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

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

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ABSTRACT. An operational method to predict hail in thunderstorms using the height of VIP-5 reflectivity echoes in combination with several weather parameters is discussed. The VIP-5 echo heights from the WSR-57 radar at Little Rock, Arkansas are compared with 300 mb heights and temperatures, 500 mb heights and temperatures, freezing level heights, vertical/totals indices and maximum storm top heights. Data collection methods and limitations of the procedure are discussed. Results indicate a distinct ability to distinguish between hail producing and non-hail producing thunderstorms. The same methodology is then applied to hail producing thunderstorms to determine if the prediction scheme can differentiate between severe versus non-severe thunderstorms using the ≥3/4" or <3/4" hail size severe criteria. The results are inconclusive.

## 1. INTRODUCTION

Severe storm identification has long been a high priority item in the National Weather Service. We have learned much about the structure of severe and non-severe thunderstorms in recent years, and much of this knowledge has been a direct result of the use of radar. However, the radar meteorologist can only infer the evolution and structure of the actual thunderstorms based on the distribution of precipitation within the storm.

Most notably, Lemon (1977, 1980) was among the first to actually correlate what we know about thunderstorm structure to certain radar derived characteristics. Imy (1987), Liles (1987), and Petrocchi (1982), among many others, have since fine-tuned some of the techniques that Lemon proposed. Still, some 10 years after Lemon's preliminary report on severe thunderstorm identification techniques and warning criteria, there remains a significant need for operationally effective means of detecting severe storms with conventional radar.

A by-product of Lemon's publications was the establishment of certain radar derived warning criteria in the National Weather Service. One such criterion within this set (and one which this paper will focus on) is the height of the VIP-5 reflectivity echo. In the Southern Region, a height of 30,000 ft is specified as a minimum for issuance of a severe thunderstorm warning. In the Central Region, the criteria for VIP-5 height is also fixed, although at 27,000 ft. (These numbers are based on heights from a rotating antenna.) Based on personal experience, and the observations of other radar meteorologists, these values often appear either too high or too low as indicators of severe weather.

However, as this paper will go on to show, "predetermined" VIP-5 height thresholds can be of use to the radar meteorologist - if properly used. More specifically, VIP-5 heights can be of great value in the detection of hail.

Throughout 1984, the author examined VIP-5 heights and maximum top heights of 97 thunderstorm cases in Arkansas. The VIP-5 heights were compared to several upper air characteristics measured as close as possible to the time of thunderstorm occurrence. These characteristics were: 300 mb heights and temperatures, 500 mb heights and temperatures, freezing level heights, and vertical and total totals indices. VIP-5 reflectivity heights were also compared to their corresponding maximum top heights. The results indicated a distinct ability to distinguish between storms that produced hail and those that did not. Efforts to distinguish between severe hailstorms (3/4" or greater) and non-severe thunderstorms proved to be inconclusive. This unfortunate turn of events does not necessarily render results of this paper entirely useless. It is suggested rather, that results of this study can be effectively used to supplement existing techniques and criteria now used for severe storm identification. Furthermore, the results of this paper clearly show the need for normalization of such radar derived severe weather indicators before they can be of any operational use.

## 2. DISCUSSION

### a. Data Collection and Use

From paper overlays taken from the WSR-57 radar at Little Rock, Arkansas 97 VIP-5 thunderstorms were selected for study. To insure a seasonal distribution, cases were selected from all months of 1984, excepting January and December, when no severe weather occurred. The storm distribution was not even however. Typically, concentrations were heaviest during the late spring and early summer with a minimum in severe activity during the aforementioned winter months (Doswell _et al_., 1983). So, rather than comparing thunderstorms through a month by month distribution, it was decided to compare VIP-5 heights to corresponding upper atmospheric data which themselves followed general seasonal variations.

VIP-5 thunderstorms were selected for study if the storms were between 25 and 100 nmi from the radar site, and a radar overlay was drawn within 15 minutes of hail occurrence. Radar derived VIP-5 heights were taken with the use of an RHI overlay for top correction, and all measurements were taken with a non-rotating radar beam.

The atmospheric parameters were taken from the WSFO Little Rock upper air site only. Data from 12Z and 00Z soundings were both used. However, visual interpolation between the two was done whenever deemed appropriate in order to approximate conditions at the time of storm occurrence.

From these data sets mentioned above, graphs were constructed to compare the VIP-5 height of all cases to their corresponding upper air parameters (500 mb height and temperature, 300 mb height and temperature, freezing level height, and the stability indices). In addition, VIP-5 heights were compared to the maximum top heights for each storm. These graphs are presented in Figures 1 through 6.

b. Results

The 97 thunderstorm study cases were divided into 3 separate groups.

1 - Those that produced hail 3/4 inch or larger - 38 cases.
2 - Those that produced hail smaller than 3/4 inch - 29 cases.
3 - Those that produced no hail - 30 cases.

(1) Hail Versus No Hail

A fairly definite distinction was observed between those storms that produced hail and those that did not. This distinction was found to be present using each upper atmospheric parameter except for the two stability indices. The stability parameters were then discarded from the study. By strictly eyeballing the graphs in Figures 1 through 6, a boundary could be drawn below which hail would not be expected, and above which hail would be expected. These curves are superimposed on Figures 1 through 6.

By examination of these figures, it can be seen that VIP-5 heights needed to produce hail were significantly lower in cooler air masses than those values observed in warmer air masses. In addition, it was also apparent that VIP-5 heights needed to produce hail leveled off at 31,000 ft as temperatures and heights increased. That is, after a certain set of environmental conditions were met, VIP-5 heights to produce hail "appeared" to become independent of upper atmospheric conditions. These particular conditions were most likely to be found during the summer months, which is also the time of year when vertical and horizontal shears are typically weakest in Arkansas. It is possible that this could be indicative of the relative importance of particle trajectories in hailstone formation and growth. However, in a supplemental study, no correlation between the upper level wind fields and the height of VIP-5 echoes needed to produce hail could be found.

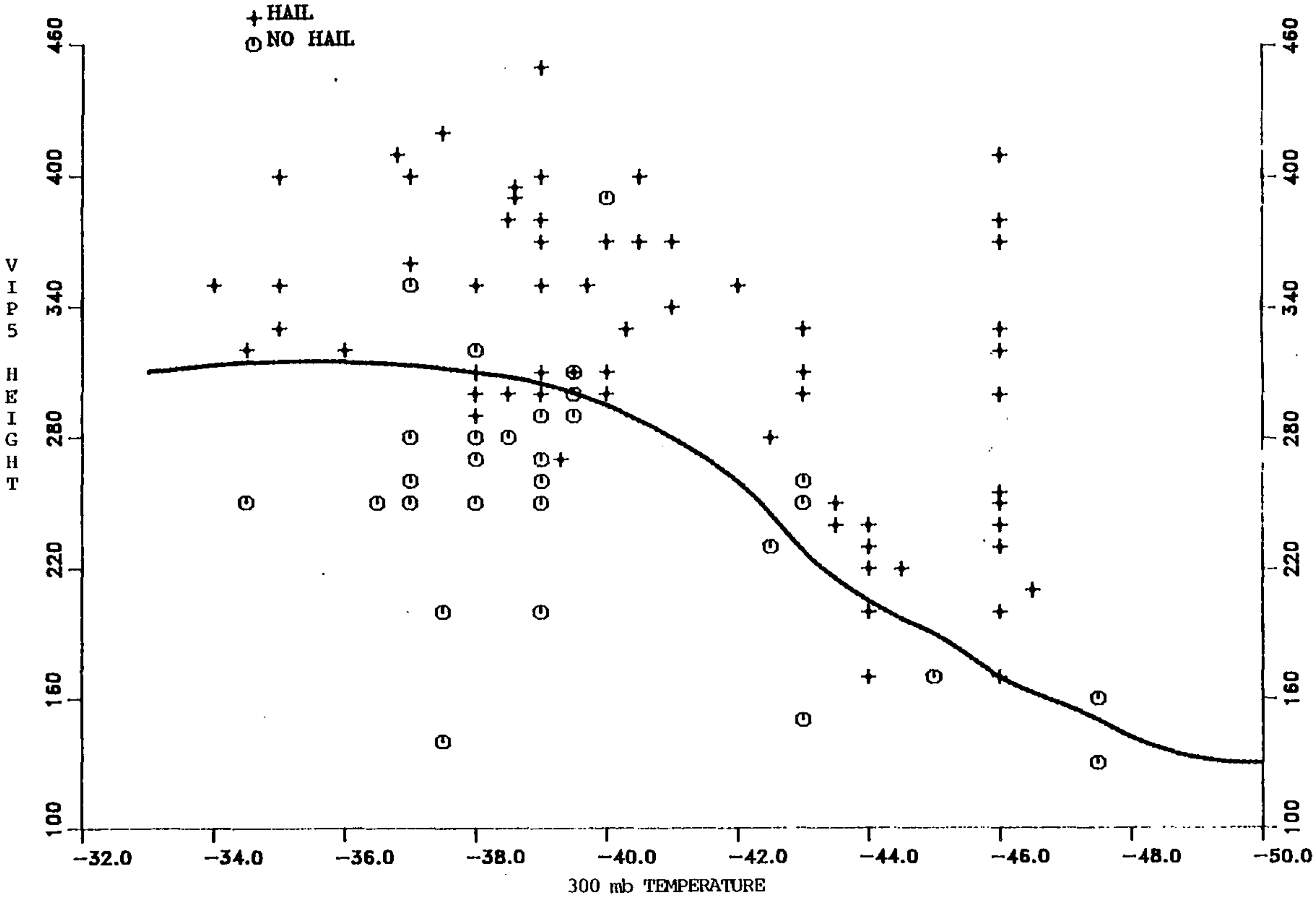

Figure 1: Scatter diagram of VIP-5 height in hundreds of ft versus 300 mb temperature in degrees C (solid line indicates hail/no hail threshold).

