Engineering Notes

Free Water at High Altitudes

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1. Introduction

FROM the beginning of the National Severe Storms Project, pilots flying the test aircraft have reported encountering extremely large amounts of water at high altitude inside the storms. Erosion and structural damage sustained by the aircraft during some of the storm flights have pointed to the presence of much water and large hail.

Some airborne instrumentation for measuring water content was assembled, installed on an F-100F aircraft, and tested inside thunderstorms in May and June 1962.[1] In the storm of May 20, 1962, there occurred a very large concentration of water and a succession of unusual events which considerably affected the instrumentation, the aircraft and its occupants, and the ground-based weather radar. The rain encountered substantially exceeds estimates presented in the Handbook of Geophysics.[2]

2. Water Content

At 1900 CST on May 20, 1962, the thunderstorm, one of a line of thunderstorms extending from Wichita Falls, Texas, to Wichita, Kansas, was 87 miles southwest of Oklahoma City. Entry into the storm was made along a heading of 050° at 29,000-ft alt. A time history of the water content along a path through the storm is shown in Fig. 1. Water content

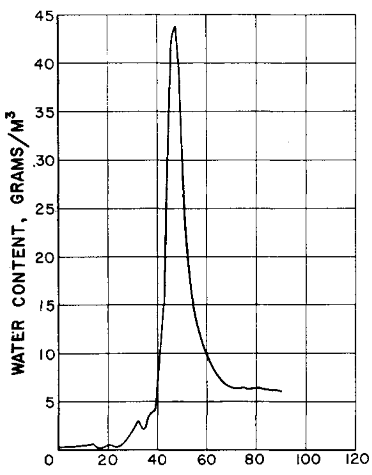

Fig. 1 Time history of free water content, May 20, 1962, 1900 CST.

was about $\frac{1}{2}$ g/m³ from the edge of the storm to the place where precipitation was first observed. A maximum of 43 g/m³ was reached near the center of the storm.

The shape of the storm is shown in Fig. 2. It was reconstructed from radar reflectivity measurements made by the WSR-57 radar. Echo contours were obtained by a step-attenuation circuit. Variation in echo contour for six intensity levels is shown for the period from 1846 to 1907 CST. Relative track of the aircraft through the storm and the profile of water content along that track are superimposed on the plan form of the echo. Analysis of photographs of the mixed video display from the IFF and WSR-57 radar provided an account of the aircraft track through the thunderstorm.

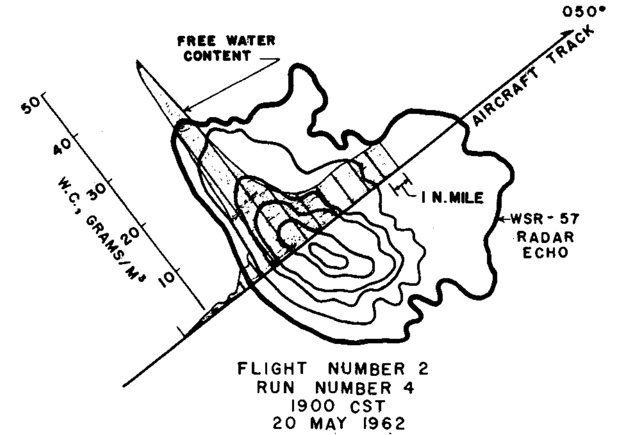

Fig. 2 Radar echo intensity and free water content profiles.

During the initial portion of the penetration the pilot reported light to moderate precipitation. Near the center of the storm, he encountered precipitation so heavy that it caused a series of compressor stalls in the engine. According to the two crew members in the F-100F, "It was just like running into a wall of water." Incidentally, the impact of water on the pilot boom was so severe that it caused the boom to separate from the aircraft. Many lightning flashes were observed at the same time that extremely heavy precipitation was encountered. A T-33 aircraft, directly below the F-100F at 23,000-ft alt, accumulated an inch of rime ice in less than a minute before being directed out of the storm.

3. Radar Reflectivity

A relationship between water content, drop size distribution, and radar reflectivity factor Z has been developed by Atlas and Bartnoff.[3] Variation of maximum radar reflectivity factor Z with time for the May 20 storm using WSR-57 (10 cm) and CPS-9 (3 cm) data was studied by Wilk[4] (Fig. 3). The 3-cm reflectivity factor showed a general increase after 1830 CST. The "spike" to $4\,0 \times 10^4$ mm⁶ m⁻³ occurred at 1859.5 CST and again from 1902 to 1907 CST. At the time of actual penetration, Z was 2.6×10^4 mm^6 m^{-3}. A corresponding time history of Z for the 10-cm radar showed two peaks at 1834 CST and 1900 CST. The peak value of 6.4×10^4 mm^6 m^{-3} corresponds within a few seconds to the time of the aircraft penetration. Difference in Z peak values at the two wavelengths suggests radical changes in the size of the hydrometeors within the thunderstorm. Some cloud particles photographed during the project revealed sizes in the neighborhood of 500 μ; many were much smaller. However, not enough particles were photographed to derive an accurate distribution. Consequently, drop size distribution at the time and altitude of the penetration is unknown.

