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T-28 AIRCRAFT OBSERVATIONS OF ALBERTA THUNDERSTORMS AND HAILSTORMS DURING THE SUMMER OF 1985

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ABSTRACT

A series of observations inside Alberta hailstorms was made with the T-28 armored research aircraft during the summer of 1985, while participating in the hail experiments being conducted by the Alberta Hail Project. This report summarizes those activities, both from the standpoint of data quality assessment and the beginnings of detailed research analysis for one case, 11 July 1985.

High quality data were obtained from penetrations of several storms. In addition, two unique measurements were made for the first time. A modification to the hail spectrometer provided 2-D hailstone images in flight, while a hailstone collection device successfully captured a hailstone in flight on two different occasions. Observations made on 11 July are presented and discussed, especially with regard to the possible hail growth mechanism in Alberta storms.

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1. INTRODUCTION

This is the final report of hailstorm research conducted with the armored T-28 aircraft by the Institute of Atmospheric Sciences (IAS) of the South Dakota School of Mines and Technology (SDSM&T) under Contract No. IAS 102.00.85, which ended on 31 March 1986. The IAS used the T-28 aircraft to make penetrations of Alberta hailstorms while participating in the hail experiments conducted by the Alberta Hail Project during the summer of 1985. The purpose of the investigations was to study the hypothesized growth trajectories of hailstones from the new growth zone (usually feeder clouds) into the main part of the storm.

Since the period of support was relatively short, the findings presented in this report should be considered preliminary. In addition to the field project activities, an assessment of data quality has been completed and a detailed analysis of data was begun during the contract period. This report provides a summary of findings to date, and it is hoped that future funding can be obtained that will permit the completion of the analysis of data gathered by the T-28 during the summer of 1985.

Section 2 reviews the flight operations of the T-28 during the project, while Section 3 provides a more detailed assessment of data quality. Section 4 provides information about the detailed analysis that has begun for the 11 July case, which was the best storm penetrated by the T-28 during 1985. Section 5 provides a summary of findings, and references are listed in Section 6.

2. FLIGHT OPERATIONS

Table 1 gives a summary of T-28 flight operations from the Alberta Hail Project during 1985. There were only six research flights during the season, which is a remarkably low number considering the normal high hail frequency in Alberta. It was a very inactive hail season.

The following are brief summaries of each research flight:

Flight 420: Only one penetration of a very active hailstorm was made because heavy icing forced the aircraft to descend after the penetration. After that, an intermittent transponder problem developed, so that positioning of the T-28 was unreliable and no more penetrations could be made.

Flight 425: This was a weak, dissipating storm. The data are so unspectacular that it is doubtful whether it will receive any further analysis attention.

Flight 426: This was a storm characterized by relatively weak updrafts and widespread weak downdrafts. Hail up to approximately 1 cm was present during Penetrations 1, 2, and 5. FSSP concentrations were very high on this flight.

Flight 427: This was obviously the best storm of the season for the T-28, which made four penetrations of it. There was a fairly large time separation between the first two penetrations and the last two penetrations because icing forced the aircraft to descend to get rid of the ice before making the last two penetrations. Hail sizes exceeded 3 cm at times, and cloud liquid water was high. This storm had no apparent feeder clouds and has been classed as a "front feeder" by personnel of the Alberta Research Council (ARC).

Flight 428: This was another weak storm, where the downdrafts were stronger than the updrafts. No hail was encountered, but the liquid water concentrations were again high. Icing was not a serious problem on this day; perhaps because the clouds were more like towering cumuli, so that the penetrations were of short duration.

Fight 429: This was also a weak storm, where the penetrations were carried out in rather widespread stratiform clouds with no apparent embedded cells. An in-cloud descent was made near the end of the flight to look for changes in the character of the particle images, especially as the aircraft passed through the freezing level. Unfortunately, the T-28 descended through cloud base before the freezing level was reached.

TABLE 1: Summary of 1985 T-28 Alberta Flight Operations

Flt	Date	Time [hrs]	Research Time Block [MDT]	Pens	NOVA Tape	PMS Tape	Hail Sensor	2D-C	Foil	Remarks
417	17 Jun	2.3								XC RAP-OLF.
418	18 Jun	1.9								XC OLF-CTB.
419	19 Jun	2.0								XC CTB-RED DEER.
420	23 Jun	1.8	1520 1610	1	Y	Y	N	Y	Partial	Heavy icing.
421	24 Jun	1.7	1505 1605		Y	Y	NA	NA	NA	Xponder check and intercomparison (R8).
422	25 Jun	0.9								Xponder check.
423	26 Jun	0.9								Xponder and hail sensor check.
424	27 Jun	1.2								Xponder check.
425	1 Jul	2.2	1850 1935	5	Y	Y	Y*	Y	Y	Dsptg storm.
426	5 Jul	1.4	1820 1910	5	Y	Y	Y	Y	Y	Small hail.
427	11 Jul	2.0	1825 1925	4	Y	Y	Y	Y	Y	Large hail.
428	17 Jul	1.9	1805 1905	4	Partial	Y	Y*	Y	Partial	TCU.
429	22 Jul	1.8	1800 1855	3	N	Y	N	Y	Partial	Wk stm. In cloud descent thru FL.
430	26 Jul	1.9								XC RED DEER-CTB.
431	26 Jul	1.5								XC CTB-OLF.
432	29 Jul	1.7								XC OLF-RAP.

TOTALS

Number of flights	16
Number of research flights	6
A/C flight hours	27.1
Number of cloud penetrations	21

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*Hail sensor worked, but no hail encountered.

3. DATA EVALUATION

3.1 General Comments

A high quality data set was obtained from several storms in Alberta, even though the occurrence of hailstorms was relatively low during the season. Brief descriptions of equipment performance are given below:

NOVA recording: The primary recording system worked well for flights up to and including the 11th of July. There were some minor recording problems on the first research flight of the season (Flight 420), in that no aircraft heading and one of the DME's may have been wrong. These were repaired following the first flight and presented no more problems during the rest of the season. On Flight 428, the spool on the magnetic tape loosened during the flight and recording stopped during Penetration No. 3. On Flight 429, the tape failed to record for an unknown reason. However, the unique feature of the T-28 data system is that it carries essentially a duplicate recording system in the Particle Measuring System (PMS) tape. Consequently, more than four of the flights have nearly duplicate recordings, while the rest of the flights have good data on one tape.

PMS recording: Even though the PMS system provided duplicate recording, there were some minor problems during the season. The true air speed, static pressure, and the manifold pressure recorded slightly low at times throughout the season. Where possible, the IAS values were used to replace the low PMS values. Also, it was possible to perform a pressure calibration on the T-28 during the field season, and these have provided a useful calibration of the data. The Forward Scattering Spectrometer Probe (FSSP) worked properly all season.

Hail sensor: For the first time, the 2-D portion of the hail sensor worked properly in flight. Hail was encountered and hail images were obtained on Flights 426 and 427. Hail was also encountered on Flight 420, but the hail sensor did not perform properly on this early season flight. The other three research flights were in weak storms with particles so small they were beneath the resolution of the hail sensor.

PMS 2-D probe: The PMS probe (2D-C) had major rehabilitation work during the previous winter and provided some of the best images ever with the T-28 system in 1985. The buffers have been dumped, so that a review of the images could be made. The preparation of appropriate particle size distributions have not been made because the IAS lacks the facilities to process the PMS images for that purpose. Fortunately, personnel at the ARC are providing this reduction, although not in time to be included in this report.

Foil impactor: In general, the foil provided good data, especially on the best research days (Flights 426 and 427). On some of the other days, portions of the foil were missing (up to 40%) for unknown reasons. However, on those days, the foil was mostly characterized by an almost complete lack of particles >1 mm maximum length. Several flights had missing punch mark holes, which are used to separate the penetrations. In any event, the foil impactor performed about as well as it ever does.

Hailstone collector: This device successfully captured a small hailstone (graupel) in flight on two different occasions (Flights 428 and 429). These data are being investigated by Nancy Knight of the Convective Storms Division at the National Center for Atmospheric Research (NCAR).

