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THE ENHANCED-V, A SATELLITE OBSERVABLE SEVERE STORM SIGNATURE

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ABSTRACT

Enhanced infrared satellite imagery is used to examine severe thunderstorms that display a warm spot accompanied by a signature called an enhanced-V. This enhanced-V is formed when strong upper level winds are diverted around an overshooting thunderstorm top. When a storm has an enhanced-V, it has a high probability of subsequently producing severe weather. Two rules for identification of an enhanced-V are established. The median lead time from enhanced-V identification to the first severe weather report was 30 minutes. A low false alarm ratio makes this identification technique a potential severe storm warning tool. However, a relatively low probability of detection indicates that there are many severe storms that do not show an enhanced-V.

1. INTRODUCTION

The potential use of satellite data to detect severe thunderstorms has barely been explored. Purdom (1975, 1979) discussed severe thunderstorm precursors such as intersecting arc cloud lines and cumulus congestus inflow lines that are observable on visual imagery. Anderson (1979) looked at anvil flow patterns of intense tornadic storms and found some to have a spiral-banded, anticyclonic outflow up to 90° to the right of the ambient wind. However, little has been done to date on quantifying how useful these techniques would be to an operational meteorologist for determining if a particular storm is severe or not.

The enhancement of infrared satellite imagery offers a unique way of observing thunderstorm growth patterns. Using an enhancement curve such as the MB (Fig. 1) (Corbell et al, 1976), which gives the most detailed cloud top temperature resolution in the -32°C to -80°C range, an analyst can monitor thunderstorm tops with considerable detail. In one case study, Adler and Fenn (1979a) found that the cloud top growth rate and the minimum cloud top temperature were useful in detecting severe storms. However, further studies showed that the critical threshold values for growth rate and minimum temperature seem to vary from case to case (Adler and Fenn, 1979b).

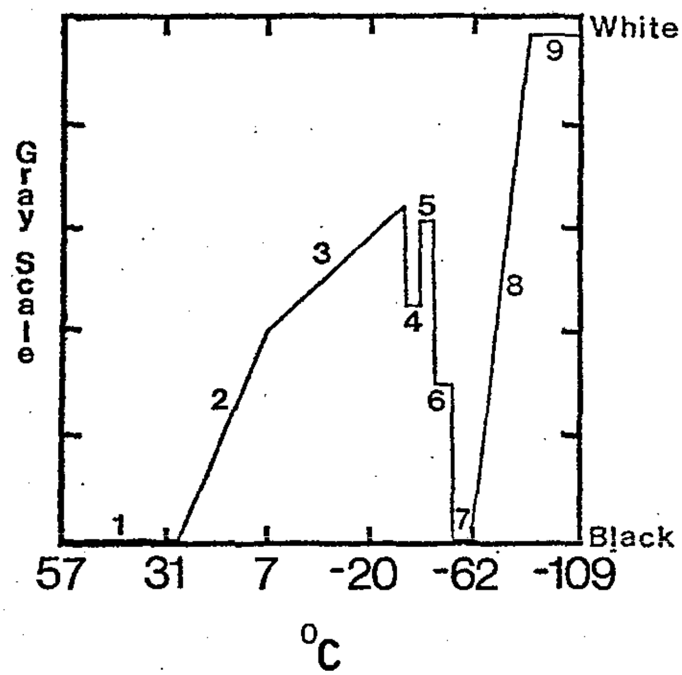


Figure 1. The MB enhancement curve (Corbell et al, 1976).

Mills and Astling (1977) noted that some severe thunderstorms display a distinctive signature on enhanced IR imagery. This signature is a warm spot on the storm's top. Three possible explanations of this signature were offered. The difference in emissivity between the overshooting top of the storm with its strong updrafts and the surrounding cirrus anvil would account for a warm spot. Since the updraft portion of the top is thicker than the surrounding cirrus, the emissivity of the central portion is higher and has a warmer equivalent blackbody temperature. Mills and Astling showed that if the emissivity of the updraft region is 20% greater than the surrounding cirrus and the cloud top has a uniform temperature, this effect accounts for temperature differences of about 15°C.

Mills and Astling also noted that warm spot could possibly be due to mixing of warmer stratospheric air with updraft air. The mixed portion of cloud would gradually acquire the stratospheric temperature and become warmer than the surrounding anvil.

A third explanation offered was that the warm spot in the anvil is caused by downward rather than upward motion. Subsidence would not only produce a depression by lowering the cloud top but also would cause adiabatic warming. Fujita (1978) embraces this concept as the caused mechanism of downbursts. The warm spot depicts a collapsing top which initiates the downburst.

In the satellite imagery, cold area adjacent to the warm spot many times resembles a V-notch on a contoured radar display. The storms over north central Oklahoma (Fig. 2) depict the features of this signature. For storm A,

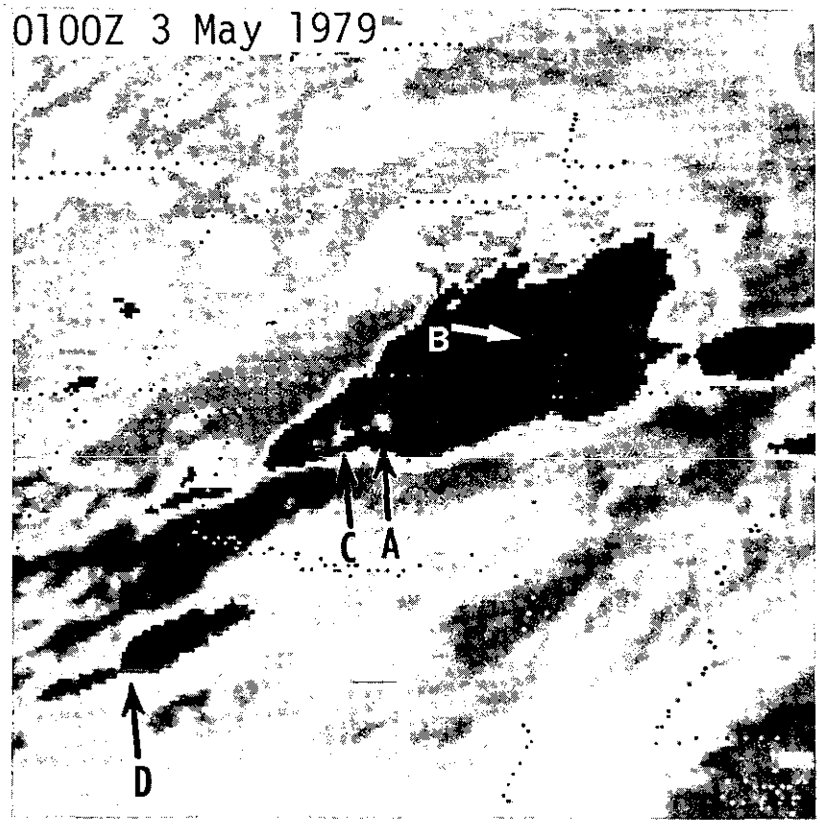


Figure 2. Satellite imagery of the lower Midwest enhanced with the MB curve (0100Z, 3 May 1979). Enhanced-V storms are noted "A" through "D".

the cold area is almost white while light gray areas form a V-shaped configuration with the cold area at the point of the V. This V-shaped configuration will be called the enhanced-V. The black area between the arms of the V is warm with even warmer gray enhancement enclosed by the black showing the warm spot. Other enhanced-V's are noted as B through D in the figure.

This paper discusses the enhanced-V and its usefulness as a severe thunderstorm detector. A case study of enhanced-V evolution is presented in the text, and several more appear in the appendix. It will be shown that the enhanced-V can be considered a useful warning tool. However, first the cause of the enhanced-V will be examined.

2. CAUSE OF THE ENHANCED-V

The interaction of the overshooting top with the upper level winds can explain the formation of the enhanced-V. As noted by Fujita (1978) an overshooting top acts to block the wind and diverts the flow around it. The resulting streamlines are similar to those of turbulent flow past a cylinder (Fig. 3). Further, the strong flow impinging on the windward side of the top erodes the updraft summit and thus cools. This air is then diverted around and past the remainder of the top and contains cloud debris which forms the enhanced-V signature of colder air.

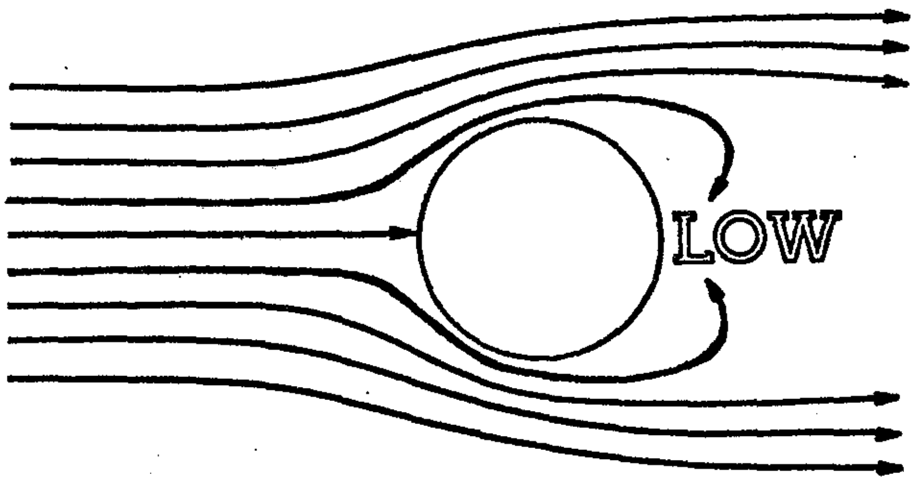


Figure 3. Turbulent flow past a cylinder showing a low pressure area developing in the wake

An explanation for the warm spot in the lee of the dome awaits further study. Observational and theoretical evidence can be cited to support warm spot formation by either downward motion or by upward motion in the lee of the overshooting top. In the first case, downward motion arises as air flows over the dome and down the back side (Fig. 4). This subsidence causes the air to warm part of the anvil to evaporate in the lee of the overshooting top. This results in the warm spot. Visual observations of a "crater" or a "trench" in the anvil were reported by Burns and Harrold (1966) and Fujita (1978). Downward motion was noted above the "crater" in the Burns and Harrold study.

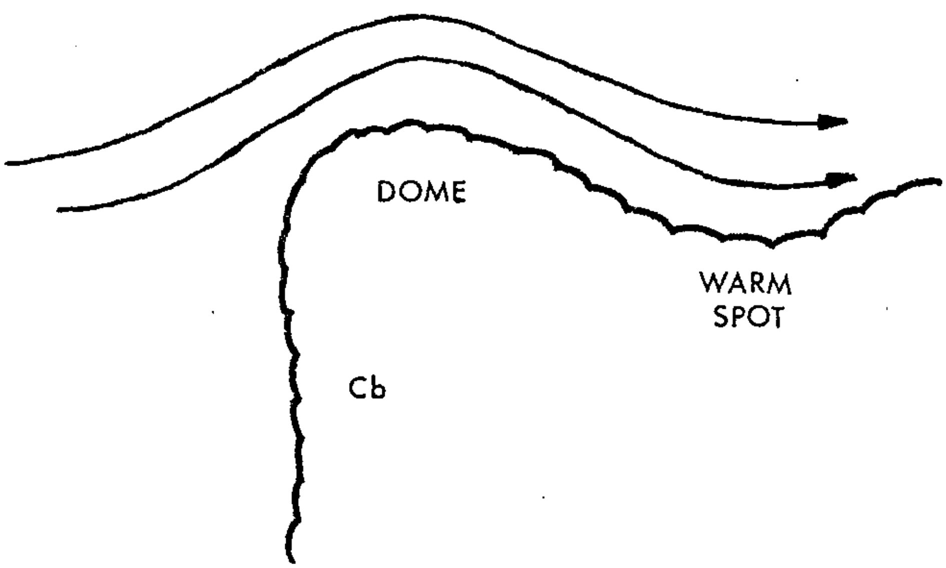
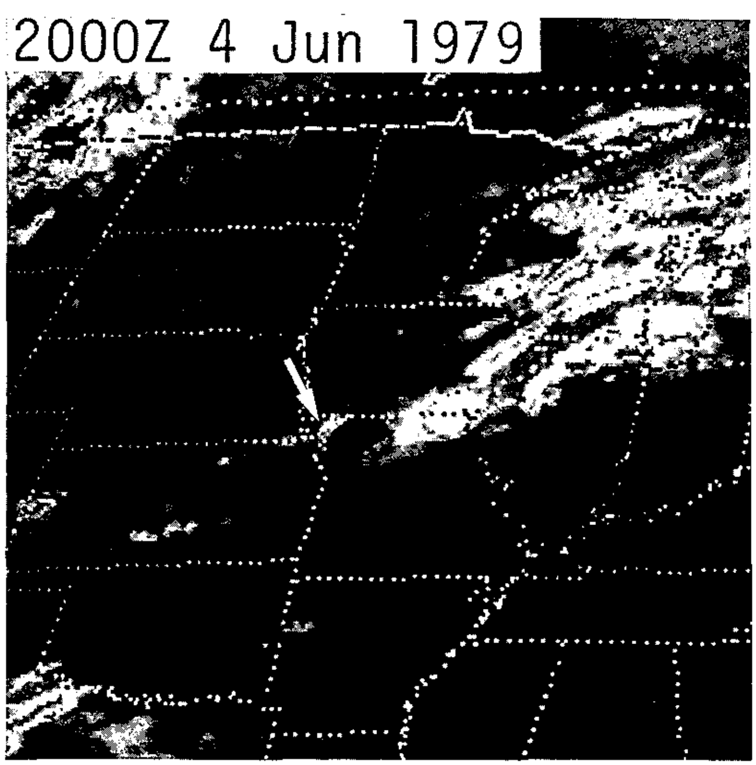


Figure 4. Flow over the top of an enhanced-V storm (adapted from Burns and Harrold, 1966).

