OPERATIONAL DETECTION OF HAIL BY RADAR USING HEIGHTS OF VIP-5 REFLECTIVITY ECHOES

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Abstract

An operational method is presented that will predict hail in thunderstorms using the height of VIP-5 radar reflectivity echoes in combination with various meteorological parameters. The VIP-5 echo heights of 97 hail and non-hail producing thunderstorm cases from the WSR-57 radar at Little Rock, Arkansas are compared under concurrent 300-mb heights and temperatures, 500-mb heights and temperatures, freezing level heights, vertical and total-totals indices, and maximum storm top heights.

Results indicate a distinct ability to distinguish between hail and non-hail producing thunderstorms when their VIP-5 echo heights are normalized with respect to many of these concurrent upper-air parameters. The same methodology is applied in an attempt to distinguish severe hailstorms from non-severe hailstorms, with inconclusive results.

Potential application of this principle to Weather Surveillance Radar 1988 Doppler (WSR-88D) severe storm detection algorithms is discussed, with an emphasis on environmental normalization of algorithms as opposed to seasonal or climatological normalization.

1. Introduction

Severe storm identification has long held a high priority among meteorologists. As such, we have learned much about the structure and behavior of severe and non-severe thunderstorms in recent years. Much of this new knowledge has been a direct result of the use of radar.

Donaldson (1961) was among the first to correlate radar reflectivity patterns to the occurrence of hail, finding that the relative frequency of hail occurrence increased greatly when the reflectivity factor at 30,000 feet was at least $10^{4.5}$ mm^6m^{-3}. Waldvogel et al. (1979) developed a real-time hail probability equation for 3-cm radars utilizing primarily the height of the 45 dBZ echo above the freezing level. That study was one of the first to consider characteristics of the thunderstorm environment as a predictor in determining hail development thresholds. Applying some of the ideas presented by Waldvogel et al. (1979), Witt (1990) developed a successful hail core aloft detection algorithm that utilizes output from WSR-88D storm analysis algorithms.

In a study that has received much attention among operational radar meteorologists, Lemon (1980) related what is known about thunderstorm structure and evolution to certain radar derived parameters. Petrocchi (1982), among many others, has since fine-tuned some of Lemon's techniques for application toward the WSR-88D Doppler radar products and algorithms. Severe storm detection techniques have also been enhanced considerably in recent years through the use of Radar Data Processor (RADAP II) related technology, much of which also has been applied to WSR-88D algorithms (Saffle 1976; Winston and Ruthi 1986; Devore 1983, 1985).

A by-product of Lemon's work was the establishment of suggested radar derived warning criteria in the National Weather Service (CR-ROML C-29-84). One such criterion within this set is the height of the DVIP (Digital Video Integrator and Processor) level 5 reflectivity echo (hereafter referred to as VIP-5). In the Southern Region, a VIP-5 (51-57 dBZ) height of 30,000 feet was specified as a suggested minimum for issuance of a severe thunderstorm warning based on radar. In the Central Region, the VIP-5 height criterion was set at 27,000 feet. (These thresholds are based on heights extracted from a rotating antenna.) Based on personal experience, and the observations of other radar meteorologists, these fixed values have proven to be rather inconsistent as indicators of severe weather.

However, as this study will show, VIP-5 height thresholds for conventional radars can provide meteorologists with useful information when normalized with respect to certain characteristics of the environment in which the thunderstorm is occurring. Such normalized thresholds can then effectively supplement other existing techniques and criteria now used for severe storm identification. This is especially true for the detection of hail. This principle could have important implications for the development and application of certain WSR-88D severe storm detection algorithms.

2. Data Collection and Approach

From paper overlays taken at the WSR-57 radar at Little Rock, Arkansas, 97 VIP-5 thunderstorms were selected for this study. Maximum top, maximum VIP-5 height, and maximum reflectivity were extracted from these overlays for each thunderstorm. To ensure a seasonal distribution of thunderstorms, cases were selected from all months of 1984 except January and December, when no severe weather occurred. To qualify for inclusion in this study, a VIP-5 thunderstorm needed to be between 25 and 100 n mi. from the radar site. In addition, if a particular thunderstorm was a hail producer, a complete radar overlay must have been taken within 15 minutes of hail occurrence. For other, non-hail producing storms, a maximum VIP-5 height was extracted without any such time constraint. All VIP-5 heights were measured with a Range Height Indicator (RHI) overlay for top correction, and all measurements were taken with a non-rotating radar beam. Ground truth was obtained primarily through Local Storm Reports for Arkansas.

Storm distribution throughout the year was not even. Typically, concentrations were heaviest during the late spring and early summer months with a minimum in thunderstorm activity in the winter (Kelly et al. 1985). As expected, VIP-5 heights measured through the course of the year showed considerable month-to-month, week-to-week, and even day-to-day variability. Thus, rather than evaluate thunderstorms on a smoothed month-by-month, or seasonal climatology, it was decided to compare VIP-5 heights with concurrent rawinsonde data-derived parameters for each event.

Upper-air parameters used in this study were 300-mb height and temperature, 500-mb height and temperature, freezing level height, vertical-totals index, and total-totals index. These parameters were extracted from 1200 UTC and 0000 UTC soundings taken at the WSFO Little Rock upper-air site only. A subjective interpolation between the two soundings was done to approximate conditions at the time of thunderstorm occurrence when appropriate.

Using these data sets, maximum thunderstorm VIP-5 heights were compared with each upper-air parameter primarily for the purpose of distinguishing hail producing storms from non-hail producing storms under various environmental conditions. A similar comparison was made in an attempt to distinguish severe hailstorms from non-severe storms.

3. Limitations and Potential Error Sources

A study of this type is often subject to various, unavoidable limitations and errors. Use of the 10-cm wavelength WSR-57 radar presents some limitations in the use of VIP-5 and maximum top heights. All heights were taken directly from the RHI scope with the help of an RHI overlay for top corrections due to standard refraction of the radar beam in the atmosphere. However, no corrections were made for non-standard refraction of the radar beam. In many cases involving an unstable atmosphere, subrefraction of the radar beam will be the rule. Therefore, heights are often underestimated by the radar during times of severe weather. Errors of this type, along with errors due to the azimuth and range resolution of the radar, tend to increase in magnitude as distance from the radar increases. Thus, a 100 n mi. maximum limit was arbitrarily imposed on storm selection. A 25 n mi. minimum restriction was also imposed due to height distortions from side lobe return (transmitted electromagnetic energy not contained within the defined 2 degree beam width of the radar) off the radar beam.

The upper-air parameters taken from the 1200 UTC and 0000 UTC rawinsonde observations were subject to the usual spatial and temporal resolution problems. Some attempt was made to lessen the error due to temporal resolution by the use of a subjective interpolation whenever appropriate. The magnitude of errors involved with these resolution problems are not known.

The greatest potential error sources, though, probably come from ground truth verification accuracy, and time constraints on radar overlay observations.

Hales (1987) points out that analysis of the distribution of severe weather reports across the country is biased toward large population densities and distance from the warning office. Arkansas is a dramatic example. Grant and Pulaski counties in central Arkansas are adjacent to each other, yet Grant county has only about 5% the total population of Pulaski county. Thus, a severe thunderstorm event has a much greater chance of going unreported in Grant county. This then increases the chance of a contaminated sampling of thunderstorms in a study of this type. These biases were not factored into this study. Of note is that Pulaski county is within 25 n mi. of the radar site, and all thunderstorm events in this heavily populated county were excluded from this study.

Further contamination may arise in the manner in which the public, spotter groups, and law enforcement officials report hail sizes. For example, what was really ½ inch hail may be reported as ¾ inch hail by the observer. One event is considered severe while the other is not. For more detailed discussion on these topics, see Doswell (1985) and Kelly et al. (1985).

Finally, a time constraint on having a radar overlay done within 15 minutes of hail occurrence increases the probability of not actually recording the maximum VIP-5 height in a particular storm. This depends, of course, on the number of overlays done during that particular time frame. Once again, it is unknown how many thunderstorm cases were affected and how large any errors might be.

4. Results

The 97 thunderstorm cases were grouped as follows:

1) Those storms that produced hail—67 cases,
   a. Those storms that produced hail less than ¾ inch—29 cases,
   b. Those storms that produced hail ¾ inch or larger—38 cases,
2) Those that produced no hail—30 cases.

Using these cases, comparisons of two types were made under the various environmental conditions encountered. Initially, VIP-5 heights in hailstorms were compared to VIP-5 heights found in non-hail producing thunderstorms, and secondly, VIP-5 heights in severe hailstorms were compared to those found in non-severe hailstorms.

A. Hail versus No Hail

When comparing observed VIP-5 heights under various environmental conditions, a fairly definite distinction was observed between those storms that produced hail and those that did not. This distinction was found to be present for each upper-air parameter in this study except for the two stability indices. Since no relationship was found between the degree of stability (using those indices) and the height of the VIP-5 reflectivity echo in hailstorms, the total-totals and vertical-totals indices were dropped from the remainder of the study.

For the other parameters, visual inspection of the plotted VIP-5 height data in Figures 1–6 revealed a boundary below which hail generally *did not* occur, and above which hail generally *did* occur. These VIP-5 reflectivity hail threshold curves are superimposed on Figures 1–6 (solid lines).

Examination of these figures also revealed that as the environmental parameters tended toward colder values, VIP-5 heights needed to produce hail decreased significantly. This was true for each upper-air parameter considered. It is also apparent that VIP-5 height thresholds for the development of hail tended to level off after 31,000 feet as upper-air temperatures and heights increased. The reason for the latter observation is not entirely clear, although experience has shown this part of the curve to be less reliable under warm weather regimes.