Table 2 shows a summary of selected observations by penetration for each of the research days. The temperatures of the penetrations were mostly colder than -15°C, and observations of equivalent potential temperature were lower than the peaks observed in T-28 penetrations in U.S. storms (Heymsfield and Musil, 1982; Musil et al., 1986). Generally, the peak downdrafts were stronger than the peak updrafts, and the peak liquid water concentration as measured by the FSSP ranged between about 1 - 3 g m^{-3}. The strongest values of turbulence were observed on Flight 427, which also was the most intense storm penetrated. Hail was observed on all the pentrations of Flight 427 and three of the five penetrations of Flight 426. The maximum sized particles on Flight 427 exceeded 3 cm.

3.2 Vertical Velocity

Since vertical velocity is of prime importance in hailstone growth, it is important to compare the methods used to calculate it from the T-28 data. Figure 1 shows a plot of several variables for Penetration 1 on 11 July. Shown are plots of turbulence, equivalent potential temperature, temperature, and pressure, plus the results of dual methods for calculating vertical velocity and liquid water concentration (LWC). The last two sets of curves provide a mechanism for graphically comparing vertical velocity and LWC.

Two methods are currently being used at the IAS to calculate vertical velocity using T-28 observations. The older method, based on work by Auer and Sand (1966), essentially uses aircraft rate-of-climb, plus correction factors for changes in manifold pressure and indicated air speed. In addition, several years ago, an energy correction term (Cooper, 1978), which accounts for changes in kinetic energy, was added as a further refinement in the calculation of vertical velocity for the T-28. This is labeled "Coop Up" in Fig. 1. The newer method is derived from work done by Lenschow (1976) and is based on the aircraft equations of motion. Both methods have been described by Kopp (1985), who compared them for a strong supercell case described by Musil et al. (1986). The results suggested that Kopp's method

TABLE 2: Synopsis of 1985 Observations by Penetration

Flt/Date	Pen	In [MDT]	Out [MDT]	$\tilde{T}$ [°C]	Max U [m/s]	Min U [m/s]	Max LWC [g/m^3]	Max Turb [$\varepsilon^{1\;3}$]	Hail	Max Size [cm]	Max θc [K]
420/23 Jun	1	153310	153841	-20	16	- 7	3.0	11	Y	unk	319
425/ 1 Jul	1	190655	190844	-16	5	- 9	0.3	7	N	--	329
	2	191201	191423	-17	2	- 8	1.7	11	N	--	328
	3	191805	191950	-17	3	- 3	1.2	10	N	--	327
	4	192210	192336	-17	2	- 9	1.1	6	N	--	325
	5	192512	192621	-18	2	- 5	1.1	6	N	--	325
426/ 5 Jul	1	183315	183632	-17	2	- 8	0.8	9	Y	0.9	328
	2	184312	184651	-17	4	- 9	1.6	12	Y	1.1	327
	3	184900	185157	-17	4	- 6	1.5	8	N	--	326
	4	185558	185847	-17	1	- 6	1.1	7	N	--	328
	5	190056	190337	-17	2	-17	1.1	9	Y	0.6	327
427/11 Jul	1	182942	183243	-16	15	-10	2.4	15	Y	5.0	331
	2	183746	184135	-17	6	-11	2.0	12	Y	5.0	329
	3	191421	191723	-17	13	-13	3.0	11	Y	5.0	328
	4	192040	192303	-17	16	-21	2.9	10	Y	4.0	329
428/17 Jul	1	181316	181544	-20	1	- 6	0.1	6	N	--	314
	2*	185327	185421	-20	8	- 9	2.7	--	N	--	314
	3*	185720	185819	-19	7	-18	2.4	--	N	--	316
	4*	190126	190241	-19	6	-10	1.4	--	N	--	315
429/22 Jul	1*	183400	183733	-17	8	-12	1.0	--	N	--	NA
	2*	183832	184718	-16	5	- 9	1.3	--	N	--	NA
	3*	184757	~185500	-16 to - 4	6	- 8	0.6	--	N	--	NA

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*Estimated from FSSP.

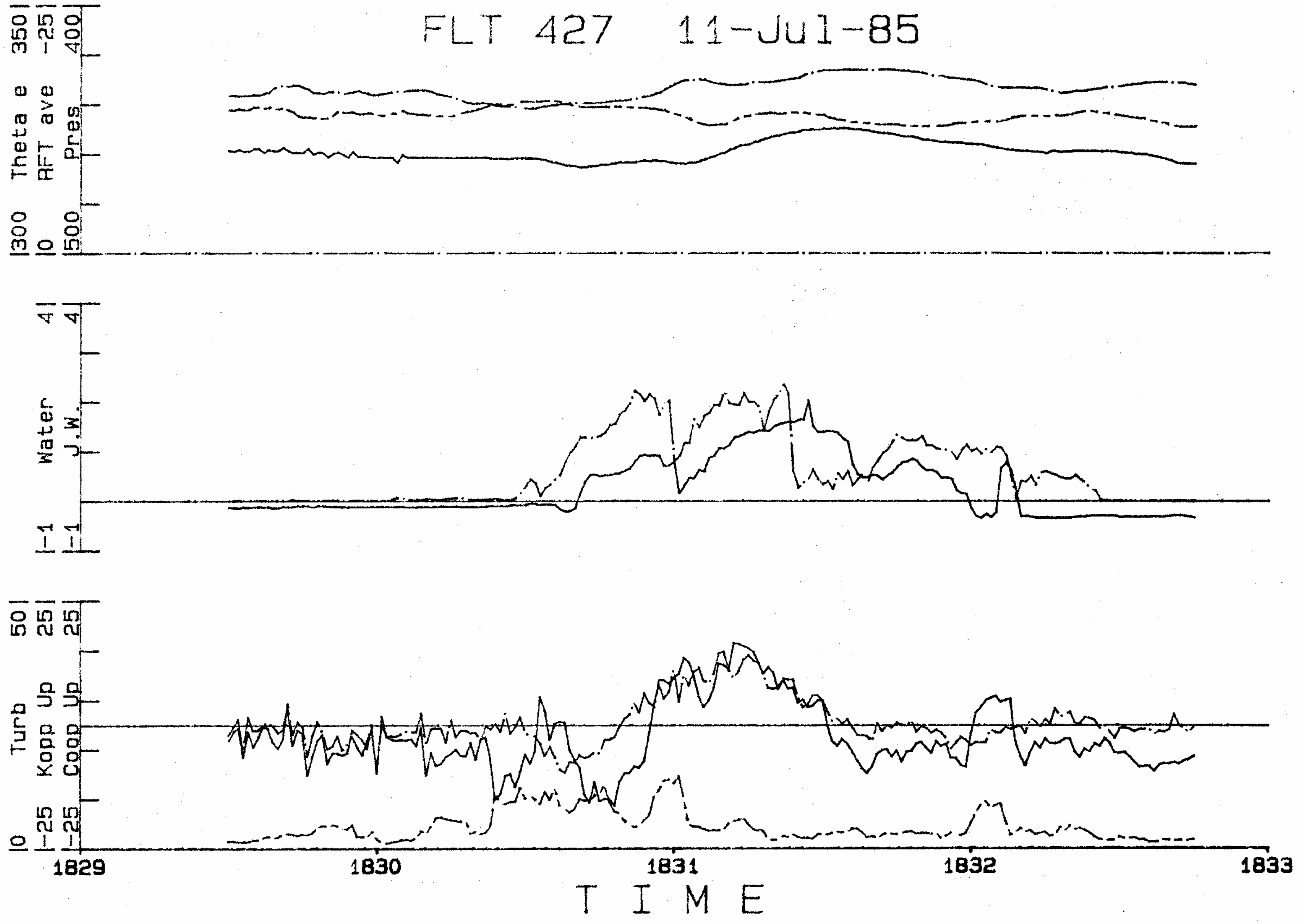

Fig. 1: Summary of T-28 data for Penetration 1 on 11 July 1985. Upper panel: Equivalent potential temperature - °K (dashed), reverse flow temperature - °C (dash-dot), pressure - mb (solid); Middle panel: FSSP water - g m^{-3} (dash-dot), J-W LWC - g m^{-3} (solid); Lower panel: Kopp vertical velocity - m s^{-1} (dash-dot), Cooper vertical velocity - m s^{-1} (solid), turbulence - $\varepsilon^{1/3}$ (dashed).

(labeled "Kopp Up" in Fig. 1) leads to better estimates of vertical velocity, and the Alberta data provide an excellent opportunity to make further comparisons.