Assuming, for example, that the hydrometers were water spheres of a single size, the diameter suggested by the Z measurement of 6.4×10^4 mm^6 m^{-3} would be about 10,000 μ (or 10 mm). Interpreting the relationship of Atlas and Bartnoff and assuming a maximum drop diameter of 10,000 μ (or 10 mm), the median drop size would be about 400 μ (or 0.4 mm). If the maximum droplet were smaller, the median

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Table 1 Water content data obtained in some thunderstorms

Date	Run, no.	Time, CST	Altitude to nearest 100 ft	Temperature, °C Ambient	Temperature, °C Std. atm.	Water content g/m³	Water content lb water/lb air	Comment
May 8, 1962	1	1629	30,900		−46°	13.8	0.0312	All 4 runs passed through same storm. In addition, 4th run passed through a neighboring storm.
	2	1641	31,000		−46°	11.9	0.0270	
			30,300		−44°	13.9	0.0309	
	3	1652	32,000		−48°	12.1	0.0285	
			31,600		−47°	10.8	0.0251	
	4	1709	31,000		−46°	13.6	0.0309	
May 20	1	1604	34,300		−53°	3.0	0.0077	Runs 1 through 4 were made through the same storm, 5 and 6 each were made through separate storms.
	2	1614	34,700		−53°	1.2	0.0032	
	3	1625	34,200		−53°	3.5	0.0090	
	4	1640	27,400		−39°	4.5	0.0090	
	5	1651	27,200		−39°	6.8	0.0134	
	6	1703	26,900		−38°	7.8	0.0151	
May 20	1	1831	33,300		−51°	6.7	0.0166	Runs 1, 2, and 3 passed through the same storm, run 4 passed through a neighboring one.
	2	1839	34,300		−53°	9.5	0.0231	
	3	1849	34,100		−52°	4.9	0.0124	
	4	1900	29,100		−42°	43.7	0.0922	
May 31	1	1835	34,000	−52°	−52°	5.3	0.0134	Only runs 2 and 4 were made in the same storm.
	2	1841	34,700	−52°	−54°	3.0	0.0079	
	3	1850	34,800	−52°	−54°	2.5	0.0067	
	4	1858	34,700	−53°	−53°	4.3	0.0113	
June 5	1	1708	34,900	−45°	−54°	7.6	0.0207	Runs 1, 2, and 3 passed through one storm. It appeared to disintegrate into two storms as the 4th pass began.
			34,800	−52°	−54°	5.9	0.0155	
			34,800	−51°	−54°	5.9	0.0155	
	2	1718	34,900	−51°	−54°	5.4	0.0144	
			34,600	−48°	−53°	9.6	0.0254	
	3	1726	34,900	−49°	−54°	7.6	0.0204	
			33,700	−45°	−52°	8.7	0.0226	
	4	1850	30,300	−38°	−44°	3.9	0.0090	

droplet would naturally have to be larger in order to produce the large amount of water that was encountered.

It can be seen in Fig. 3 that radar reflectivity increased for several minutes prior to the penetration and then decayed after the penetration. This suggests that the penetration took place about the same time that the storm reached maturity.

4. Other Storms

Table 1 reports the maximum water content measured on each penetration, the altitude at which it was encountered and, on a few occasions, the ambient temperature. The temperature pickup was not functioning properly for the other flights. Vertical temperature structure for the Standard Model Atmosphere is shown in the table merely as a base with which to compare the ambient temperature.

Water content was highly variable largely due to the choice of where (in orientation and direction) the penetration was made in the storm and the degree of maturity of the storm. Because a penetration is roughly a straight line pass through a storm, the precipitation encountered on a penetration may not adequately represent all regimes of rain existing throughout the entire cross section of the storm at the altitude at which the penetration was made. Furthermore, not all the penetrations on a particular flight were made through the same cell of a storm (see comments, Table 1).

On May 8, two cells, about 120 naut miles west of Oklahoma City were aligned in a northwest-southeast direction. The strongest cell was probed three times on east-west headings. Both cells were penetrated on the fourth probe on a southeast heading. Four samples of water content were taken in

Table 2 Fields of water

Run	Max. water content, g/m³	Sustained water content, g/m³	Sustained dist, naut miles
1	13.8	11.6	11
2	11.9	9.5	4
	13.9	12.0	7
3	12.1	10.2	6
	10.8	6.9	9
4	13.6	10.2	10
		8.8	23
		7.1	30

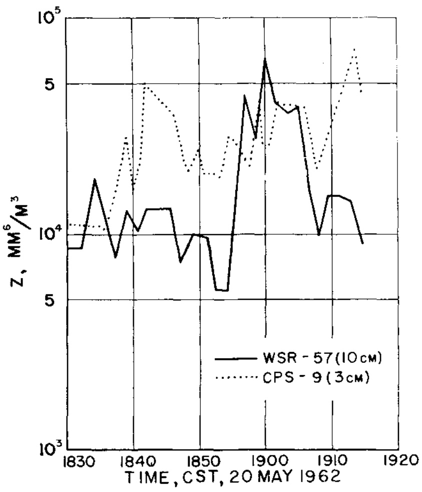

Fig. 3 Variation of radar reflectivity factor with time.

