The Enhanced-V: A Satellite Observable Severe Storm Signature

DONALD W. MCCANN

National Severe Storms Forecast Center, Kansas City, MO 64106

(Manuscript received 14 January 1982, in final form 30 November 1982)

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 is 30 min. 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. If an enhancement curve is properly chosen, 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 of growth rate and minimum temperature seem to vary from case to case (Adler and Fenn, 1979b).

Mills and Astling (1977) noted that some severe thunderstorms display a distinctive "warm spot" on the storm's top when viewed in enhanced IR imagery. 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 could 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 the 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) espoused the concept of cloud top collapse as the causal mechanism of downbursts. The warm spot depicts a collapsing top which initiates the downburst.

In satellite imagery enhanced by the operational MB[1] curve [Fig. 1 (from Corbell *et al.*, 1976)], the cold area adjacent to the warm spot often 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, 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. The V opens in the direction of anvil expansion. 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–D in the figure.

[1] The MB curve is one of a number of curves used by the National Earth Satellite Service to enhance infrared images. Each of these curves is known by a two-letter name. The MB curve is designed to give cold thunderstorm tops the most detail.

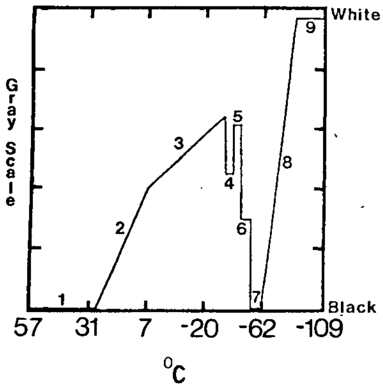

FIG. 1. The MB enhancement curve (Corbell *et al.*, 1976).

The intent of this paper is to show that the appearance of an enhanced-V in a thunderstorm top is a potentially useful warning criterion. For completeness, a brief summary of current ideas on the formation of the enhanced-V is given, but a thorough examination of the dynamics involved is beyond the scope of this study.

2. Theories on the 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 while being diverted around and past the remainder of the top. This flow carried cloud debris which forms the enhanced-V signature of colder air.

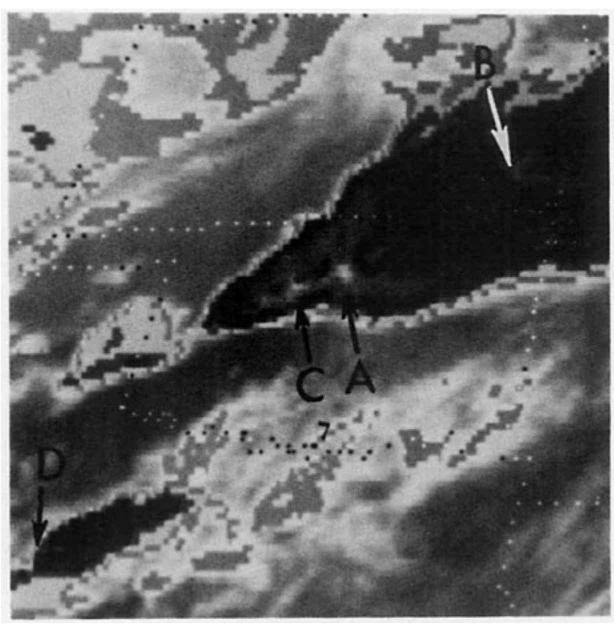

FIG. 2. Satellite imagery of the lower Midwest enhanced with the MB curve. Enhanced-V storms are noted as A–D.

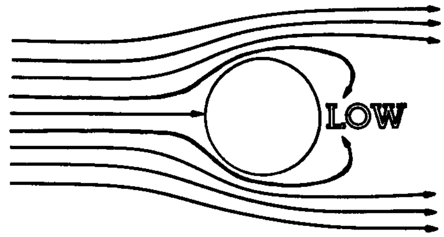

FIG. 3. Turbulent flow past a cylinder showing a low pressure area developing in the wake.

