Thunderstorm Water Contents and Rain Fluxes Deduced from Radar

SPIROS G. GEOTIS

Dept. of Meteorology, Massachusetts Institute of Technology, Cambridge

(Manuscript received 21 April 1971, in revised form 30 July 1971)

ABSTRACT

Total instantaneous water contents of several intense thunderstorms were calculated from smoothed representations drawn from quantitative radar observations; values typically ranged from 10^8–10^9 kg. Rain rates and accumulations were obtained from reflectivity measurements near the surface. The rainfall rates of the storms were about 10^5–10^6 kg sec^{-1} with total accumulations averaging 10^9–10^{10} kg. Dimensions and durations of the storms are also given.

1. General description

The thunderstorms, or perhaps more correctly, hailstorms, described in this paper are defined as storms which appear on the radar as echoes with physical dimensions of the order of 10 km and maximum reflectivities corresponding to values of $Z_e \geqslant 10^{5.5}$ mm^6 m^{-3}. The high reflectivities are confined to small "cores" of the order of 1–3 km in size. When viewed at close range with fine resolution these "cores" are found to be composed of even smaller maxima and minima, but we will not be concerned with these here.

Typically, thunderstorm echo histories are characterized by a relatively rapid growth, a decibel or two of radar signal per minute, until Z_e values of 10^5–10^6 mm^6 m^{-3} are reached. The intensity then stays roughly constant, within a few decibels, for periods ranging from 15–20 min to a few hours, followed by a decay which is somewhat slower than the growth rate. The tracks of these storms range from a few tens of kilometers to well over a hundred. In this study there is a bias toward the more intense storms since they were the ones which naturally drew the observers' attention and resulted in the accumulation of the data needed for the calculations. Total water contents and rain fluxes were computed for selected times during the intense, or quasi-steady state, periods of eight storms. The water content includes both water and ice particles detected by the radar but does not include cloud water content.

2. Methods of measurement and analysis

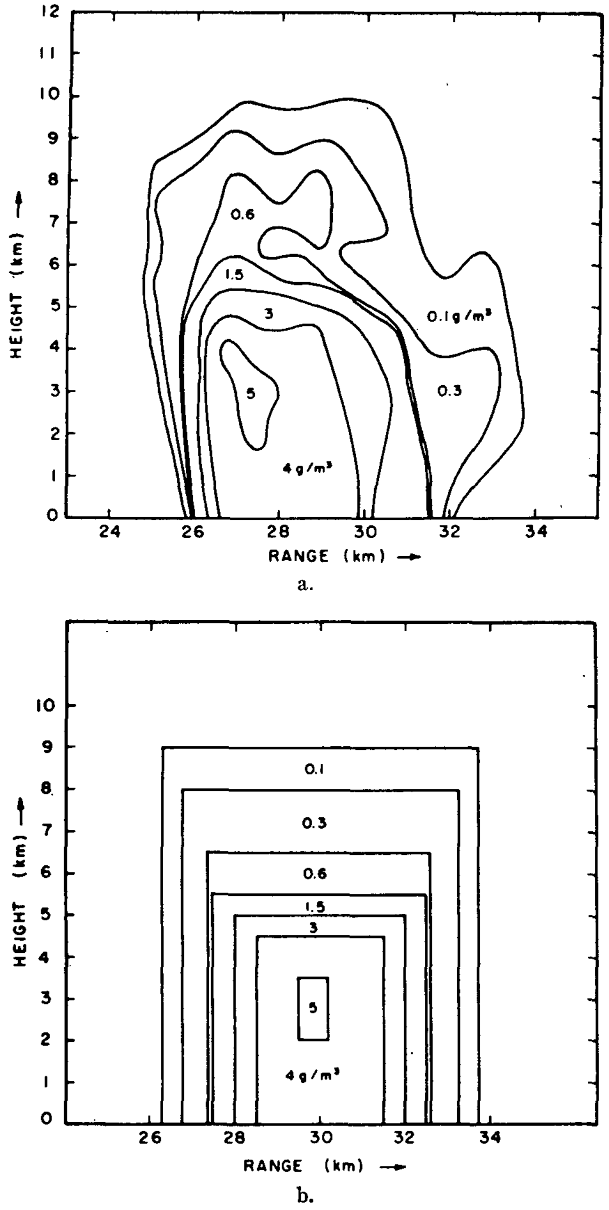
The radar used in the study was an SCR 615-B operating at a wavelength of 10.7 cm. It has a 3^c conical beam and range resolution of $\sim$225 m. The data were in the form of PPI and RHI photographs of averaged and range-normalized intensities quantized in approximately 5-db steps. As the routine mode of operation is PPI movies, the PPI data are relatively continuous for most of the storms with occasional interruptions for RHI's. Full RHI coverage of a storm in one azimuth requires less than a minute while a sequence of PPI photographs takes approximately 2 min for the complete intensity range at one elevation angle.

