Severe Storm Identification with Satellite Microwave Radiometry: An Initial Investigation with Nimbus-7 SMMR Data

by

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(NASA-CR-176431) SEVERE STORM IDENTIFICATION WITH SATELLITE MICROWAVE RADIOMETRY: AN INITIAL INVESTIGATION WITH NIMBUS-7 SMMR DATA (Wisconsin Univ.) 15 p HC A02/MF A01 CSCL 04B G3/47
N86-15821
Unclas
05043

Abstract

The severe weather characteristics of convective storms as observed by the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) are investigated. Low 37 GHz brightness temperatures (due to scattering of upwelling radiation by precipitation size ice) were related to the occurrence of severe weather (large hail, strong winds or wind damage, tornadoes and funnel clouds) within one hour of the satellite observation time. During 1979 and 1980 over the United States there were 263 storms which had very cold 37 GHz signatures. Of these storms 15% were severe. The SMMR detected hail, wind, and tornadic storms equally well. Critical Success Indices (CSI's) of 0.32, 0.48, and 0.38 were achieved for the thresholding of severe vs. nonsevere low brightness temperature events during 1979, 1980, and the two years combined, respectively. Such scores are comparable to skill scores for early radar detection methods. These results suggest that a future geostationary passive microwave imaging capability at 37 GHz, with sufficient spatial and temporal resolution, would allow the detection of severe convective storms. This capability would provide a useful complement to radar, especially in areas not covered by radar.

1. Introduction

The remote identification of severe thunderstorms is typically accomplished with ground based methods such as radar (Atlas, 1964; Battan, 1973). So far, the use of satellite data in the detection of convection with possible embedded severe weather has been based upon cloud top parameters measured at the visible and infrared wavelengths (e.g. Adler and Fenn, 1979).

Here we address the possible utility of satellite passive microwave observations for the detection of severe thunderstorms. Because clouds are relatively transparent at certain microwavelengths, the attenuation effects of precipitation size hydrometeors (both liquid and frozen) can be measured with a satellite borne microwave radiometer. Initial investigations with data from the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR - Gloersen and Barath, 1977) have revealed that thunderstorms over land have a low 37 GHz brightness temperature when compared to the radiometrically warm land background due, primarily, to attenuation of the upwelling radiation by precipitation size ice particles. These brightness temperatures (T_B) decrease approximately linearly with increasing rain rates, as determined by radar (Spencer *et al.*, 1983a) with T_B as low as 163 K being observed within an intense Kansas thunderstorm, and by theoretical modeling studies (*ibid.;* Wu and Weinman, 1984). This decrease in T_B is considerably stronger than that expected from the attenuation by liquid raindrops alone, due to the high ratio of scattering to absorption (and thus emission) inferred from the relatively small real part of the index of refraction for ice.

It is reasonable to investigate the extent to which this ice signature is an (indirect) measure of storm severity. One might expect that most storms with severe characteristics also would have updrafts capable of lifting great quantities of water well above the freezing level and creating a layer of large ice particles. A broad, deep, dense layer of such particles would be detectable with passive microwave methods. Indeed, radar methods for severe storm detection typically utilize the strength of some upper level reflectivity.

Here we will first screen the Nimbus 7 SMMR data for the storms with intense ice scattering signatures, then relate the strength of this signal to the existence of severe weather. Unfortunately, because of the Nimbus 7 SMMR sun synchronous polar orbit, limited angular field of view, and alternate day duty cycle, the probability of observing any given severe storm is very small. Nevertheless, by screening a large volume of SMMR data it is possible to identify a sufficient number of storms to address the possible utility of future satellite microwave observations for severe storm monitoring, should they ever be made available routinely and in real time.

The primary focus of the present investigation will be the SMMR 37 GHz channel. This is because, of all the SMMR frequencies (37, 21, 18, 10.7, and 6.6 GHz), the 37 GHz channel has both the greatest sensitivity to scattering by hydrometeors and the smallest field of view (27 km, vs. 46, 55, 98, and 148 km, respectively) of the SMMR channels.