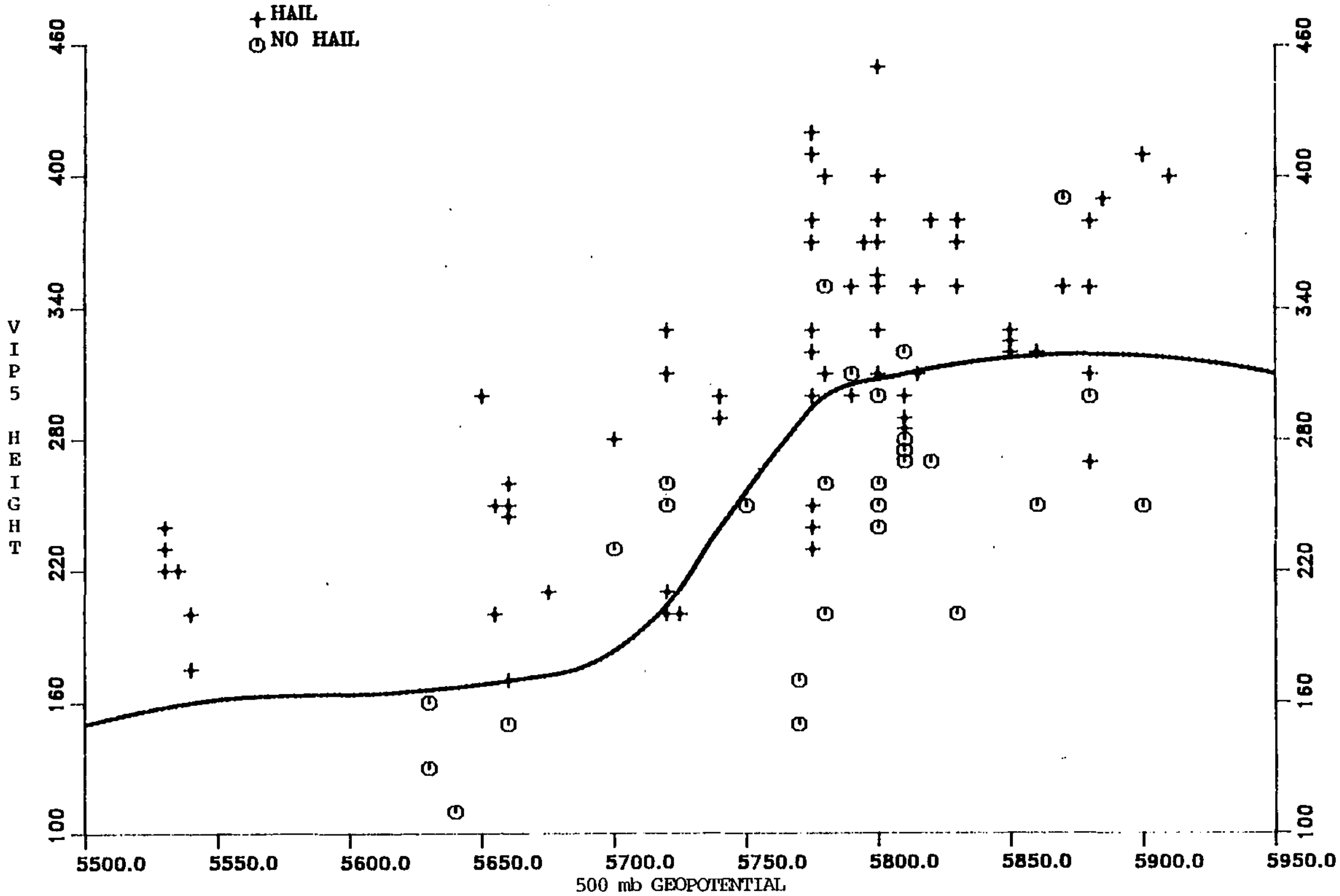

Figure 2: Scatter diagram of VIP-5 height in hundreds of ft versus 500 mb height in meters (solid line indicates hail/no hail threshold).

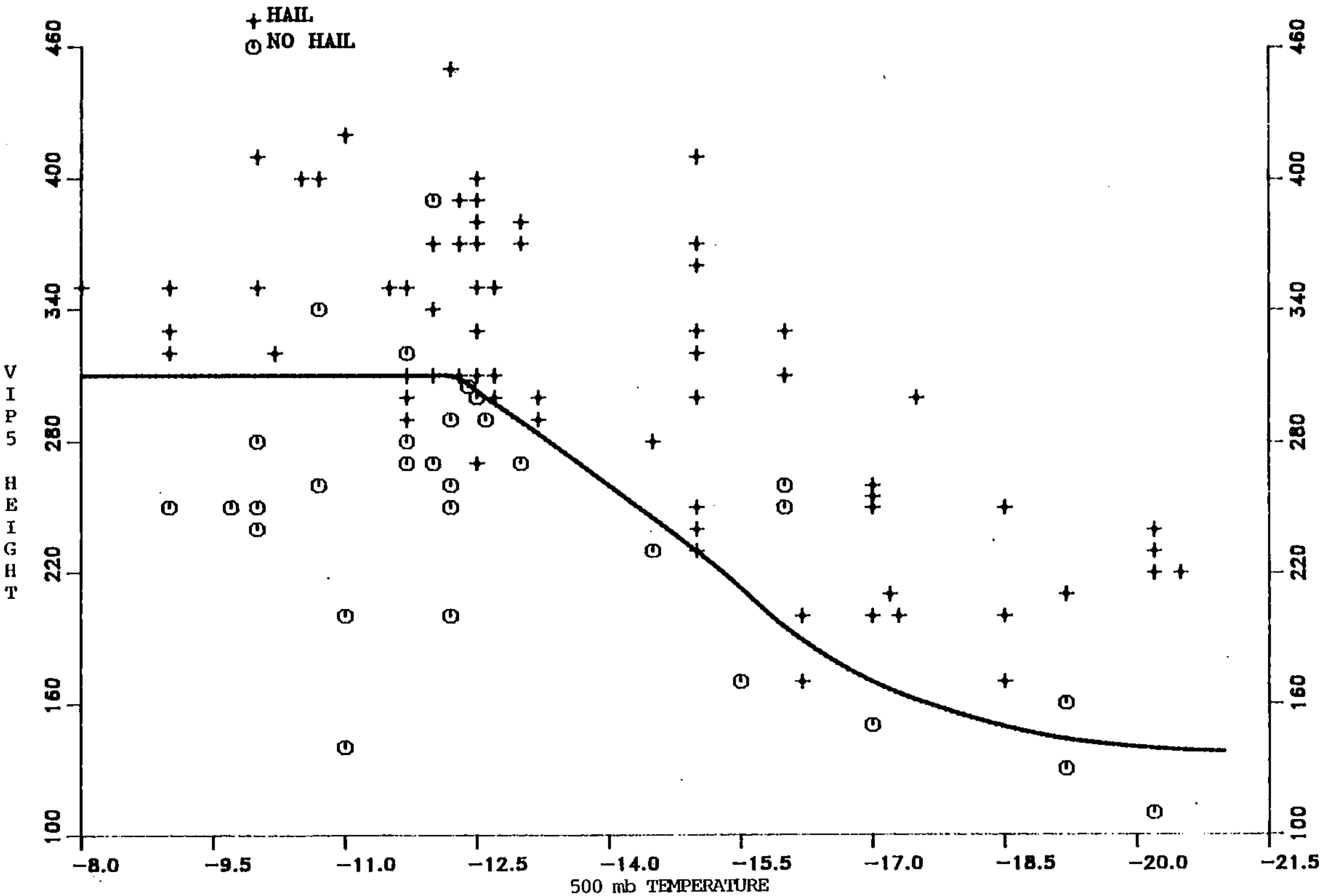

Figure 3: Scatter diagram of VIP-5 height in hundreds of ft versus 500 mb temperatures in degrees C (solid line indicates hail/no hail threshold).