Laboratory studies of flow over dome-like objects show an upward hydrodynamic pressure gradient occurs in the lee of the dome (Chien et al, 1951). This would result in upward rather than downward motion. This upward motion would cause anvil cirrus upstream from the overshooting top to be lifted and mixed with warmer stratosphere air and would force the development of a warm spot. Fujita's (1974) observation of leaping cirrus fragments above the main anvil level support this argument. This mechanism differs from the second possibility discussed by Mills and Astling (1977) in that downstream anvil air, not updraft air, is being mixed.

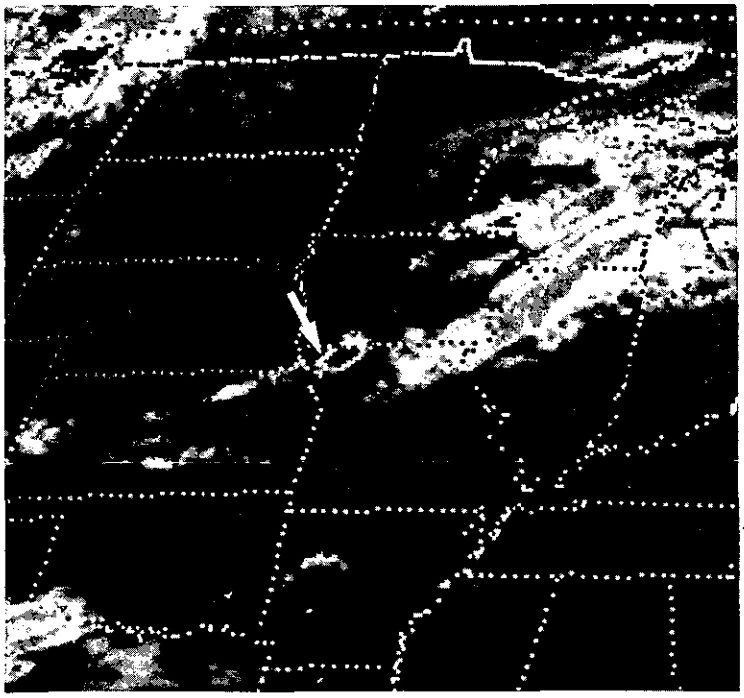
3. CASE STUDY - 4 JUNE 1979

It is instructive to examine the life cycle of an enhanced-V storm. A hail and wind storm which crossed the Kansas City area on 4 June 1979 is examined in detail. This storm was associated with the gust that caused the collapse of the roof of the Kemper Arena, Kansas City's multipurpose auditorium. Other case studies are presented in the appendix. The satellite imagery in these case studies are enhanced using the MB curve. The chronology of this storm is as follows:



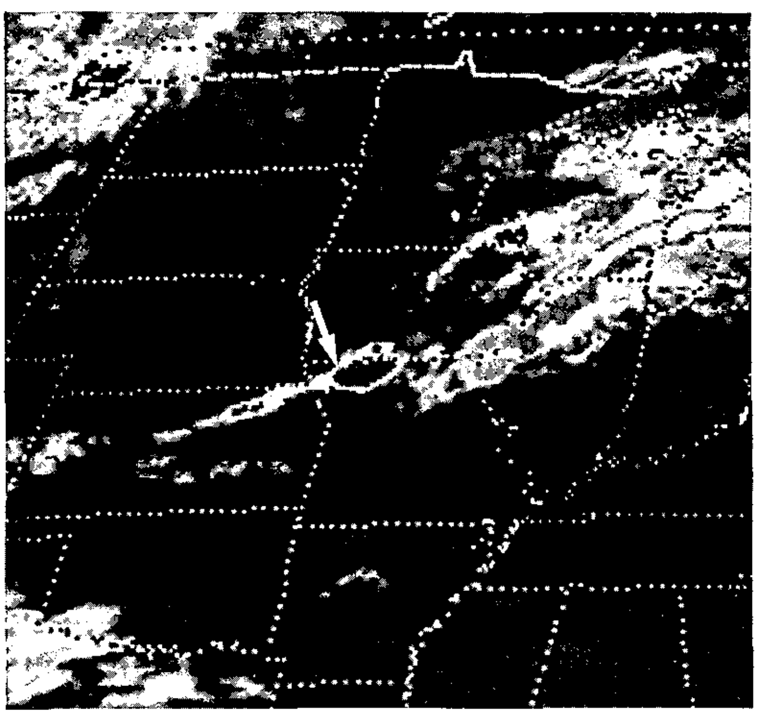
2000Z: The storm begins in extreme northwest Missouri (shown by the arrow). Its movement during the following 6 hours is to the south southeast.

Figure 5a. 2000Z, 4 June 1979.



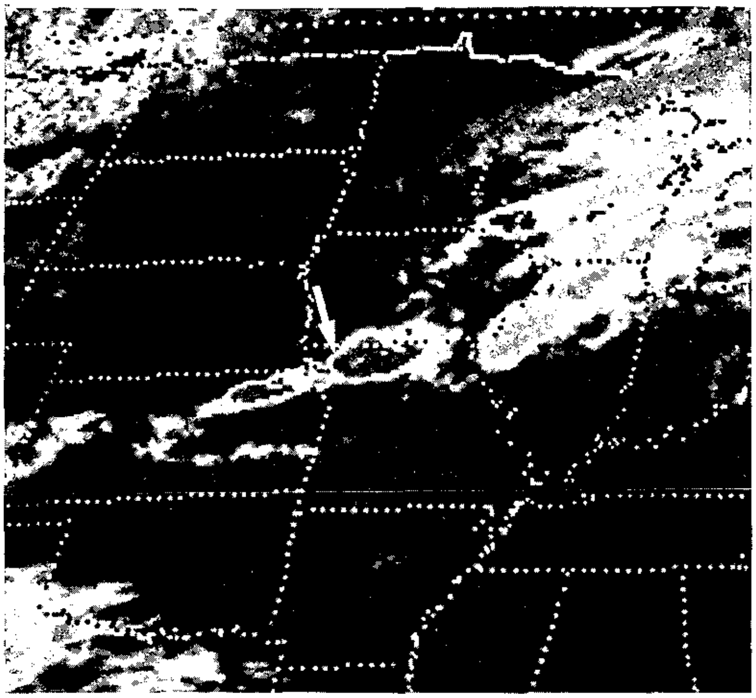
2030Z: The storm grows rapidly about tripling in size.

Figure 5b. 2030Z, 4 June 1979.



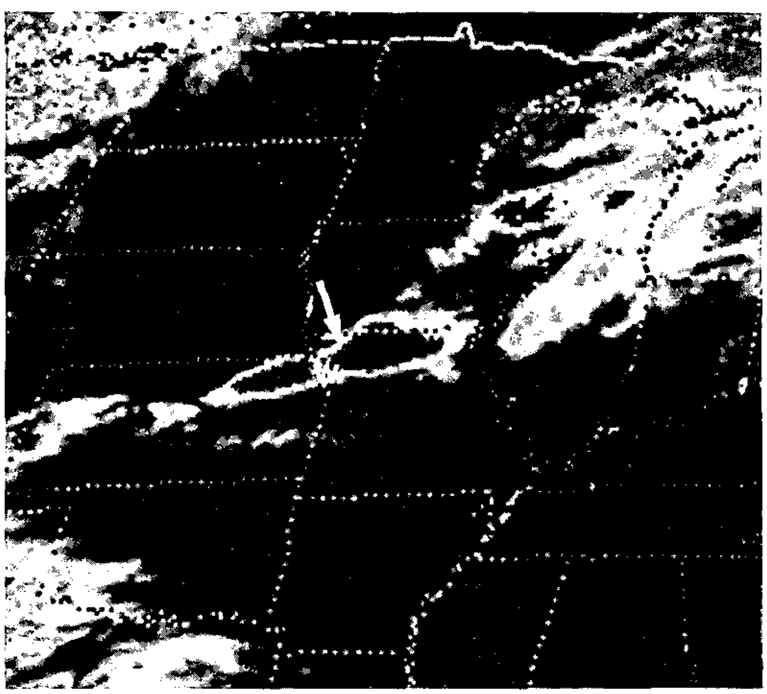
2100Z: The storm continues to grow rapidly. A black enhancement appears indicating cooler temperatures associated with an overshooting dome.

Figure 5c. 2100Z, 4 June 1979.



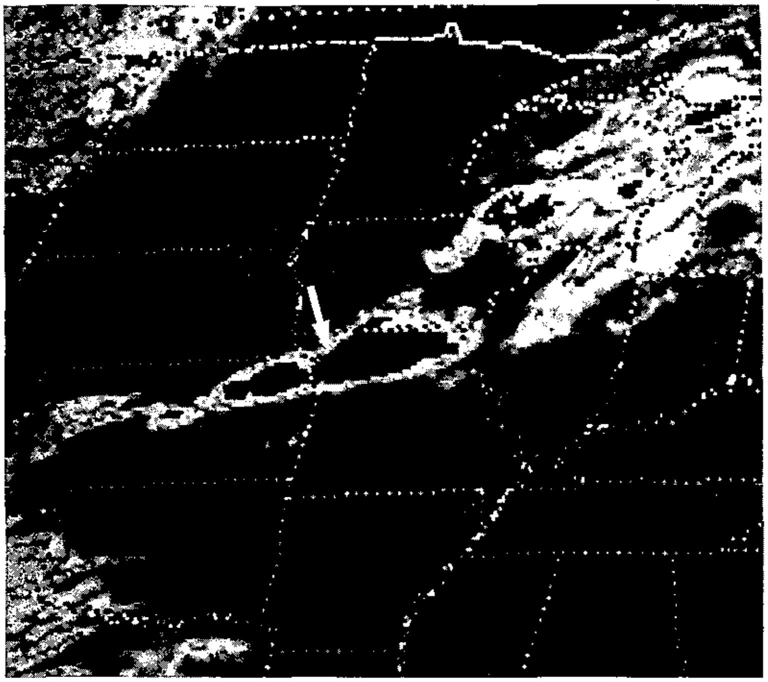
2130Z: The black enhancement area increases in size and cooler internal lighter gray indicates further growth is present. A warm spot, the first indication of enhanced-V formation also appears.

Figure 5d. 2130Z, 4 June 1979.



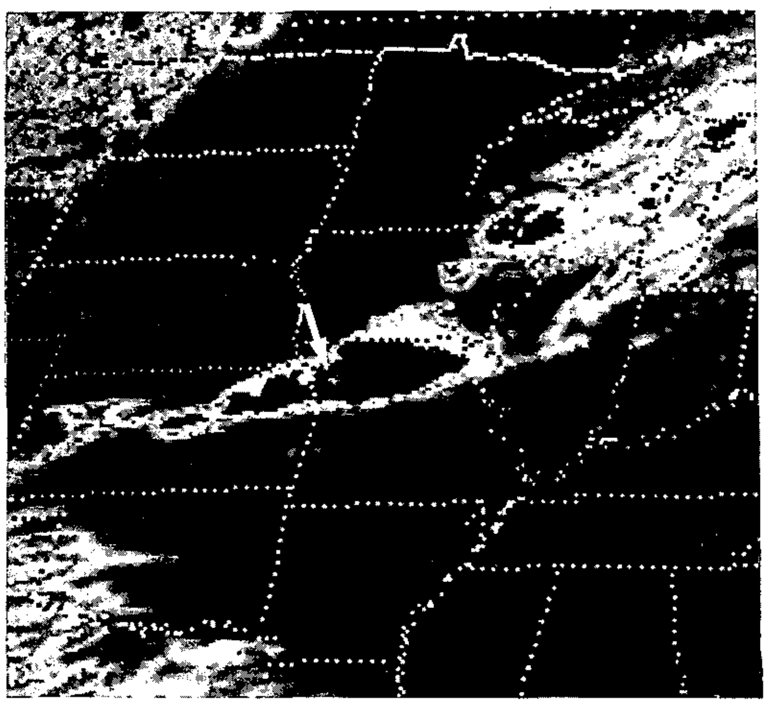
2200Z: The black-enhanced area becomes an enhanced-V. However, the lower level enhancement that indicated the warm spot is gone. The storm becomes severe at this time with wind damage being reported in southern St. Joseph, Missouri (indicated by the "W" in the picture).

