}$ 407	382	167	88	2.2	1.1	0.6	0.18	0.05	0.024
	$\bar{T}_c$ 0.51	$\bar{W}_c$ 0.65(0.66)	N_d 407	385	187	91	2.7	1.7	1.1	0.33	0.07	0.040
	$\bar{T}_m$ 0.73	$\bar{W}_m$ 0.88(1.03)	$\bar{N}_m$ 648	617	253	147	4.5	2.7	1.7	0.57	0.12	0.071
	T_m 1.69	W_m 1.30	N_m 756	729	314	220	7.2	5.4	3.4	1.67	0.26	0.200
IV	$\bar{T}$ 0.32	$\bar{W}$ 0.31(0.31)	$\bar{N}$ 490	453	156	13	1.6	1.0	0.4	0.01	0.004	0.0008
	$\bar{T}_c$ 0.42	$\bar{W}_c$ 0.36(0.41)	N_d 490	478	168	25	1.9	1.6	0.7	0.11	0.009	0.001
	$\bar{T}_m$ 0.68	$\bar{W}_m$ 0.54(0.55)	$\bar{N}_m$ 687	658	234	31	3.6	2.9	1.3	0.18	0.030	0.020
	T_m 1.53	W_m 1.07	N_m 729	709	287	73	6.2	4.2	4.1	0.32	0.094	0.038

* Values in parentheses are estimated from droplet distribution shown in the table on the assumption of a regular droplet size distribution in each range of measurements.