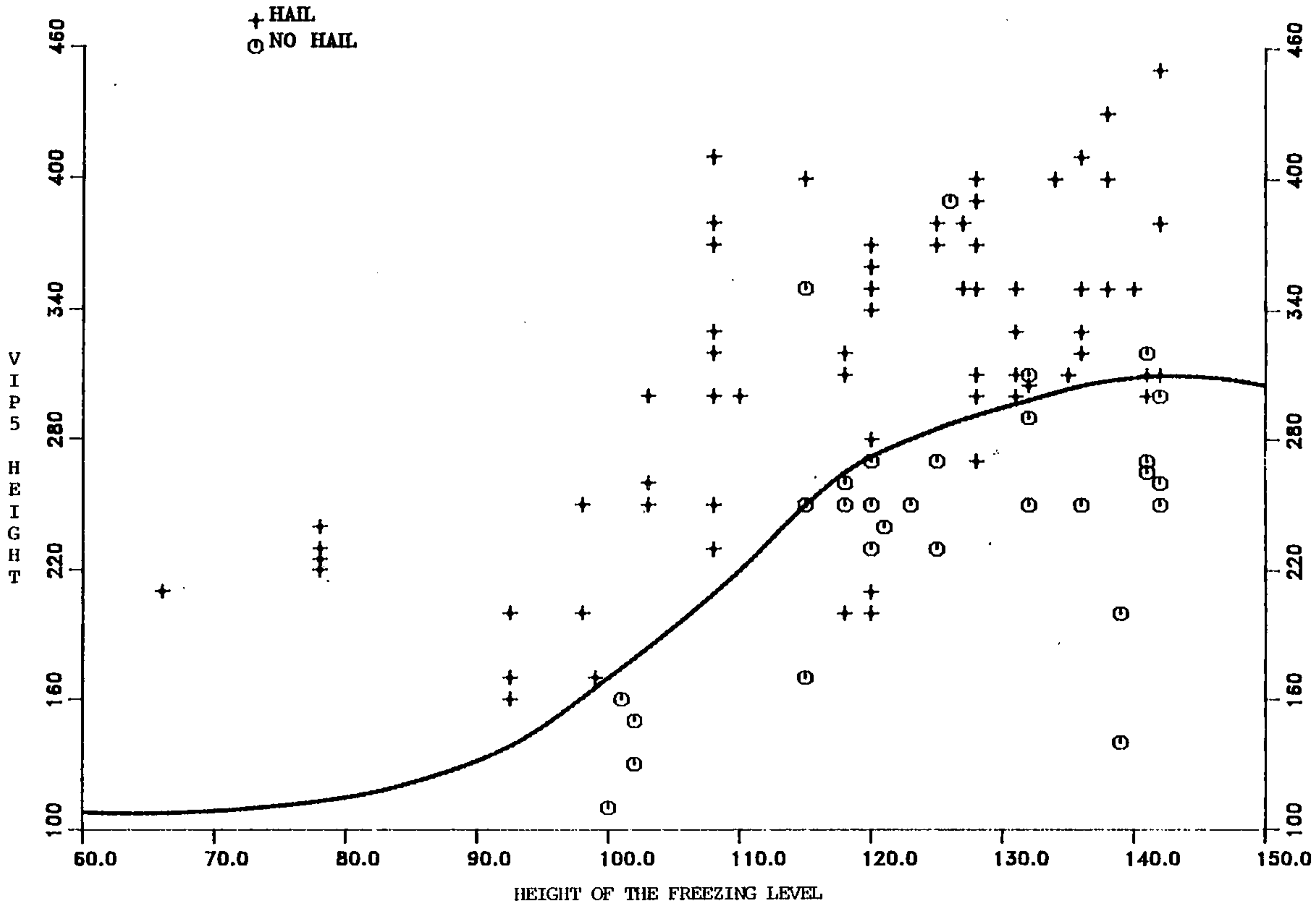

Figure 4: Scatter diagram of VIP-5 height in hundreds of ft versus freezing level height in hundreds of ft (solid line indicates hail/no hail threshold).

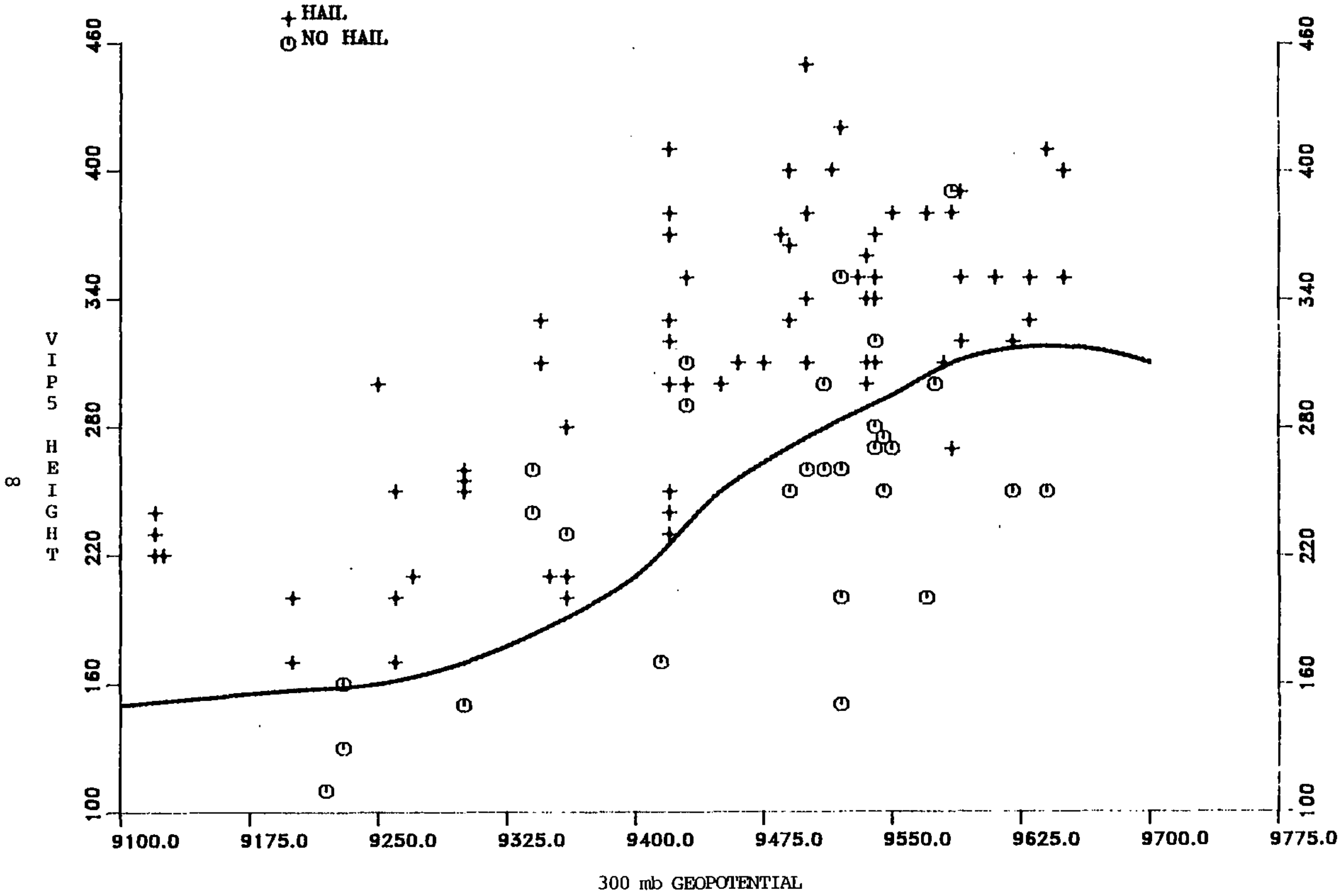

Figure 5: Scatter diagram of VIP-5 height in hundreds of ft versus 300 mb height in meters (solid line indicates hail/no hail threshold).