Figure 5e. 2200Z, 4 June 1979.



2230Z: The enhanced-V becomes larger with the minimum cloud top temperature lower than the previous pictures. The storm remains severe with reports of 4 1/2 cm hail and wind gusts nearly 40 m sec^{-1}.

Figure 5f. 2230Z, 4 June 1979.



2300Z The storm continues to grow. The white-enhanced overshooting top calls attention to the large enhanced-V just north of Kansas City. Severe hail and winds are still accompanying the storm.

Figure 5g. 2300Z, 4 June 1979.

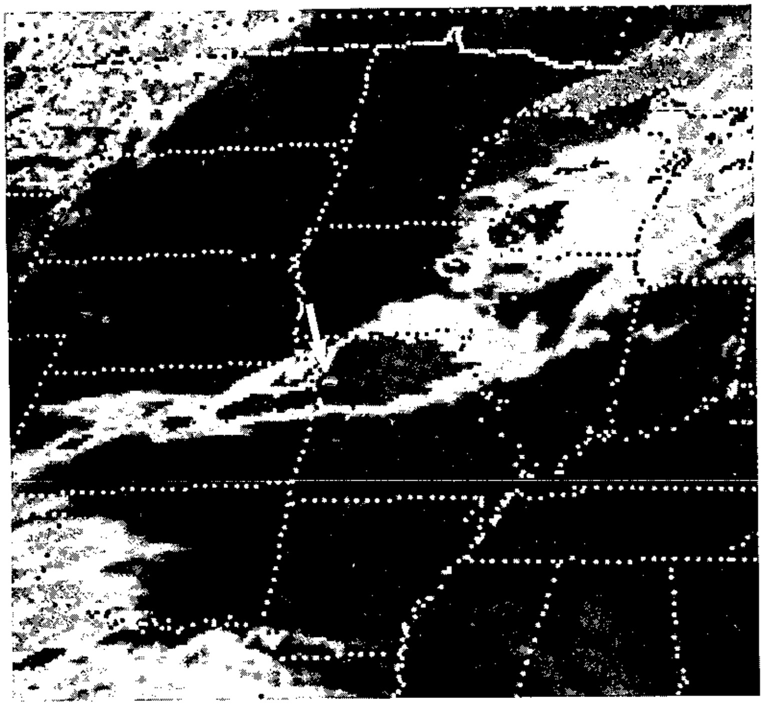


Figure 5h. 2330Z, 4 June 1979.

2330Z: The storm is causing extensive damage along its path through northern Kansas City. The enhanced-V continues to dominate the appearance of the storm on the imagery.

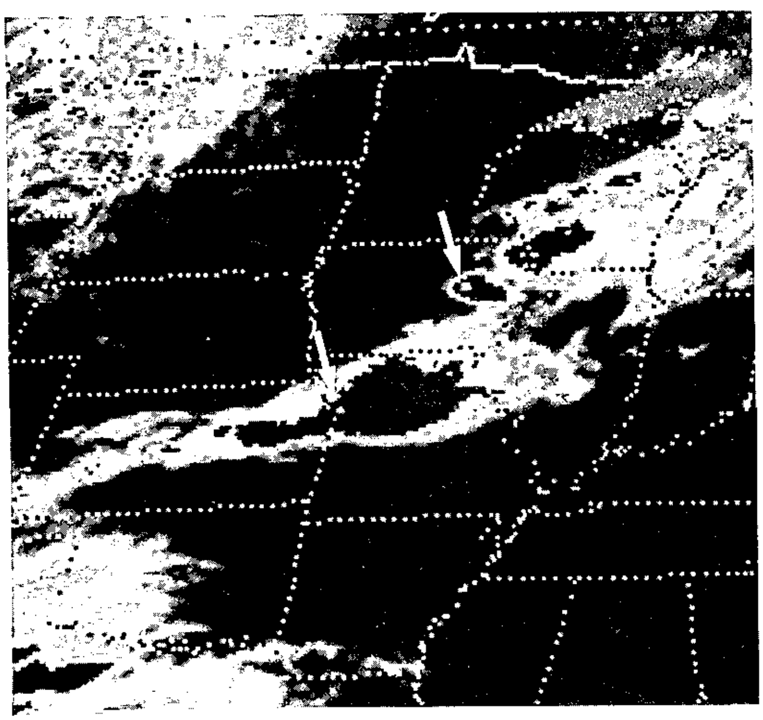


Figure 5i. 0000Z, 5 June 1979.

0000Z: The storm moves into the downtown portion of Kansas City. Just after this time the Kemper Arena roof begins to cave in. The storm in east central Iowa (shown by the arrow) shows a poorly defined enhanced-V (mainly a large warm spot). A different enhancement curve probably would show the enhanced-V better. The Iowa storm subsequently produces 6 cm hail at 0015Z.

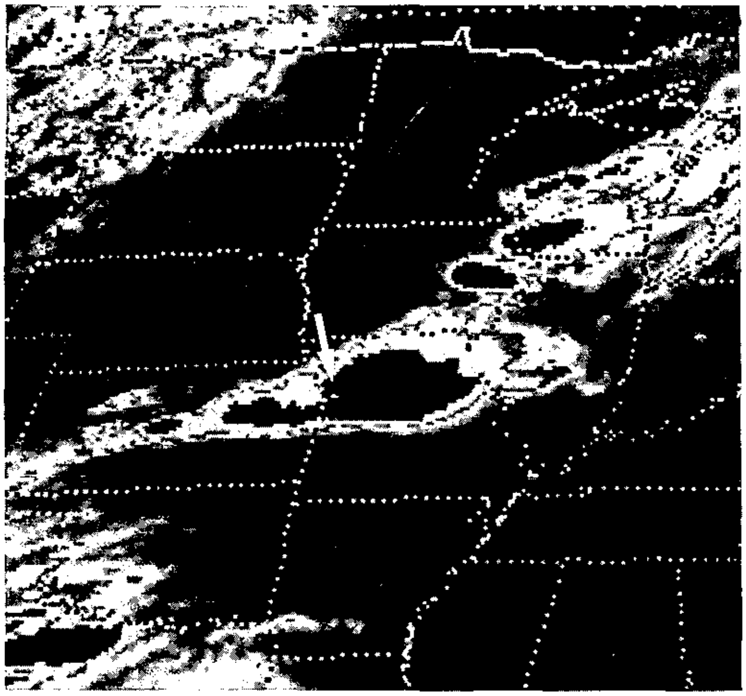


Figure 5j. 0030Z, 5 June 1979.

0030Z: The Kansas City storm shows signs of weakening. Although the minimum top temperature remains about constant, the size of light gray enhancement is slightly smaller than it was at 0000Z. The severe weather with this storm ceases at about this time.

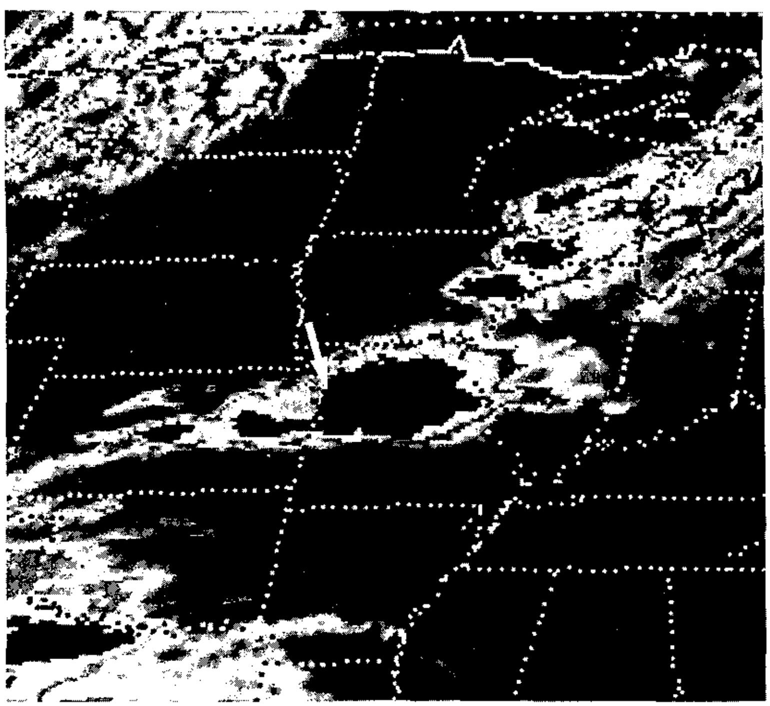
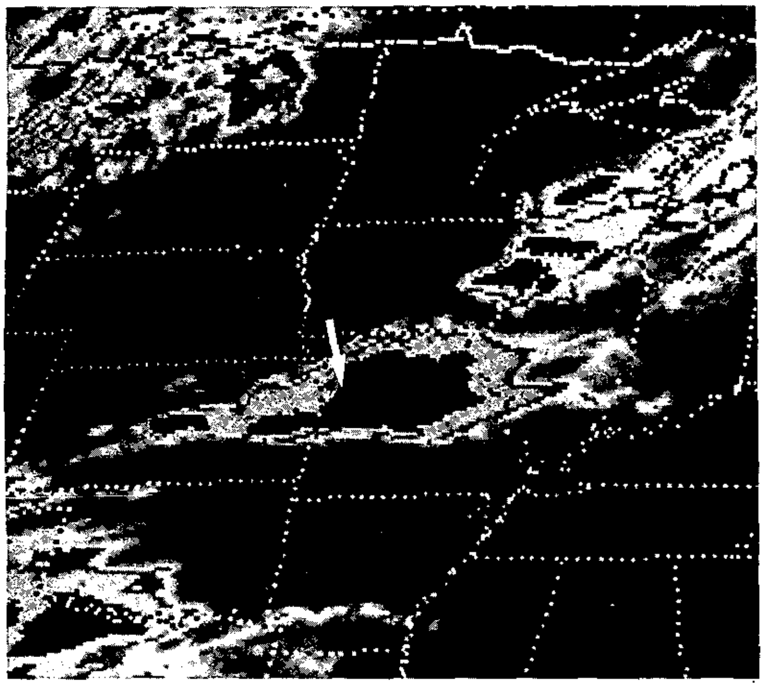


Figure 5k. 0100Z, 5 June 1979.

0100Z: The storm loses a substantial portion of its cold enhancement, and the enhanced-V begins to lose its definition.



0130Z: Although still a large storm, the enhanced-V has disappeared and the area of black enhancement continues to decrease.

Figure 51. 0130Z, 5 June 1979.

4. ANALYSIS OF THE ENHANCED-V

The 4 June 1979 case study shows how the enhanced-V can identify potentially severe thunderstorms. To see if the enhanced-V is a characteristic signature of severe storms in general, nearly every half-hourly MB enhanced IR satellite picture from April through July, 1979 was examined. For each picture that indicated an enhanced-V storm, a check into the severe weather log at the National Severe Storms Forecast Center (NSSFC) was made to see if it had associated severe weather. While doing this, it became apparent that two rules refining the enhanced-V are necessary. First, the enhanced-V must be associated with a growing thunderstorm. By "growing" it is meant that the colder IR enhancement contours are getting larger and/or the minimum cloud top temperature is lowering and thus indicating upward penetration of an overshooting dome. This is very similar to the Scofield-Oliver (1977) method for rainfall estimation except that no quantitative measurements are necessary. In making the decision on whether a storm is growing, one must compare the latest picture of the storm to the previous one. This is necessary, since sometimes the eroding anvil of a dissipating non-severe storm will appear as an enhanced-V. Second, once the enhanced-V is recognized, a storm should be considered severe as long as it continues to grow, even if the enhanced-V disappears. Since the MB enhancement curve uses threshold values for color changes, an enhanced-V may become obscured from recognition. However, if the storm is continuing to grow, it must still be regarded as an active severe thunderstorm.