2. Data and analysis

SMMR data from calendar years 1979 and 1980 over the United States (U.S.) east of 105° W at were analyzed at full resolution with the objective of isolating those events - which we shall call "storms" - that had strong volume scattering signals. The definition of a "storm" is intended to encompass all convective storms that include as a subset those storms with severe characteristics.

Screening for storms was accomplished by a multiple frequency method outlined by Spencer and Santek (1985). This work (and others published previously, e.g. Weinman and Guetter (1977); Grody (1984)) showed that a single SMMR channel can not be used to unambiguously identify convective storms over land. Because other geophysical phenomena (wet land, lakes, oceans, snow fields) also have low brightness temperatures one needs a method by which these different features can be separated. Because precipitation and snow fields are volume scatterers of microwave radiation, their cooling effect on the T_B is a strong function of wavelength, with the cooling increasing with frequency (Grody, 1984). Emissive surfaces such as water and wet ground have cooling effects which decrease with frequency. Thus, the isolation of the volume scatterers was achieved by requiring that

$$T_B^{H18} - T_B^{H37} \leq 20^{\circ}\,C, \qquad (1)$$

where H18 and H37 correspond to the horizontally polarized 18 and 37 GHz SMMR channels, respectively. This condition roughly corresponds to a footprint average rain rate of at least 20 mm/h (Spencer, 1984), or a snow depth of at least 30 cm (Kunzi, et al. 1982). The further separation between the snow and rain classes was based upon the SMMR observed characteristics of snow fields and rain systems in the 37, 21, and 18 GHz data. This separation is possible due to the difference in thermometric temperatures of the environments in which snow cover and rain storms are contained, and is described by Spencer and Santek (1985).

While is is difficult to identify all storms that might be severe (as it is with radar), it will be shown that the screening procedure used here results in a sample of storms in which those near the screening threshold are seldom severe. This suggests that few severe storms were omitted by the screening procedure.

Maps of all SMMR 37 and 18 GHz footprints satisfying the above criteria during were produced by computer. Where clusters of storms were indicated in the maps, it was required that a relative minimum by at least ten degrees exist for a separate storm to be identified. The center of the SMMR observed storm was defined to be at the location of the coldest 37 GHz brightness temperature.

Severe storm reports were obtained from the National Severe Storm Forecast Center (NSSFC) and from the late reports contained in Storm Data during 1979 and 1980. For a severe report to be attributed to a SMMR observed storm, it was required that the report be within some maximum distance and one hour of the SMMR storm location and time, respectively. The distance requirement was based upon SMMR navigation errors (10 to 20 km), instrument viewing angle parallax errors (up to 10 km), and the distance that can often separate the precipitating portion of a storm (that the SMMR sees) from the severe weather event (up to 10 km for tornadoes and hail, up to 30 km for wind damage). The one hour time window was based upon the likely length of time that a severe report could be associated with a given storm entity, as well as the uncertainties in the reported times of severe weather events. These events have a predisposition for occurring on the hour or half hour (Robert Adler, personal communication). Additionally, each case was individually analyzed to assure that the time difference was consistent with the spatial separation, based upon the likely direction and speed of storm motion. Taken together, these sources of error were translated into requirements that a wind damage report be within (50 + 55f) km of the SMMR observed storm and that a tornado or hail event be within (30 + 55f) km, where f is the fraction of an hour that separates the SMMR observation time from the severe weather time, and 55 (km/h) is the assumed speed of a typical storm.

3. Results

During 1979 and 1980 there were 263 individual storms observed by the SMMR over the U.S. east of 105° W that satisfied Eq. 1, of which 39 (15%) resulted in reports of severe weather. Fig. 1 shows the locations of the 37 GHz footprints having the lowest T_B within each storm. The total number of footprints satisfying Eq. 1 was much larger because a storm is typically composed of several to many footprints. Most of the storms occurred over the Great Plains, and the majority at midnight.