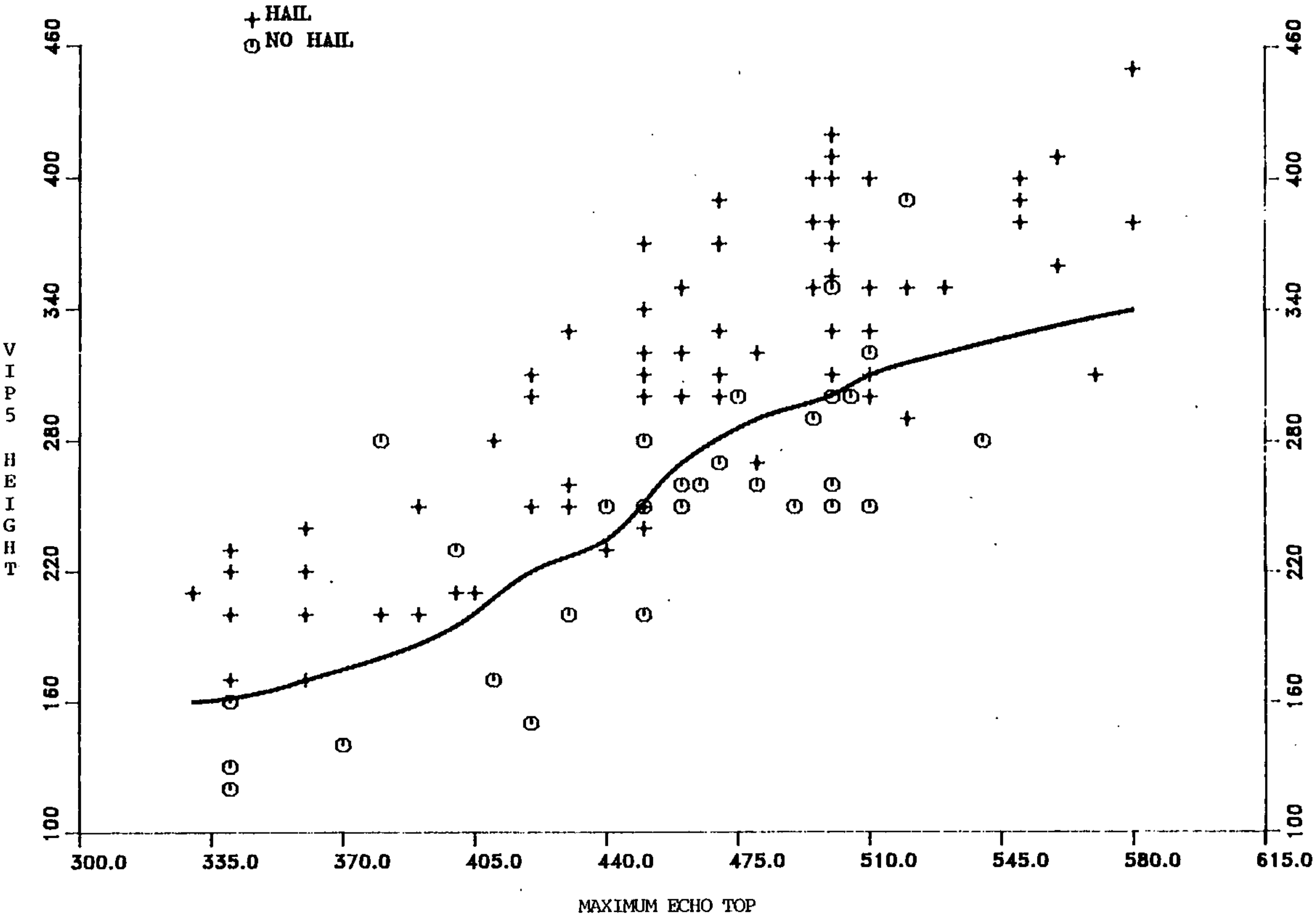

Figure 6: Scatter diagram of VIP-5 height in hundreds of ft versus maximum top height in hundreds of ft (solid line indicates hail/no hail threshold).

As a measure of the success of these upper air characteristics as predictors of a minimum VIP-5 height needed to produce hail, Donaldson's now familiar critical success index (CSI) was used. Critical success index is defined as a function of probability of detection (POD) and false alarm ratio (FAR). The CSI can be determined from the following equation:

$$CSI = 1/((1/POD)+(1/(1-FAR))-1)$$

where

POD = # of events warned for/(# of events warned for + # of unwarned events), and where
FAR = # of false alarms/(# of false alarms + # of events warned)

Using these indicators, statistics were computed for each upper air parameter as a hail predictor when related to VIP-5 height (see Figures 1 through 5):

1-500 mb temperature: POD = .92 FAR = .10 CSI = .83
2-500 mb height: POD = .86 FAR = .10 CSI = .78
3-300 mb temperature: POD = .88 FAR = .12 CSI = .79
4-300 mb height: POD = .98 FAR = .13 CSI = .85
5-Freezing level height: POD = .94 FAR = .10 CSI = .85

An attempt was made to further improve upon these scores by testing the predictability of VIP-5 heights derived from all five upper air parameters COLLECTIVELY. However, results indicated no improvement over the CSI's from the individual parameters. Weighting factors (based on CSI's) were applied to 60 test thunderstorm cases with results as follows:

POD = .93 FAR = .18 CSI = .77

Also of interest is Figure 6, which presents a relationship between VIP-5 heights and maximum top. It is interesting to note that given no other parameters, 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 versus no hail verification statistics in this study compare rather well to CSI's from a set of hail criteria used by Petrocchi (1982) in development of a hail algorithm. However, predictors used in that study were entirely radar derived quantities. Included as predictors were mid level reflectivity of at least 50 dBz, mid level overhang, echo top over a mid level overhang, 30 dBz echo to at least 8 km, and a southward tilt of the storm, among others. Critical Success Indices for that study were quite similar to those in this study.

### (2) Severe Hailstorms Versus Non-severe Hailstorms

Attempts in this study to distinguish between large hail (3/4 inch or greater) and small hail produced inconclusive results. This is graphically shown by Figures 7 through 12. Superimposed upon these figures are the curves representing the division between storms that produced hail and those that did not. Once again using those curves as predictors, verification statistics were computed for large hail versus small hail for each upper air parameter, and also for maximum top data. Because of the nature of verifying large hail versus small hail, false alarm ratios can often be misleading. In this case, it is felt that a false alarm percentage may be more appropriate. False alarm percentage (FAP) is defined as (# of false alarms)/(total # of non-severe hail events). The results are as follows:

1-500 mb temperature: POD = .95 FAR = .46 CSI = .53 FAP = .83
2-500 mb height: POD = .87 FAR = .48 CSI = .48 FAP = .79
3-300 mb temperature: POD = .92 FAR = .47 CSI = .51 FAP = .79
4-300 mb height: POD = 1.00 FAR = .42 CSI = .58 FAP = .93
5-Freezing level height: POD = 1.00 FAR = .45 CSI = .55 FAP = .83
6-Maximum top height: POD = .89 FAR = .49 CSI = .48 FAP = .83

In an attempt to again improve these numbers, threshold VIP-5 heights to produce severe size hail were increased by 10% for each upper air parameter (also shown on Figures 7 - 12). Verification results for the new threshold VIP-5 heights for large hail are presented below.

1-500 mb temperature: POD = .76 FAR = .40 CSI = .50 FAP = .66
2-500 mb height: POD = .76 FAR = .36 CSI = .53 FAP = .55
3-300 mb temperature: POD = .76 FAR = .36 CSI = .53 FAP = .48
4-300 mb height: POD = .84 FAR = .37 CSI = .56 FAP = .66
5-Freezing level height: POD = .78 FAR = .38 CSI = .53 FAP = .59
6-Maximum top height: POD = .77 FAR = .40 CSI = .51 FAP = .52

Obviously, attempts to improve the CSI by increasing minimum thresholds for hail development were fruitless. 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 in that 1982 study.

### c. Limitations

Use of the 10 cm 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. However, no corrections were made for non-standard refraction of the radar beam in the atmosphere. In many cases involving an unstable atmosphere, subrefraction of the radar beam will be the rule. That is, heights are generally underestimated by the radar during periods of severe weather. Since most all radar

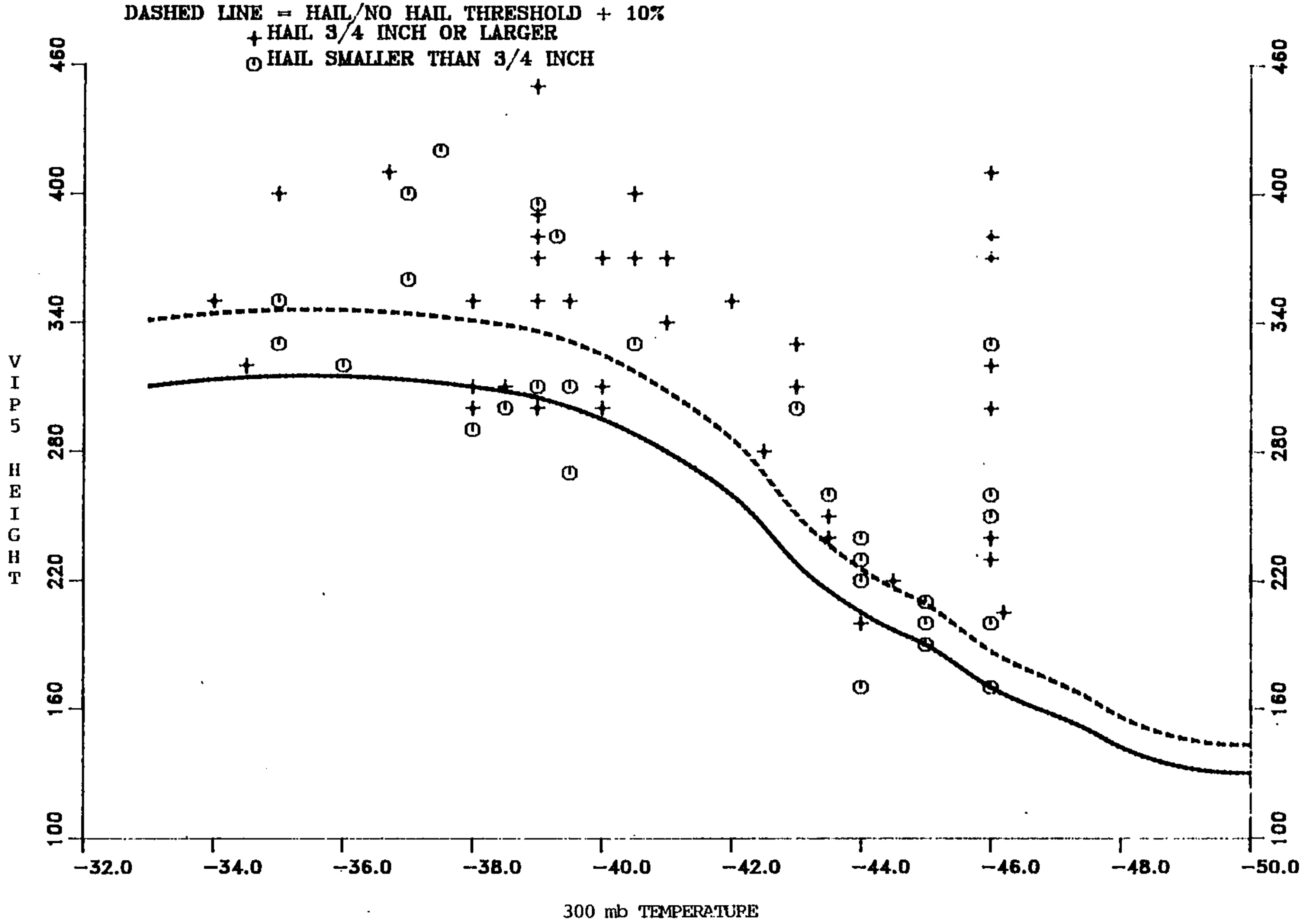

Figure 7: Scatter diagram of VIP-5 height in hundreds of ft versus 300 mb temperature in degrees C (solid line indicates hail/no hail threshold).