In his article on radar identification of severe storms, Lemon (1977) emphasized the importance of looking for radar indications of a strong updraft. Since the enhanced-V, as defined by the rules above, also indicates a strong updraft, the enhanced-V should also have a predictive capability similar to Lemon's radar technique. To examine this, each storm that was indicated severe by an enhanced-V was checked for associated severe weather within one hour after the picture time. The results are summarized in Table 1. It is seen that when a storm has an enhanced-V, it has a high probability of being severe afterwards. Because of this low false alarm ratio (FAR), the enhanced-V signature can be used for a warning criterion, if the picture could get into the hands of those responsible for issuing warnings in time. The seasonal decrease in verification from spring to mid-summer may or may not be significant. The area most affected by severe weather moves from the lower Mississippi Valley in April westward and northward into the less populated areas of the high plains by June and July. Since severe weather reports are population biased (Doswell, 1980), it is more difficult to get verifying reports in these low population areas.

TABLE 1

	APRIL	MAY	JUNE	JULY	TOTAL
Ratio enhanced-V's associated severe weather within 60 minutes to all enhanced-V's	110/150 73%	180/241 75%	185/277 67%	133/216 61%	608/884 69%
Ratio severe reports 60 minutes after enhanced-V to all severe reports	140/504 28%	173/565 31%	189/925 20%	143/725 20%	645/2719 24%
Critical Success Index	.25	.28	.19	.17	.21
Ratio tornadoes verified	31/119 26%	38/111 34%	19/149 13%	13/132 10%	101/511 20%
Ratio F2 tornadoes verified	22/40 55%	10/15 67%	6/14 43%	0/7 0%	38/76 50%

The second line in the table is the probability of detection (POD). The low POD indicates that there are many severe storms that do not show an enhanced-V; so the operational meteorologist cannot rely on this signature by itself to indicate severity. Perhaps by using an enhancement curve other than the MB, the POD would improve.

While the low POD leads to a relatively low Critical Success Index (CSI) as defined by Donaldson et al, (1975), the enhanced-V CSI is considerably better than the CSI of .05 for the National Weather Service warning program (Pearson and David, 1979). While the enhanced-V appears to perform worse than Lemon's (1977) radar technique or the satellite technique of Adler and Fenn (1979a) of combining cloud top growth rate and minimum cloud top temperature, it must be emphasized that CSI's cannot be meaningfully compared. This statistic is heavily dependent upon the observed relative frequency of severe storm occurrences. Thus, the Lemon study and the Adler and Fenn study, which examined only limited areas on days with significant severe weather, cannot be compared with this study which considered four consecutive months over most of the United States. If only two outbreak days in this enhanced-V study are considered, the statistics (Table 2) compare favorably to those other studies. However, the true test of any severe thunderstorm detection technique is in its everyday application over a wide geographical area.

TABLE 2

	POD	FAR	CSI	
Radar: 13 selected days in Oklahoma (Lemon, 1977)	.93	.24	.71	(30 storms)
Satellite: 6 May 1975 (Adler and Fenn, 1979a)	.73	.31	.55	(15 storms)
Enhanced-V: 10 April 1979	44/76 .58	1/28 .04	.57	(6 storms)
Enhanced-V: 2-3 May 1979	130/161 .81	29/150 .19	.68	(42 storms)

Table 1 also shows little difference in the POD of tornadoes to that of reports of large hail and strong winds. However, when the stronger tornadoes (F2 or greater on the Fujita-Pearson (1973) scale) are considered, the POD increases markedly. Additionally, all storms that produced an F4 tornado during the period had an enhanced-V associated with them before the tornado occurred.

Since many times severe weather is reported after the enhanced-V has developed, a lead time is possible. Lead time is defined as the time between enhanced-V development and the time of the first severe storm report. Fig. 6 shows that a majority of storms have a positive lead time, i.e., the enhanced-V forms before the first report. The median lead time is 30 minutes and the mean 31 minutes. Seventy-four percent of the lead times fall between no lead time and one hour lead time.

Fig. 7 shows how long an enhanced-V exists. In most cases, the enhanced-V is a relatively short-lived phenomenon with a median persistence of one hour. However, two storms exhibited an enhanced-V for nine hours.

The winds aloft that formed some of the enhanced-V's were estimated from the NSSFC maximum wind chart. Only those enhanced-V's that were within 3 hours of rawinsonde time were considered. The median and mean wind speeds were

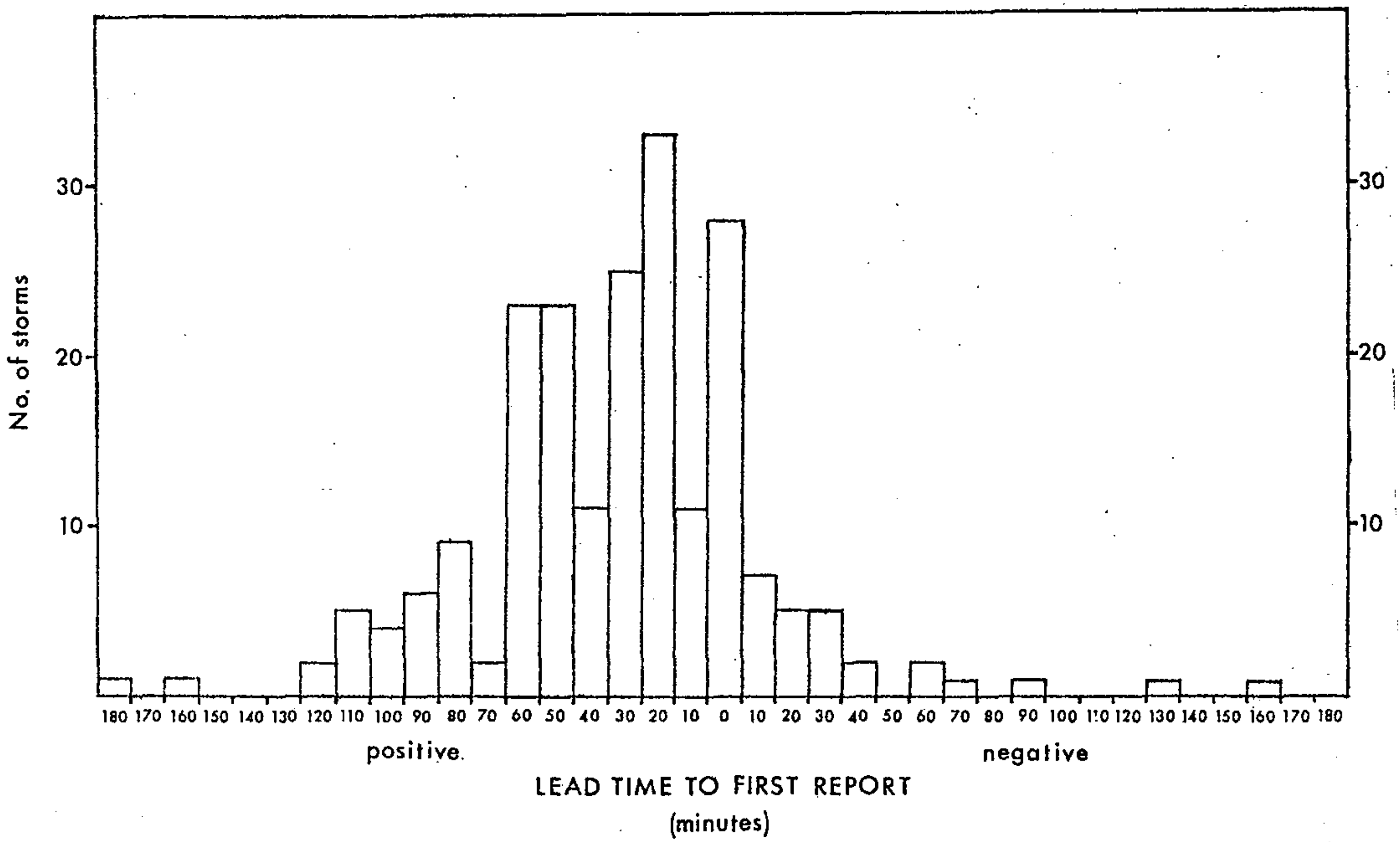


Figure 6. Lead times and the number of storms in 10 minute intervals centered on the times along the abscissa. A positive lead time indicates that the enhanced-V occurred before the first severe report.

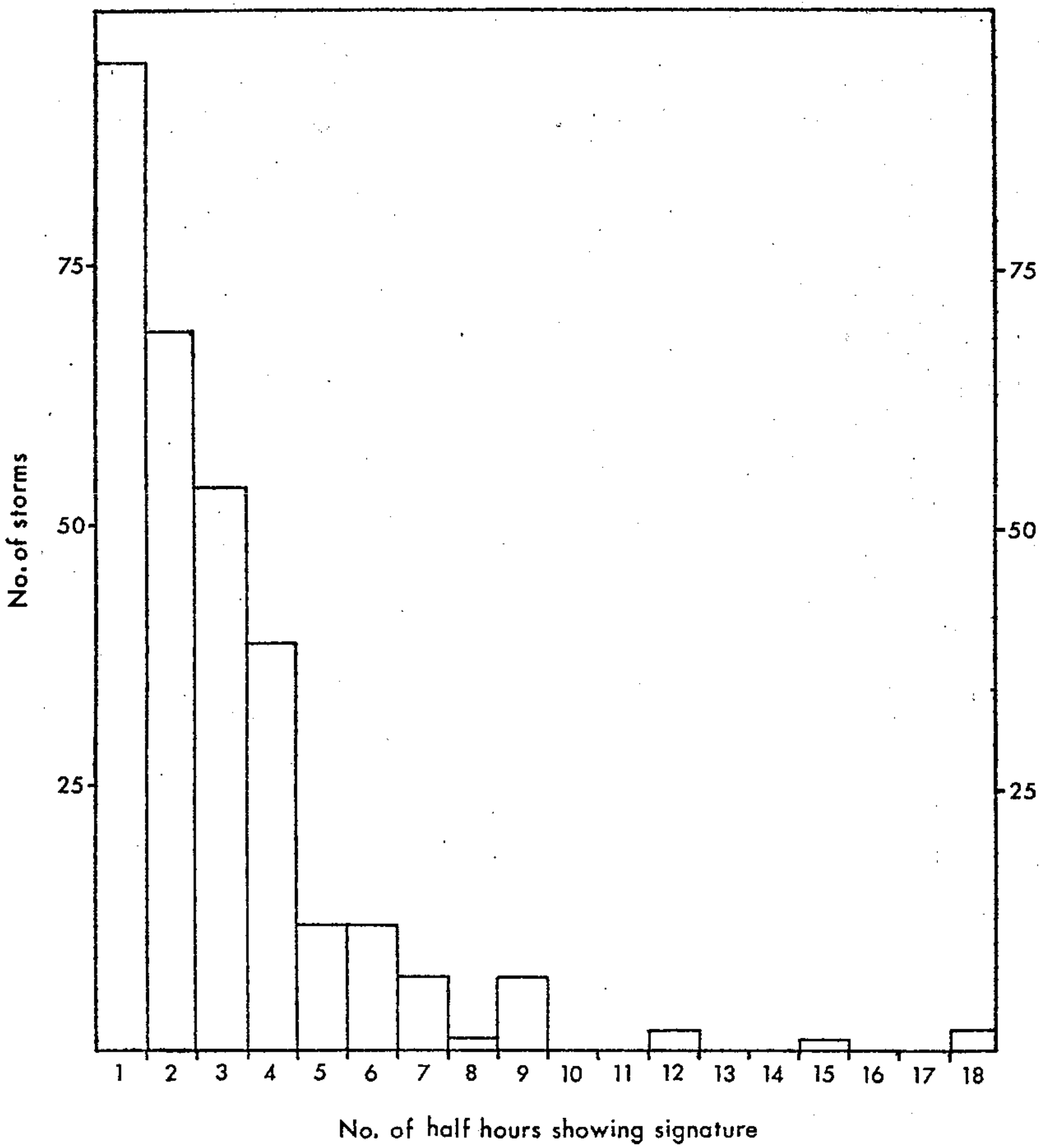


Figure 7. The number of pictures (taken each half hour) of enhanced-V persisted for each storm.

both 35 m sec^{-1} with a range from 20 m sec^{-1} to 60 m sec^{-1}. This is stronger than the average wind speed of 26 m sec^{-1} at 12 km above ground level found by Darkow and McCann (1977) for tornadic storms. This indicates better than average severe storm conditions at jet level existed for enhanced-V storms.