The calculations were carried out on smoothed cylindrical representations drawn from RHI photographs or PPI photographs at different elevation angles or from a combination of the two. Fig. 1a is a typical vertical cross section of a thunderstorm drawn from an RHI photograph and Fig. 1b the corresponding simplification. Cylindrical symmetry was assumed for the calculations. Liquid water content values were obtained from the radar reflectivities using the relation $Z=2.1\times10^4M^{1.43}$ (Z in mm^6 m^{-3}, M in gm m^{-3}) which had been derived from drop size distributions in local summer rains. The relation $Z=400R^{1.3}$ (R in mm hr^{-1}), based on the same distributions, was used to obtain the rainfall rate from the radar reflectivities near the surface.

Our best estimate of the standard error in the radar measurements is ±2.5 db. This, coupled with the scatter in the Z vs M and Z vs R relations, plus uncertainties regarding the composition and size of particles above the 0C isotherm, probably limit the accuracy of the calculations of radar detectable water content and rain flux to around a factor of 2.

3. Results and discussion

Calculations of the total water detected by the radar at one time and the total rain flux were carried out for each of the eight storms at some time during its quasi-steady-state period. The results and other pertinent data are summarized in Table 1. The "track" columns give the duration, in time and in distance co-



a.

b.

FIG. 1. Vertical cross section, a., of typical thunderstorm drawn from quantitative RHI photographs, and its simplification, b., for use in calculations.

vered, over which the peak reflectivity of each storm approximated or exceeded the empirical hail threshold of $Z_e = 10^{5.5}$ (Geotis, 1963).

In the calculations of water content, allowance was made above the 0C level for the transition from all rain (and hail) below to all ice (snow and hail) well above. Owing to its lower dielectric constant, ice scatters less effectively than water; for the same size and number of particles the reflectivity is only one-fifth as great if they are composed of ice rather than of water. The precise composition of particles within these storms is, of course, not known, but estimates based on other observations

TABLE 1. Various parameters obtained from radar measurements of eight severe thunderstorms.

Date	Time (EST)	Azimuth	Range to-storm center (km)	Diameter (km)	Height (km)	Volume (km³)	Track length (km)	Track duration (hr)	Total water content (kg)	Average rain-fall rate (kg sec⁻¹)	Accumulated rainfall (kg)
6 June 1961	1455	300°	23	7	12	4.6×10^2	16	0.3	9.1×10^8	5.7×10^5	6.2×10^8
30 June 1961	1500	210°	24	16	11	2.3×10^3	160	4	4.2×10^9	2.8×10^6	$4\ \times10^{10}$
1 July 1964	1340	314°	35	16	13	2.7×10^3	95	2.3	1.8×10^9	7.2×10^5	$6\ \times10^9$
1 July 1964	1650	213°	55	10	12	$8\ \times10^2$	65	1.2	1.2×10^9	7.4×10^5	3.2×10^9
5 August 1964	1710	207°	29	6	8	1.7×10^2	30	1.3	1.8×10^8	1.1×10^5	5.2×10^8
10 August 1965	1703	339°	29	7.5	10	4.1×10^2	26	1	4.4×10^8	4.1×10^5	1.5×10^9
13 August 1965	1633	248°	40	23	12	5.3×10^3	26	1.3	$5\ \times10^9$	2.1×10^6	9.9×10^9
7 June 1966	1225	305°	35	6	8	2.3×10^2	24	0.8	$2\ \times10^8$	2.2×10^5	6.3×10^8
	Average			11.4	10.8	1.5×10^3	55	1.53	1.7×10^9	9.6×10^5	5.3×10^9