The comparisons show quite similar results in relatively quiet regions of the cloud, but rather large differences often occur in other places, such as near 183035, 1831, and 1832 MDT. In many cases, the differences are thought to be a result of inadvertent pilot response that cannot be completely accounted for by the old method. These regions are almost invariably characterized by strong turbulence, which further supports this contention. Based upon the results shown in Fig. 1, plus the fact that similar differences occurred in the data from the other penetrations on 11 July, it is felt that the values calculated by the Kopp method provide better estimates of vertical velocity and will be used throughout the remainder of this report.

3.3 Liquid Water Concentration

Cloud liquid, also an extremely important factor in hailstone growth, can be compared in Fig. 1. Two methods have also been in use for calculating LWC using T-28 observations. One method shows a plot of the LWC as determined from the Johnson-Williams (J-W) hotwire device, while the other method determines LWC from an integration of cloud droplet size distribution as measured by the FSSP.

The J-W device tends to fluctuate more than the FSSP and drifts even to the point of showing negative values at times when the FSSP indicates that substantial amounts of cloud liquid were present (subsequent to 1832). The amount of drift shown in Penetration 1 is not so unusual during T-28 penetrations, but on Penetration 2 (Fig. 2), there was a wide region of cloud liquid indicated by the FSSP, while the J-W showed only an extremely small region around 1840.

Such large discrepancies are not acceptable, and they present a large uncertainty in the J-W data. An examination of the other T-28 data suggests that the J-W data appears to be okay at times, but is not consistently that way. Therefore, we have accepted the FSSP data as being more representative of the true value of cloud liquid in the Alberta data. Accordingly, the FSSP data will be used in all further discussions in this report.

3.4 Hail Sensor Data

For the first time in 1985, a modification to the hail spectrometer carried on the T-28 provided 2-D hailstone images in flight. Several buffers from the hail spectrometer near 183110 in Penetation 1 are shown in Fig. 3.

Good images are readily apparent (see A in Fig. 3), some as large as 2 - 3 cm in diameter. However, some problems exist, although the extent of their effect is unknown at this time. Some extremely large particles (B) are evident which are probably a result of shedding from

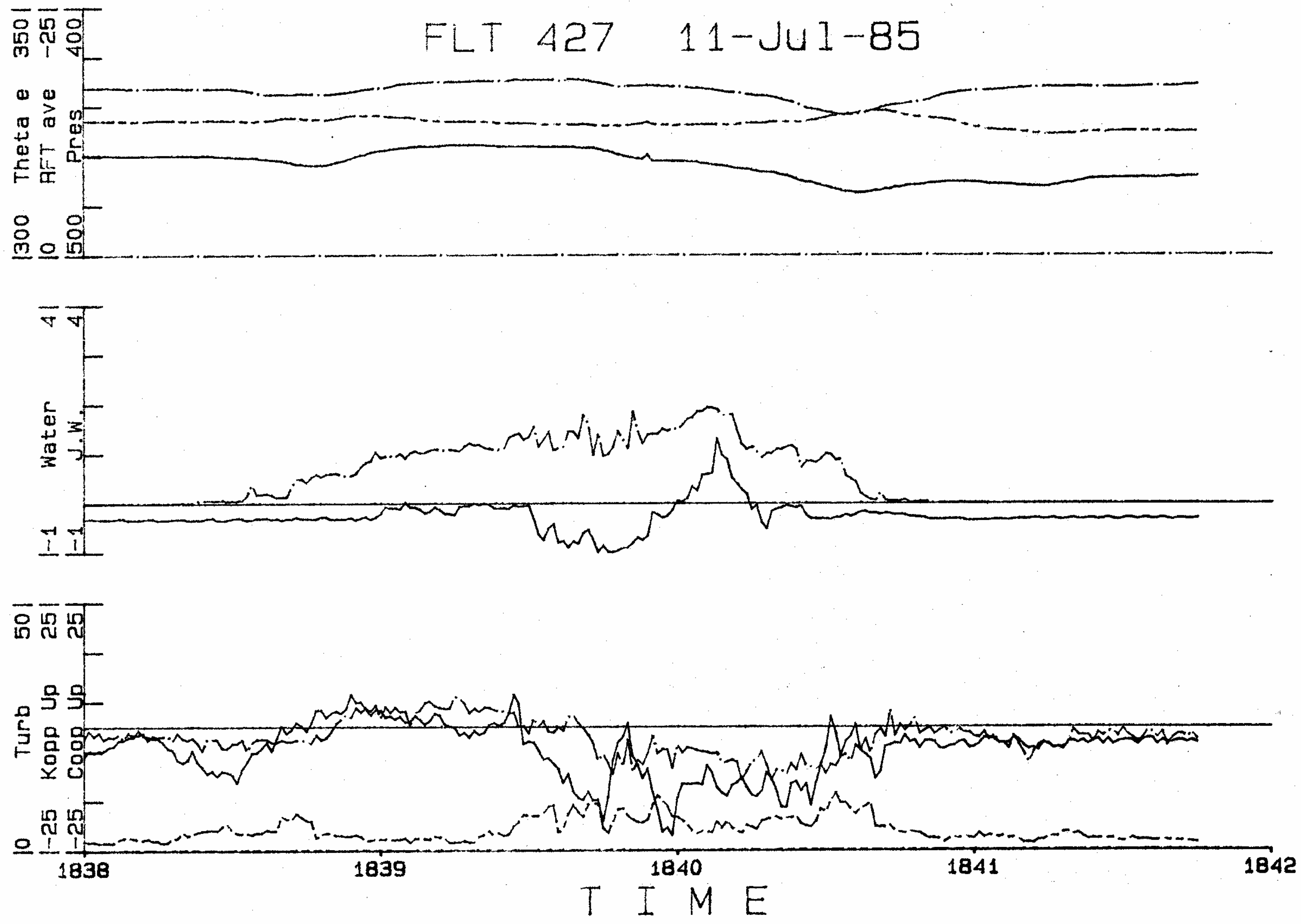

Fig. 2: Same as for Fig. 1, except for Penetration 2.

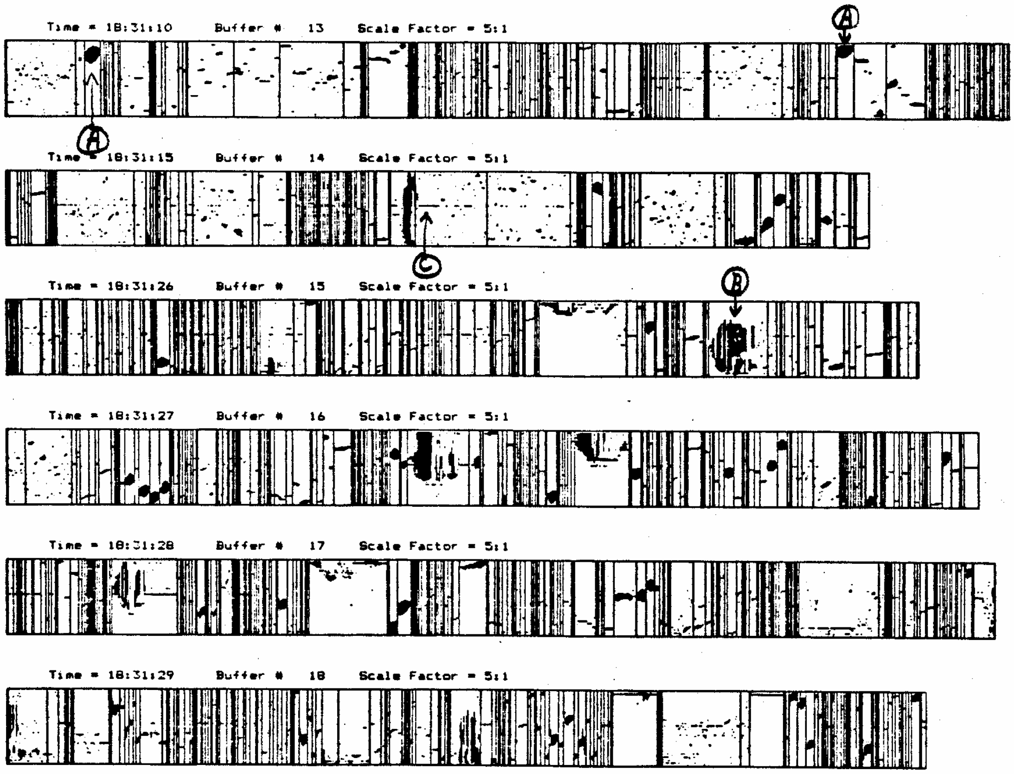

Fig. 3: Dump of several buffers from hail spectrometer between 183110-183129 MDT. Images appear five times smaller than actual particles. (A) Image > 3 cm diameter; (B) Shed broken up particle; (C) Weak intermittent diode malfunction.

the forward portion of the hail spectrometer. Some of these large particles also appear to be causing some sort of saturation problem in the hail sensor so that they appear partially broken up. A weak intermittent diode is also evident (C), as shown by the nearly continuous signal occurring at times near the middle of the buffer.