The location of severe weather with respect to the enhanced-V may be deduced from knowledge of the distribution of severe weather with respect to the storm's updraft. Lemon (1979) noted that severe weather is generally coincident with or slightly south of the updraft of a storm moving toward the northeast. Because of the viewing angle of the present satellite (geostationary at 70°W longitude), the enhanced-V has to be shifted southeastward 8 to 20 km to find its location with respect to the surface (Fujita, 1978). Therefore, the severe weather should be located 5 to 25 km south or southeast of the apparent position of the coldest cloud top. This location corresponded well with actual reports of severe weather. Since this is less than the width of a typical county, a combination of storm movement and satellite indicated storm location should allow the operational meteorologist to issue a severe weather warning utilizing the enhanced-V technique.

5. CONCLUSION

A severe weather warning criterion must be judged by four standards. It should be fast and easy to use without requiring much time-consuming computation or measurements. It should detect as much severe weather as possible. It should provide a favorable lead time to the severe weather event. And, lastly, it should not overwarn.

The enhanced-V performs well on three of the four standards. In most cases, an enhanced-V can be instantly recognized by an operational meteorologist. The only time consuming factor is the comparison of the previous picture to judge the storm's growth pattern.

With a 30 minute lead time, it becomes imperative that the time it takes for the picture to be taken, processed, and disseminated to the operational meteorologist be as little as possible. Presently, this time is about 35 minutes or a complete wipe-out of the average lead time. This time could be reduced if systems such as the one described by Reynolds (1980) were implemented.

The detection of enhanced-V's would be improved if a variable enhancement curve were used. It is likely that more storms in the study period would have shown an enhanced-V if the curve were different from the MB. One improvement would be to adjust the MB curve up or down along the temperature scale so that the black enhancement (segment 7 in Fig. 1) ends at the temperature where a lifted parcel temperature crosses over the sounding at upper levels and becomes negatively buoyant (Fig. 8). As suggested by Reynolds (1980), this crossover temperature would be an improvement upon the tropopause temperature since many times the crossover level will be significantly lower or higher than the tropopause. Further, the temperature of the overall cloud top anvil more closely corresponds to the crossover temperature than to the tropopause temperature (Roach, 1967).

Those readers who desire additional training in enhanced-V identification on satellite imagery are referred to the appendix where additional case studies and pictures are presented.

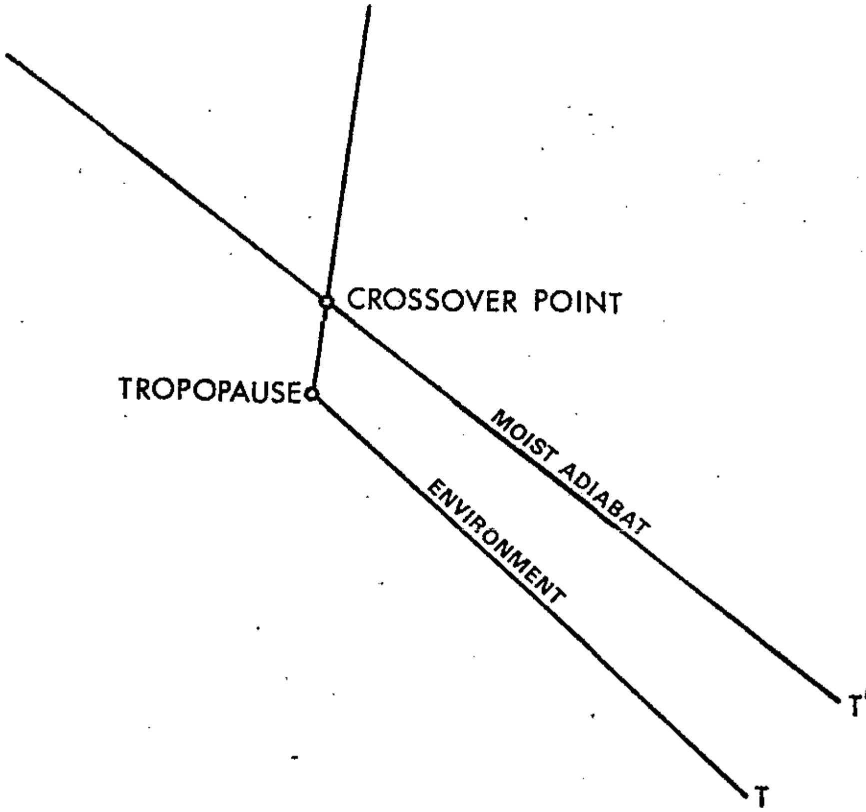


Figure 8. Schematic of the upper part of a typical severe weather temperature sounding showing the tropopause and the crossover point of an updraft parcel lifted from near the surface.

6. ACKNOWLEDGEMENTS

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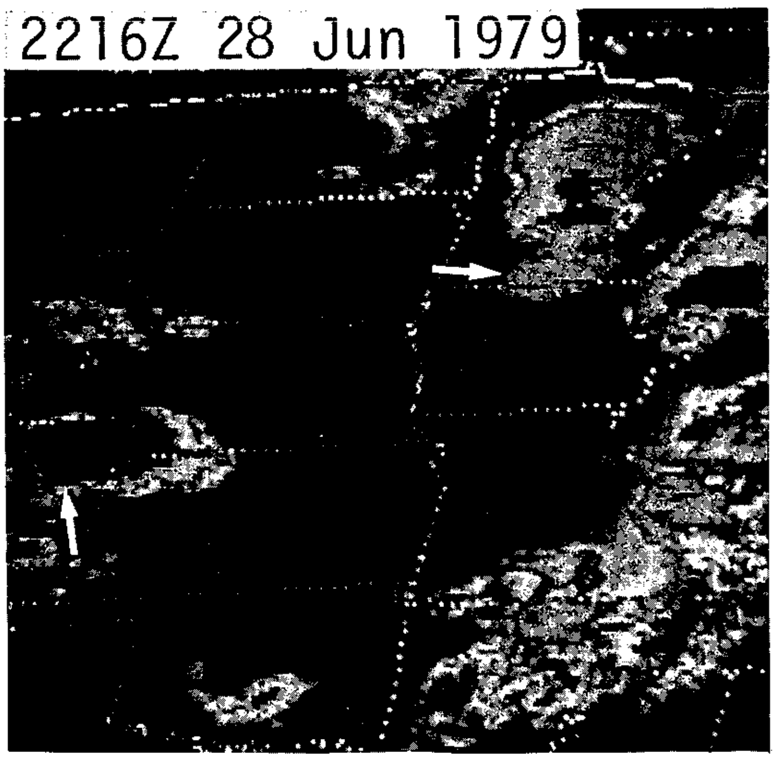
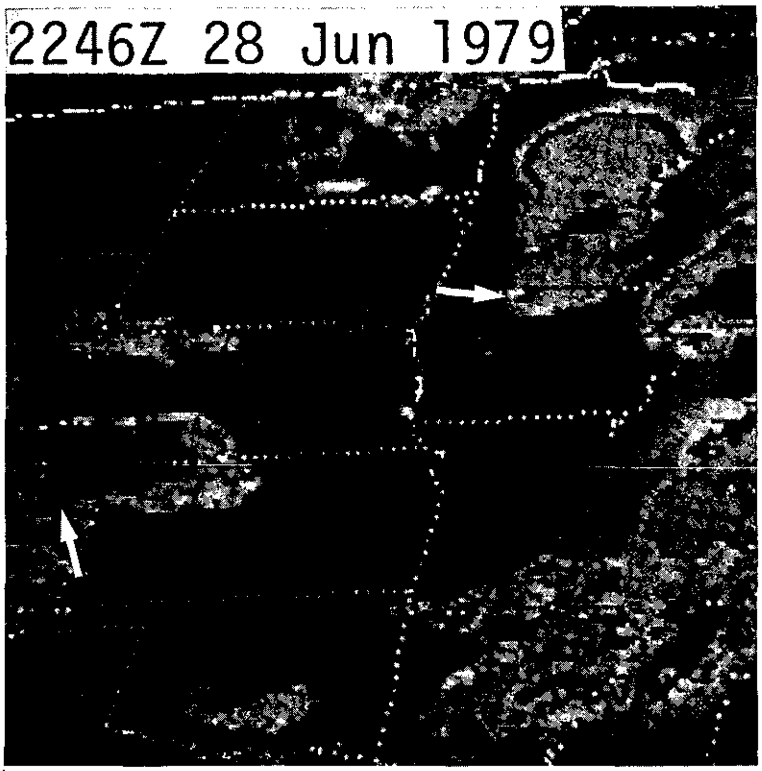
8. APPENDIX

More case studies are presented here in the appendix in order to further acquaint those operational meteorologists with the characteristics of the enhanced-V. Emphasis is placed on the problems one may encounter using the techniques described in the main text.

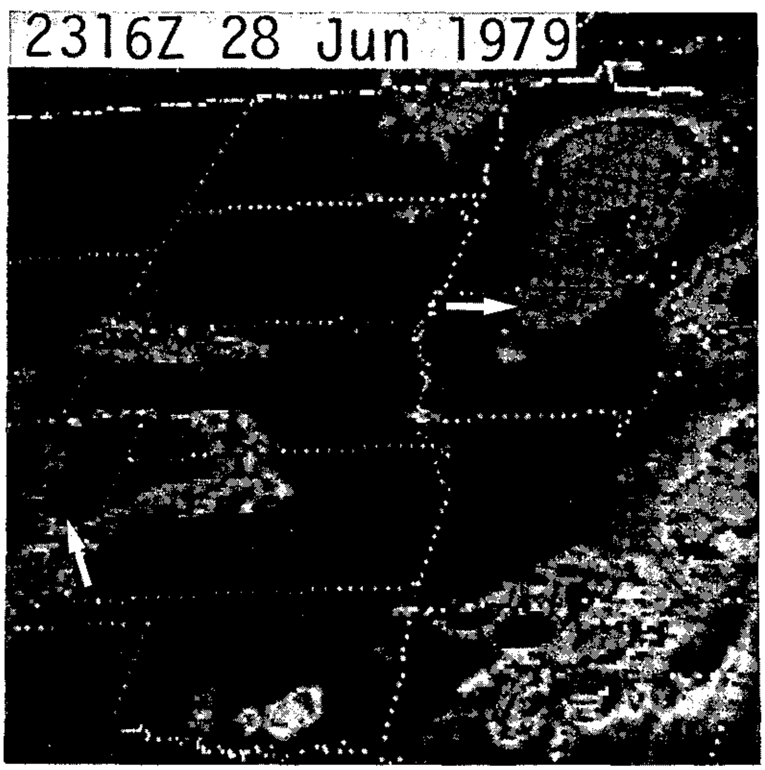
The first example is 28 June 1979. While several severe storms showed enhanced-V's, this day was highlighted by a severe tornadic storm that hit both Algona and Manson, Iowa, killing five. For this storm, the sequence of events is as follows:



2216Z: The main storm in question is just entering northern Iowa from the north. It formed about two hours previous to this picture and had already produced large hail and two tornadoes in Minnesota beginning at 2100Z. It does not have an enhanced-V using the MB curve. Perhaps a different enhancement curve would have indicated one, but the data do not permit resolution of this question. Also in the picture is a storm in northeast Colorado which had shown an enhanced-V since the 2116Z picture. A tornado was reported with this storm at 2210Z. The different appearance of the Colorado storm and the Iowa storm is due to a substantially lower tropopause and thus warmer storm tops over Iowa.



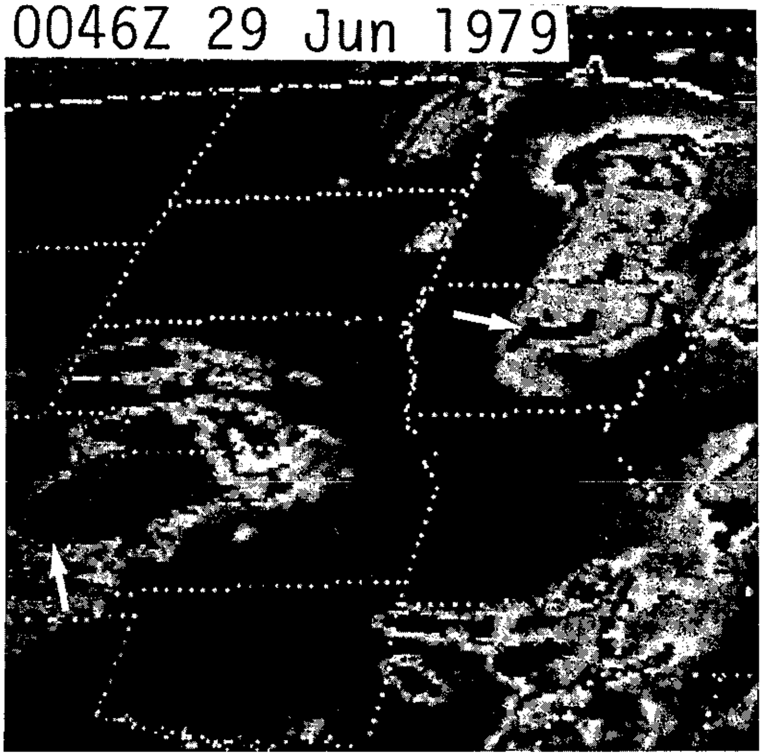
2246Z: The Iowa storm continues severe along the Iowa-Minnesota border but it still has not produced an enhanced-V. The Colorado storm also continues to grow. While this storm may have remained severe during this time, there were no further severe weather reported until 0045Z. This possibly could be because of the low population density of eastern Colorado.