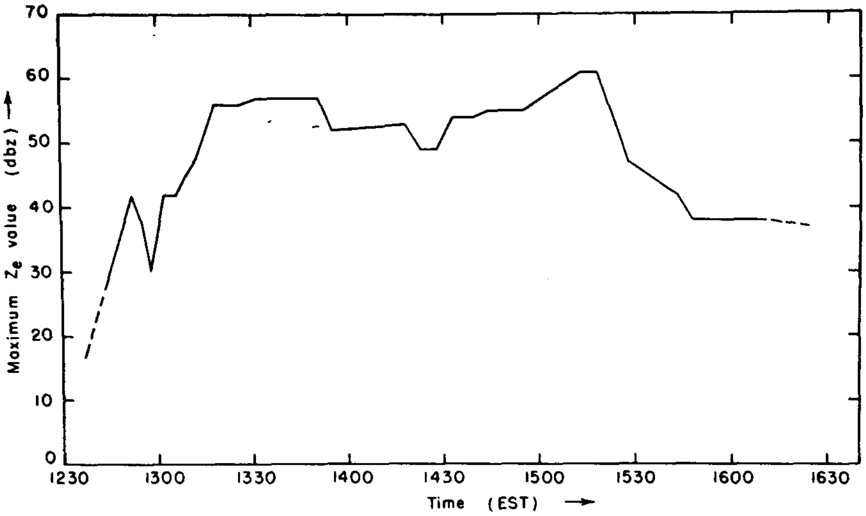


FIG. 2. Maximum reflectivity (dBz = 10 log Z_e) reached by storm on 1 July 1964 plotted as a function of time. This is the storm shown in Table 1 at an azimuth of 314°.

have been made. Flight data from Ohio and Florida thunderstorms given in *The Thunderstorm* showed essentially all snow above 8 km and a mixture of snow, rain and hail down to the 0C level. In comparisons of radar measurements at 3 and 10 cm in intense thunderstorms in New England (Austin, 1966), strong attenuation in the 3-cm signal was noted up to 5 km and none above 7–10 km, depending upon the intensity of the storm. Accordingly, we have assumed scattering by all water particles up to 5 km, all ice above 8 km, and a gradual transition between. For levels above 5 km, the Z_e values and water contents computed for water particles were scaled upward to values five times greater at 8 km and above. Implicit in this procedure is the assumption that particle size distribution is the same throughout the storms, an assumption which may be physically unrealistic but is perhaps as good as any on the average.

In the "cores" exhibiting hail reflectivities the liquid water content was limited to 5 gm m^{-3} and the rainfall rate to 100 mm hr^{-1}, hopefully realistic maxima based on drop size and raingage measurements made at the ground in thunderstorms here.

Figs. 2 and 3 are plots of maximum reflectivity and total instantaneous rainfall rate, both as a function of time, for one of the storms of 1 July 1964. The graphs terminate at the times when the storm echo merged with that of nearby storms. The core could be followed until 1610 (all times EST) whereas the total outline, necessary for the rainfall calculations, could not be delineated from neighboring echoes after 1448. The intense periods of the storms lasted from 20 min to 4 hr over distances of 16–120 km. Total instantaneous water content, in the form of particles detectable by the radar, ranged from approximately 10^8 kg in the smaller storms to well over 10^9 kg in the larger ones. Likewise, total rain fluxes varied from around 10^5 kg sec^{-1} to somewhat over 10^6 kg sec^{-1}. Multiplying the latter by the track times, the period during which the bulk of the rain falls, gives the accumulated rainfall, the last column in Table 1. Braham (1952) reported values of 3×10^5 to 10^9 kg of accumulated rainfall from thunderstorm cells in Ohio, values in good agreement with those reported here if we allow for the bias toward the more intense storms in this study.