An evaluation of the hail spectrometer is currently underway. Generally, it is felt that the spectrometer behaved fairly well, but there is a possibility that some changes or adjustments to the hailstone distributions may have to be made at a later date. Just what needs to be done at this point is not exactly known, but it is likely that some manual counting and sizing of stones from the 2-D portion will have to be compared with output from the 1-D portion of the spectrometer. Also, comparisons can be made between the upper end of the 2D-C data and the lower end of the hail spectrometer distribution to determine how well the overlap region between the two devices fits. At this point, conclusions cannot be drawn, although it is felt that many of the characteristics of the hailstone distributions are adequately represented by the 1-D portion of the hail spectrometer data. They are certainly sufficient to discuss some of the analysis that has begun for the 11 July case.

4. 11 JULY ANALYSIS

The storm penetrated on 11 July 1985 was by far the best storm of the season for the T-28. Four penetrations were accomplished and large hail was encountered on each of them. A detailed analysis of the data gathered on this day was begun during the contract period, with the main concentration of effort involving the hail observations. Despite some of the uncertainties mentioned in Section 3, it is not anticipated that they will seriously affect the discussions in this section.

4.1 Hailstone Size Distributions

The hailstone size distribution summarized for each penetration on 11 July are given in Figs. 4-7. In Penetration 1 (Fig. 4), good images were present to about 4 cm so that high confidence in the data is possible to sizes that large. Some of the 4- and 5-cm hailstone counts may be questionable, but those problems need additional study. The total concentrations of hailstones will not be affected very much by erroneous counts of large stones because the existing high concentrations of small stones overwhelm that calculation.

The time of observation in Fig. 4 indicates the time when hail was observed during the penetration. The hail was continuous during that entire time period, although the concentrations fluctuated a great deal when considered on smaller time scales than presented here. The time corresponds to a hail region of approximately 9 km in this case, which is a relatively large region of continuous hail. It appears that the hailstones do not conform exactly to an exponential distribution, although no attempt was made to fit any curve to the distributions. A comparison of the presence of hail with radar reflectivity was not possible because the latter was not available to be included in this report.

Comparing the hailstone size distributions of Penetrations 1 and 2 (Figs. 4 and 5), shows that Penetration 2 had a larger region of hail (approximately 13 km across). There were more stones in Penetration 2 (note scale change on ordinate); in fact, the concentrations in each individual size category tended to be larger. Thus, the average total number concentration and equivalent ice water concentration were also larger. The reasons for the higher values are not known, except the flight track for Penetration 2 carried the airplane through the higher reflectivity regions north and east of the strong updraft region. Penetrations 3 and 4 (Figs. 6 and 7) have distributions that were more similar to those found in Penetration 1.

The mass concentrations shown here make use of the assumption that ice has a density of 0.9 g cm^{-3}. Thus the mass concentrations are somewhat higher than those found by other investigators (see, for example, Heymsfield, 1978). A comparison of hailstone masses shows that, on the average, Heymsfield's method gives hailstone masses that

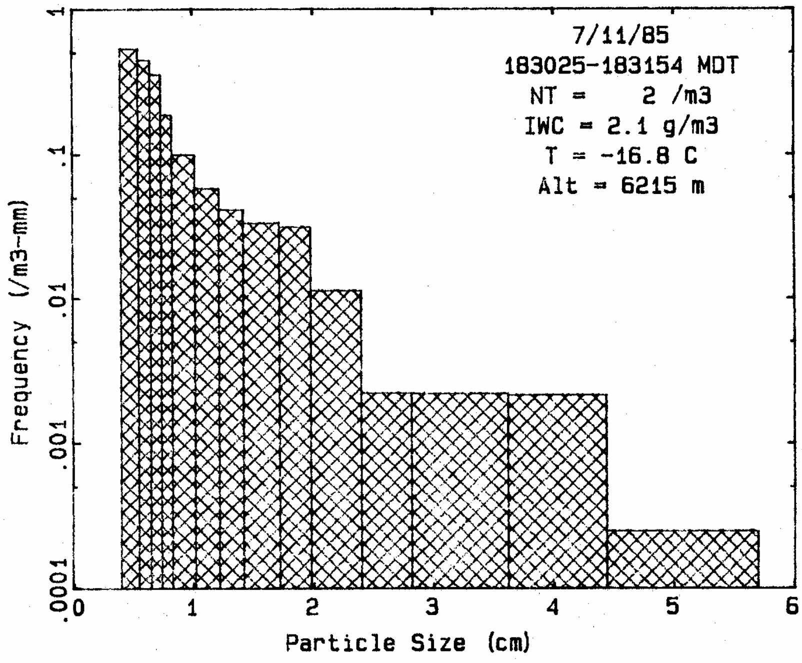

Fig. 4: Hailstone size distribution for Penetration 1 for 11 July 1985 from 1-D portion of hail spectrometer. Inset indicates time when hail was observed and averages for total concentration (NT), equivalent hail water (IWC), temperature (T), and altitude (ALT) for that period. Ordinate has units of m^{-3} mm^{-1} of size interval.

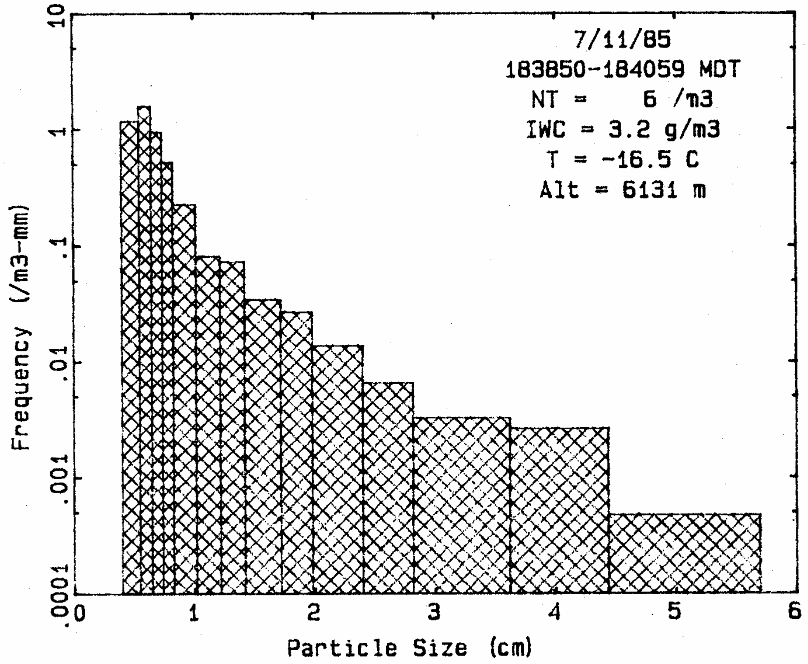

Fig. 5: Same as Fig. 4, except for Penetration 2.

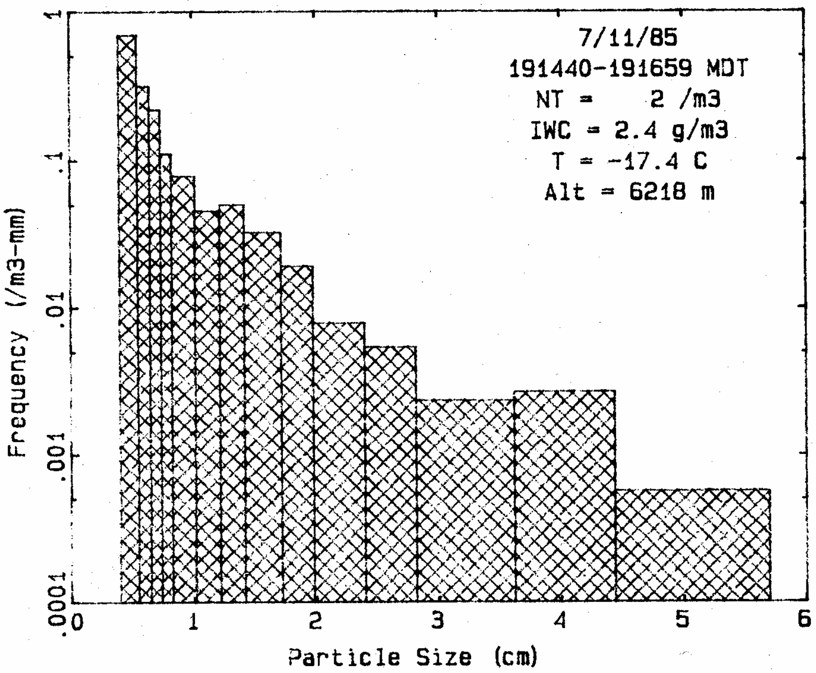

Fig. 6: Same as Fig. 4, except for Penetration 3.