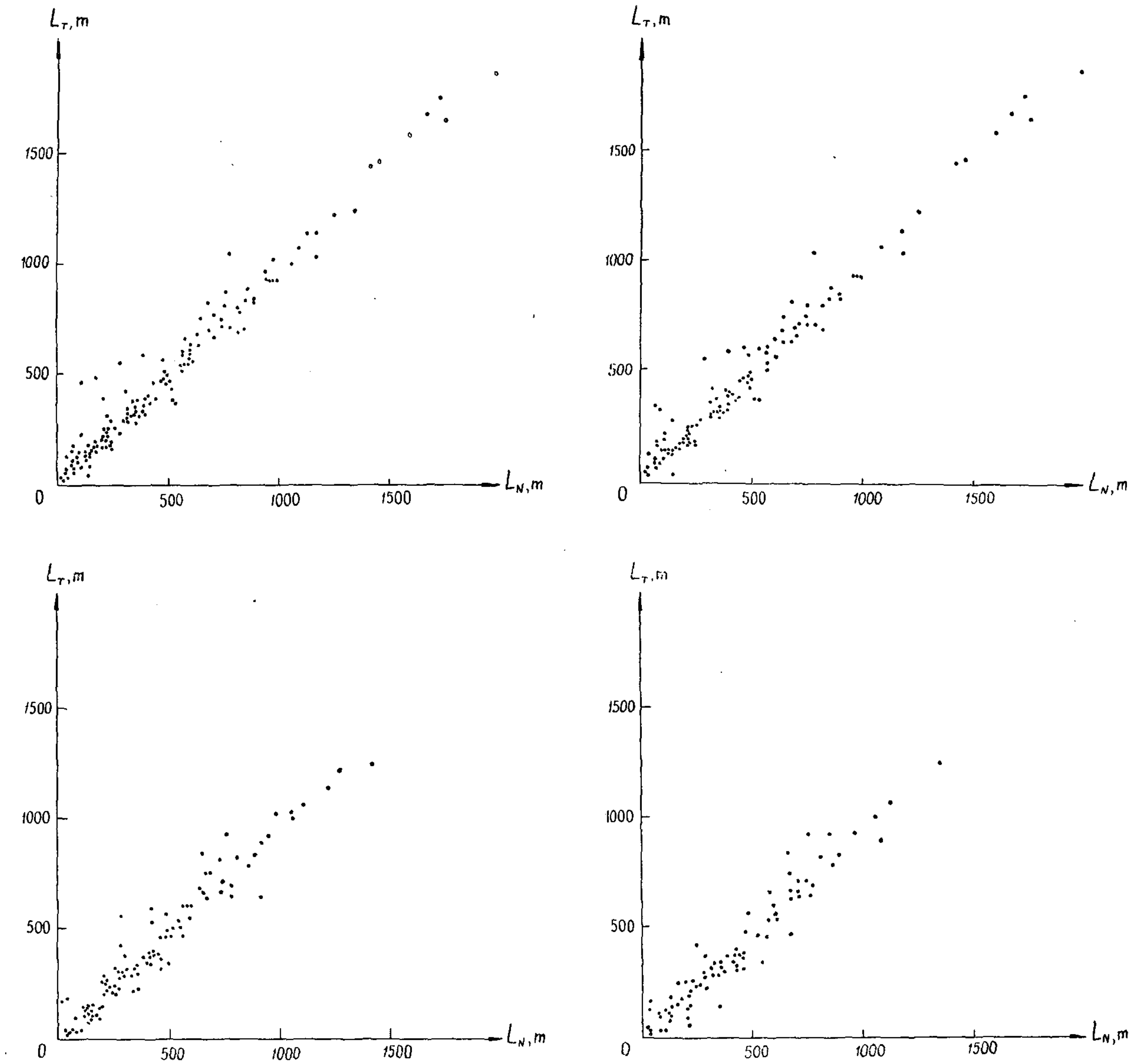

FIG. 2. The distance between the cloud edge and points with maximum droplet concentration in droplet zones (L_N) vs the distance to points with maximum temperature in the corresponding convective columns (L_T). Parts a–d represent zones with droplet diameters exceeding 5, 15, 38 and 57 μm, respectively. All distances are in meters.

the droplet zones and maximum temperature excess of convective columns were considered.

This comparison shows that the distance from the cloud edge up to the point in the droplet zones where the maximum droplet concentration is observed, coincides as a rule with the distance to the point in the corresponding convective column where the maximum temperature excess occurs (Fig. 2). This coincidence is true for all droplet zones; the correlation coefficients varied from 0.90–0.98.

Thus, the maximum droplet concentration for all sizes is observed as a rule in the "warmest" parts of the convective columns.

Since the most suitable conditions for further condensation and growth of cloud droplets are in convective updrafts, it was natural to anticipate a correlation between the maximum temperature excess in the convective columns and the maximum concentrations of various size droplets. However, such a correlation appeared to exist only during the period of intensive development, i.e., in cloud groups II and III (Fig. 3); the correlation coefficient values vary within the range 0.5–0.7. In cloud groups I and IV the relationship appeared to be weak.

As is seen from Table 2, mean sizes of droplet zones decrease with increasing droplet diameter, from zones equal to the mean cloud size (considerably larger than those of convective updrafts) to some size less than the mean size of the convective columns. The number of droplet zones first increases due to their division to some value close to the number of convective columns, then decreases since in some zones, or more precisely, in some convective columns, there are no droplets of comparatively large sizes.

If we select droplet zones whose mean sizes and numbers are approximately equal to the mean sizes and numbers of convective columns, such zones will normally coincide with convective columns. Thus, the smallest droplet diameter in these zones can be considered as some critical size[2] above which droplets are observed as a rule only inside the convective columns.

For the clouds of groups II, III and IV the mean sizes of convective columns appeared to be approximately equal to 140, 160 and 150 m, respectively. Zones with droplet diameters exceeding, respectively, 30, 40 and 30 μm have approximately the same sizes. Thus, in the clouds considered here (with the exception of group I clouds) droplets with diameters $>$30–40 μm are mostly concentrated inside the convective updrafts.

5. Large droplets in clouds

As cumuli develop, their macro- and microstructure parameters vary considerably. When the cloud grows (groups I–III) not only cloud temperature excess and liquid water content but the number of convective columns, their sizes, temperature excess, liquid water content and droplet zone sizes increase as well (Tables 2 and 4). In the dissipation stage the values of all parameters mentioned above, with the exception of droplet zones with sizes exceeding 5 and 10 μm, decrease slightly. However, it is difficult to estimate the rate of decrease of these parameters, since only one series of measurements was conducted in the dissipating stage.