To measure the success of these upper-air parameters as predictors of a VIP-5 height threshold needed to produce hail, Critical Success Index (Donaldson et al. 1975) was used. Critical Success Index (CSI) is defined by the National Weather Service (NWS 1982) as a function of probability of detection (POD) and false alarm ratio (FAR) where

$$\text{POD} = \frac{\text{NUMBER OF WARNED EVENTS}}{\text{TOTAL NUMBER OF EVENTS}} \quad (1)$$

$$\text{FAR} = \frac{\text{NUMBER OF FALSE WARNINGS}}{\text{TOTAL NUMBER OF WARNINGS}} \quad (2)$$

$$\text{CSI} = [(\text{POD})^{-1} + (1\text{-FAR})^{-1} - 1]^{-1}. \quad (3)$$

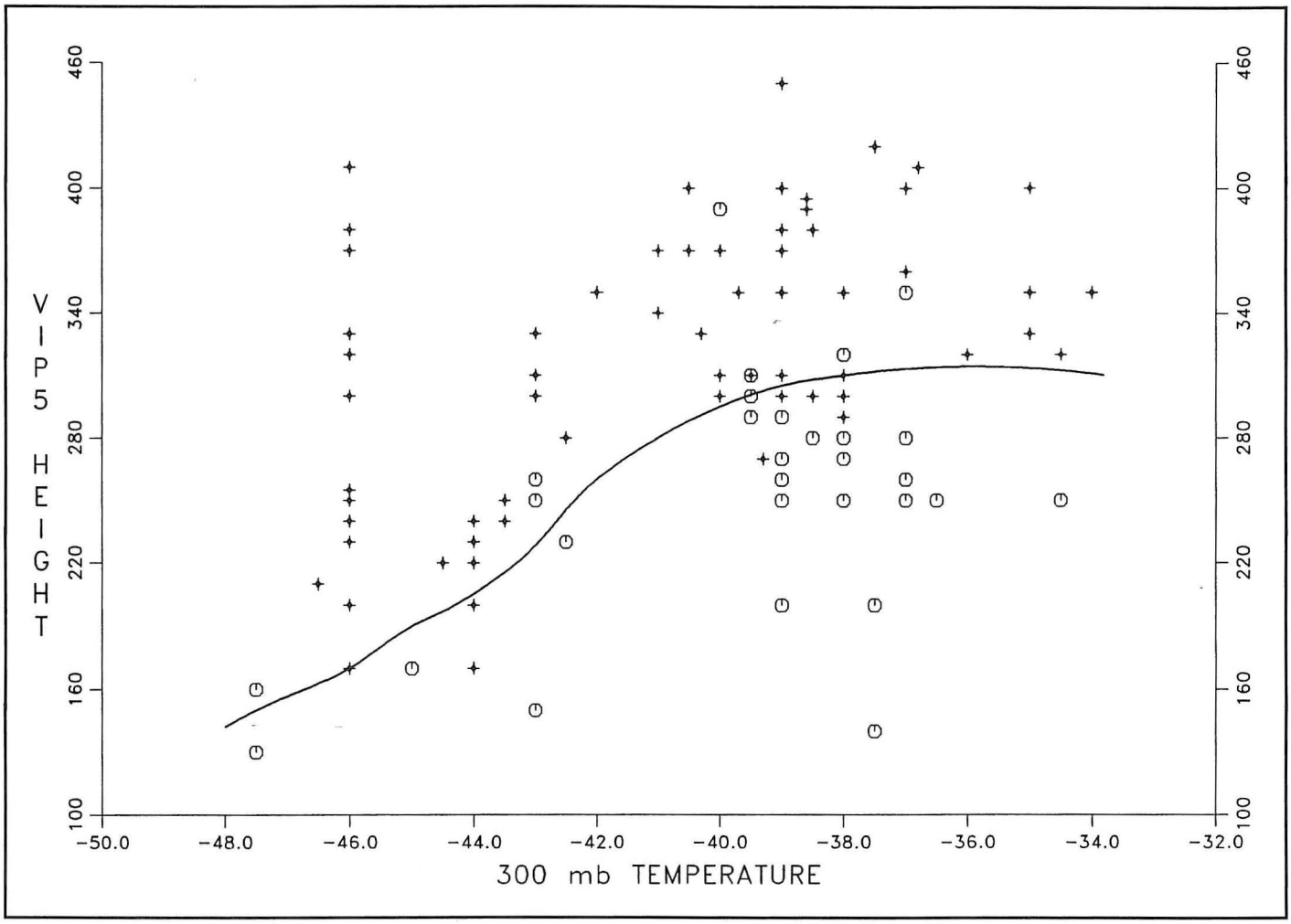

Fig. 1. Scatter diagram of VIP-5 height in hundreds of feet versus 300-mb temperature in degrees C. (solid line indicates hail/no hail threshold). A "+" indicates hail and a "o" indicates no hail.

Verification scores, using equations 1–3, are given in Table 1. These statistics are based on taking the cases above the threshold curves in Figures 1–5 and considering them as forecasts of hail, and taking cases below the threshold curves and considering them as forecasts of no hail.

Also of interest are the results shown in Figure 6, which presents the relationship between VIP-5 height and maximum echo top. Given no other parameters as input, the relationship of VIP-5 height to maximum top can be indicative of the presence of hail in a thunderstorm. Using the curve shown in Figure 6 as the boundary between storms that produced hail and those that did not, verification statistics were as follows:

POD = .88 FAR = .14 CSI = .77.

The hail vs. no hail Critical Success Indices in this study compare favorably to CSI's from a set of hail criteria used by Petrocchi (1982) in Oklahoma for development of a hail algorithm. However, predictors in that study were entirely radar derived quantities with no consideration given to characteristics of the thunderstorm environment. Predictors used by Petrocchi (1982) were midlevel reflectivity of at least 50 dBZ, mid level overhang, echo top over a midlevel overhang, 30 dBZ echo to at least 8 km, a southward tilt of the storm, cell movement to the right or left of the mean motion of all cells, maximum reflectivity at any level of at least 55 dBZ, and a direction of tilt to the right and/or behind the direction of cell movement.

B. Severe Hailstorms versus Non-Severe Hailstorms

Attempts in this study to distinguish between large hail ¾ inch or larger) and small hail produced inconclusive results. This is graphically shown in Figures 7 through 12. Superimposed on these figures for reference are the curves (solid lines) representing the hail/no hail thresholds arrived at in section A. While these thresholds proved to be excellent indicators of hail in thunderstorms, their value as indicators of large hail was considerably less. Once again using those threshold curves, verification statistics were computed (Table 2), but this time for large hail versus small hail for each upper-air parameter and maximum top data.

Because of the nature of verifying large hail versus small hail in this manner, the false alarm ratios can be misleading. In this case, it was felt that a false alarm percentage may be

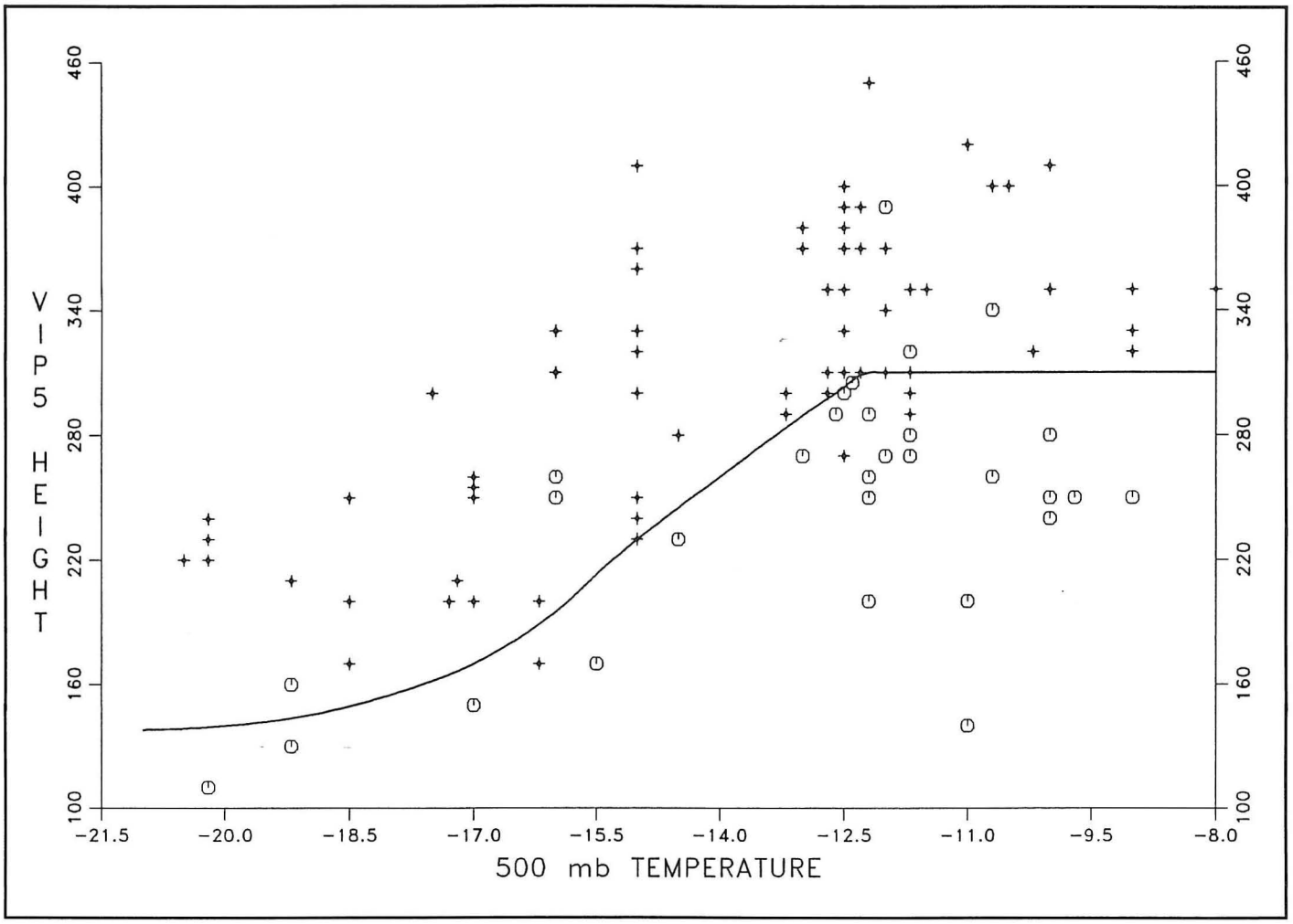

Fig. 2. Scatter diagram of VIP-5 height in hundreds of feet versus 500-mb temperature in degrees C. (solid line indicates hail/no hail threshold). A "+" indicates hail and a "o" indicates no hail.