The percentage of SMMR observed severe storms that fell in the wind, hail, and funnel or tornado classes was calculated. These percentages were compared to those from all severe weather reports contained in the NSSFC log within 2 h of the SMMR observation times (Table 1). It can be seen that the two distributions are nearly identical, indicating that, to the extent that the SMMR can detect severe thunderstorms, it does not discriminate according to severe weather type.

Table 1 Categorical breakdown of severe weather types associated with SMMR screened storms and all severe reports within 2 h of the SMMR observation time.

	Wind	Hail	Tornados and Funnels
SMMR storms (82 reports)	52.4%	29.3%	18.3%
All severe (1965 reports)	52.5%	30.0%	17.6%

The extent to which the minimum 37 GHz brightness temperature within each storm is quantitatively related to the incidence of severe weather is illustrated in Fig. 2, a histogram plot of the percentages of the SMMR storms for which severe weather was reported. Clearly, as the brightness temperatures decrease, the probability that the storm is severe increases. At the highest storm brightness temperatures there were very few severe reports. Thus, even though the volume scattering threshold implied by Eq. 1 is somewhat arbitrary, apparently it was sufficiently conservative to include most of the severe storms that did not have very low brightness temperatures.

In order to translate the information in Fig. 2 in to a quantitative measure of storm detection ability, we utilized the Critical Success Index (CSI - Donaldson, 1975). This index is made up of a probability of detection (POD) and a false alarm ratio (FAR). Table 2 shows all possible combinations of predicted and observed events, with x, y, z, and w representing the number of cases in each category. The CSI ($=x/(x+y+z)$) rewards a high probability of detection ($POD=x/(x+y)$) and a low false alarm ratio ($FAR=z/(x+z)$). A CSI of 1 indicates perfect skill and 0 indicates no skill.

Table 2 Categories for predicted and observed events.

		Prediction	
		severe	non severe
Event	severe	x	y
	non severe	z	w

For each of the 263 storms picked by the screening procedure during 1979 and 1980, the lowest T_B^{H37} was compared to the NSSFC severe reports and optimum thresholds which maximized the CSI were chosen (Table 3).

Table 3 CSI, FAR, and POD scores for best thresholds of minimum T_B^{H37} within the SMMR observed storms.

Years	Total Storms	% Severe	Threshold	POD	FAR	CSI
1979	141	13.5%	213 K	0.58	0.63	0.32
1980	122	16.4%	203 K	0.60	0.29	0.48
Both	263	14.8%	203 K	0.55	0.45	0.38

For the 1979 storms the 213 K threshold (below which severe weather was predicted) led to a CSI of 0.32, while for 1980 a 203 K threshold led to an improved CSI of 0.48. The significantly higher score in 1980 is felt to be a result of improved reporting of severe weather events in the log, with 73% more total reports that in 1979. Therefore, the 1980 score (CSI=0.48) might be more representative.

In a variation of the method described above for the SMMR intensity classification of a storm, the three lowest T_B within each storm were averaged and again compared to severe weather reports. With a threshold of 207 K, this method had a resulting CSI of 0.38 for 1979 and 1980 combined. This is the same result that the single footprint method gave (Table 3). This suggests that the areal extent of low brightness temperatures is well correlated with the magnitude of the lowest single brightness temperature.

A third technique used both the 18 and 37 GHz channels, that is, the value computed in Eq. 1, as a predictor. Because a brightness temperature difference greatly reduces the effects that thermometric temperature variations have on the T_B at a single frequency (Spencer et al., 1983b; Spencer, 1984) and has facilitated measurements of precipitation it was expected to do well. On the contrary, this approach led to a somewhat lower CSI of 0.34 for 1979 and 1980 combined. This result might be due to differences in the treatment of data. The precipitation studies used brightness temperatures over several footprints, whereas here we have used individual footprints. Because the 37 GHz and 18 GHz footprints are not coincident, and because the 18 GHz footprints cover four times the area of the 37 GHz footprints, comparisons on a footprint by footprint basis can be misleading. Thus, for screened SMMR data it appears that the lowest horizontally polarized 37 GHz brightness temperature is the best indicator of storm severity.