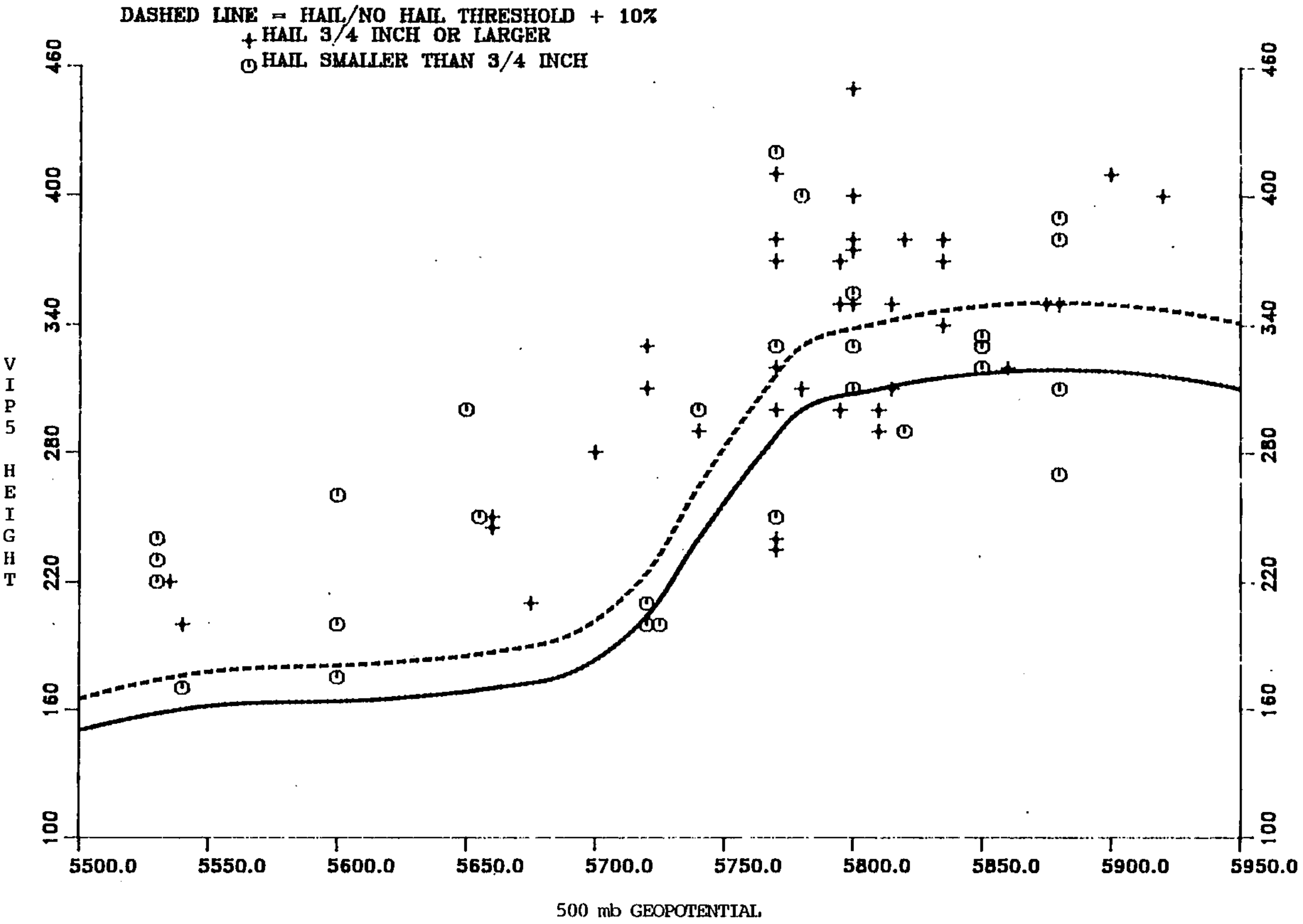

Figure 8: Scatter diagram of VIP-5 height in hundreds of ft versus 500 mb height in meters (solid line indicates hail/no hail threshold).

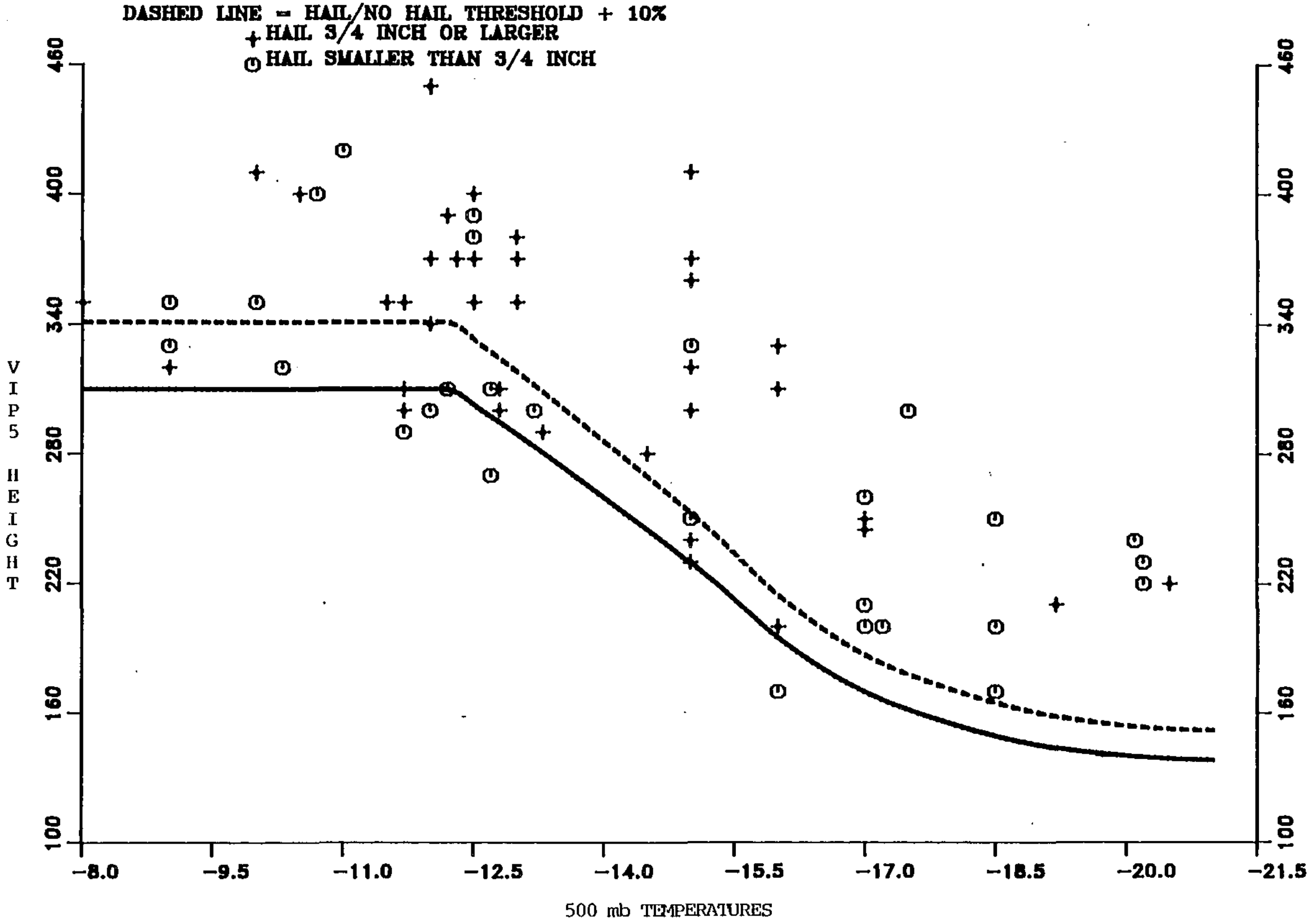

Figure 9: Scatter diagram of VIP-5 height in hundreds of ft versus 500 mb temperatures in degrees C (solid line indicates hail/no hail threshold).