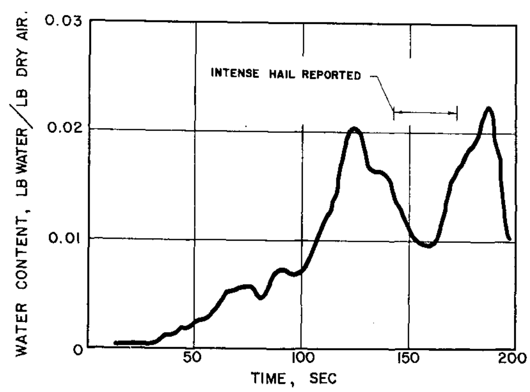

Fig. 4 Water content profile, run-3, June 5, 1963.

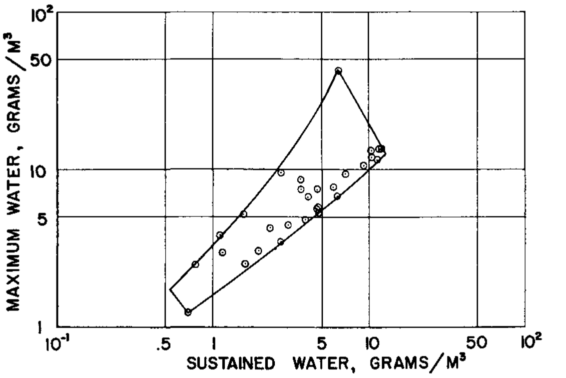

Fig. 5 Comparison between maximum and sustained water content.

the strong cell between 1629 CST and 1713 CST. In addition to the large water contents, this storm contained significant amounts of water spread uniformly and sustained over a distance, as shown in Table 2.

On June 5, the first three runs were made through a storm located about 120 miles northwest of Oklahoma City. The storm was rather stationary and did not seem to move at all. One particular characteristic of interest, noticeable also in the May 31 storm, but more distinctly in this one, was the unusual number of times narrow bands or shafts of water were encountered on a pass through a storm. Along the 30-naut miles flight path of the first penetration, water content oscillated, built up, and receded by as much as 1 g/m^3 six times. Two or three smaller peaks were also noted during this probe. Effects of gusts and drafts were not evaluated.

The aircraft passed through the core of the storm on the third penetration and two columns of water can be distinctly seen in Fig. 4. Although the water content did not exceed 9 g/m^3, heavy precipitation caused a few compressors to stall in the engine as the peak of the second column of water was encountered. An area of intense hail lasting for about 30 sec (covering a track of about 4 naut miles) was encountered as indicated on Fig. 4. The hail may not have completely evaporated before reaching the compressor discharge (instrumentation bleed-off point); this may account for the large change in water content during the encounter with hail.

Areas of heavy electric field activity and lightning inside storms may have some effect on the water distribution and may help to explain some of these unusual findings. Gusts and drafts, as well as electric field activity and lightning, must be evaluated in an effort that is undertaken to assess the distribution of water and hail inside severe storms.

5. Fields of Water

It was briefly mentioned earlier that large amounts of water, prolonged and sustained over a distance of 10 miles or more, were often encountered on some passes through a storm. Figure 5 shows some results obtained from all the tests. Circled dots represent the water data shown in Table 1 and water that was prolonged and sustained for one minute or more (8 naut miles of flight or more) for each pass through a storm. The general pattern, composed of data taken from 15 storms, shows that some samples of precipitation were over four times as heavy as the steady precipitation.

6. Summary

An infrared instrument, especially modified and fabricated to measure water content, was installed on a jet aircraft and tested inside some thunderstorms in the vicinity of Oklahoma City, Oklahoma, in May and June 1962. In the course of the investigation, 22 penetrations were made into 15 storms, and continuous measurements of water content were acquired during each penetration.

It was found that at altitudes between 26,000 and 35,000 ft some mature storms contained water of more than 10 g/m^3, and that near the center of one mature storm, extra-heavy precipitation measured 43 g/m^3 at 29,000 ft alt. In one storm, large "fields" of water measuring about 10 g/m^3 at 31,000-ft alt were found to have been sustained for distances as great as 11 miles.

References

[1] Roys, G. P., "Airborne instrumentation system for measuring meteorological phenomena inside thunderstorm," Aeronaut Systems Div., TDR-63-231 (May 1963).

[2] *Handbook of Geographics for Air Force Designers* (Air Force Cambridge Research Center, Air Research Development Command, U. S. Air Force, 1957), 1st ed., Chap. 6.

[3] Atlas, D. and Bartnoff, S., "Cloud visibility, radar reflectivity, and drop-size distribution," J. Meteor **10,** 143–148 (1953).

[4] Wilk, K. E., "Preliminary results in the investigation of the liquid water content in thunderstorms" (1963), unpublished study.