The timing of the severe weather events compared to the SMMR observation time is illustrated in Fig. 3, a time line display of the 82 severe reports associated with the 39 severe storms observed by the SMMR. The severe reports, regardless of type, are rather evenly distributed about the SMMR observation time. To a first approximation, this result suggests that there is potential for prognostic use of rapidly imaged microwave data for severe storm detection for at least half of all severe storms. Because it can be reasonably assumed that the SMMR severe signature in most cases began prior to the time of the SMMR overpass, the actual number of storms for which a signature existed before the severe weather time would have been larger than half of the total.

Although there were not enough severe storms in our sample to stratify the data according to region, there is a definite latitudinal dependence in the T_B associated with the severe storms (Fig. 4). The severe storms in the northern U.S. had slightly warmer T_B than those in the south. This might be due to lower tropopause heights in the north, which would imply lower storm tops, smaller ice depths, and thus less scattering. It was also noted that most of the very cold storms for which there were no severe reports occurred where the population density was low. An example of this is a storm that occurred in a rural part of extreme southern Texas (Jim Hogg County). Not only were the 37 GHz brightness temperatures as cold as 180 K, the GOES-East infrared observations (Hemysfield et al., 1983) carried the "cold V" signature which also has been associated with severe storms.

Some limited comparisons can be made between the CSI scores in Table 3 and scores that have been reported for radar storm detection methods. Donaldson (1975) reviewed seven conventional radar schemes which had CSI values ranging from 0.15 to 0.39. Most of these schemes involved either vertically integrated liquid water (VIL) greater than some threshold, or the strength of the reflectivity at some relatively great height within the storm. Donaldson also noted that doppler radars produce significantly better scores than those measuring only reflectivity. This has been confirmed by a more recent study involving Oklahoma storms and an intensive reporting network, for which a CSI of 0.62 was reported (Burgess and Devore, 1979). One recent evaluation of a convention radar method (McGovern et al., 1984) is quite optimistic. This method, the National Weather Service's experimental RADAP II (RAdar DAta Processor) Severe Weather Probability (SWP) algorithm that is slated for inclusion in the NEXRAD (next generation radar) network, was evaluated during the 1983 severe weather season in Oklahoma. Through June 30 of that year, there were 132 severe storms covered by the Oklahoma City radar, for which the algorithm returned a CSI of 0.74, indicating a very high degree of skill. It should be noted that it is difficult to compare scores from different studies when the period of study, the region, and the severe weather reporting effort can all vary between studies.

4. Conclusions and Recommendations

37 GHz radiation emanating from the tops of thunderstorms over the U.S. contains considerable information on the probability of severe weather occurring within those storms. Cold 37 GHz brightness temperatures are correlated with the occurrence of severe weather within one hour of the satellite observation time. The types of severe storms that are revealed by the satellite do not differ from the climatologically expected fraction falling in wind, hail, and funnel categories. Half of the severe weather events associated with the SMMR observed storms occurred after the satellite observation time. Assuming that this variation is not due to errors in reported times of severe weather, it indicates some predictive skill. To the extent that the SMMR severe signatures actually began before the SMMR imaged the storm, this prognostic value would be increased. Therefore, one might expect that some quasi continuous imaging capability from a satellite would increase the lead time in many cases. Unfortunately, the potential predictive skill of passive microwave observations can not be further quantified because of the poor time sampling characteristics of the SMMR instrument.

More research is needed to substantiate the predictive and monitoring value of a satellite microwave storm detection instrument. High altitude overflights of storms with multifrequency instrumented aircraft would improve our understanding of how the cold brightness temperatures vary with wavelength and time during a storm's life cycle.

Acknowledgments

We would like to express our gratitude to Dr. James Dodge, without whose confidence this work would not have been possible. Dr. David Martin helped in the formulation of the storm report acceptance criteria, and provided general advice. Dr. Per Gloersen provided the 1979 SMMR data, and Paul Hwang helped us obtain the 1980 SMMR data. This work was supported by NASA contract NAG5-391, and by Universities Space Research Association under NASA contract NAS8-347-67.