more appropriate. False alarm percentage (FAP) is defined as;

$$\text{FAP} = \frac{\text{Number of False Alarms}}{\text{Total Number of Non-Severe Hail Events}} \quad (4)$$

In an attempt to improve upon these numbers, the VIP-5 height hail thresholds arrived at in section A were increased by 10% for each predictor in Table 2. These increased threshold values are depicted as dashed curves on Figures 7–12, with recomputed verification results listed in Table 3.

Efforts to improve CSI's (for ¾ inch hail or larger) by increasing the minimum thresholds were unsuccessful. By attempting to improve false alarm ratios and percentages, probability of detection is sacrificed and vice-versa. This same inability to distinguish hail sizes with an acceptable level of accuracy was also found by Petrocchi (1982).

5. Discussion and Implications

Radar meteorologists face one of the greatest challenges in operational meteorology today. That is, to determine which thunderstorms are capable of producing severe weather, before severe weather phenomena actually occur. Obviously, this is no easy task, as NWS severe local storm verification statistics bear out (Kelly and Schaefer 1982; Grenier et al. 1987).

During the early and mid 1980s, the various NWS regional headquarters supplied field radar sites with guidance for a minimum VIP-5 height for issuance of a severe thunderstorm warning based on radar (30,000 feet in Southern Region and 27,000 feet in Central Region). Unfortunately, these policies regarding VIP-5 height thresholds have not consistently worked. The results of this study have shown severe hailstorms can occur across a very wide variety of VIP-5 heights above and below those thresholds.

Certainly, the failure of such fixed VIP-5 height thresholds can be largely attributed to the wide variety of atmospheric environments in which thunderstorms occur. In general, this study has shown that the warmer the thunderstorm environment, the higher the VIP-5 height threshold for hail production. Therefore, in order for such a radar-derived characteristic of thunderstorms to be most useful as an indicator of severe weather, it should first be normalized with respect to certain characteristics of the individual thunderstorm environment.

As an example, consider the sample soundings in Figures

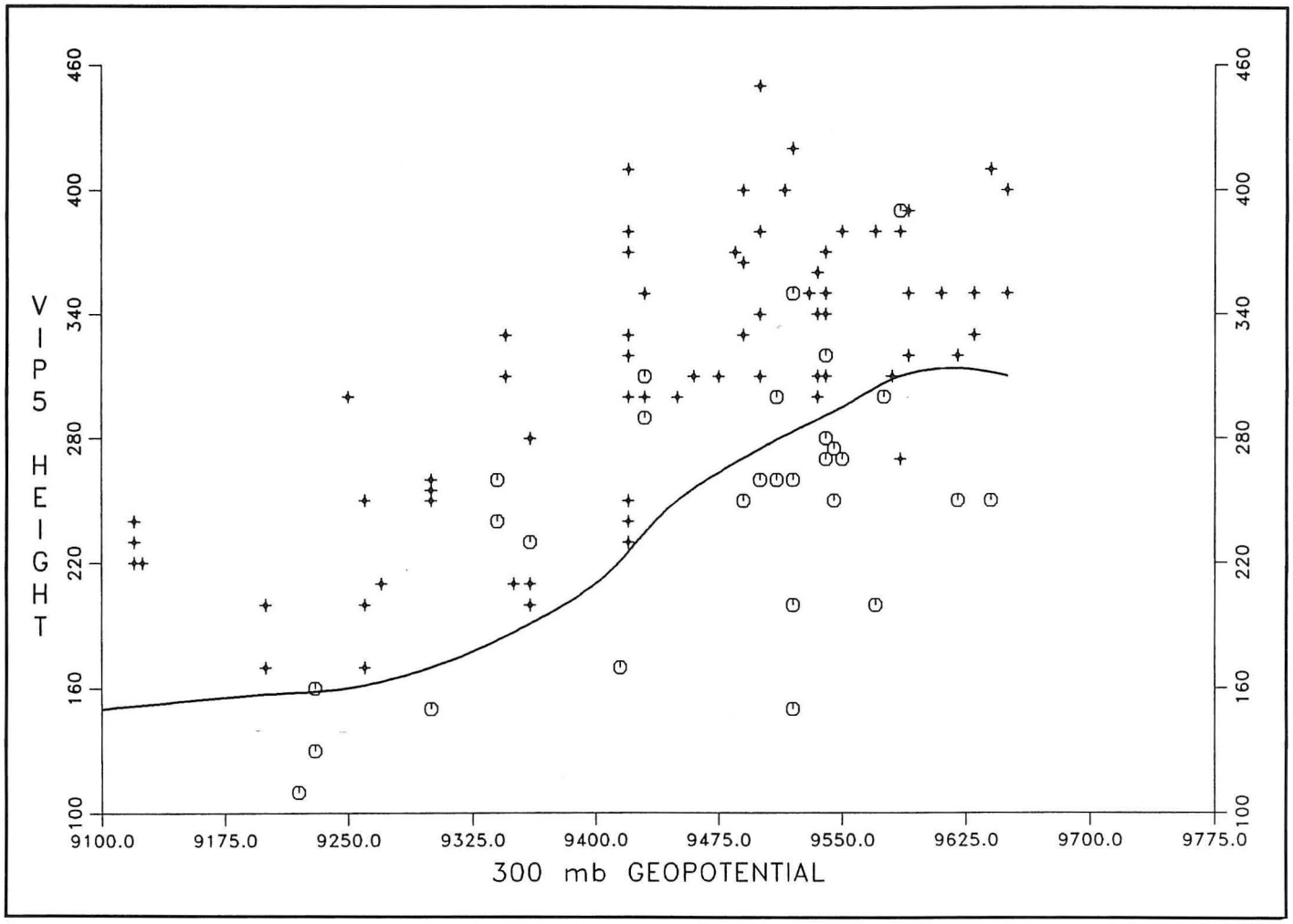

Fig. 3. Scatter diagram of VIP-5 height in hundreds of feet versus 300-mb height in meters. (solid line indicates hail/no hail threshold). A "+" indicates hail and a "o" indicates no hail.

13 and 14. Figure 13 is a sounding taken at Oklahoma City (OKC), and Figure 14 is a sounding taken on a different day at St. Cloud, Minnesota (STC). For simplicity, factors such as vertical wind shear, relative inflows, low level forcing, precipitation drag, dynamic pressure effects, etc., have been set equal between the two sample soundings. Thus, the primary difference between the two environments is essentially thermal.

Given these environmental differences though, one would not expect the vertical reflectivity profiles of hail producing thunderstorms in each airmass to be the same. Due to the higher Equilibrium Level at STC, one might expect storm tops in the STC airmass to be approximately 6000 feet higher than in the OKC airmass. However, based on the results of this study, hail occurrence (possibly severe) could be expected when the vertical extent of the VIP-5 reflectivity echo reached just 23,000 feet in the cooler environment at OKC, and 31,000 feet in the STC airmass. Obviously, to apply a single hail development threshold to both of these differing airmasses would be incorrect, without first normalizing for certain characteristics of the individual environments.

This example is somewhat simplified, but is not without some validity. There are many other factors that must be considered when evaluating the potential severity of a particular thunderstorm. Specifically, one must consider the manner in which a thunderstorm interacts with its environment. These interactions generally influence the characteristic form that a thunderstorm eventually takes and the longevity of its updraft(s), which are extremely important predictors of storm severity (Weisman and Klemp 1982; Doswell 1985).

It has also long been recognized that vertical wind shear plays a critical role in providing an environment favorable for hail production (Marwitz 1972a,b,c; Kitzmiller and McGovern 1990). These sheared environments are conducive for tilting of the thunderstorm updraft, thus allowing possible development of an enhanced, quasi-state storm structure such as those seen in supercell storms (Marwitz 1972a,c; Doswell 1985). While vertical shears play a primary role in the development of hailstorms, this study has not investigated a possible relationship between the *degree* of vertical wind shear and VIP-5 height thresholds for hail development. Therefore, it is suggested that the results of this study be used only as a supplement to operational techniques that examine shear-induced storm properties such as storm tilt, mid-level overhang, etc. (Lemon 1980; Petrocchi 1982).