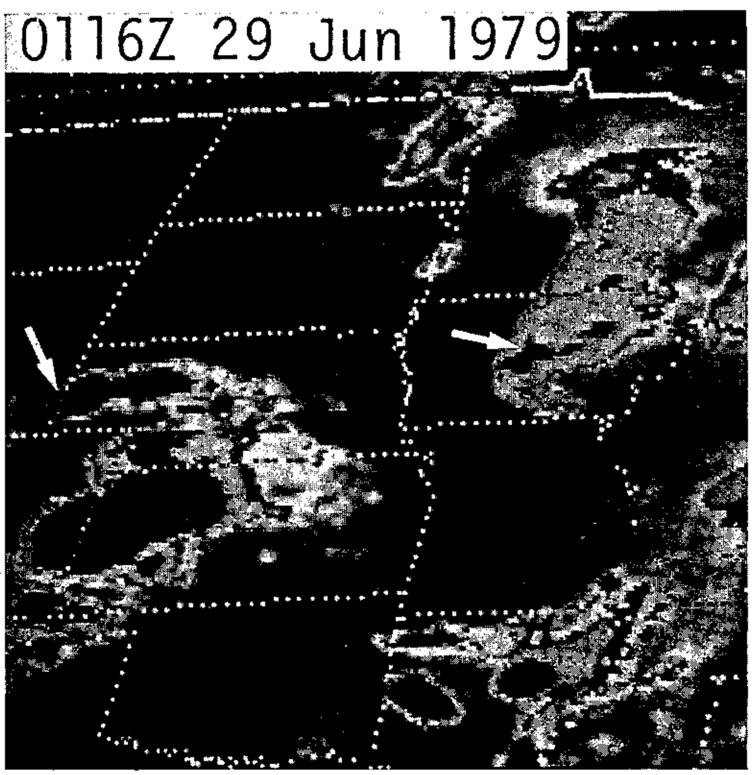
2316Z: The Iowa storm remained severe, producing tornadoes at 2312Z, 2325Z, 2331Z, and 2340Z, the last being the Algona killer tornado. Some hint of an enhanced-V is shown in the image by the darker enhancement. The Colorado storm continues to grow but the V-shape of the light gray enhancement disappears. Since growth was continuing it still should be regarded as severe.

2346Z: The Iowa storm forms an enhanced-V. The Manson killer tornado will begin at 0002Z. The eastern Colorado storm continues to grow in the light gray area of the coldest tops.

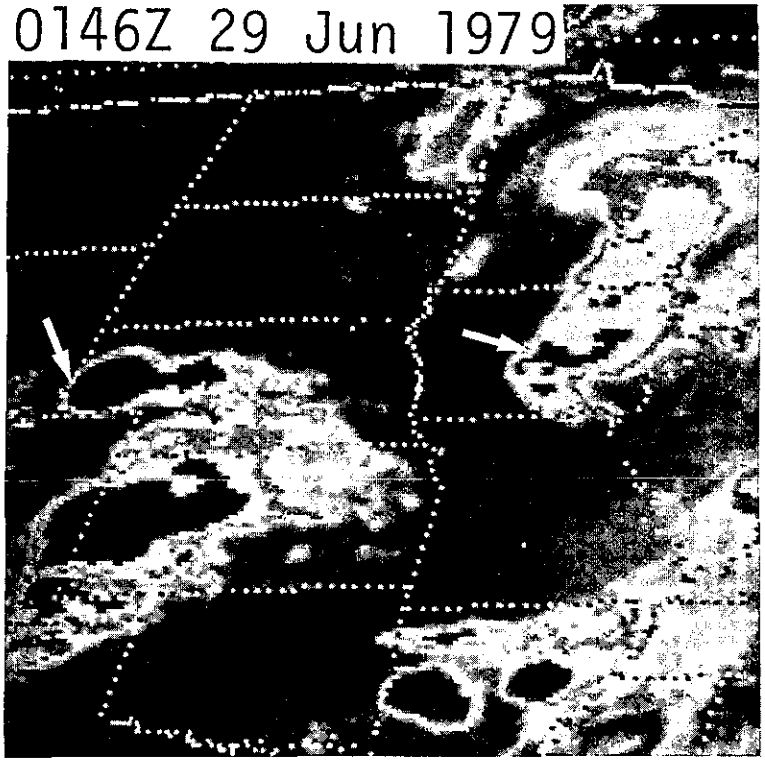
0016Z: The Iowa storm loses most of the enhanced-V definition, but the darker area expands thus indicating continued severity. The eastern Colorado storm continues to grow and will produce another tornado at 0045Z.



0046Z: The enhanced-V returns to the Iowa storm, although a darker enhanced area from a newly developed storm to the southwest has merged into the V. The Colorado storm appears weaker, so further severe would not be expected, but severe wind gusts occur at 0050Z.

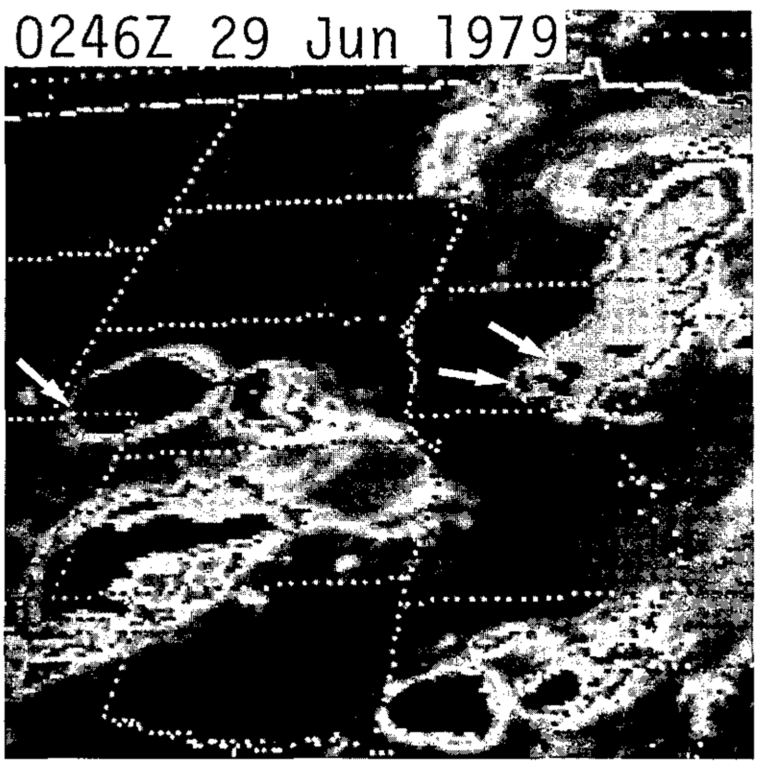


0116Z: The Iowa enhanced-V continues to grow and merge with the storm to the southwest. A new enhanced-V storm has developed along the Nebraska-Wyoming border. It began producing severe weather at 0050Z and continued to cause severe weather until 0210Z.

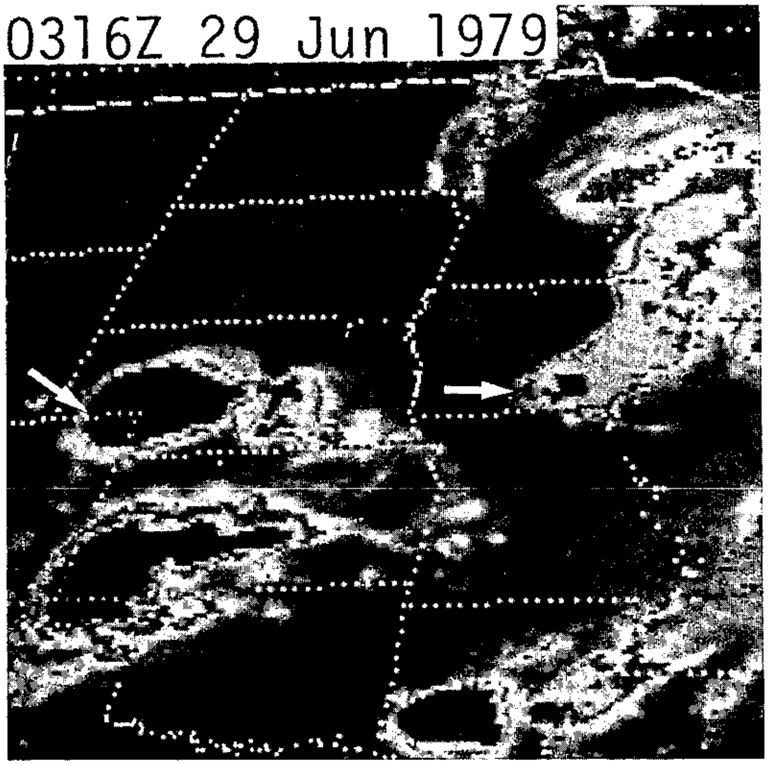


0146Z: The Iowa storm remains severe with reports of small tornadoes and large hail. The Nebraska storm has also grown rapidly from the previous image.

0216Z: No data is available.

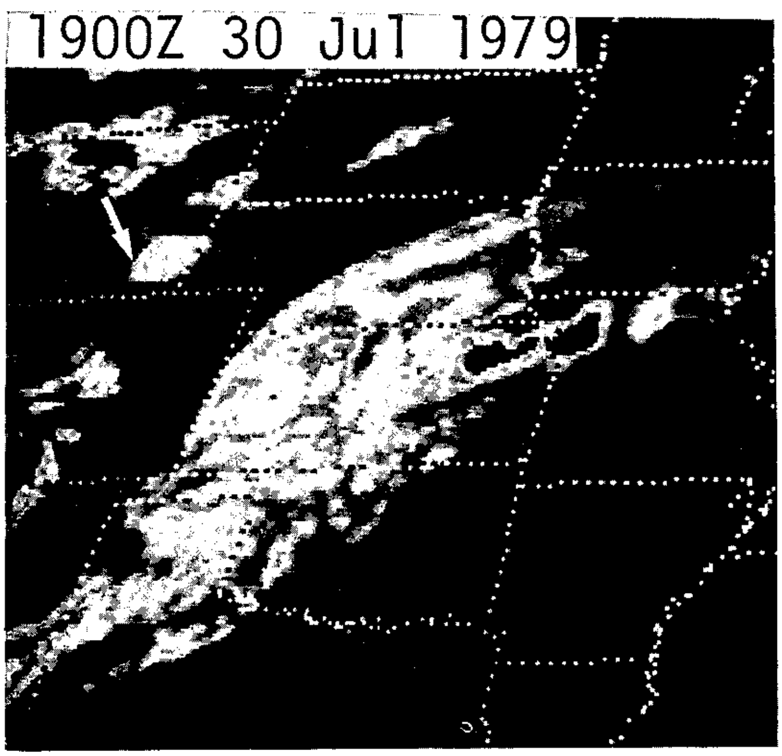


0246Z: The main Iowa storm appears to weaken, but a smaller storm to the southwest shows a weak enhanced-V. A report of hail and severe winds at 0305Z is associated with this smaller storm. The Nebraska storm continues to show a strong enhanced-V signature, however no severe weather is reported after 0210Z.