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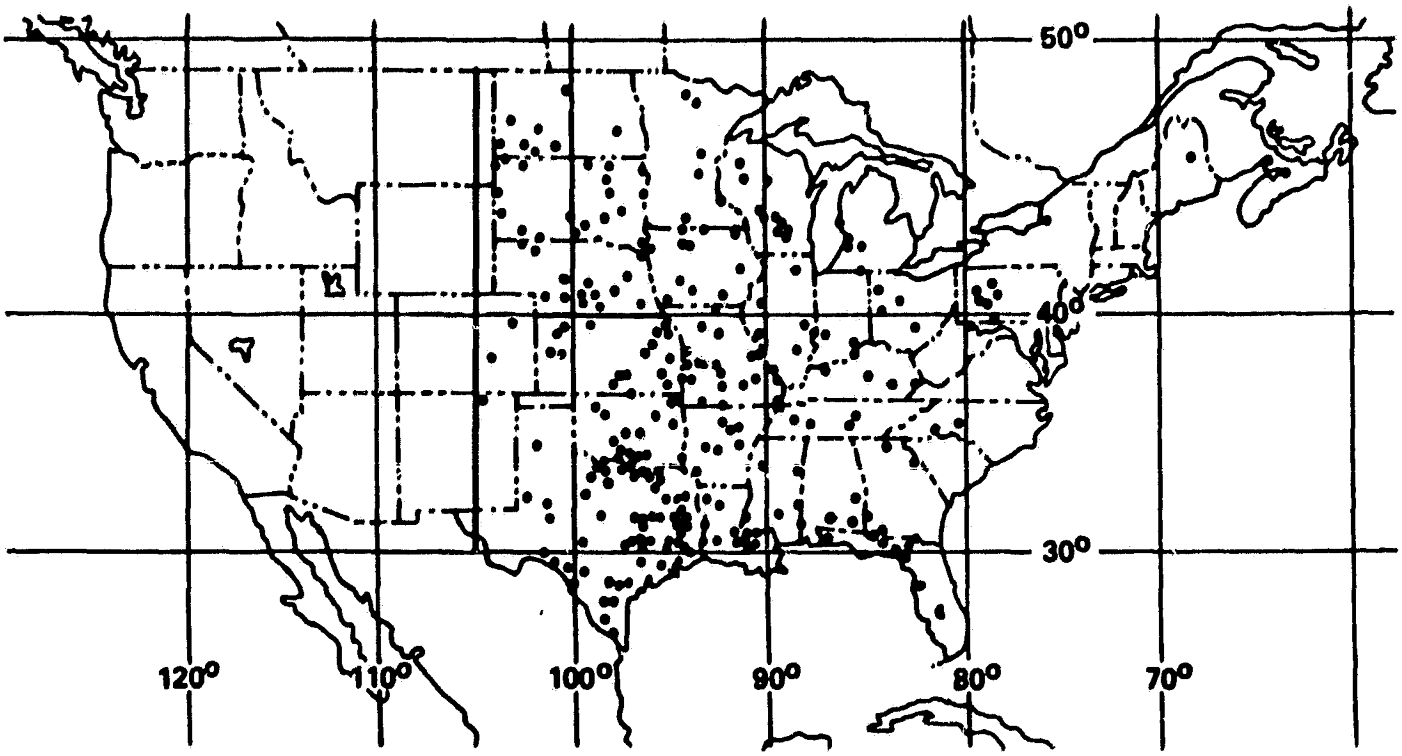

Figure 1 Geographical distribution of the locations of individual storms (coldest 37 GHz footprints) found during the screening of the 1979 and 1980 SMMR data over the United States east of 105° W.