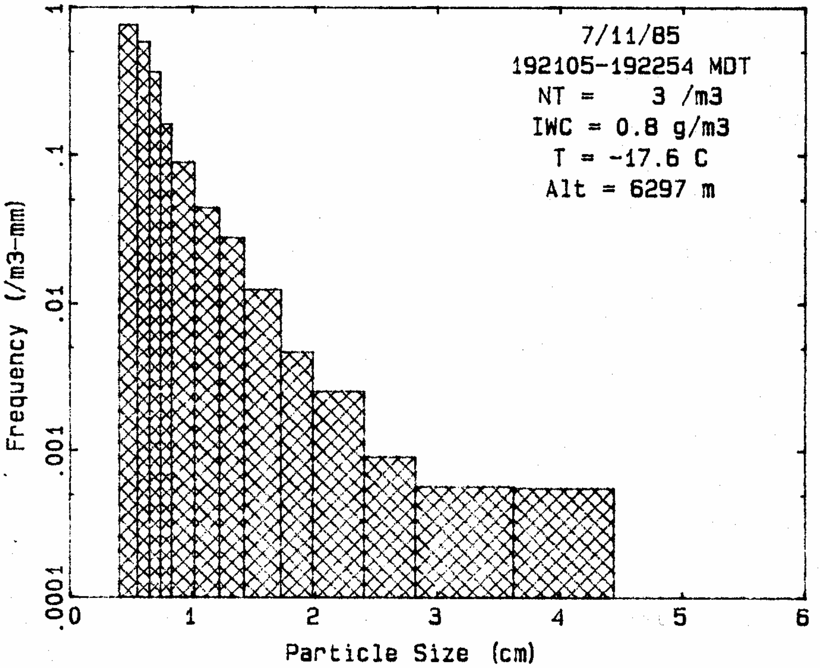

Fig. 7: Same as Fig. 4, except for Penetration 4.

are between 20-30% lower than those which assume a constant density. The percentage difference is even greater for the smaller size hailstones where Heymsfield's method may be more correct, because the density of them has been observed to be lower than 0.9 (Knight and Heymsfield, 1983).

Hailstone size distributions have been made for as low as 5-sec time intervals for each of the penetrations; however, no further analysis of them has been accomplished at this time. Also, studies need to be done which fit the hailstone observations to some type of curve and to determine the possible effects of uncertainties in the 2-D portion of the hail spectrometer. The penetrations also need to be fit into the context provided by the radar reflectivity.

4.2 Location of Hail

The location of the hail with respect to the other measurements can be seen for each penetration in Figs. 8-11. In these figures, the water equivalent of hail (IWC) and the total concentration (NT) for 5-sec time periods are plotted along with the FSSP cloud water, the Kopp vertical velocity, and turbulence.

In Penetration 1, the hail is found primarily near the edges of the updraft region where the vertical velocities are less, or even become, downdrafts. There is hail throughout essentially the entire LWC region indicating that virtually all the hail observed is still growing by accretion.

In Penetration 2 (Fig. 9), most of the hail is found after about 1840 in a relatively large downdraft region. The region of hail found near 1839 is questionable because this appears to have been a time period when the hail sensor was malfunctioning. As in Penetration 1, most of the hail is found in the region of LWC. This phenomena is also noted in Penetrations 3 and 4 (Figs. 10-11). However, the pronounced tendency for hail along the edges of the updraft regions as found in Penetration 1 did not occur in the other penetrations. Of course, the penetrations did not pass through the same portion of the storm in each case.

4.3 Hail Growth Process

In Section 4.2, it was obvious that the hailstones encountered were still growing because they were consistently found in regions of liquid water. In fact, when the mass of hail which is accreting is compared with the total mass of hail found in each penetration, nearly 100% of the hail is still in a growth environment when encountered by the T-28.

4.3.1 Hailstone motions

The number and mass concentrations of hail in conjunction with cloud liquid water help to delineate the hail growth regions

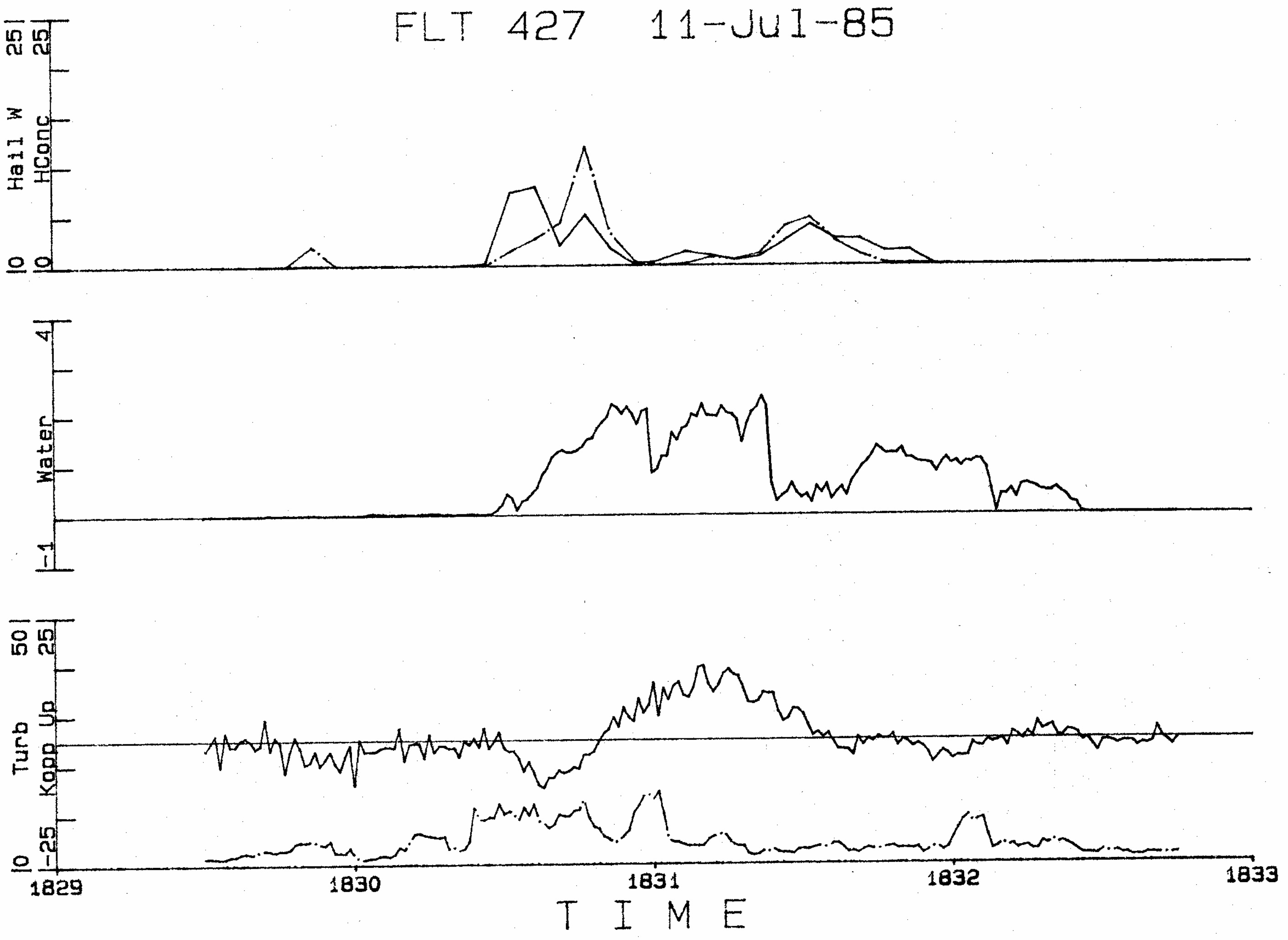

Fig. 8: Summary of T-28 data for Penetration 1 on 11 July 1985. Upper panel: Equivalent hail water - g m^{-3} (dash-dot), hailstone number concentration - m^{-3} (solid); Middle panel: FSSP liquid water - g m^{-3}; Lower panel: Kopp vertical velocity - m s^{-1} (solid), turbulence - $\varepsilon^{1/3}$ (dash-dot).