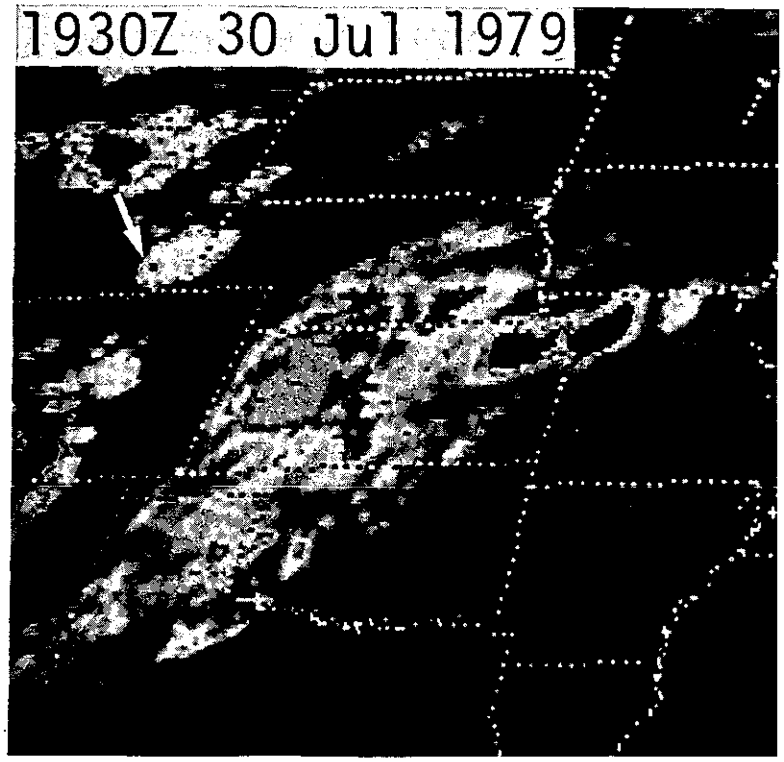


0316Z: Both the Iowa and the Nebraska storms weaken and no longer produce severe weather.

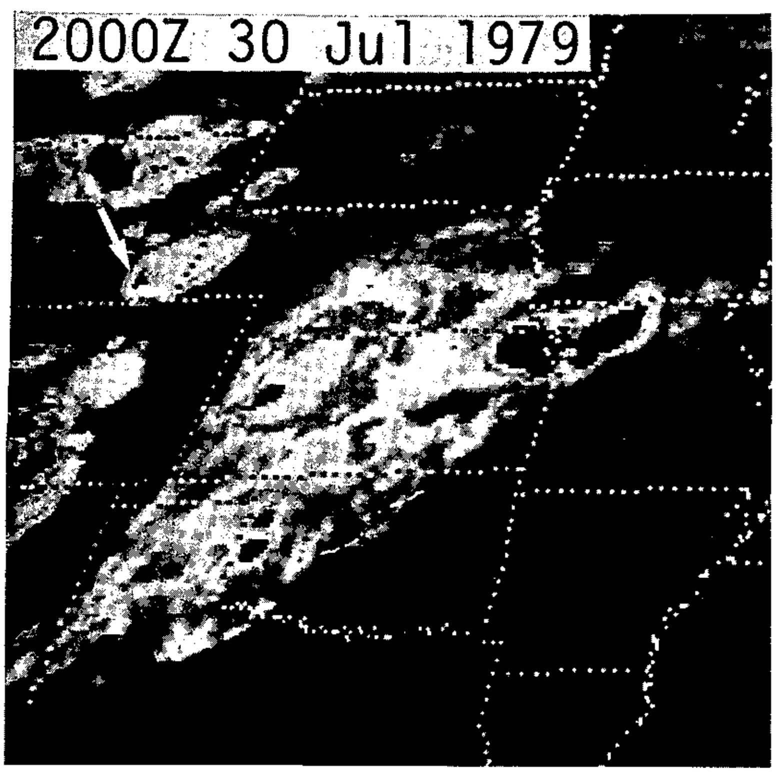
The next case is 30 July 1979. This day was highlighted by a severe hail-storm that produced hail up to 10 cm in diameter for almost an hour at Ft. Collins, Colorado. Of note is that the hail killed a young child, only the second death due to hail in this century.



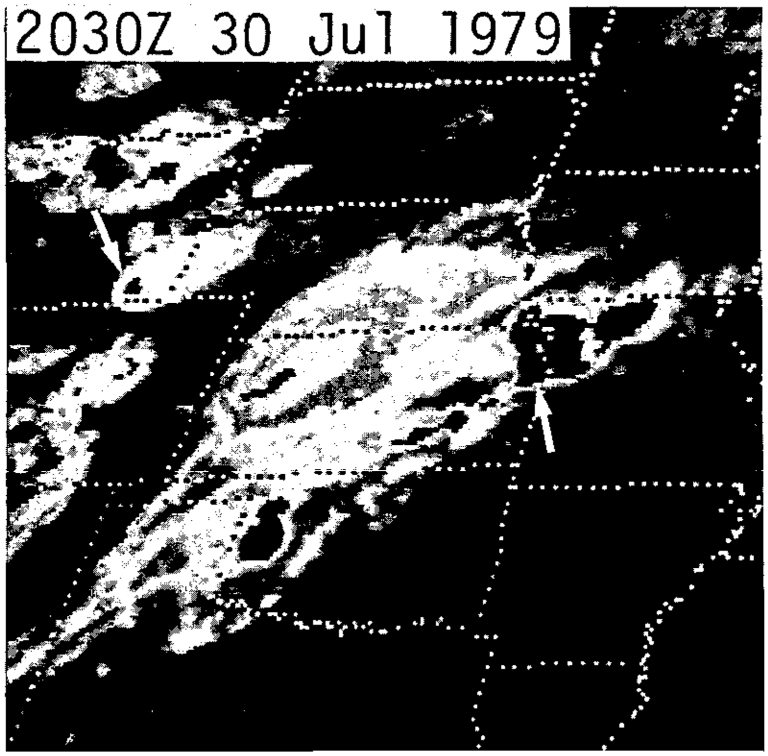
1900Z: The storm began in southwest Wyoming about 1800Z. It shows no enhanced-V.



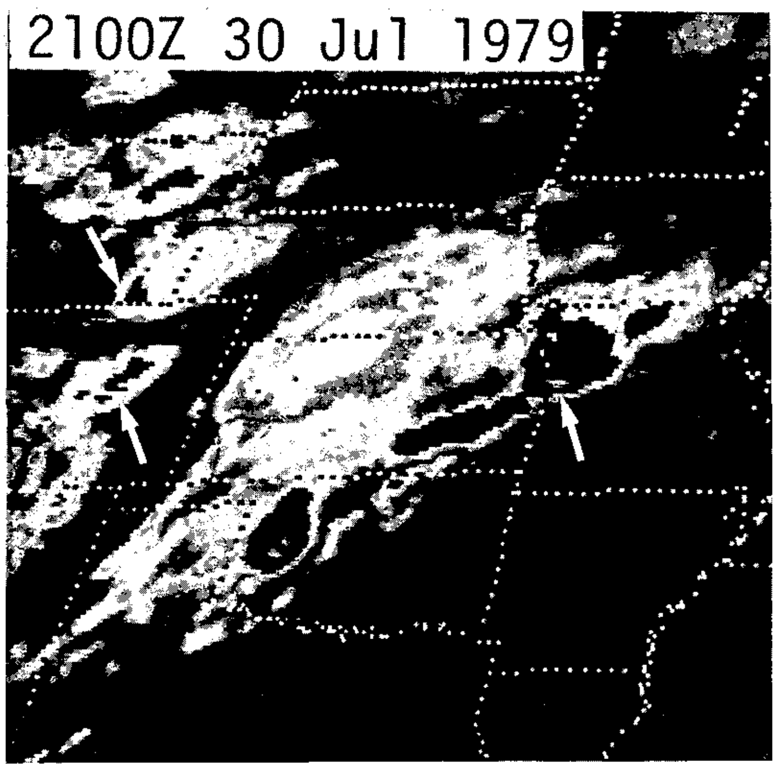
1930Z: A darker enhancement begins to show up, but no enhanced-V is present.



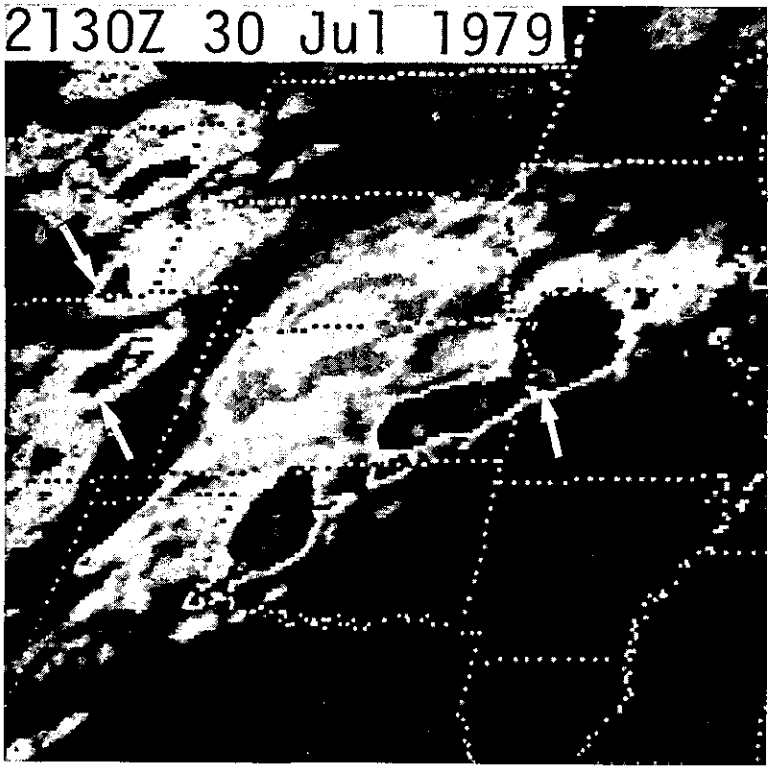
2000Z: A small enhanced-V appears in the image. The first severe report is a tornado southwest of Cheyenne at 2030Z.



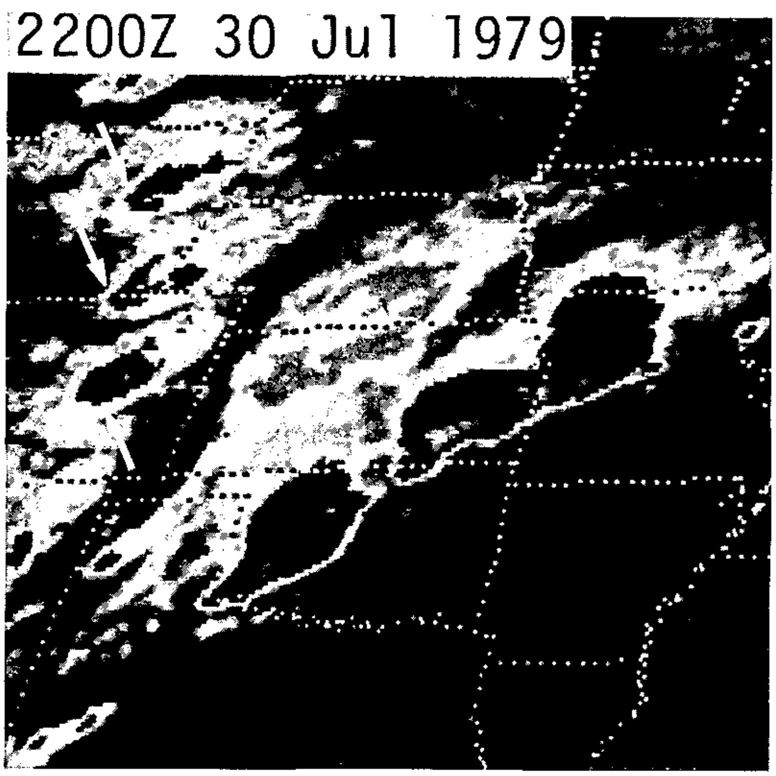
2030Z: The Wyoming storm moves slowly southward and continues to grow. Large hail is reported at 2050Z and 2100Z. Also a storm just west of Kansas City forms an enhanced-V. A wind gust with this storm began about this time.