Some of the results and ideas presented in this study may

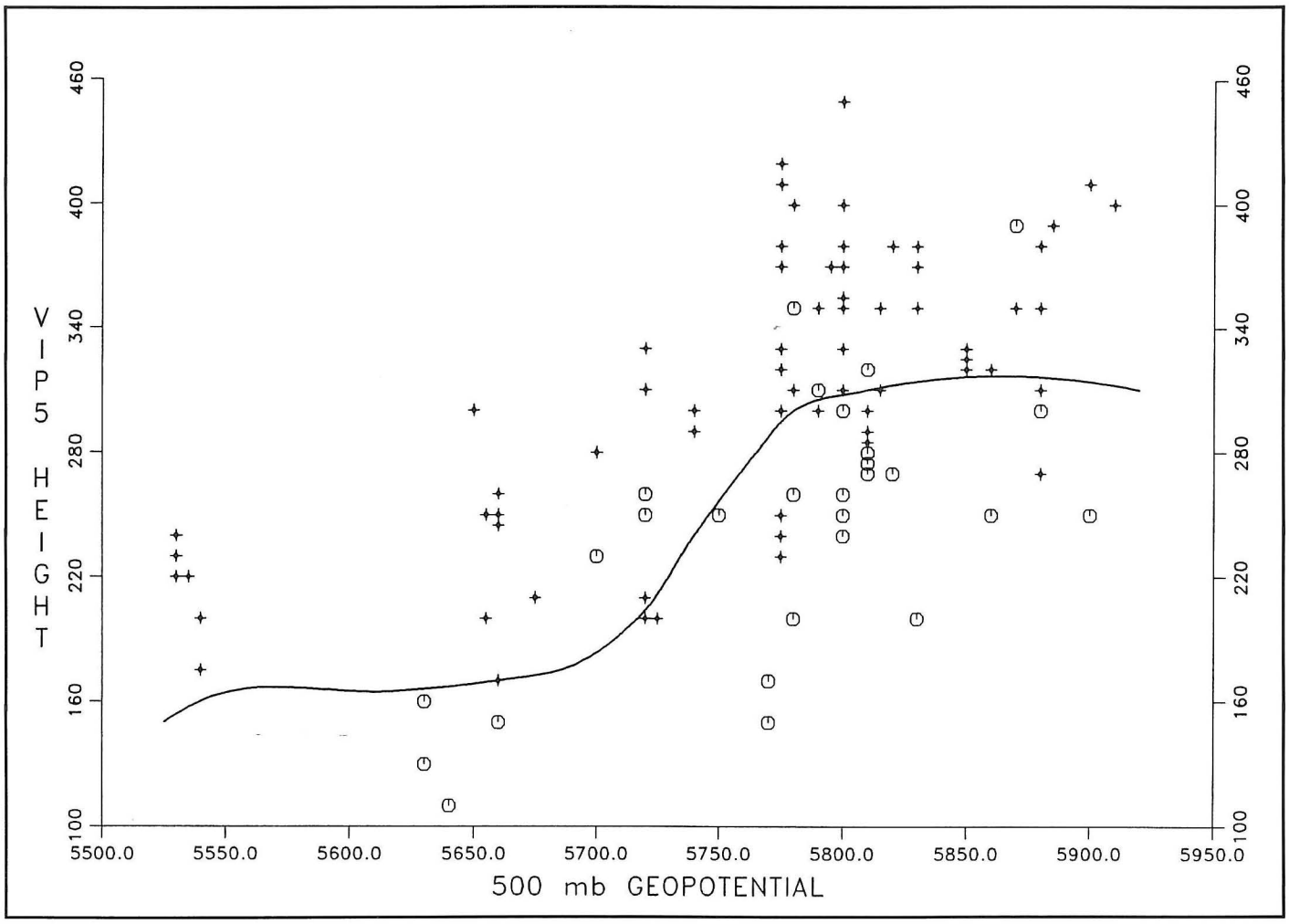

Fig. 4. Scatter diagram of VIP-5 height in hundreds of feet versus 500-mb height in meters. (solid line indicates hail/no hail threshold). A "+" indicates hail and a "o" indicates no hail.

also have important implications for the development of certain WSR-88D severe storm algorithms. In particular, some of these algorithms may depend heavily on Vertically Integrated Liquid (VIL) signatures and Severe Weather Probability (SWP) methodology developed through the use of RADAP II technology (Greene et al. 1971; Elvander 1977; Winston and Ruthi 1986; Winston 1988).

In a similar study to this one, Beasley (1986) found average VIL (and SWP) for severe hailstorms exhibited significant seasonal and diurnal variations. He was able to recognize the need to normalize his VIL and SWP data set before effectively applying them as severe weather indicators in Oklahoma. As such, he developed a set of seasonally normalized regression equations for estimating hail size.

Beasley's research also found average VIL in hailstorms not only varied significantly by season (an average of 35 kg m^{-2} in February to an average of 70 in June), but that absolute VIL in these storms could vary significantly within a given month by as much as 50 kg m^{-2} (Fig. 15). This result is consistent with observations made in this study. Such month-to-month, week-to-week, and even day-to-day variations in actual hailstorm VILs are also likely related to the wide spectrum of atmospheric environments in which severe thunderstorms occur.

Given this, it may be more appropriate to normalize VIL attributes with respect to the thunderstorm environment, rather than seasonally or climatologically (or not at all), when evaluating potential storm severity. By doing so, the effects of deviations from climatology on the performance of certain WSR-88D severe storm detection algorithms should be greatly minimized. For example, consider a large springtime 500-mb low pressure system moving from the central Rockies into the central Plains states. An outbreak of hail producing thunderstorms occurs on Day 1 ahead of the low in the abnormally warm airmass ahead of the advancing cold front. However, hail producing thunderstorms also develop on Day 2, near the cold-core 500-mb low in essentially the same location that hail occurred on Day 1. A climatologically attuned algorithm would be unable to adapt to the change in VIL (or VIP) attributes of thunderstorms brought about by the change in environment from Day 1 to Day 2.

Failure to normalize VIL thresholds with respect to environment not only makes hail detection algorithms susceptible to deviations from climatology, but also may tend to build regional dependence into certain algorithms. Jendrowski (1988) found such a regional dependence when evaluating the performance of the OKC derived SWP regression equations at another location (Amarillo, TX). It was suggested in that

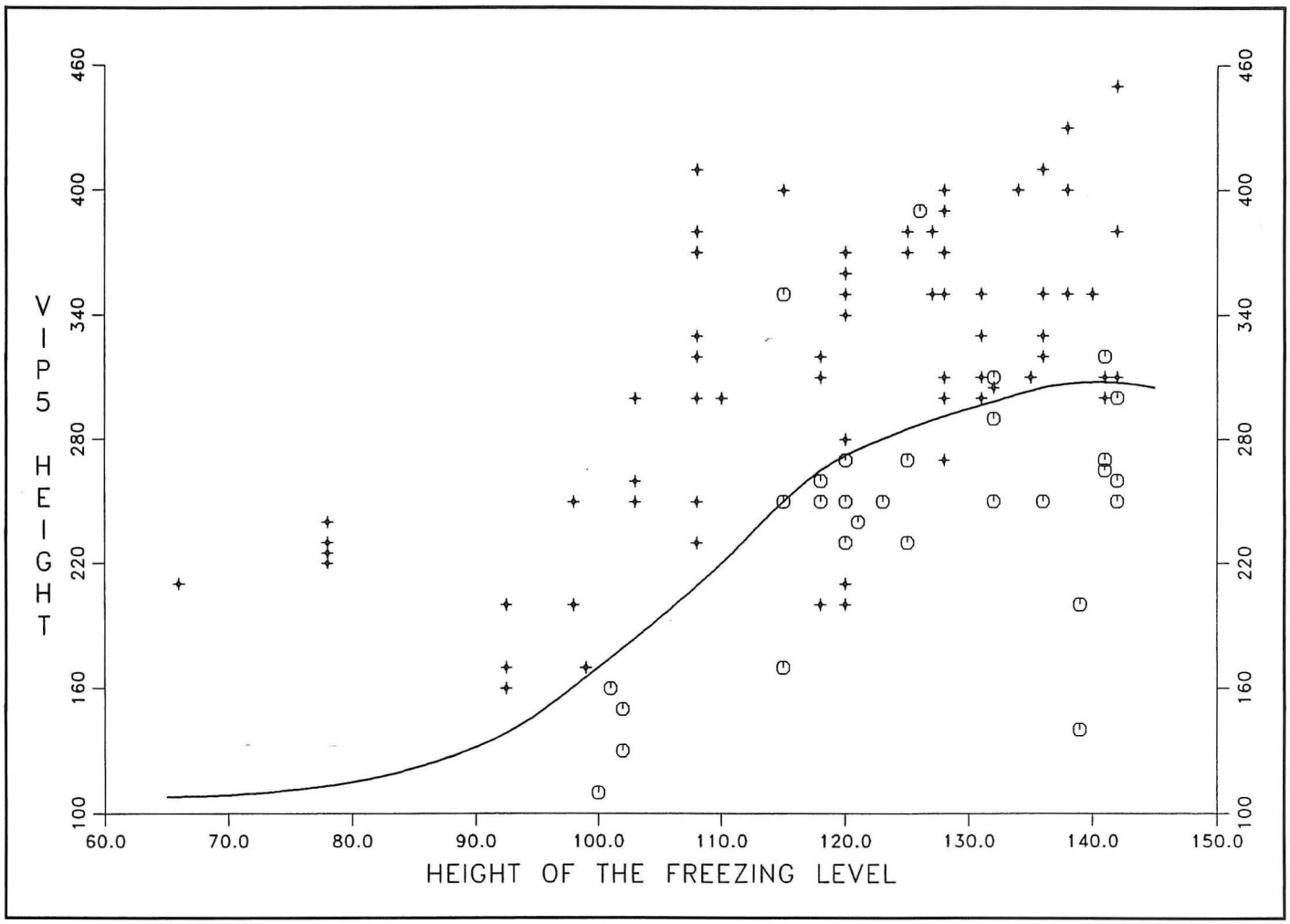

Fig. 5. Scatter diagram of VIP-5 height in hundreds of feet versus freezing level height in hundreds of feet. (solid line indicates hail/no hail threshold). A "+" indicates hail and a "o" indicates no hail.

study that deviations from climatology may well have influenced this regional dependency.