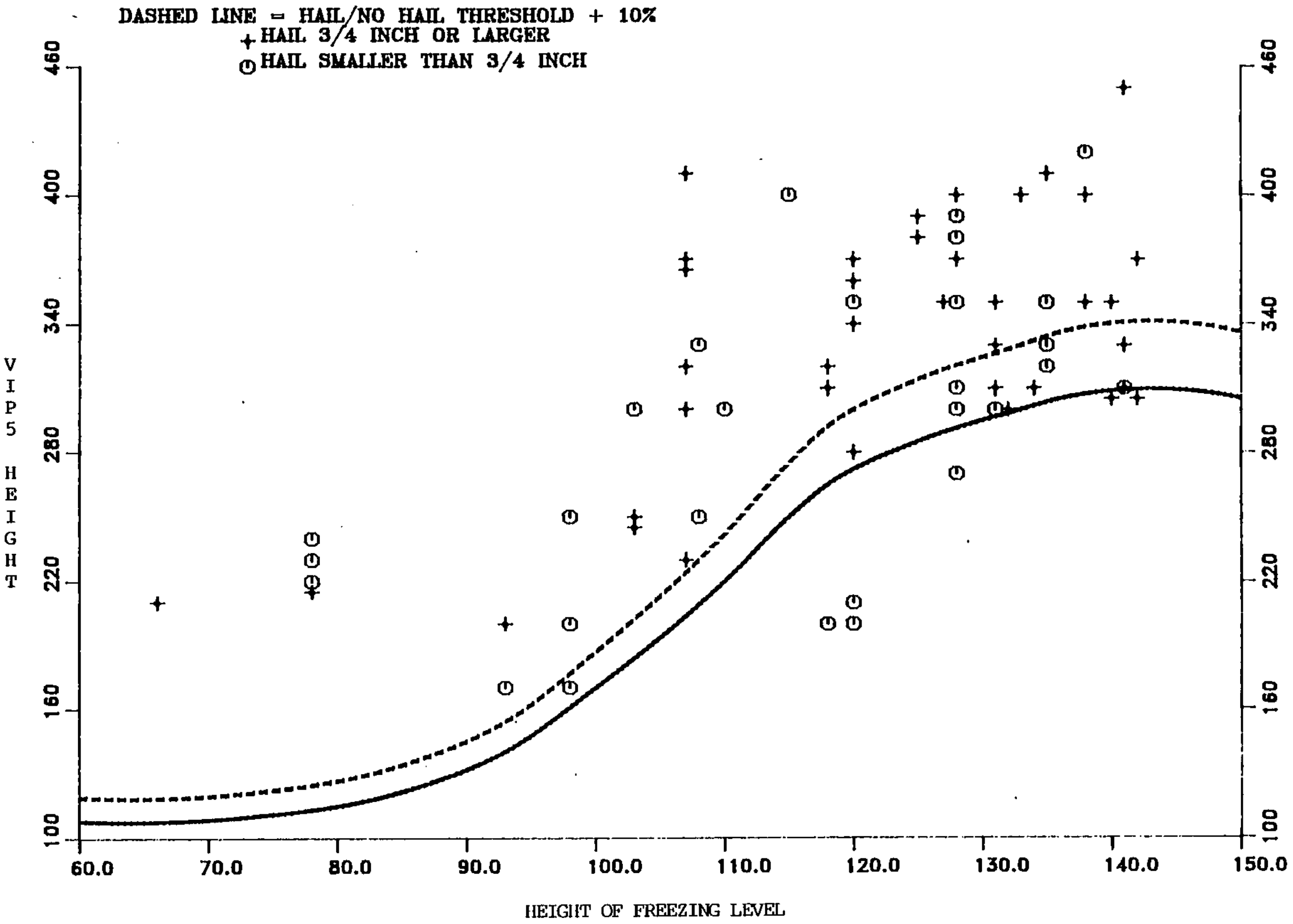

Figure 10: Scatter diagram of VIP-5 height in hundreds of ft versus freezing level height in hundreds of ft (solid line indicates hail/no hail threshold).

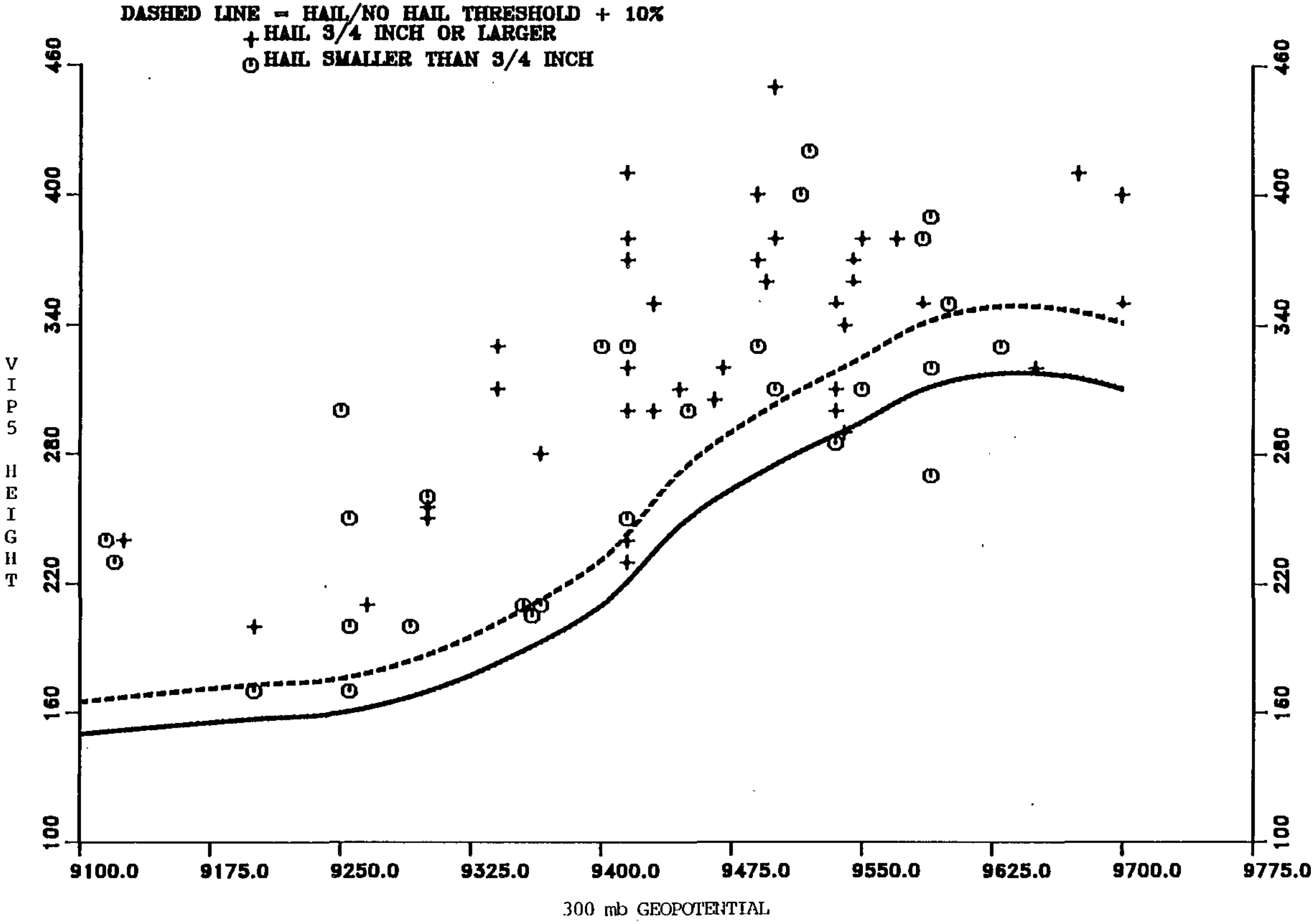

Figure 11: Scatter diagram of VIP-5 height in hundreds of ft versus 300 mb height in meters (solid line indicates hail/no hail threshold).