Observational and theoretical evidence can be used 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 is forced as the air that flowed over the dome comes down the back side (Fig. 4). This subsidence causes the air to warm resulting in the warm spot. Visual observations of a "crater" or a "trench" in the anvil indicative of evaporation into warm subsiding air were reported by Burns and Harrold (1966) and Fujita (1978). Downward motion was noted above the crater in the Burns and Harrold study.

In contrast, laboratory studies of flow over domelike objects show an upward hydrodynamic pressure gradient occurs in the lee of the dome (Chien, 1951). This would induce upward rather than downward motion. Such upward motion would cause anvil cirrus downstream from the overshooting top to be lifted and mixed with warmer stratospheric air forcing 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 the 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

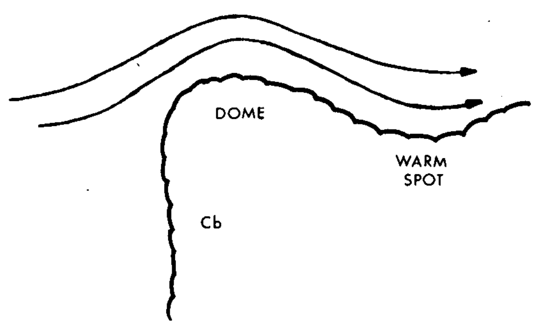

FIG. 4. Possible flow structure over the top of an enhanced-V (adopted from Burns and Harrold, 1966).

crossed the Kansas City area on 4 June 1979 is examined in detail. This storm was associated with the collapse of the roof of the Kemper Arena, Kansas City's multipurpose auditorium. The satellite imagery in this case study is enhanced using the MB curve. The chronology of this storm is as follows (refer to Fig. 5):

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

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

2100 GMT: The storm continues to grow rapidly. A black enhancement appears indicating cooler temperatures (−59.2 to −62.2°C) associated with an overshooting dome.

2130 GMT: The black enhancement area increases in size. An internal lighter gray appears indicating even cooler tops. A light area, the "warm spot", indicative of enhanced-V formation also appears.

2200 GMT: The black-enhanced area becomes an enhanced-V. However, the light shade that indicated the warm spot is gone. Wind damage is being reported in southern St. Joseph, Missouri (indicated by the W in the picture) at this time.

2230 GMT: The enhanced-V becomes larger with the minimum cloud top temperature lower than the previous pictures. The storm remains severe. Hailstones with diameters up to 4½ cm and wind gusts of nearly 40 m s^{-1} are associated with it.

2300 GMT: The storm continues to grow. The white-enhanced overshooting top indicates a large enhanced-V just north of Kansas City. Severe hail and winds are still accompanying the storm.

2330 GMT: 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.

0000 GMT: The storm moves into the downtown portion of Kansas City. Just after this time the Kemper Arena roof caves in. A 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 0015 GMT.

0030 GMT: 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 0000 GMT. No severe weather was reported with this storm after this time.

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

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

4. Analysis of the enhanced-V

The 4 June 1979 case study illustrates how the enhanced-V signature can guide meteorologists to recognize potentially severe thunderstorms. In order to determine if the enhanced-V is a characteristic signature of severe storms in general, every available half-hourly MB enhanced IR satellite picture from April through July 1979 was examined. For each picture that contained 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 was associated with severe weather. This log is a quantization of the reports in the NOAA publication *Storm Data* and contains additional reports of lesser damage not found there.

While doing this, it became apparent that two rules refining the definition of 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. This rule is very similar to that used by Scofield and Oliver (1977) 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 brightnesses for color changes, an enhanced-V may become obscured from recognition by slight cloud top temperature changes. However, if the storm is continuing to grow, it should still be regarded as an active severe thunderstorm. A quantitative definition of an enhanced-V is very difficult. The problem is similar to defining quantitatively a hook echo or a V-notch signature on radar. While the outstanding cases are easy to recognize, experience is needed to recognize enhanced-V's in marginal cases.