While it is unclear whether storm climatology at OKC could be applied to AMA, it is clear that it could not be applied to other locations such as Minneapolis, Chicago, Memphis, or Denver. However, while severe storm environments do vary widely for a single location, perhaps only a handful of environments can really be considered unique to their geographic locations. High plains thunderstorm environments and certain dryline environments are two examples (Bluestein and Parks 1983; Schultz and LeFebvre 1986).

In most cases, it is more appropriate to say that the *frequency of occurrence* of various severe storm environments differ from region to region. With this in mind, there may be little reason for VIL or VIP attributes for storms in a particular environment over eastern Kansas to differ greatly from those in a near identical environment over northern Illinois or southeastern Arkansas, regardless of time of year.

The versatility of using environmentally normalized hail detection algorithms may allow for similar equations to be used at Memphis and Des Moines, or Birmingham and Indianapolis. Such algorithms would have to, 1) contain a large database to cover the wide spectrum of thunderstorm environments across the radar network, and 2) be interactive to allow the forecaster to input appropriate rawinsonde derived parameters at each location on a day-to-day basis. This would then allow the algorithm(s) to better adapt to individual weather situations at a given location.

6. Conclusions

To a high degree of accuracy, the presence of hail can be detected in a thunderstorm by relating radar reflectivity and certain upper-air characteristics of the thunderstorm environment. By using current or predicted sounding parameters for a given weather situation, the radar meteorologist can effectively predict a VIP-5 height threshold which will yield hail on that particular day.

The major advantage of such a scheme is that a hail prediction threshold can often be established on a potential severe weather day even before the first raindrop falls. This is contingent on the user's ability to accurately anticipate pertinent environmental conditions at the time of thunderstorm occurrence.

Operators of conventional 10-cm radars can extract threshold values directly from the curves superimposed on the

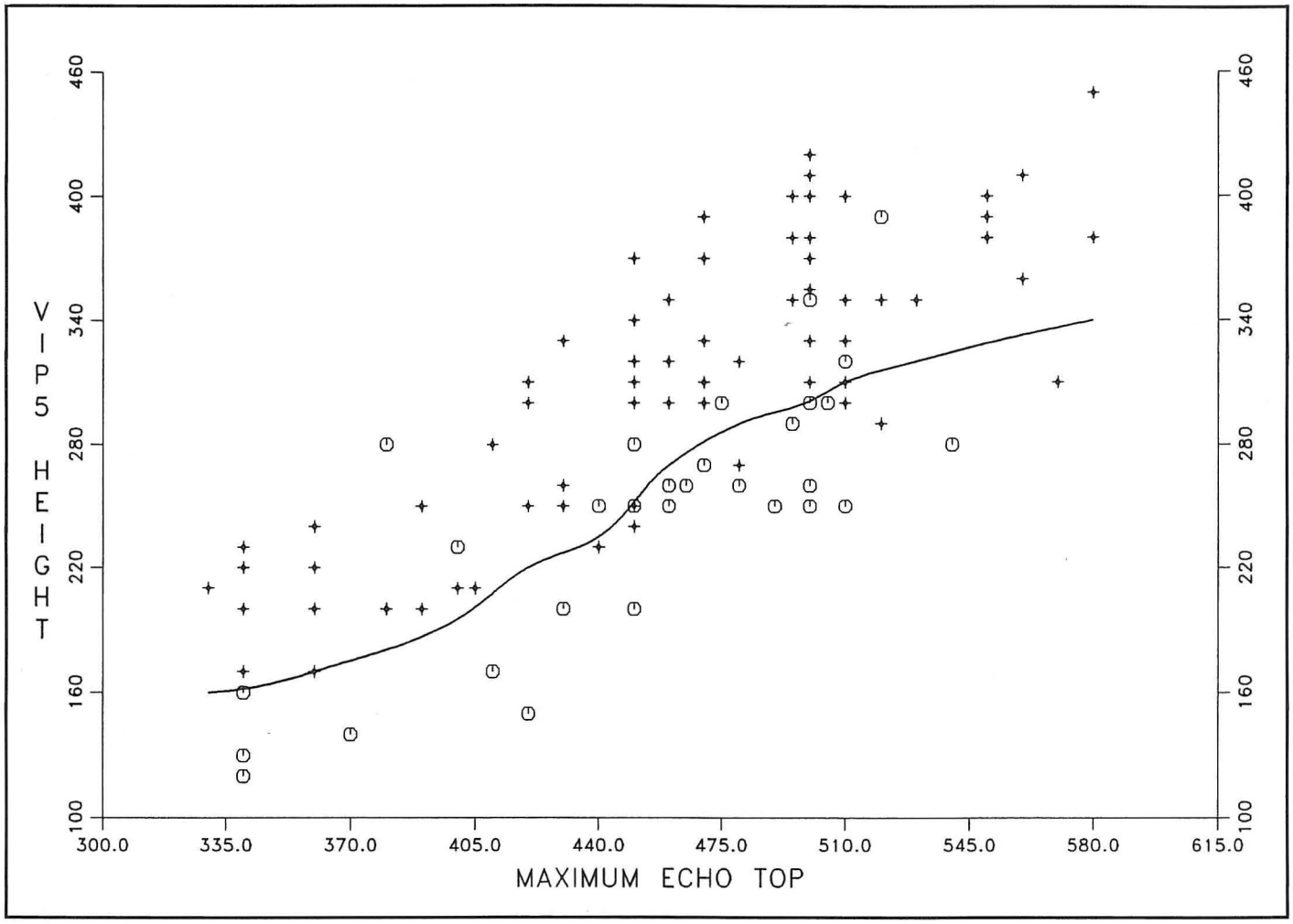

Fig. 6. Scatter diagram of VIP-5 height in hundreds of feet versus maximum top height in hundreds of feet. (solid line indicates hail/no hail threshold). A "+" indicates hail and a "o" indicates no hail.

Table 1. Verification scores for each upper-air parameter as a predictor of hail when related to VIP-5 height.

Parameter	POD	FAR	CSI
300-MB Height	.98	.13	.85
300-MB Temperature	.88	.12	.79
500-MB Height	.86	.10	.78
500-MB Temperature	.92	.10	.83
Freezing Level Height	.94	.10	.85

graphs with this study. Extracting predicted VIP-5 heights from two or three of the upper-air parameters should be sufficient to arrive at a workable "VIP-5 height of the day" needed to produce hail. In particular, 300-mb height, freezing level height, and 500-mb temperature seem to work best as predictors in this regard.

These predictors will not always give identical VIP-5 height thresholds for a given event. Which values the operator ultimately chooses will depend to a large extent on personal experience and perhaps the geographical region of the radar site. While results of this study may be best suited for the south central or southeastern United States, there may be application of this principle to other geographical regions as well.

The inability to distinguish between a severe hailstorm and a non-severe hailstorm however, continues to be a problem. Thus it is recommended that predicted VIP-5 heights for hail formation be used only as a *supplement* to existing severe storm identification techniques and criteria. It is very important that other current operational techniques for non-Doppler radars be used to help distinguish severe hailstorms from non-severe storms and to establish effective lead times.

Finally, this study has shown that for certain radar-derived characteristics of thunderstorms to be operationally useful as indicators of hail, they must first be normalized with respect to the thunderstorm environment. This could have important implications for the development and application of certain WSR-88D severe storm detection algorithms. The performance of algorithms that are normalized with respect to season or climatology, rather than thunderstorm environment, may be susceptible to deviations from climatology and exhibit regional dependencies.