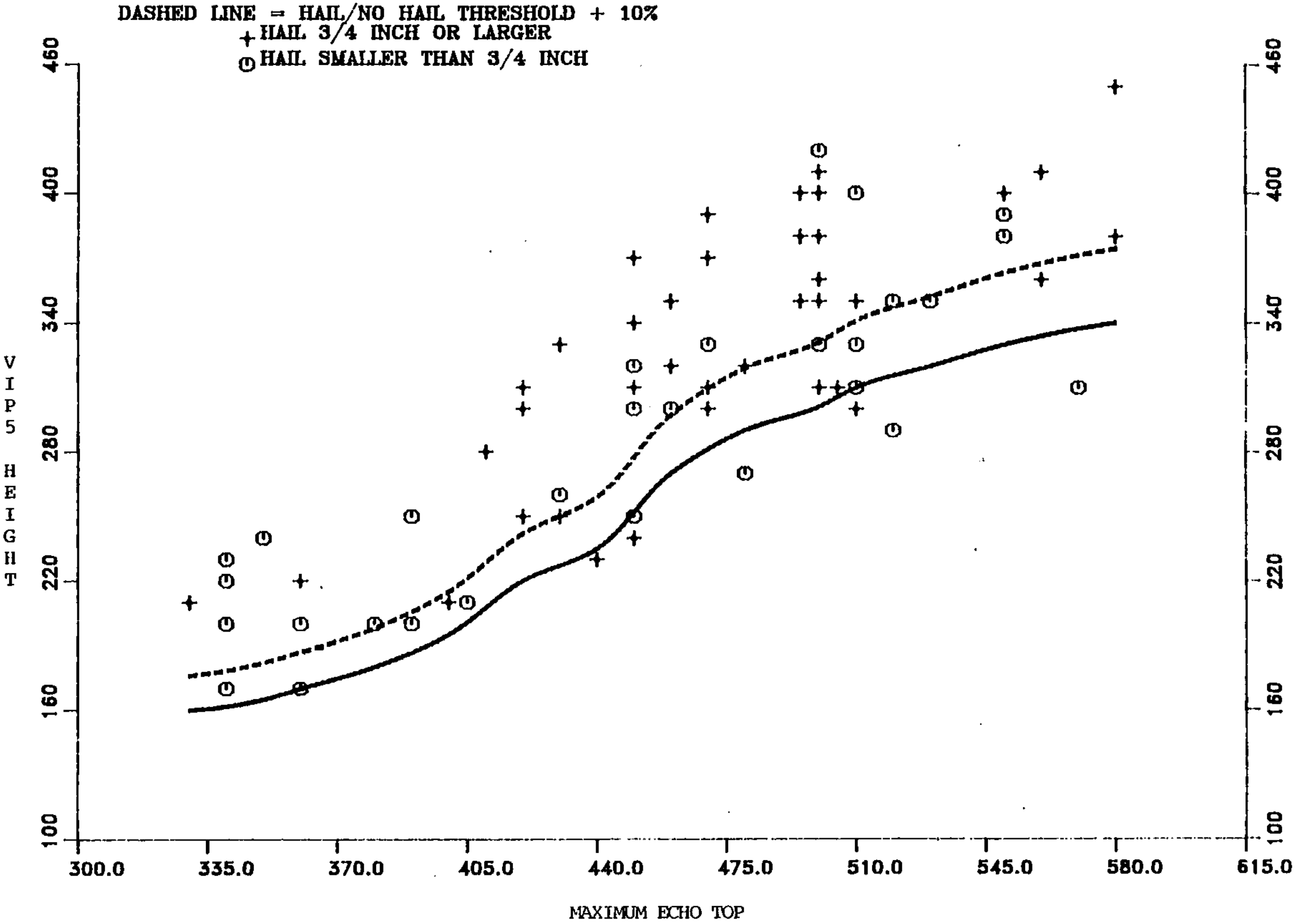

Figure 12: Scatter diagram of VIP-5 height in hundreds of ft versus maximum top height in hundreds of ft (solid line indicates hail/no hail threshold).

errors increase in magnitude as distance from the radar site increases, a 100 nmi maximum limit was arbitrarily imposed on storm selection. A 25 nmi minimum restriction was also imposed due to height distortions from "side lobe return" off the radar beam.

Upper air characteristics taken from the 12Z and 00Z soundings were subject to the usual spatial and temporal resolution problems. Some attempt was made to eliminate the time constraints by the use of interpolation whenever appropriate. However, only soundings from LIT were used while thunderstorm cases from within a 100 nmi radius of the station were selected. The magnitude of the errors involved here are not known.

Also, problems concerning hail reports, and time constraints on radar overlays should be discussed. Hales (1987) points out that analyses 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 (Hales 1987). Grant and Pulaski counties are adjacent to each other, yet Grant county has only about 5% the total population of Pulaski county. Thus, a severe event has a greater chance of being reported in Pulaski county. Furthermore, this increases the chance of a contaminated sampling of thunderstorms in a study such as this. These biases were not factored into this study and the effects also are not known. However, the effects are minimized somewhat since Pulaski county is within 25 nmi of the radar site. All hail events in this heavily populated county have been excluded from this study.

Further contamination may arise in the manner which the public reports hail sizes. One person's marble size hail may be another's dime size hail. One is considered severe while the other is not. For an interesting discussion on these topics see Doswell (1985).

Finally, a time constraint of 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 storm. This depends of course, on the number of overlays done during that particular time frame. Once again, it is not known how many of the thunderstorm cases were affected by this and how large the resultant errors might be. Also, one final and very important point must be made, and that is lead times were NOT considered in this study.

## 3. CONCLUSIONS

Radar meteorologists face one of the greatest challenges in operational meteorology today. That is, to determine which storms are capable of producing severe weather before severe weather actually occurs. This is no easy task, as one look at severe local storm verification statistics will attest to.

We are taught, in general, that those storms which achieve the strongest updrafts are most likely to become severe. In order to determine potential thunderstorm severity, radar meteorologists generally attempt to infer updraft strength from the appearance of radar echoes. One of the most popular ways of doing so (but certainly not the only method), is by measuring the height of the VIP-5 reflectivity echo.

To this end, the various NWS regional headquarters have supplied radar field sites with guidance for a minimum VIP-5 height for issuance of a severe thunderstorm warning (30,000 ft southern region...27,000 ft central region...etc.). By now, experienced NWS radar operators know that regional policies regarding VIP-5 heights do not consistently work; and, indeed, results of this study do show that severe weather can occur across a wide spectrum of VIP-5 heights.

However, I suspect that while most radar operators know regional policies regarding VIP-5 heights are flawed, many do not understand why, or in what ways they can actually use VIP-5 heights.

In the meantime, the operator is still faced with the all important question; At what point does (will) a thunderstorm produce severe weather? To even consider the question, one must first examine the relationship between updraft strength and storm severity.

As previously mentioned, we are taught, in general, that those storms which achieve the strongest updrafts are most likely to become severe. While this statement is certainly true, I believe it is too broad as stated, and at times, can actually be misleading.

To crudely illustrate the relationship between updraft strength and thunderstorm severity, consider the sample soundings in Figures A and B. Figure A is a sounding taken at OKC, with Figure B at STC. (These soundings were taken on separate days, and their locations are irrelevant to the problem. Their sounding characteristics are by no means unique to their locations!)

By considering influences on each sounding (such as low level warm, moist advection, and diurnal heating), we can arrive at a potential convective buoyancy (at 500 mb) of about 10 degrees C at each location. A quick look at these soundings makes it obvious that there is a high potential for thunderstorms. Furthermore, just the degree of instability is certainly enough to arouse the interest of a severe weather forecaster.

Comparing the two soundings, there are far more differences than similarities. First of all, notice the environment at OKC is much cooler than at STC, and the equilibrium level (EL) at OKC is some 6000 ft lower than at STC. Also, although instabilities at the two locations are similar, notice the larger positive area on the STC sounding.

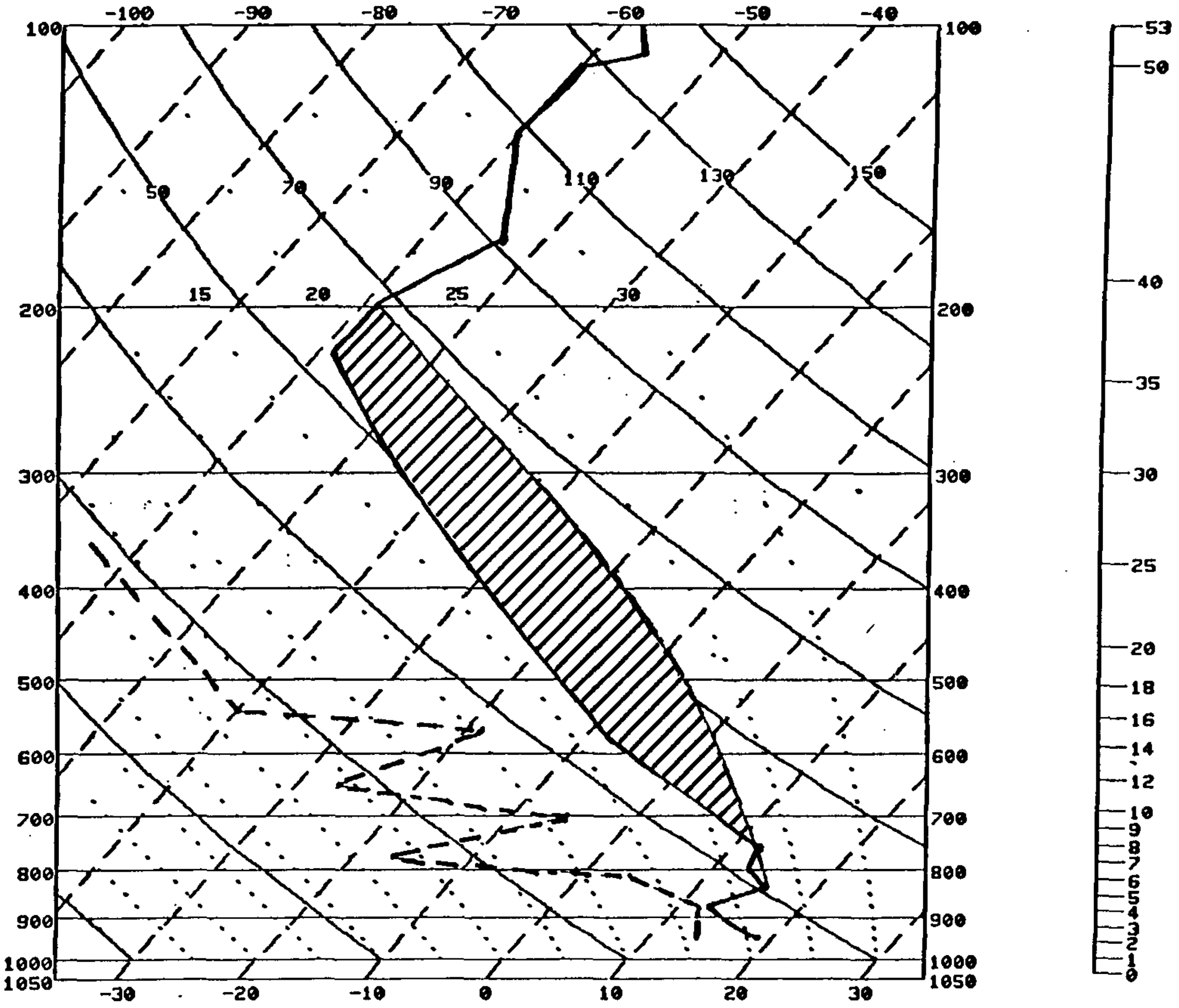

Figure A: Skew T-Log P presentation of sounding from Oklahoma City (OKC) used for comparison only.