As might be expected, the accumulated rainfall increased with both lifetime and total instantaneous water content, being somewhat better correlated with the

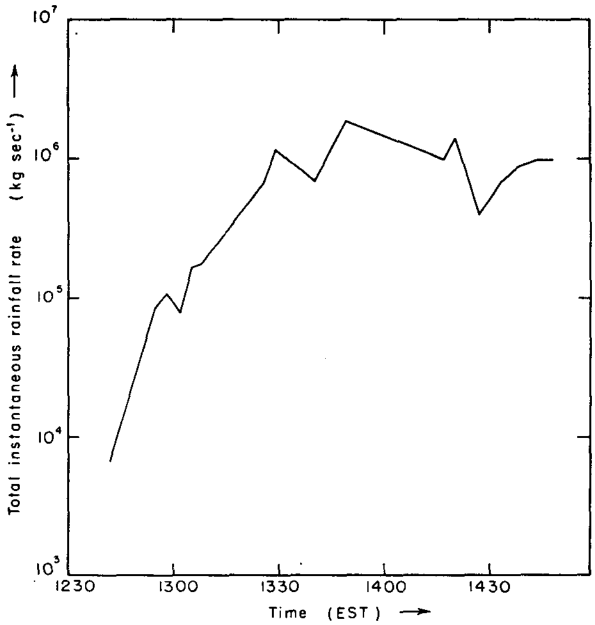


FIG. 3. Total instantaneous rain flux deduced from radar for storm on 1 July 1964 plotted as a function of time. This is the same storm as in Fig. 2.

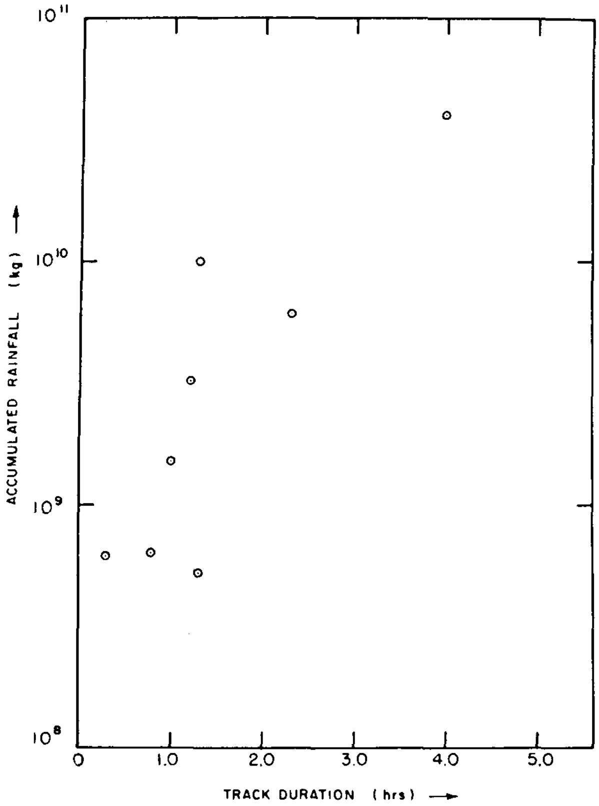


FIG. 4. Accumulated rainfall vs lifetime for eight storms.