This subject has been one of much debate in recent years. While some of the results and ideas presented in this paper are not new or unexpected, perhaps it will stimulate an exhaustive investigation into the important problem of sea-

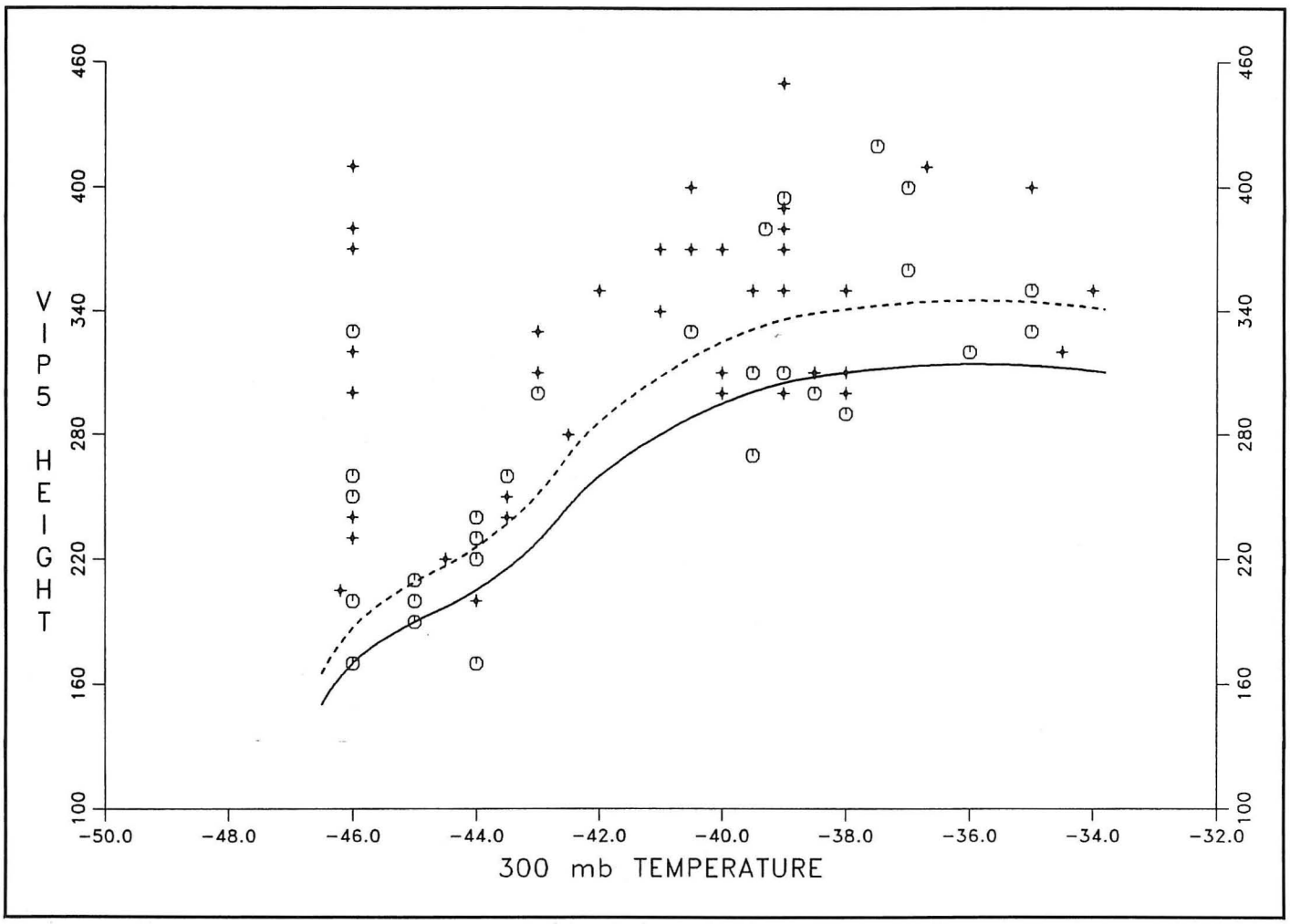

Fig. 7. Same as Figure 1, except that a "+" indicates hail >= ¾ inch, a "o" indicates hail < ¾ inch, and the dashed line is the hail/no hail threshold curve + 10%.

sonal and regional dependence of certain severe storm detection algorithms.

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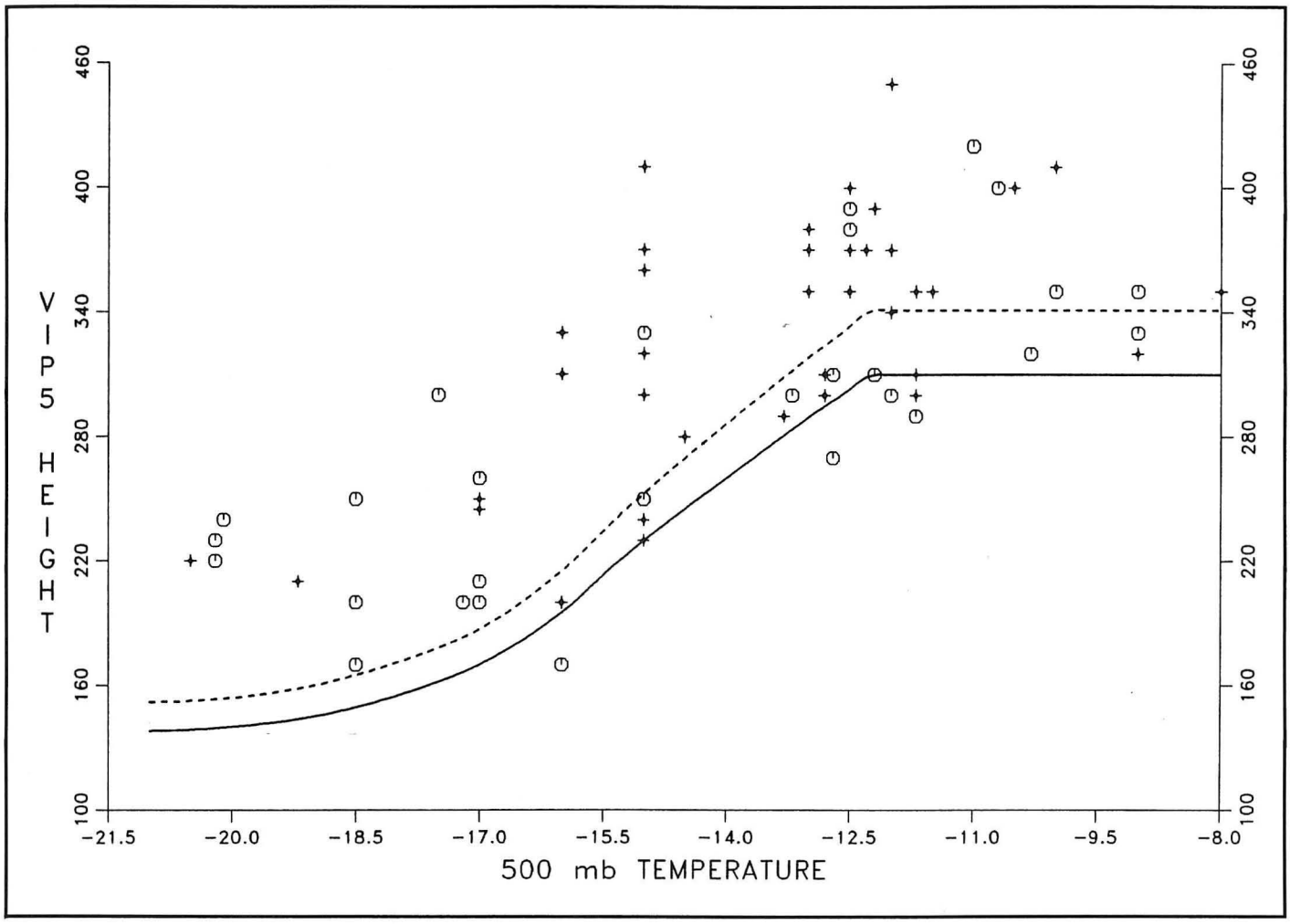

Fig. 8. Same as Figure 2, except that a "+" indicates hail >= ¾ inch, a "o" indicates hail < ¾ inch, and the dashed line is the hail/no hail threshold curve + 10%.

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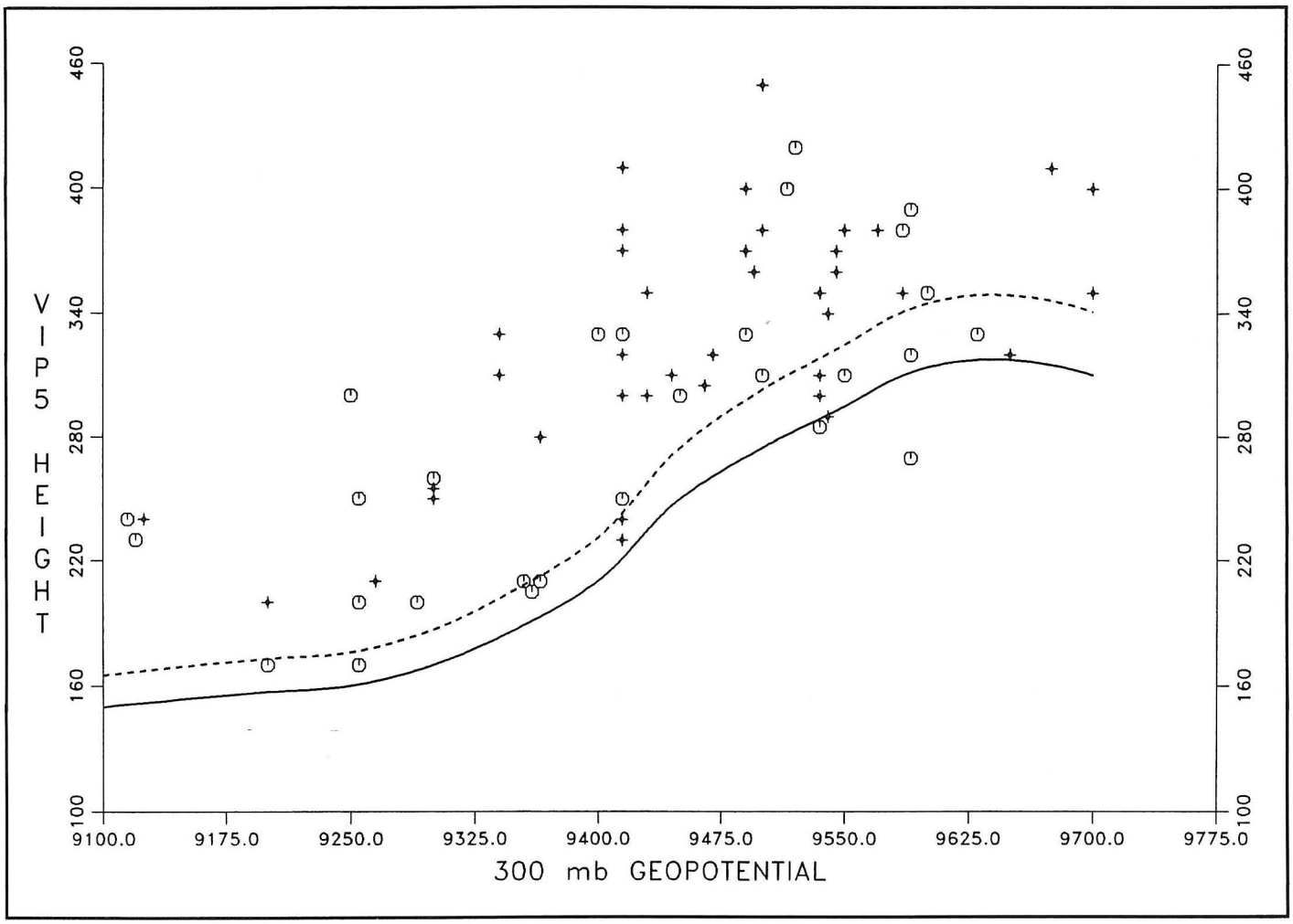