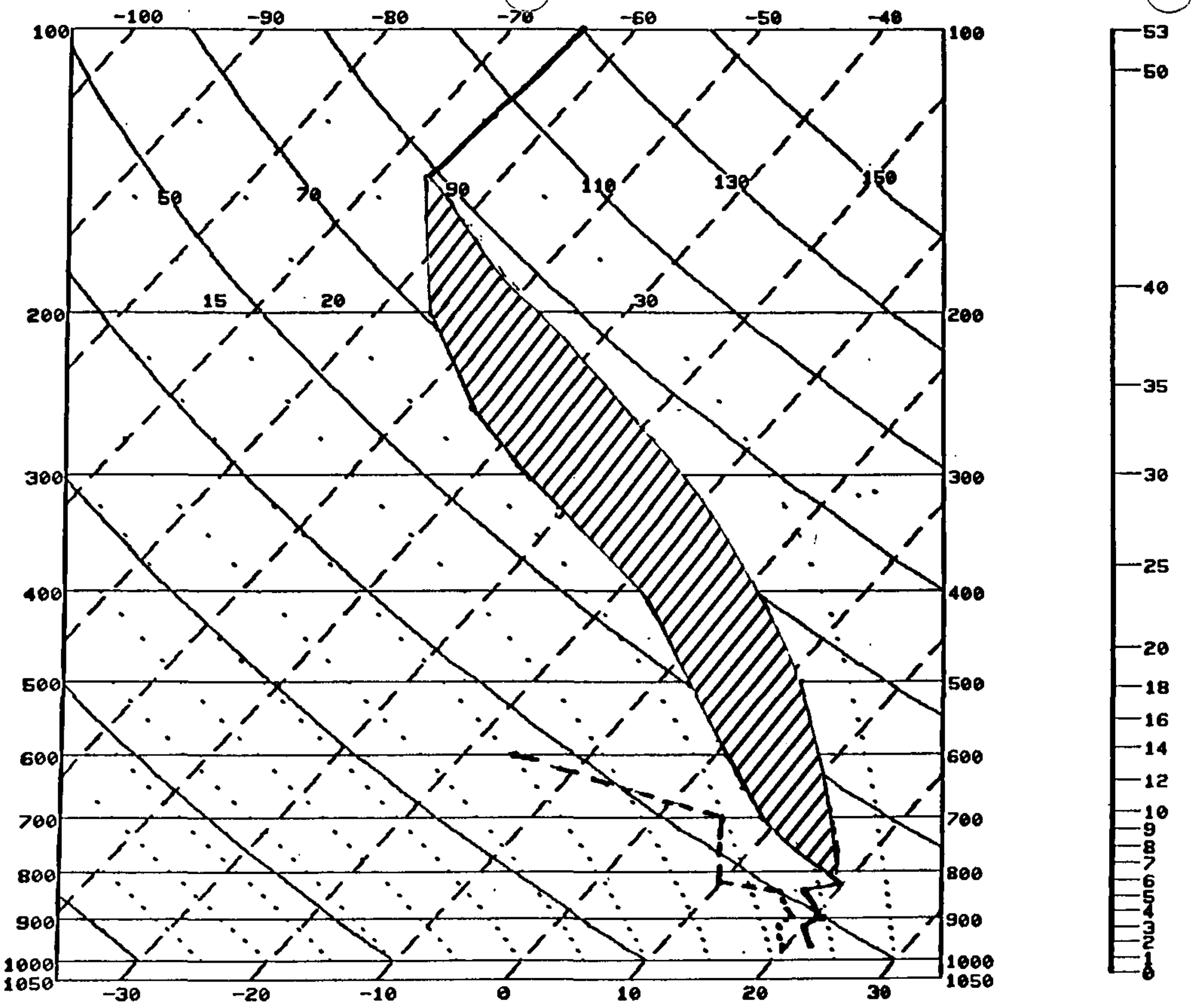

Figure B: Skew T-Log P presentation of sounding from St. Cloud (STC) used for comparison only.

If we use a simple pure parcel theory argument, and consider other things[1] equal, we can readily see that a greater updraft speed is theoretically possible at STC due to the larger positive area. (Although maximum upward acceleration would be nearly the same at the two locations.) Based on this, can we then say that storms at STC are more likely to produce severe weather than those at OKC? Experience tells us this is not necessarily true, despite the potentially stronger updraft speeds at STC!

Recalling that the EL at STC is 6000 ft higher, we can at least surmise that storms at STC will likely be higher than at OKC. Furthermore, we might also infer that VIP-5 heights will also be higher (see Figure 6). But, considering the other environmental parameters used in this study, we could have hail occurrence (possibly severe) at OKC when the VIP-5 height has reached just 23,000 ft. At STC, the threshold value would be at least 31,000 ft. Does this suggest that a stronger updraft speed is actually needed at STC, in this case, to support the occurrence of hail on the ground? If so, then this is probably a direct consequence of the warmer air mass.

Then in what ways are updraft strengths really related to thunderstorm severity? Based on the arguments made here, I would suggest that as an indicator of thunderstorm severity, we must consider updraft strengths relative to thunderstorm ENVIRONMENT. Surely, updraft strengths needed to produce severe weather vary as widely as severe thunderstorm environments.

We should then say, within a given atmospheric environment, those storms that are able to achieve the strongest updrafts are those most likely to become severe. To apply a certain absolute updraft speed that produces hail in one environment to other, differing environments is incorrect. It is precisely for these reasons that for certain radar derived characteristics of thunderstorms to be operationally useful as indicators of severe weather, they must first be normalized. In the case of VIP-5 heights, results of this study make this abundantly clear.

Although the argument presented here is certainly an oversimplified approach to the problem, I believe the conclusions are not without some validity. But, we must remember there are many factors which contribute to updraft strength beside buoyancy effects. In turn, storm severity is not always determined SOLELY by updraft strength relative to it's environment. We know certain storm "types" actually consist of multiple updrafts, and these updrafts can alter their environment in ways not always apparent to the radar operator.

Interestingly, the simplified scenario I have chosen to illustrate, most closely resembles the process in a storm type that has long been a thorn in the side of radar meteorologists. The "pulse" severe storm is a short lived

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[1] Some "other things" being low level dynamic forcing, precipitation drag, vertical and horizontal shears, momentum transport, relative inflow, etc.

severe storm consisting of an intense singular updraft. Evidence continues to grow linking a significant percentage of severe events to this type of storm (Liles 1987).

Clearly, the operational problems facing the radar meteorologist are quite complex. We know that characteristics of all severe storms are not alike, and the radar operator must use a variety of tools at his/her disposal to have any hope of distinguishing those thunderstorms that are severe from those that are non-severe.

## 4. RECOMMENDATIONS

It has been shown that to a fairly high degree of accuracy, hail can be detected in a thunderstorm by relating VIP-5 heights and certain upper air characteristics. By using current or predicted sounding characteristics in a given situation, the radar meteorologist can predict a VIP-5 height which will yield hail on that day. The major advantage of such a scheme is that a hail production threshold can often be established on a potential severe weather day even before the first raindrop falls. This, of course, would be contingent upon the user's ability to accurately anticipate certain environmental conditions at the time of actual thunderstorm occurrence. In many cases, it may be sufficient for predicting VIP-5 height thresholds for hail production in mid afternoon convection.

Operators of 10 cm radars can extract threshold values directly from the curves superimposed on the graphs with this study. (Some reworking of this study's results is definitely suggested for 5 cm radar sites.) One or two of the upper air parameters should be sufficient to arrive at a "VIP-5 height of the day". Any more might merely result in redundant predictability. Although one could use all five upper air parameters, be aware that they will not always give identical VIP-5 height thresholds within a given situation. Which parameters to choose should depend on the individual weather situation and the personal experience of the radar meteorologist. In addition, users should be aware that experience has shown the weakest part of each curve to be on the higher end. That is, for various reasons, the 31,000 ft threshold in warmer air masses will occasionally be too low as an indicator of hail in a thunderstorm.

While results of this study may be most useful in the southeastern part of the country, I believe there may practical use in other areas east of the Rockies. Some notable exceptions are recognizable however. Some "low precipitation" thunderstorms along drylines and in the high plains may produce hail without ever exhibiting a VIP-5 echo on radar. This also may be true on occasion in the gulf coastal regions during the winter months.

Inability to distinguish between a severe hailstorm and a non-severe hailstorm however, continues to be the bottom line. It is primarily for this reason 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. Other techniques such as the tilt sequence must be used to distinguish between severe hailstorms and non-severe hailstorms, and also to effectively establish decent lead times. This is especially true in the case of supercell storms. Predictive VIP-5 heights may be most useful in detection of hail in short lived pulse storms, and to a slightly lesser extent in multicell, squall line, and supercell storms. Clearly, more work in this area needs to be done.

## 5. ACKNOWLEDGEMENTS

Special thanks go to David Imy for his ideas, suggestions, and many hours of helpful discussion. Thanks also go to Charlie Liles, and the staff of WSFO Little Rock for their input into this project.

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