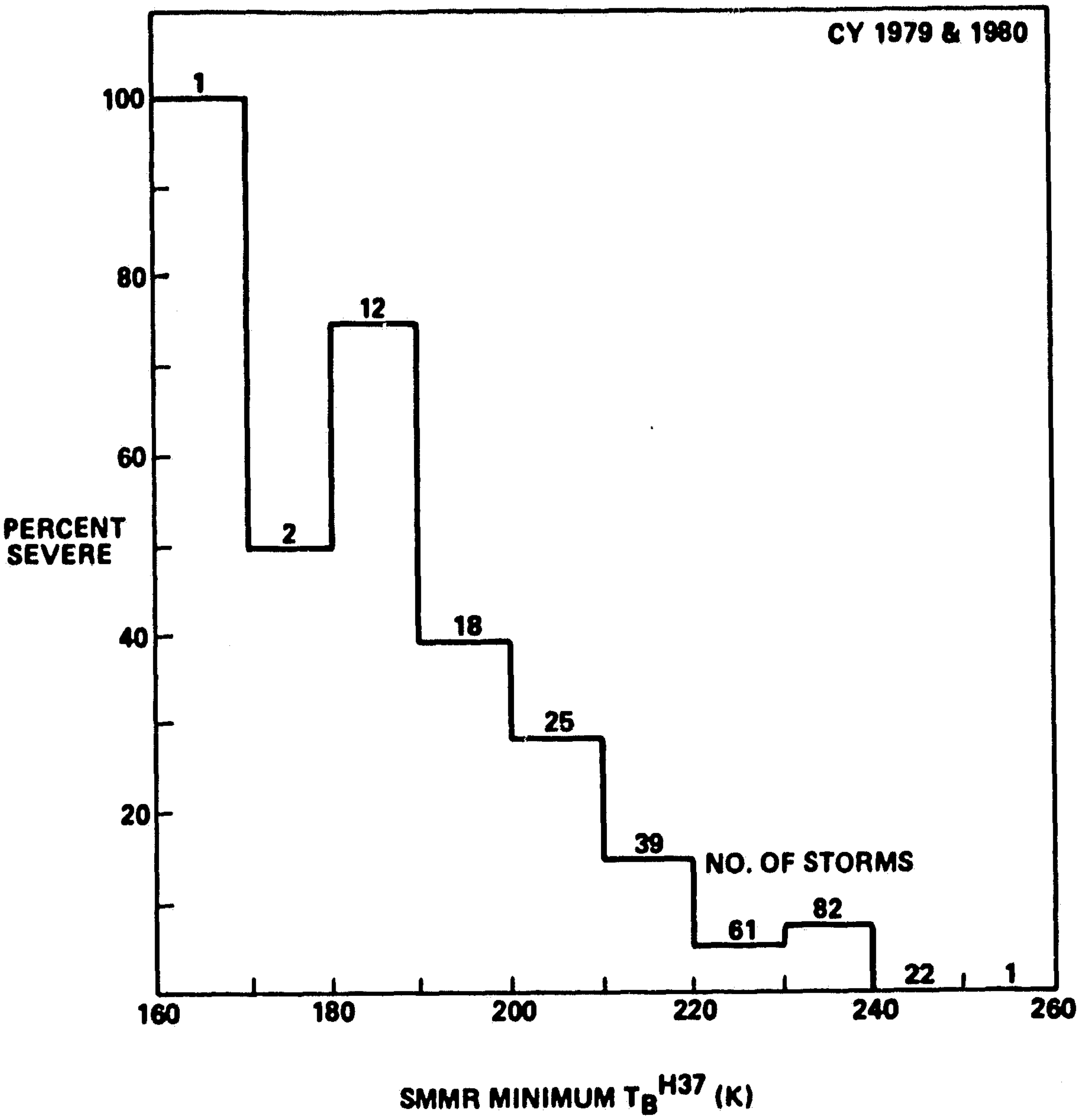

Figure 2 Percent of 1979 and 1980 SMMR screened storms that were severe as a function of the minimum 37 GHz brightness temperature observed within that storm. The number of storms in each T_B interval is also shown.