Fig. 9. Same as Figure 3, except that a "+" indicates hail >= ¾ inch, a "o" indicates hail < ¾ inch, and the dashed line is the hail/no hail threshold curve + 10%.

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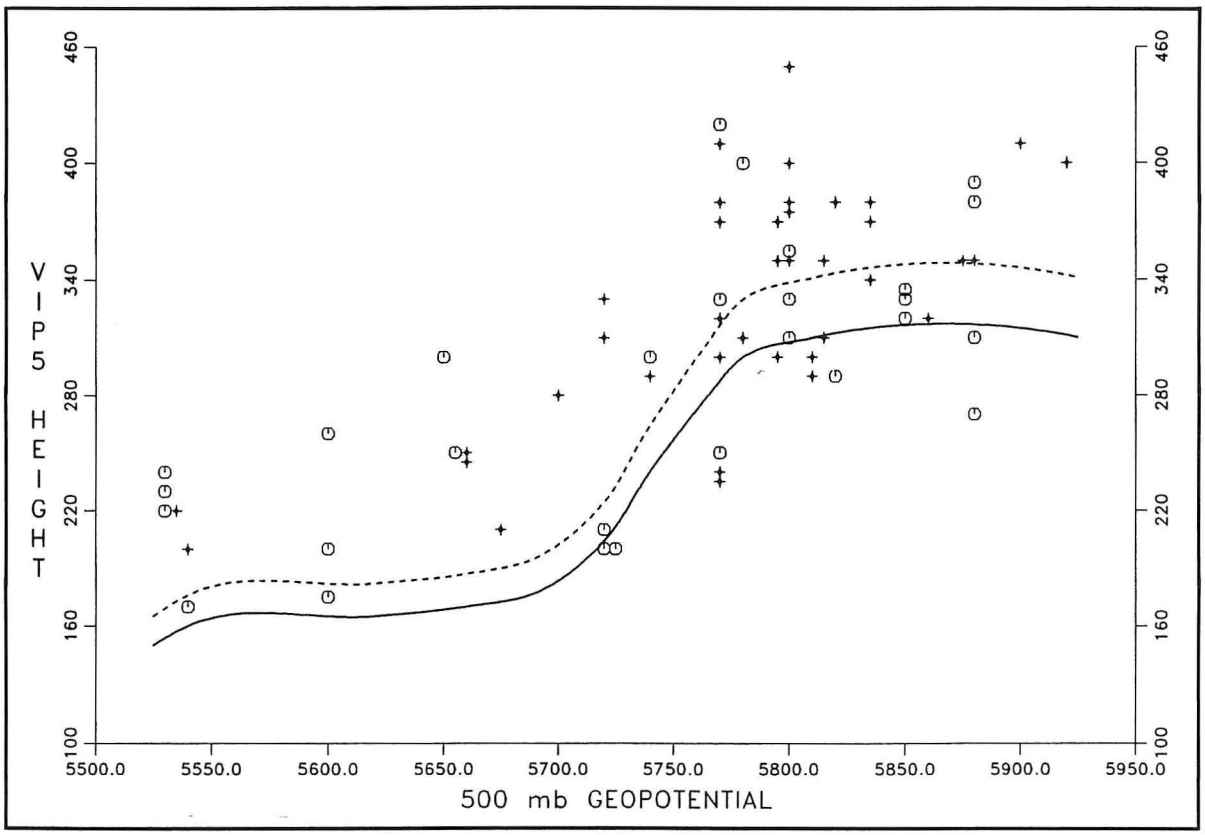

Fig. 10. Same as Figure 4, except that a "+" indicates hail >= ¾ inch, a "o" indicates hail < ¾ inch, and the dashed line is the hail/no hail threshold curve + 10%.

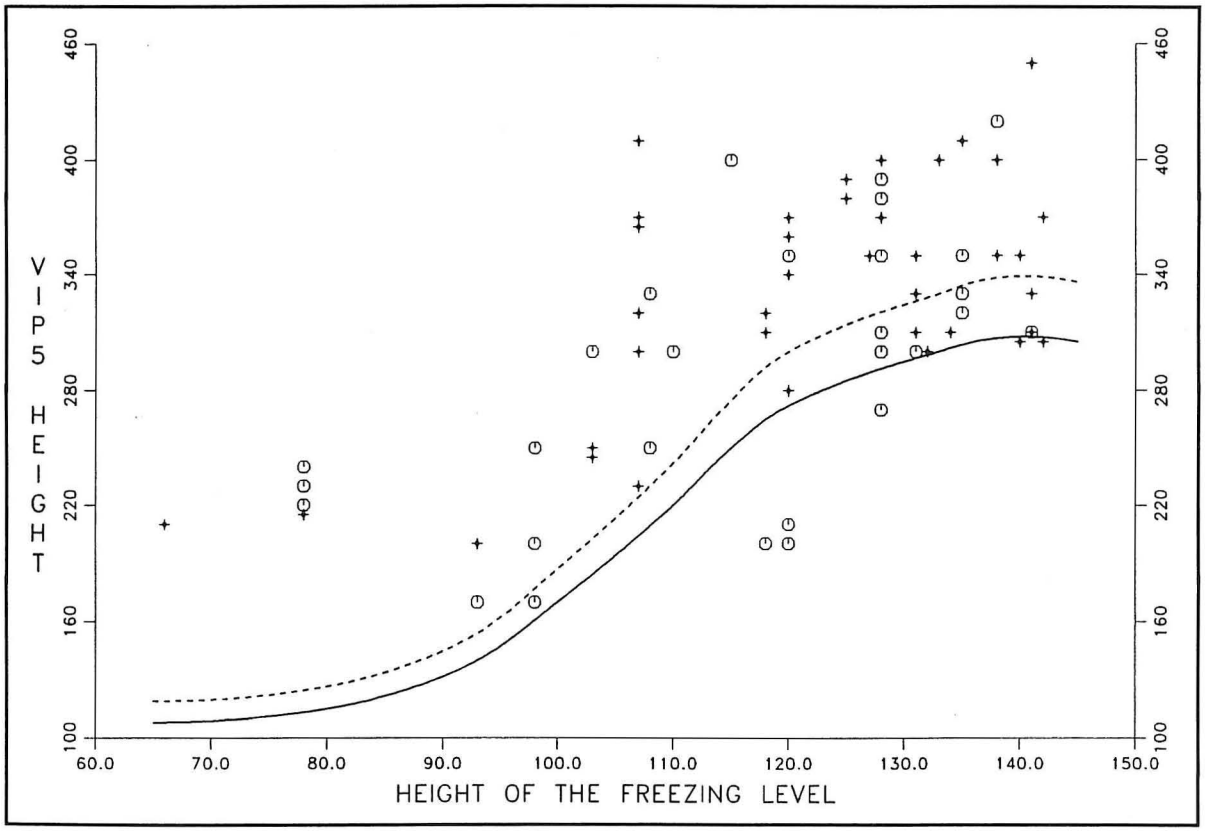

Fig. 11. Same as Figure 5, except that a "+" indicates hail >= ¾ inch, a "o" indicates hail < ¾ inch, and the dashed line is the hail/no hail threshold curve + 10%.