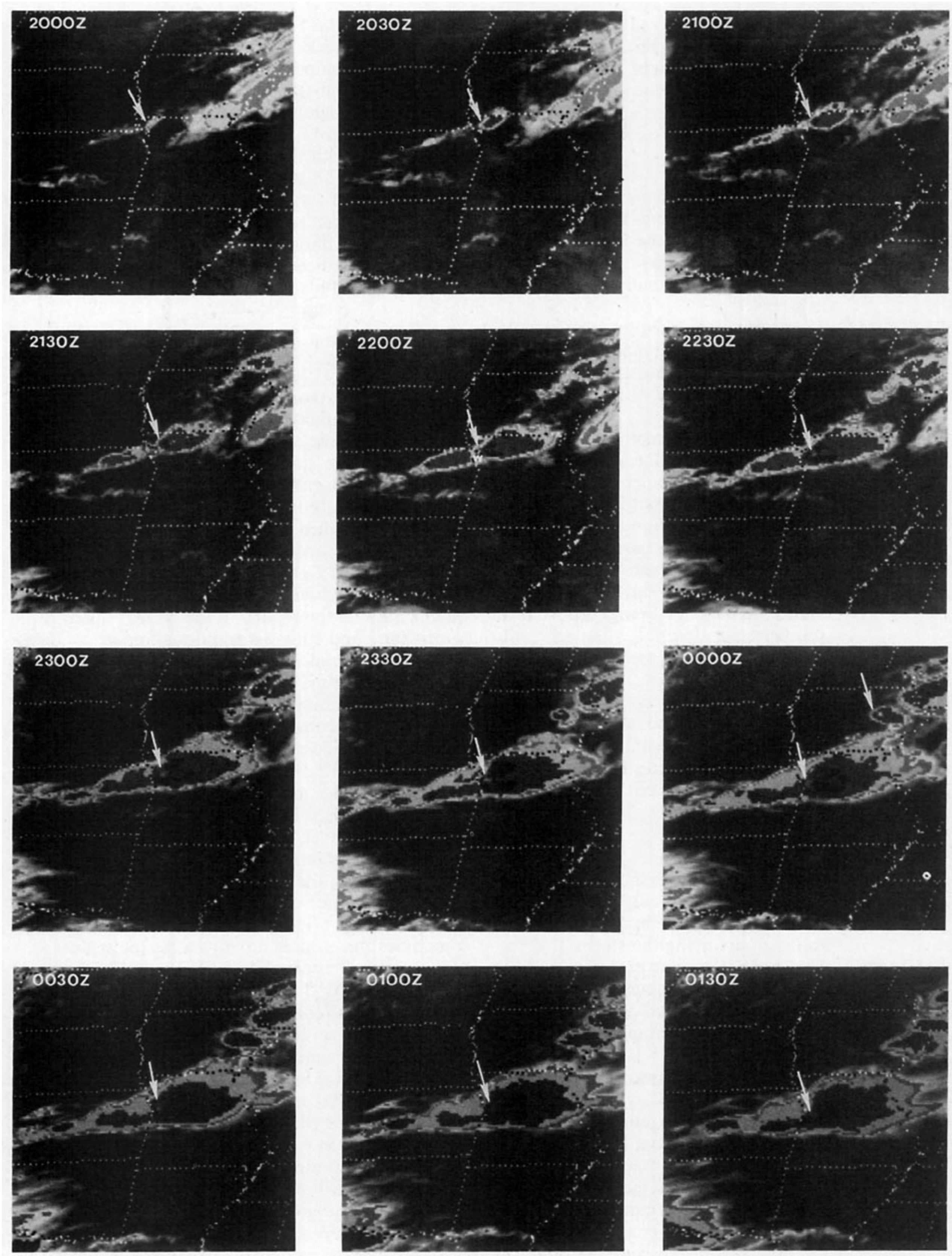

FIG. 5. Satellite imagery of the upper Midwest on 4–5 June 1979 enhanced with the MB curve.

TABLE 1. Enhanced-V verification statistics.