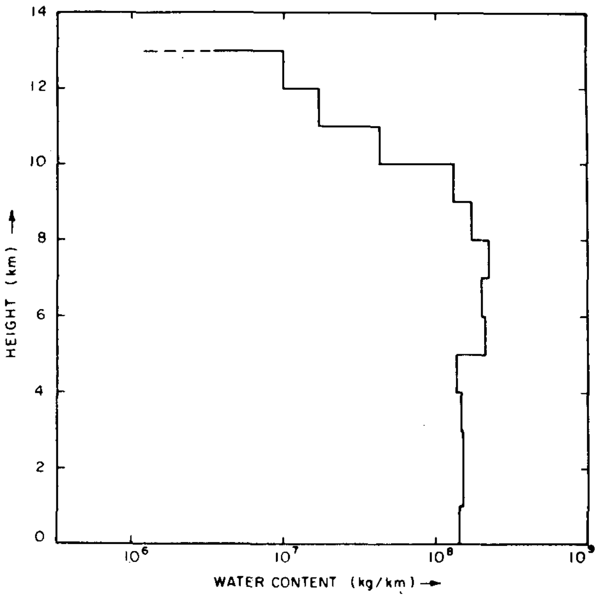


FIG. 6. Vertical distribution of water content for the average of eight thunderstorms.

latter. This may be seen in Figs. 4 and 5 where accumulated rainfall is plotted against track duration and water content, respectively. With the exception of two storms in Fig. 5, the points fall nearly on a straight line such that the accumulated rainfall amounts to approximately three times the instantaneous water content. It is interesting to note that the two exceptions involved extremes in duration. No significant correlation was found between water content and storm lifetime.

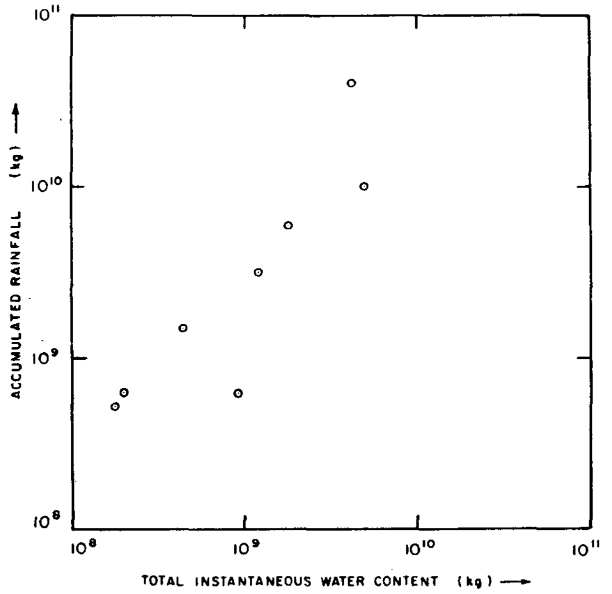


FIG. 5. Accumulated rainfall vs instantaneous water content for eight storms.

Water in the form of cloud drops not detected by the radar would increase the water content values somewhat. The mean overall liquid water content detected by the radar for the eight storms was approximately 1 gm m^{-3} so that cloud distributed throughout at a concentration of a few tenths of a gram per cubic meter would add of the order of 20–30%.

The vertical distribution of water content for an average of the eight storms is shown in Fig. 6. It can be seen that the distribution is approximately constant up to 10 km and then drops off more or less exponentially above. This same behavior is observed in the individual storms although the drop-off occurs at different heights.

It should be emphasized that while the eight storms are pretty well spread across the size range of thunderstorms in New England, there is a bias toward the more intense ones. Since the reflectivity in all of them reached the empirical threshold of $Z_e = 10^{5.5}$ [determined in a previous study (Geotis, 1963)], it is highly likely that all eight were producing hail; for several of them, hail at the ground was confirmed.

4. Conclusions

Dimensions, water contents, and rainfall rates computed from radar measurements of eight New England hailstorms have been summarized. On the average, a storm is about 11 km in both height and diameter with a volume of 1000–1500 km^3. It has a quasi-steady-state period of 1.5 hr during which it covers a distance of 55 km. At any time during this period it contains approximately 2×10^9 kg of water. It deposits rain on the earth at a rate of 10^6 kg sec^{-1} for a total accumulation of 5×10^9 kg of water.

Acknowledgments. The research reported in this paper was performed under National Science Foundation Grant GA-10426.

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