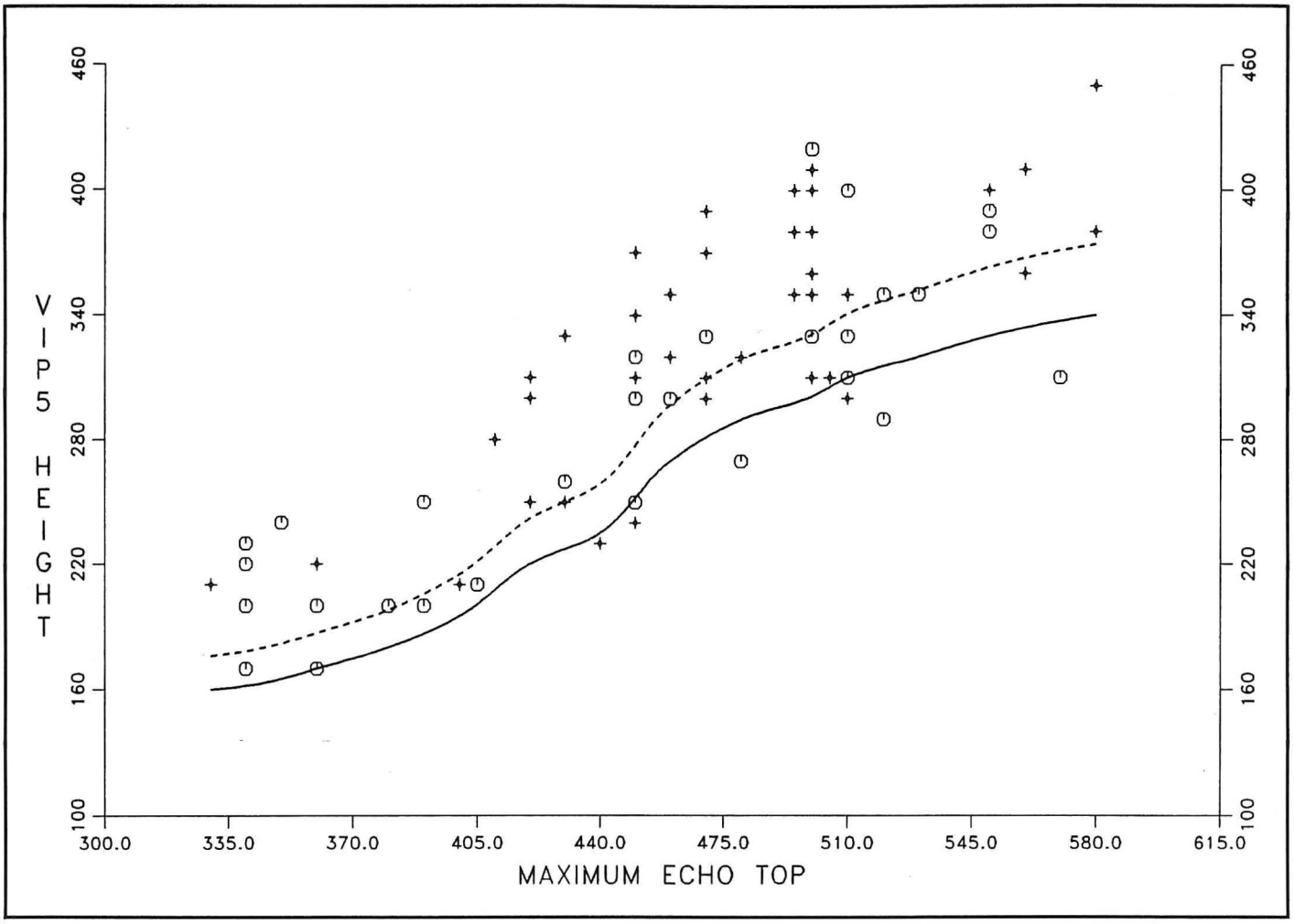

Fig. 12. Same as Figure 6, except that a "+" indicates hail >= ¾ inch, a "o" indicates hail < ¾ inch, and the dashed line is the hail/no hail threshold curve + 10%.

Table 2. Verification scores for each upper-air parameter as a predictor of large hail (¾ inch or larger) when related to VIP-5 height hail detection thresholds (solid line in Figures 7–12).

Parameter	POD	FAR	CSI	FAP
300-MB Height	1.00	.42	.58	.93
300-MB Temperature	.92	.47	.51	.79
500-MB Height	.87	.48	.48	.79
500-MB Temperature	.95	.46	.53	.83
Freezing Level Height	1.00	.45	.55	.83
Maximum Top Height	.89	.49	.48	.83

Table 3. Verification scores for each upper-air parameter as a predictor of large hail (¾ inch or larger) when related to VIP-5 height hail thresholds plus 10%. (dashed line Figures 7–12).

Parameter	POD	FAR	CSI	FAP
300-MB Height	.84	.37	.56	.66
300-MB Temperature	.76	.36	.53	.49
500-MB Height	.76	.36	.53	.49
500-MB Temperature	.76	.40	.50	.66
Freezing Level Height	.78	.38	.53	.59
Maximum Top Height	.77	.40	.51	.52

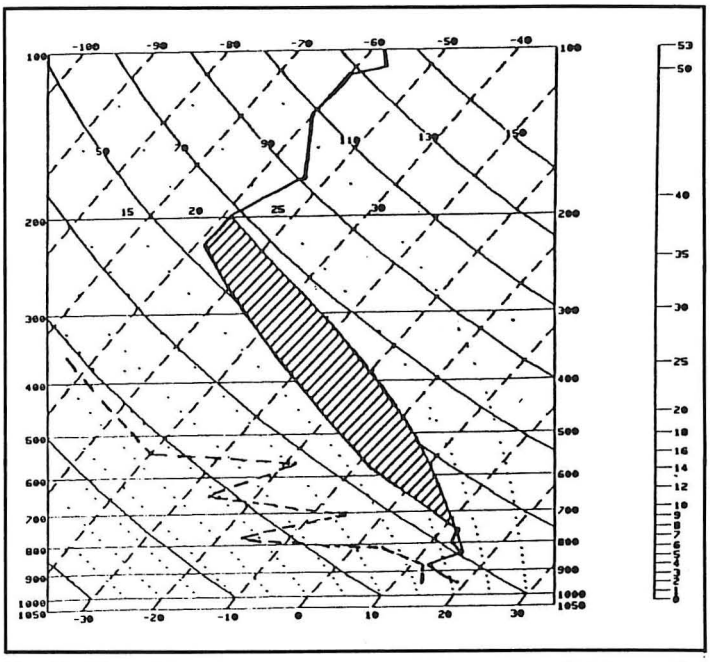

Fig. 13. Skew T-Log P presentation of a sounding from Oklahoma City (OKC) used for comparison only.

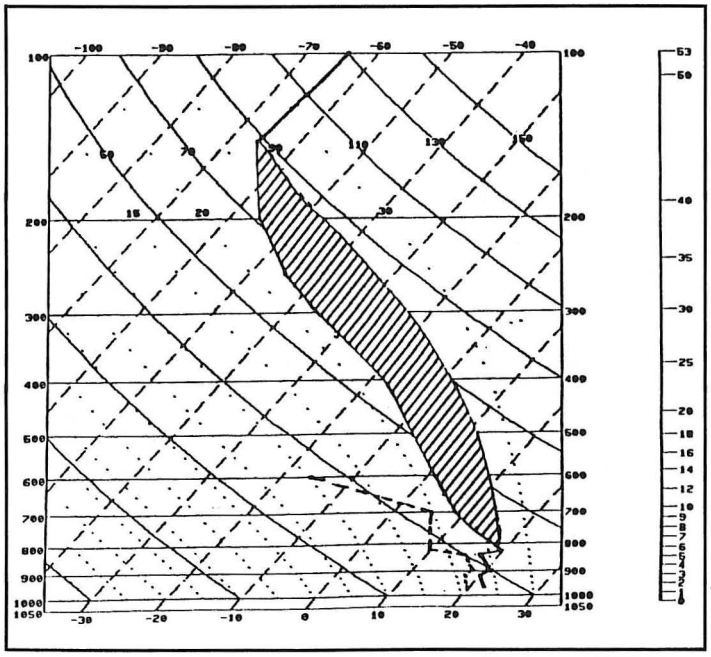

Fig. 14. Skew T-Lop P presentation of a sounding from St. Cloud (STC) used for comparison only.

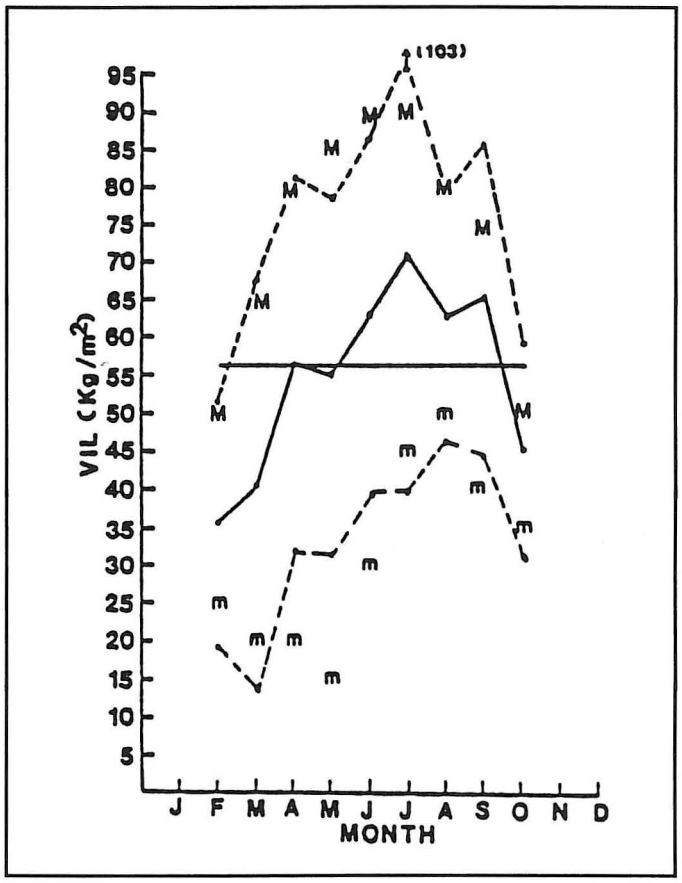

Fig. 15. Monthly variation of average VIL accompanying severe hail events (solid line) and the 95 percent confidence intervals about the monthly variation (dashed lines). Absolute extremes of VIL observed during severe weather as shown by upper and lower case M's. (from Beasley 1986).