	April	May	June	July	Total
Ratio of enhanced-V's associated severe weather within 60 min to all enhanced-V's	110/150 73%	180/241 75%	185/277 67%	133/216 61%	608/884 69%
Ratio of severe reports 60 min 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	0.25	0.28	0.19	0.17	0.21
Ratio of tornadoes verified	31/119 26%	38/111 34%	19/149 13%	13/132 10%	101/511 20%
Ratio of F2 tornadoes verified	22/40 55%	10/15 67%	6/14 43%	0/7 0%	38/76 50%

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 suggests the presence of a strong updraft, the enhanced-V should have a predictive capability similar to Lemon's radar technique. To examine this predictive potential, each storm that was indicated severe by an enhanced-V was checked for associated severe weather in the 1 h subsequent to 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 becoming severe. Because of the low false alarm ratio (FAR), the enhanced-V signature can be thought of as a valid indicator of severe convection. It has operational utility, if the picture could get into the hands of those responsible for issuing warnings in a timely manner. 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.

The second line in the table is the probability of detection (POD) of severe reports. The numerators in this ratio and in line 1 are of a different nature and are not comparable. More than one event may occur within 60 min of enhanced-V detection (line 2); in addition since there is a 30 min image interval but a 60 min verification period, one report may verify more than one enhanced-V image (line 1). 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. However, it is believed that the lack of adequate temperature resolution in the MB curve at temperatures warmer than −62°C (Fig. 1) lowered the POD in the storms which had tops that were not measured that cold.

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 0.05 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 can be meaningfully compared only among representative populations of storms. 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 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,

TABLE 2. Verification statistics for the Enhanced-V technique and two other techniques on days with significant severe weather.

	POD	FAR	CSI	
Radar: 13 selected days in Oklahoma (Lemon, 1977)	0.93	0.24	0.71	(30 storms)
Satellite: 6 May 1975 (Adler and Fenn, 1979a)	0.73	0.31	0.55	(15 storms)
Enhanced-V: 10 April 1979	44/76 0.58	1/28 0.04	0.57	(6 storms)
Enhanced-V: 2–3 May 1979	130/161 0.81	29/150 0.19	0.68	(42 storms)