The droplet concentration in the process of cloud development varies in a rather complex manner (Table 4). For example, the mean concentration of cloud droplets with sizes up to 15 μm decreases in the process of cloud growth (when the cloud transforms from group I–III) approximately by a factor of 2; in clouds of group IV, the dissipating stage, the concentration of droplets of these sizes increases again. The large-droplet concentration, vice versa, increases with cloud thickness in cloud groups I–III, and then (in clouds of group IV) decreases.

Let us consider in detail the concentration of large droplets in clouds. Droplets with diameters $>$70 μm were noted at all stages of cloud development. However, in the initial stage (group I) they were observed only in one cloud as individual droplets which did not form a separate droplet zone. (In the remaining four clouds of group I, diameters of the observed droplets

[2] According to observations (Vulfson *et al.*, 1968), most convective columns in homogeneous cumuli of fair weather with thickness of about 1000 m could be considered as droplet zones with droplet diameters above 20 μm.

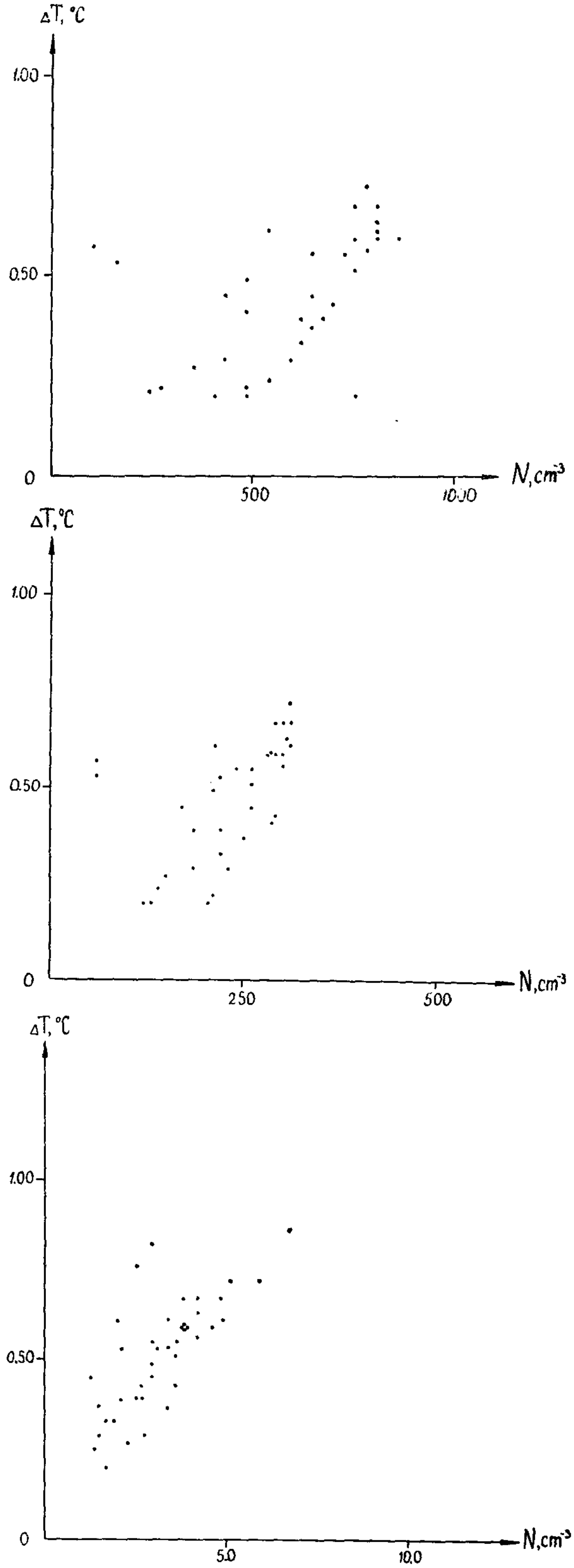

FIG. 3. Maximum temperature (ΔT) in convective columns as a function of maximum droplet concentration (N) in the corresponding droplet zones in group II clouds. Parts a-c represent droplet zones with diameters exceeding 3, 10 and 27 μm, respectively.