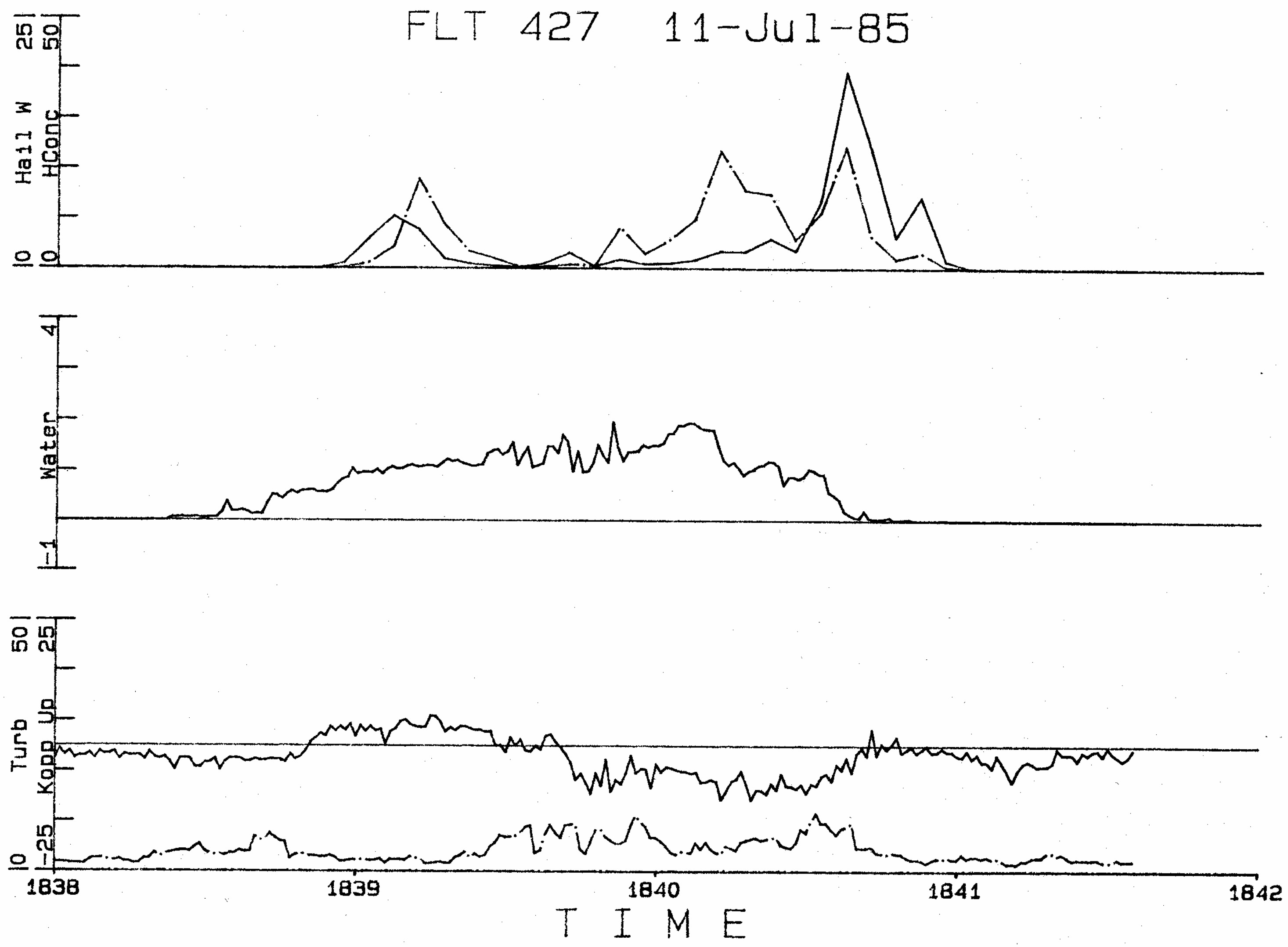

Fig. 9: Same as Fig. 8, except for Penetration 2.

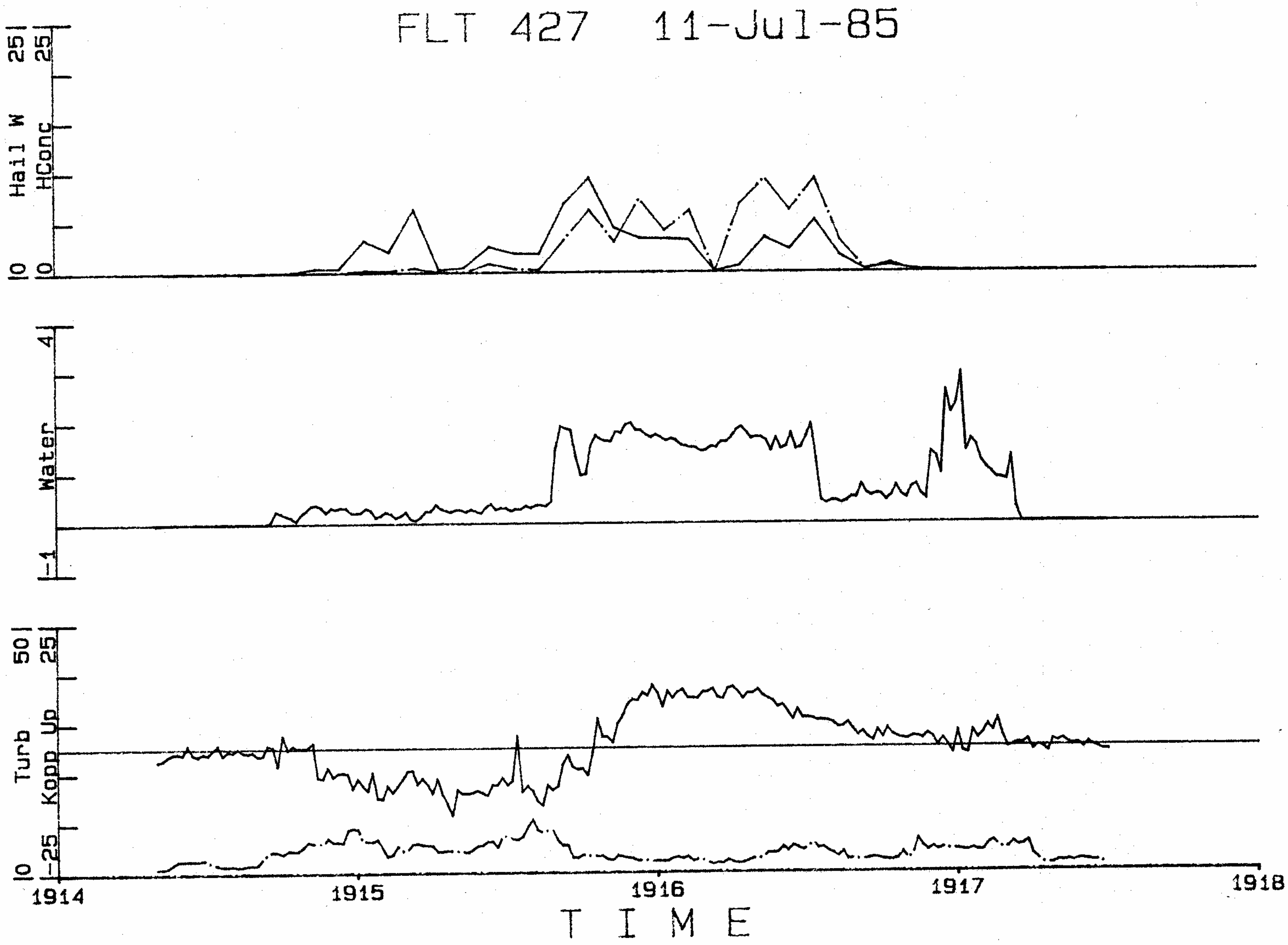

Fig. 10: Same as Fig. 8, except for Penetration 3.