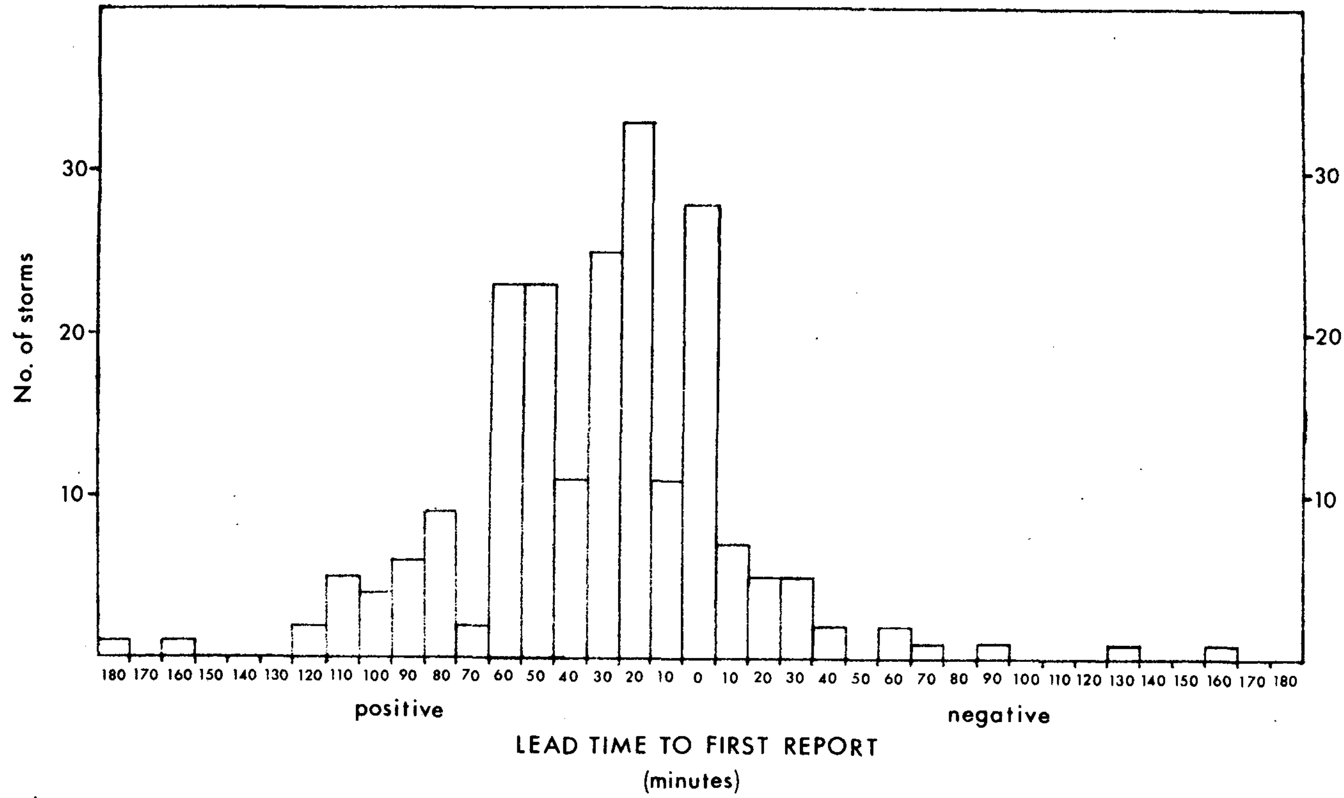

FIG. 6. Lead times to the first report and the number in each category during the 10 min interval centered on the indicated time. A positive lead time indicates that the enhanced-V occurred before the first severe report.

all four storms that produced an F4 tornado during the period had an enhanced-V associated with them before the tornado occurred.

Since severe weather is often reported after an enhanced-V has been identified, a lead time is possible. Lead time is defined as the time between the observation of an enhanced-V 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 min and the mean 31 min. 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 (two 30 min images). However, two storms exhibited an enhanced-V for nine hours.

The winds aloft that were associated with some of the enhanced-V's were estimated from the analyzed NSSFC maximum wind chart. Only those enhanced-V's that were within 3 h of rawinsonde time were considered. The median and mean wind speeds were both 35 m s^{-1} with a range from 20 to 60 m s^{-1}. This is faster than the average wind speed of 26 m s^{-1} at the maximum wind level (12 km above ground) found by Darkow and McCann (1977) for tornadic storms. This indicates stronger than average kinematic forcing 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 generally coincides with the updraft of a storm moving toward the northeast. Because of the viewing angle of the present satellite (geostationary at 70°W), the enhanced-V has to be shifted southeastward 8–20 km to find its location with respect to the surface (Fujita, 1978). Therefore, the severe weather should be located 5–25 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 has the potential of allowing 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 computa-