TABLE 5. Liquid water content in clouds (%) due to droplets of various sizes.

Cloud group	Water content due to droplets with diameters (μm) of 3–5	5–10	10–15	15–27	27–32	32–38	38–52	52–57	57–70
I	1.1	63.8	35.1						
II	0.2	16.5	43.7	26.6	4.2	2.9	3.7	1.8	0.4
III	0.1	7.8	13.3	68.9	2.4	1.9	3.3	1.8	0.5
IV	0.4	21.2	47.3	17.8	2.6	4.4	6.0	0.2	0.1

did not exceed 32 μm). The presence of such large droplets during the initial stage of the cloud development probably is caused by water vapor condensation on giant condensation nuclei.

The mean concentration of droplets with diameters >70 μm is comparatively small in all groups, the values amounting to 0.1, 7, 24 and 0.8 particles per liter. The mean concentration of droplets with diameters >38 μm is considerably higher, i.e., 30, 400, 600 and 400 particles per liter. However, in spite of the comparatively small concentration of droplets, the relative extent or the area of the droplet zones with diameters >38 μm in developing clouds (groups II and III) is half the cloud area, and the area of zones of droplets with >70 μm is one-third the cloud area (Table 3).

Thus, the data indicate that the process of coagulation growth of droplets can start at a comparatively early stage of cloud development.

6. Contribution of various size droplets to liquid water content

The data in Table 4 were used to calculate the contribution of various size droplets to the liquid water content in clouds. Table 5 presents the results of the calculation. The table shows that the droplet size contributing most to liquid water content in clouds increases with cloud development and slightly decreases in dissipating clouds. Thus, droplets with diameters of 5–10 μm contribute most to the liquid water content (64%) in clouds of group I, droplets with diameters of 10–15 μm to the liquid water content in clouds of groups II and IV (44 and 47%, respectively), and those of 15–27 μm to the clouds of group III (69%).

Probably in thicker clouds the main contribution to the liquid water content is made by still larger size droplets.

TABLE 6. Relative water content in clouds.*

Cloud group	Relative water content in clouds $\overline{w/w_a}$	$\overline{w_c/w_a}$	$\overline{w_m/w_a}$
I	0.72(0.44)	0.78(0.47)	0.81(0.66)
II	0.44(0.45)	0.51(0.53)	0.68(0.79)
III	0.26(0.29)	0.31(0.31)	0.41(0.48)
IV	0.53(0.53)	0.62(0.71)	0.93(0.95)
Mean	0.49(0.43)	0.56(0.50)	0.71(0.72)

* See footnote to Table 4.

7. Entrainment of surrounding air

To make an approximate estimate of the degree of environmental air entrainment into cumulus clouds, the ratios of measured liquid water content in clouds to the adiabatic value (w_a), i.e., to the theoretically possible water content which could be in the cloud by adiabatic lifting of moist air with the condition that all the condensed moisture remains in the cloud, were considered.

Table 6 shows mean values of the relative water content for the cloud on the whole ($\overline{w/w_a}$), for the convective column ($\overline{w_c/w_a}$), as well as maximum values ($\overline{w_m/w_a}$) for all groups of clouds.

As evident from Table 6, values of the relative water content in clouds depend considerably on the stage of cloud development; they decrease appreciably from group I to group III (by a factor of 2–3) and then increase (by a factor of 2) in group IV.

If it is assumed that the droplets contributing mainly to the water content in clouds remain in the cloud, or that the fractions of these droplets falling out of clouds of various groups do not differ considerably from each other, then according to Table 6, the degree of cloud air dilution by environmental cloudless air increases considerably while the cloud is developing (groups I–III). Thus, the greater the thickness of developing clouds the greater the amount of environmental air entrained.

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