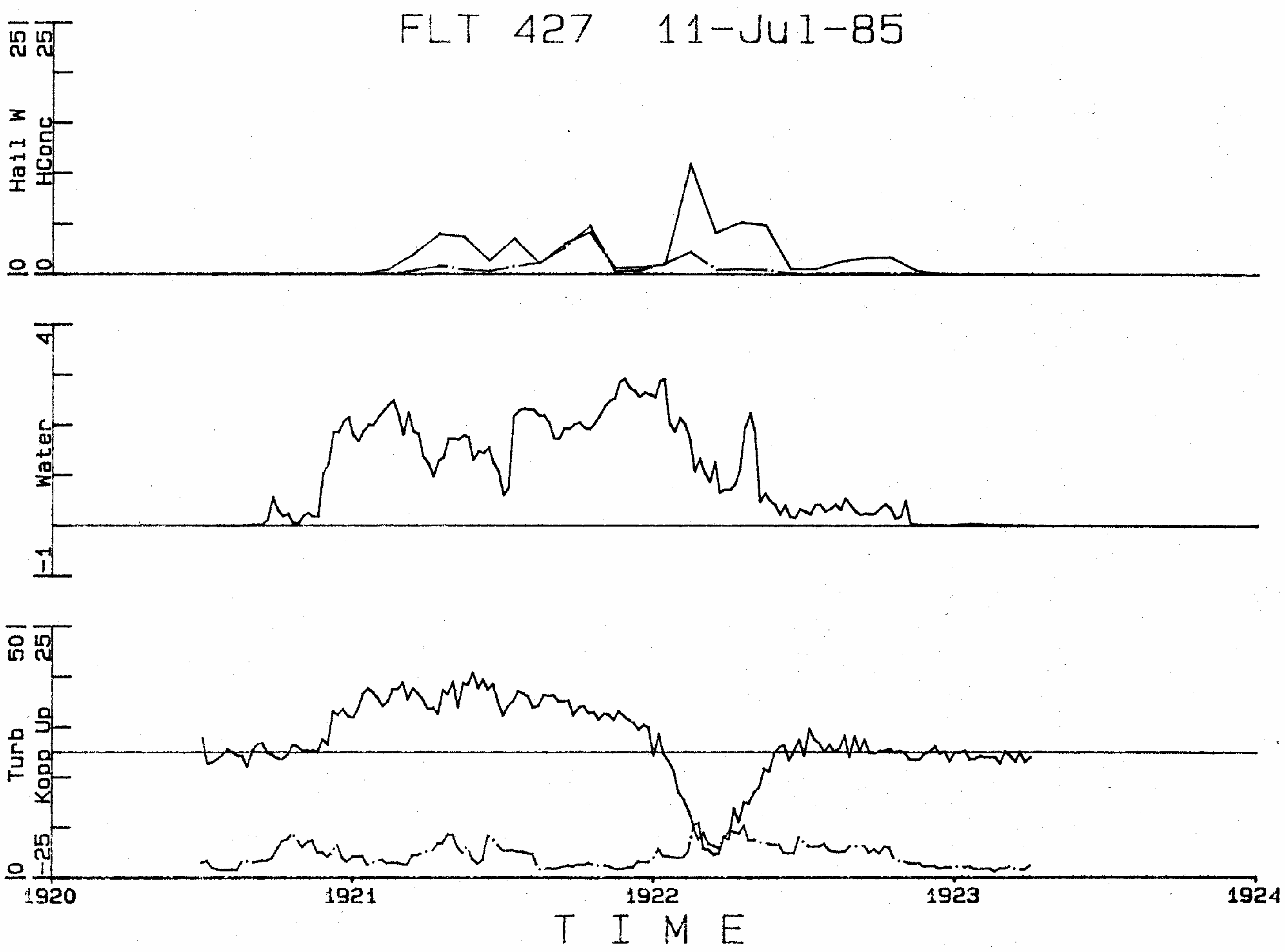

Fig. 11: Same as Fig. 8, except for Penetration 4.

(Figs. 8-11). A determination was made of which hailstones were rising by comparing T-28 related vertical velocities and calculated terminal velocities (V_t) of the observed hailstones.

A problem arises when comparing terminal velocities and vertical velocities because they are two quantities with rather large inherent inaccuracies. Thus, precise calculations are difficult. Little is known about V_t of actual hailstones in atmospheric freefall, although several investigators (e.g., Knight and Heymsfield, 1983; Heymsfield, 1978) have made recent calculations for hailstones falling near the ground. Some studies of growing particles in Doppler flow fields (Paluch, 1978; Heymsfield, 1982?; Foote, 1984) have used techniques to find V_t that are closely related to the Heymsfield study (1978). Auer et al. (1971) made measurements that resulted in similar terminal velocities, and Pflaum (1980) also found similar values from wind tunnel experiments.

All the above investigators use values of V_t that are approximately 40-60% less than those used by Musil (1970), Dennis and Musil (1973), and Nelson (1983) for hailstone sizes between 1-2 cm diameter. These authors assumed a hailstone density of about 0.9 g cm^{-3} for all stones which results in terminal velocities that are substantially higher than those mentioned in the previous paragraph. Heymsfield (1978) used an empirical formula that attempted to account for variable hailstone density, where smaller stones tended to be less dense than the larger ones. Thus, the differences between the two techniques are less for larger hailstones, although terminal velocities from the Heymsfield method tend to be smaller throughout the entire hail spectrum. In view of the fact that the observations tend to show lower terminal velocities for the smaller sizes and knowledge is limited anyway, it was decided to use the Heymsfield empirical equation for estimates of V_t.

The hailstones that were rising or falling can be seen in Fig. 12, which shows largest hail observed in 5-sec time periods during Penetration 1, as well as a plot of the maximum sized hailstone that was just balanced in the vertical velocity field at that time. The region of rising hail in the updraft is relatively small compared to the total amount of observed hail. Whenever the balanced curve (dashed) is above the maximum size hail observed, all observed hail is rising in the updraft, and when it is found below the maximum sized curve, only a portion of the hail observed is rising. In all other regions, all the hail is descending in downdraft air. In terms of mass that is rising, the amount of hail mass ascending is relatively small compared to the total amount of hail observed, ranging from <1% on Penetration 2 to about 20% on Penetration 4. In other words, even though most of the hail is growing when observed, most of it is also descending, even in the updrafts at T-28 altitudes. If hailstones of constant density of 0.9 g cm^{-3} had been assumed, the regions of rising hail mass would have have been even smaller.