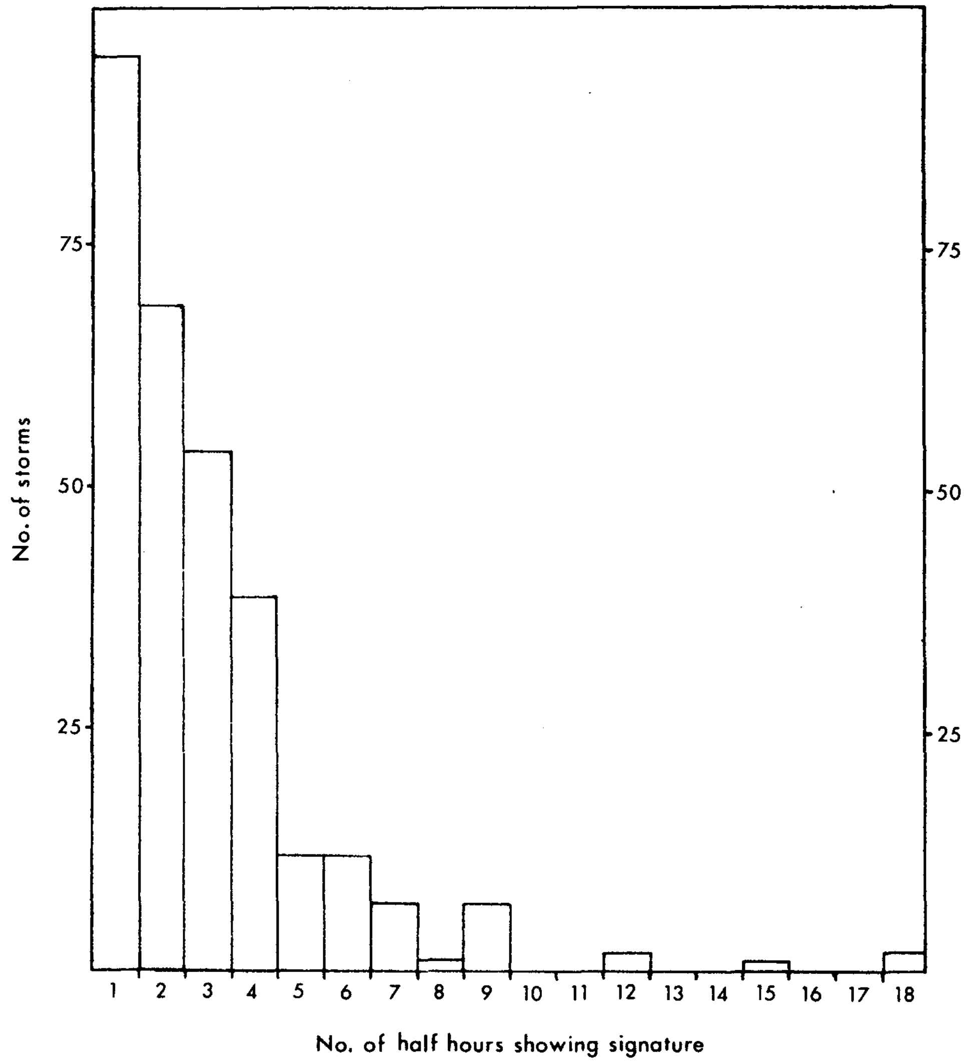

FIG. 7. Number of half-hourly images revealing signature versus number of storms.

tion or measurements. It should detect as much severe weather as possible. It should provide a favorable lead time to the severe weather event. And 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 min 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 min, equivalent to the elimination of the average lead time. This time could be reduced if a system that could directly read out and process the satellite signal such as the one described by Reynolds (1980) were implemented.

Detection of enhanced-V storms probably would be improved by more frequent images being available to the operational meteorologist. A greater lead time certainly is possible since if a storm has an enhanced-V signature on a 30 min interval image, it has to have formed sometime during the interval between images. Earlier detection would be possible. Since enhanced-V identification is subjective, the less time between images, the less time the meteorologist has to wait for the next image in order to make a decision in a marginal case. Fifteen minute interval data are available in special severe storm situations, and on a few research days an image interval as little as 3 min is possible. While problems with handling this much data in an operational mode have yet to be resolved, a shorter image interval does hold significant promise for increasing detection capabilities.

The detection of enhanced-V's also 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 (line segment 7 in Fig. 1) ends at the equilibrium temperature of the nearest upper air sounding. As suggested by Reynolds (1980), the equilibrium temperature should be an improvement on the tropopause temperature since many times the equilibrium level will be significantly lower or higher than the tropopause. In addition, the temperature of the overall cloud to anvil more closely corresponds to the equilibrium temperature than to the tropopause temperature (Roach, 1967).

Finally, the dynamical questions raised in Section 2 need to be answered by further research into the enhanced-V signature. The simple explanation of blocking flow causing the enhanced-V, while adequate, does not explain why some severe storms display an enhanced-V while others do not. Certainly the data suggest that the enhanced-V is associated with many supercell severe thunderstorms. Perhaps an enhanced-V storm and a supercell (as observed on radar) storm are one in the same. Hopefully, those with more research resources will attempt to answer these questions.

Acknowledgments. The greatest amount of thanks go to Edward Ferguson, former Manager, Satellite Field Services Station, Kansas City, Missouri for providing the several hundred satellite pictures needed for this study. Thanks also go to Roy Darrah, Steve Weiss, Richard McNulty and Joseph Schaefer for the review and constructive comments. Beverly Lambert did her usual outstanding job preparing the manuscript for publication.