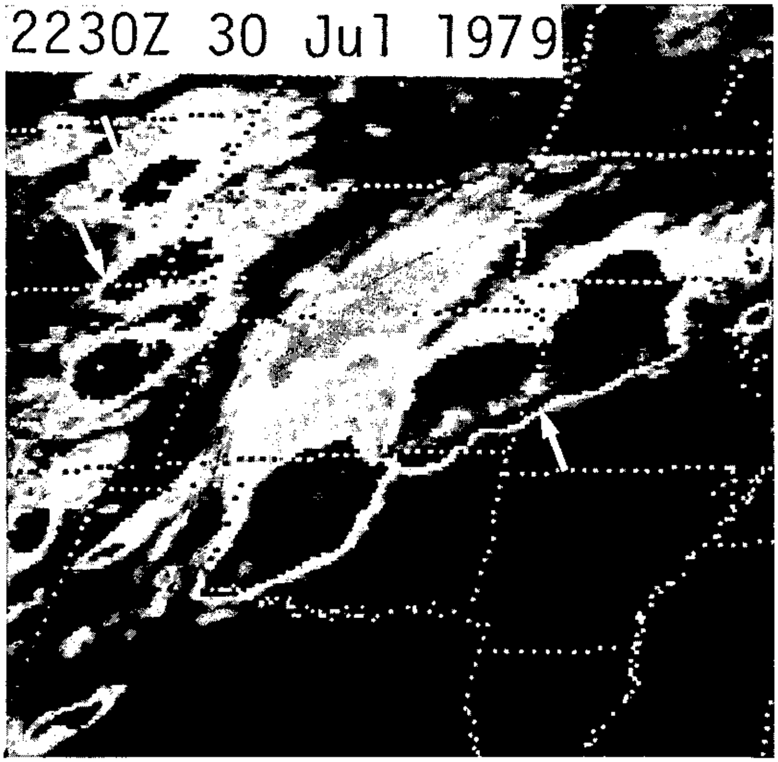
2100Z: Both the Cheyenne and Kansas City storms continue severe. A new enhanced-V appears in central Colorado. Large hail had occurred at 2036Z and 2050Z, but these are the only severe reports with this storm.



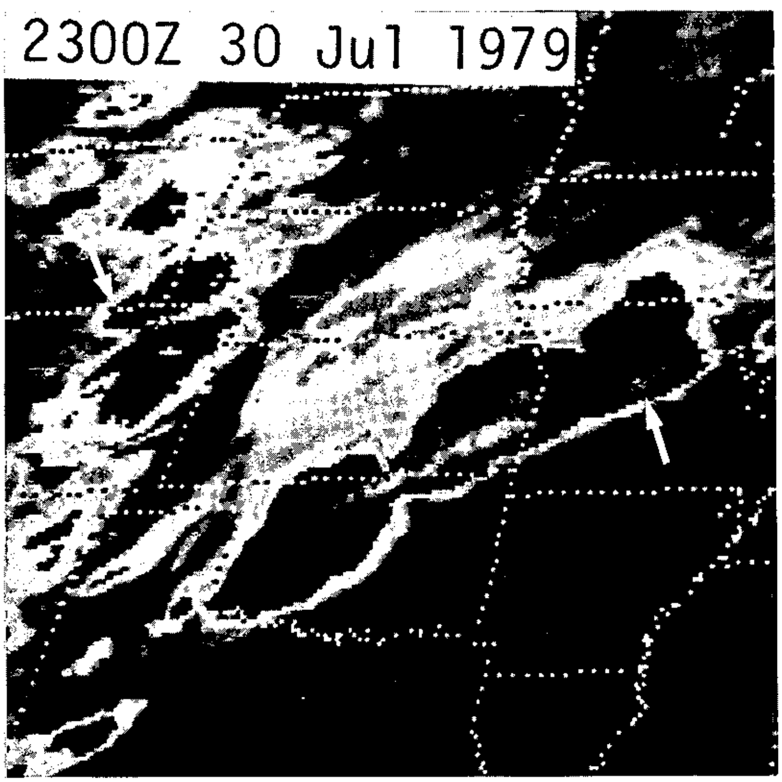
2130Z: All three storms continued to grow, but only the Kansas City storm still has severe reports associated with it.



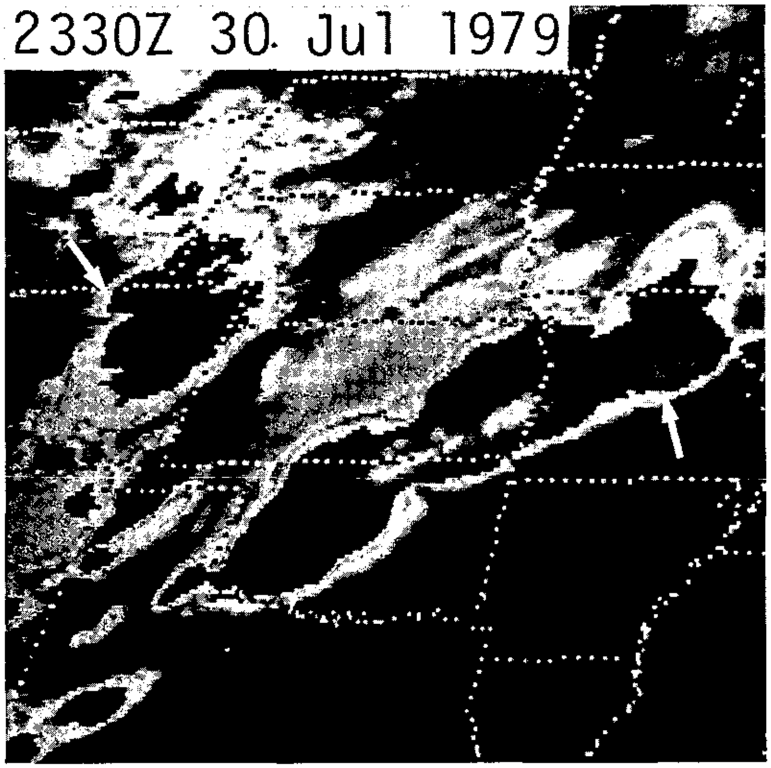
2200Z: The Colorado storms still show positive growth rates. The storm in east central Wyoming begins showing an enhanced-V, but no reports are received with this storm. The Kansas City storm weakens and should no longer be considered severe from the satellite images. Severe weather with this storm also ceased at this time.



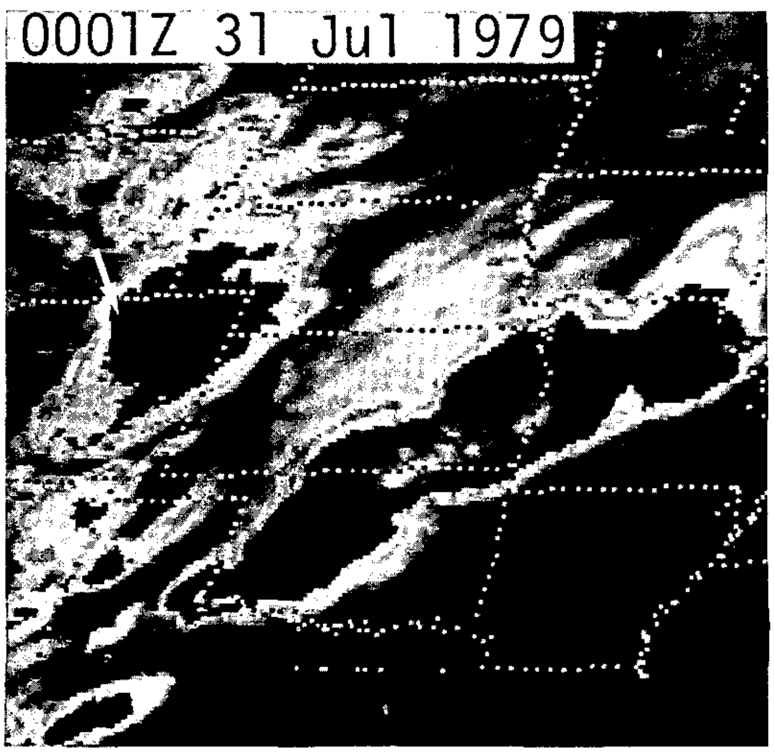
2230Z: The Ft. Collins storm and the central Wyoming storm both are growing, but the central Colorado storm weakens. A new enhanced-V storm forms along the Kansas-Missouri border south of Kansas City. There are no severe reports with this storm.



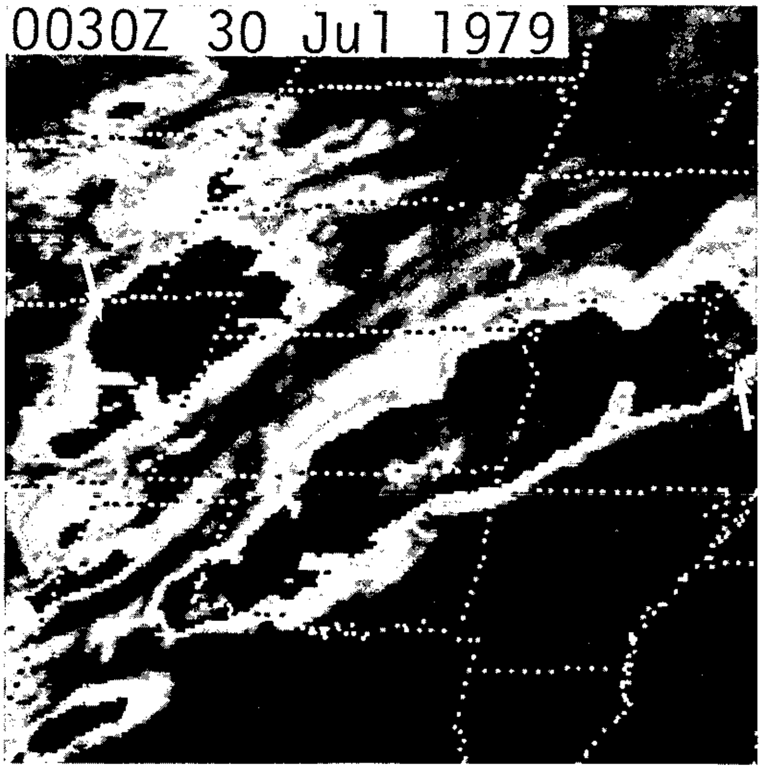
2300Z: The Ft. Collins storm begins to show black enhancement. Although by now the enhanced-V is gone, continued positive growth rate makes this storm a severe weather candidate. The Wyoming storm weakens. The Kansas-Missouri border storm weakens as fast as it had developed however, a new enhanced-V appears with the storm in central Missouri, severe wind gusts begin there at this time.



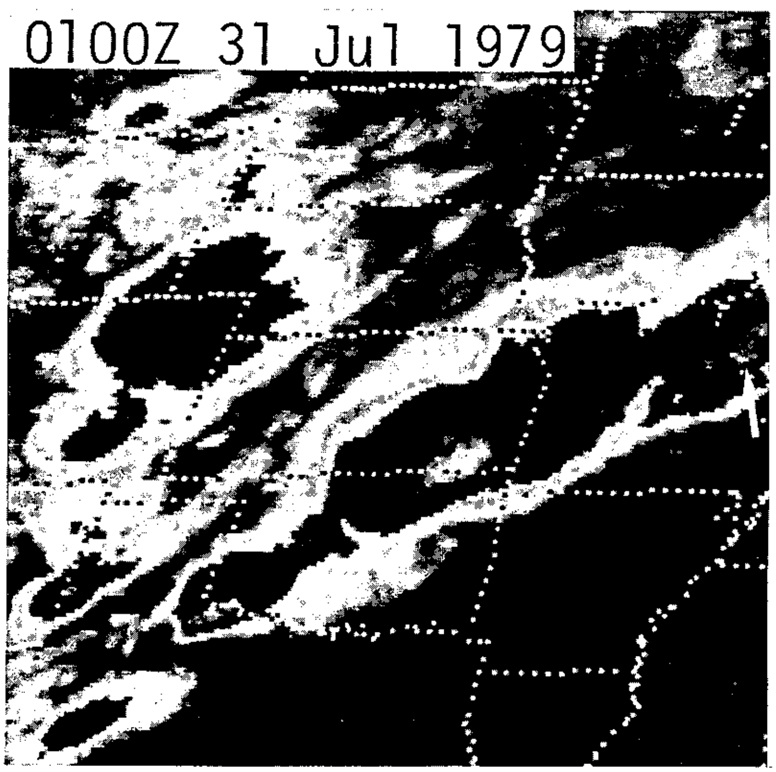
2330Z: The black enhancement on the south side of the Ft. Collins storm continues to grow. The hail at Ft. Collins starts at 2350Z. The Missouri storm also continues to be severe with an enhanced-V. Of note is that there are no reports of severe weather with the very cold thunderstorm tops in southeast Kansas. Although this is not always the case, the enhanced-V did discriminate well between the severe and non-severe storms on this day.



0001Z: The analysis of this image requires another look at the previous image. The Ft. Collins storm's enhanced top is now merged with the enhanced top to the southeast. The western extention of the black area is the Ft. Collins storm top, and, comparing it with the 2330Z image, this extension is larger than the black enhancement earlier, therefore, the storm still appears severe. The Missouri storm shows warmer enhancement levels and is decreasing in intensity.



0030Z: The enhancement of the Ft. Collins storm shows a slight decrease. The hail at Ft. Collins stopped about this time. A small enhanced-V begins to form along the Missouri-Illinois border north of St. Louis. This storm produces wind damage reports in the St. Louis area beginning at 0100Z.



0100Z: The St. Louis storm continues to develop, while the Ft, Collins storm continues to weaken.