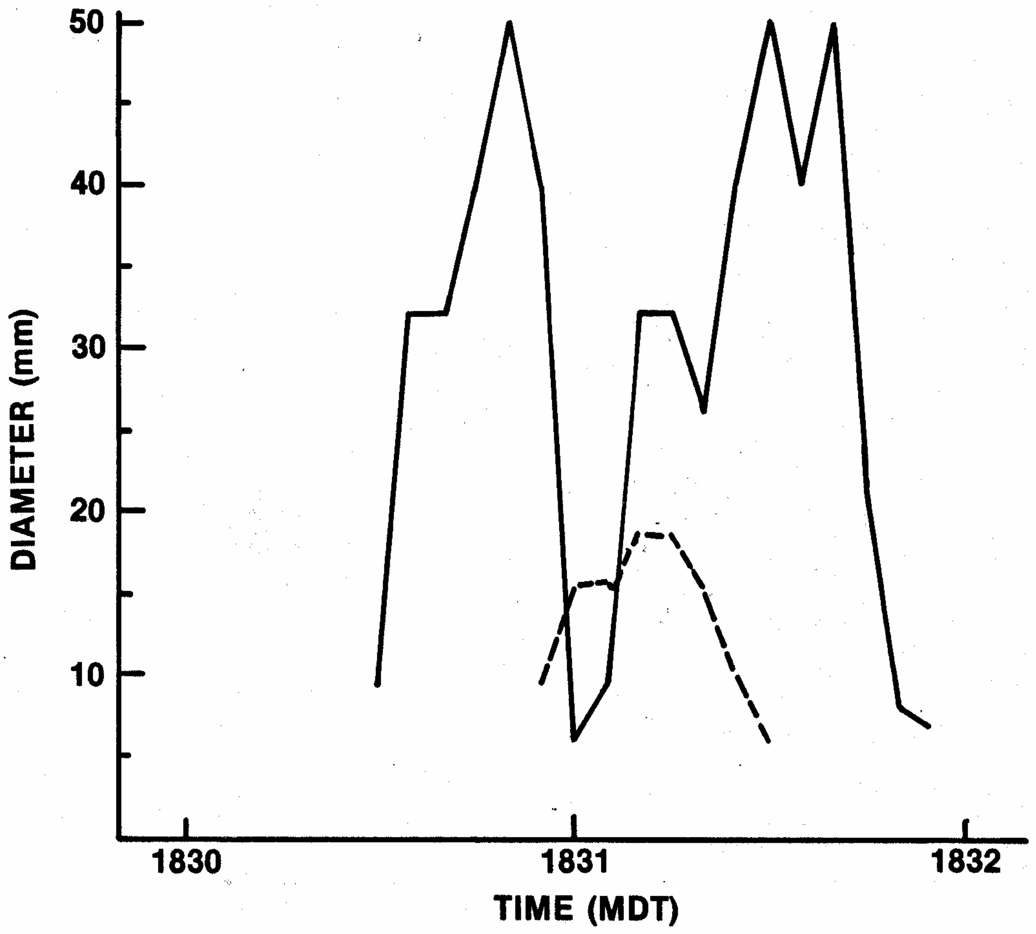

Fig. 12: Distribution of hail vs. time for Penetration 1 on 11 July 1985. Solid line shows maximum-sized hail, while dashed line shows maximum-sized hail that is just balanced in the updrafts for 5-sec time periods.

While it is true that hailstones found in downdraft regions will grow if liquid water exists, it is felt that the hail will probably deplete the liquid rather quickly in those regions (about 2 min?). This remains to be calculated with some simple depletion equations (Heymsfield and Musil, 1982). Hailstones found in the updraft certainly would have the best opportunity to continue growing because there is an ample supply of cloud liquid that is being replenished. Further investigation could provide some clues regarding the precipitation mechanism in Alberta storms.

Questions about the depletion of the cloud liquid by the hail (and other ice hydrometeors) still need further study (Heymsfield and Musil, 1982); neither have mixing processes been investigated, but a method employed by Paluch (1979) could be used. Mixing may have occurred because there are no distinct regions of high equivalent potential temperature (see Fig. 1) as is often observed in other T-28 observations (Heymsfield and Musil, 1982; Musil et al., 1986).

4.3.2 Growth mode considerations

The growth mode of hailstones in Alberta storms was investigated by computing the wet and dry growth rates of hail for a wide variety of hailstone sizes, liquid water contents, and temperatures. The presence of small ice was also considered and was found to be an important factor. The equations used to calculate the dry and wet growth regimes follow slight modifications to those used by Musil (1970) and Dennis and Musil (1973).

A sample output showing the dry and wet growth regimes for one set of conditions near those found on 11 July is shown in Fig. 13. The area to the left of the -15°C temperature curve is the dry growth region, while the area to the right outlines the wet growth region. The dashed line outlines the approximate region where the bulk of the hailstones was observed on 11 July.

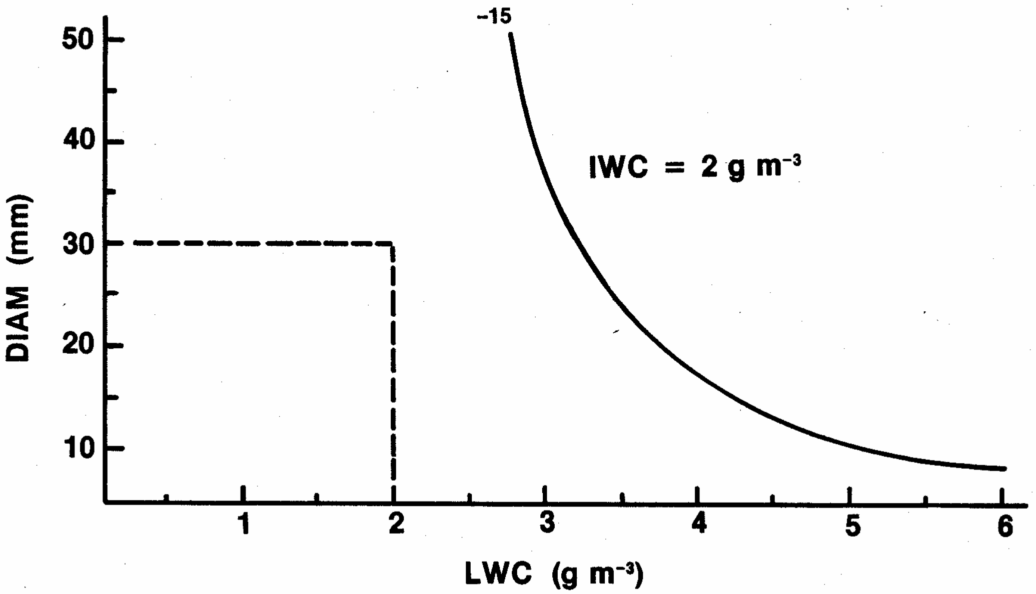

Fig. 13: Plot showing regions of dry and wet growth of hailstones for a temperature of -15°C and an IWC = 2 g m^{-3}. Inset enclosed by dashed line is within dry growth region to left of -15°C temperature curve and defines approximate region where most of the hailstones were observed with the T-28 on 11 July.

The vast majority of hailstones are well within the dry growth regime, which is not too surprising considering the cold temperature of the penetrations. Nevertheless, there is a strong suggestion that drop embryos resulting from the shedding during wet growth is not very likely, at least in the region where the hailstones were observed by the T-28. This is not to say that they cannot occur in other regions of the storm, but it would have to be at warmer temperatures in lower regions of the cloud. Of course, the production of drop embryos could result from the melting of hail closer to the ground, followed by recirculation.

Further testing and refinement are necessary, and it is planned to explore these considerations in the future. It will be necessary to define the dry/wet growth conditions in more detail than has been presented here by determining the growth mode of the hailstones using the actual conditions in which they were observed.

5. SUMMARY OF RESULTS

5.1 Data Quality

The analysis of the data gathered during 1985 in Alberta is not complete. As was originally planned, much of our analysis effort has been devoted to assessing data quality. That assessment has shown that a high quality consistent data set was obtained during the 1985 Alberta field season, despite the fact that a low frequency of hailstorms was observed. Hail was observed on three research flights, one of which (11 July) was a very active case with large hail. The completeness and high quality of the data set for 11 July permitted direct comparisons of different methods of computing vertical velocity and liquid water concentrations, which attains further refinement and greater confidence in the data set.

The 2-D portion of the hail spectrometer provided images of hailstones in flight for the first time. Although questions remain, the device seemed to work adequately and provided reasonable size distributions. A hailstone collection device carried on the aircraft successfully captured a small hailstone in flight on two different occasions. These hailstones are currently under investigation at NCAR and will be reported at a future date.

5.2 Hail Growth Mechanism

The beginnings of a detailed analysis of the data gathered on 11 July have produced some interesting preliminary results. Hail was observed over large regions of each penetration on 11 July and in a relatively continuous fashion. Furthermore, the hail was almost always observed in relatively high concentrations of cloud liquid, of the order of 1-2 g m^{-3}. This indicates the hail was still growing at the time of observation, even though further investigations showed that most of the hail was not being carried upward in the storm at the time. Most of the hailstones observed by the T-28 were growing in a dry growth regime, at least in regions of the storm that were penetrated by the T-28. Further investigations are necessary in order to determine the details of this process.

5.3 Future Plans

The primary effort should be to complete the analysis of the data gathered on 11 July. Additional work is necessary to combine the foil, hail spectrometer data, and 2D-C data in order to examine the total hydrometeor spectra measured by the T-28. Furthermore, a better understanding of the spectra will have a bearing on other parts of the analysis, such as the hail growth mechanism.

There is also a need to evaluate the hail spectrometer data in light of the observations made with the newly developed 2-D portion of the spectrometer. The hail images appear to be useful; however, there are questionable areas in the data and these must be evaluated. The number concentrations of hailstones are not likely to be affected very much in this regard, but the mass concentrations could be affected a great deal because some of the uncertainty is on the large end of the spectrum.

There is still information to be gained about the hail growth mechanism occurring in this storm. One avenue not yet explored is to make model comparisons between the aircraft observations and the results of 2D time-dependent model simulations for both bulk water and hail-category microphysics.

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