REFERENCES

Adler, R. F., and D. D. Fenn, 1979a: Thunderstorm intensity as determined from satellite data. *J. Appl. Meteor.*, **18**, 502–517.

——, and ——, 1979b: Detection of severe thunderstorms using short interval geosynchronous satellite data. *Preprints 11th Conf. Severe Local Storms,* Kansas City, Amer. Meteor. Soc., 166–171.

Anderson, C. E., 1979: Anvil outflow patterns as indicators of tornadic thunderstorms. *Preprints 11th Conf. Severe Local Storms,* Kansas City, Amer. Meteor. Soc., 481–485.

Burns, A., and T. W. Harrold, 1966: An atmospheric disturbance encountered by a Canberra over storms at Oklahoma on May 27, 1965. NOAA Tech. Memo. IERTM-NSSL 30, National Severe Storms Laboratory, Norman, OK, 20 pp.

Chein, N., 1951: Wind tunnel studies of pressure distribution on elementary building forms. Iowa Institute of Hydraulic Research, Iowa City, IA, 31 pp.

Corbell, R. P., C. J. Callahan and W. J. Kotch, 1976: *The GOES/SMS User's Guide.* National Environmental Satellite Service, Suitland, MD, 124 pp.

Darkow, G. L., and D. W. McCann, 1977: Relative environmental winds for 121 tornado-bearing thunderstorms. *Preprints 10th Conf. Severe Local Storms,* Omaha, Amer. Meteor. Soc., 413–417.

Donaldson, R. J., Jr., R. M. Dyer and M. J. Kraus, 1975: An objective evaluator of techniques for predicting severe weather events. *Preprints 9th Conf. Severe Local Storms,* Norman, Amer. Meteor. Soc., 321–326.

Doswell, C. A., III, 1980: Synoptic-scale environments associated with high plains severe thunderstorms. *Bull. Amer. Meteor. Soc.,* **61,** 1388–1400.

Fujita, T. T., 1974: Overshooting thunderheads observed from ATS and Learjet. SMRP 117, University of Chicago, 29 pp.

——, 1978: Manual of downburst identification for Project NIMROD. SMRP 156, University of Chicago, 104 pp.

——, and A. D. Pearson, 1973: Results of FPP classification of 1971 and 1972 tornadoes. *Preprints 8th Conf on Severe Local Storms,* Denver, Amer. Meteor. Soc., 142–145.

Lemon, L. R., 1977: New severe thunderstorm radar identification techniques and warning criteria. NOAA Tech. Memo. NSSFC-1, National Severe Storms Forecast Center, Kansas City, 60 pp.

——, 1979: On improving National Weather Service severe thunderstorm and tornado warnings. *Preprints 11th Conf. Severe Local Storms,* Kansas City, Amer. Meteor. Soc., 569–572.

Mills, P. B., and E. G. Astling, 1977: Detection of tropopause penetrations by intense convection with GOES enhanced infrared imagery. *Preprints 10th Conf. Severe Local Storms,* Omaha, Amer. Meteor. Soc., 61–64.

Pearson, A. D., and C. L. David, 1979: Tornado and severe thunderstorm warning verification. *Preprints 11th Conf. Severe Local Storms,* Kansas City, Amer. Meteor. Soc., 567–568.

Purdom, J. F. W., 1975: Tornadic thunderstorm on GOES satellite imagery. *Preprints 9th Conf. Severe Local Storms,* Norman, Amer. Meteor. Soc., (late paper).

——, 1979: The development and evolution of deep convection. *Preprints 11th Conf. Severe Local Storms,* Kansas City, Amer. Meteor. Soc., 143–150.

Reynolds, D. W., 1980: Observations of damaging hailstorms from geosynchronous satellite digital data. *Mon. Wea. Rev.,* **108,** 337–348.

Roach, W. T., 1967: On the nature of the summit areas of severe storms in Oklahoma. *Quart. J. Roy. Meteor. Soc.,* **93,** 318–336.

Scofield, R. A., and V. J. Oliver, 1977: A scheme for estimating convective rainfall from satellite imagery. NOAA Tech. Memo. NESS 86, National Earth Satellite Service, Suitland MD, 47 pp.