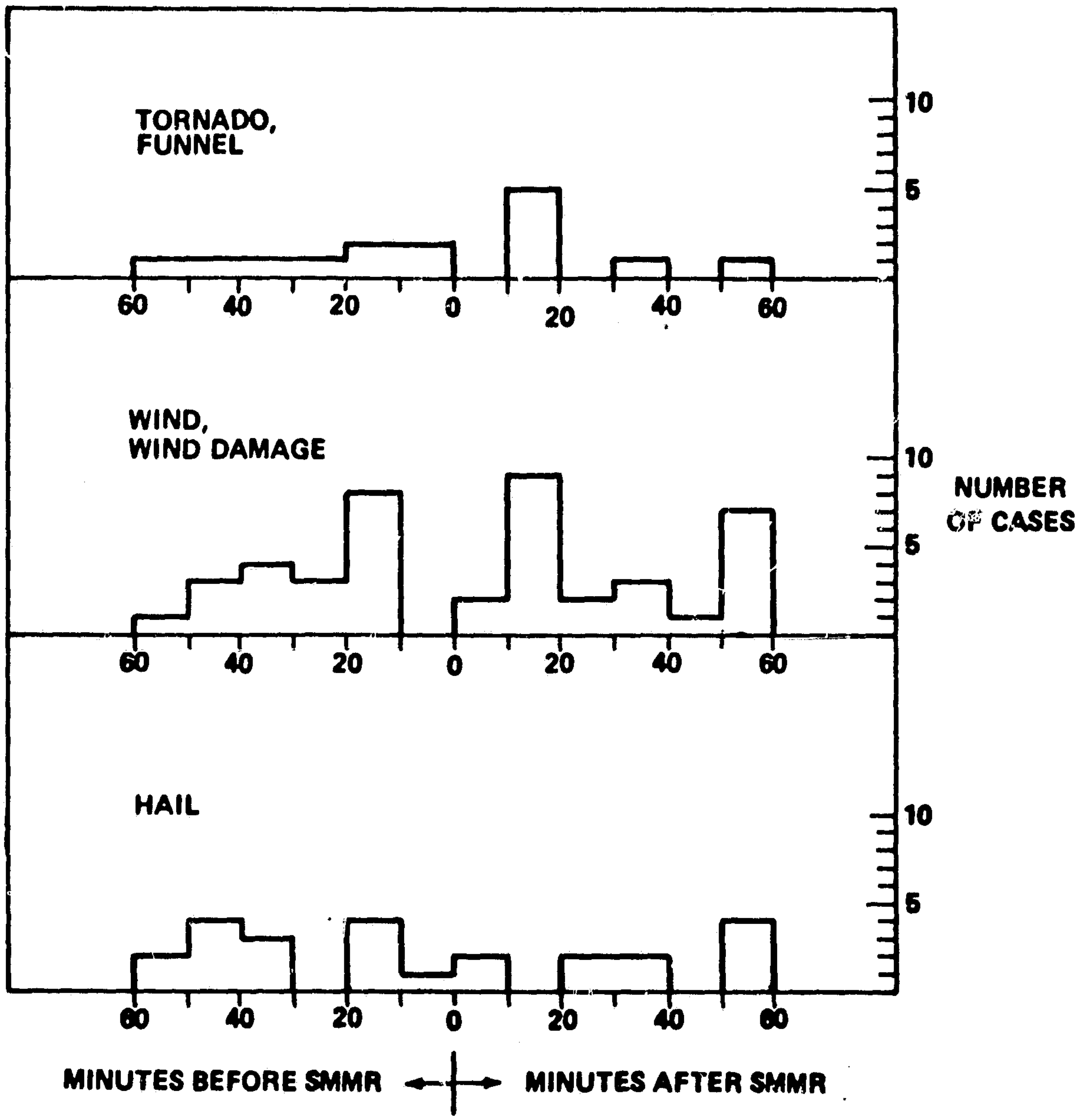

Figure 3 Frequency histogram of the time difference between SMMR observed storms and the reported times for the first severe weather reported for those storms, catagorized by severe weather type.

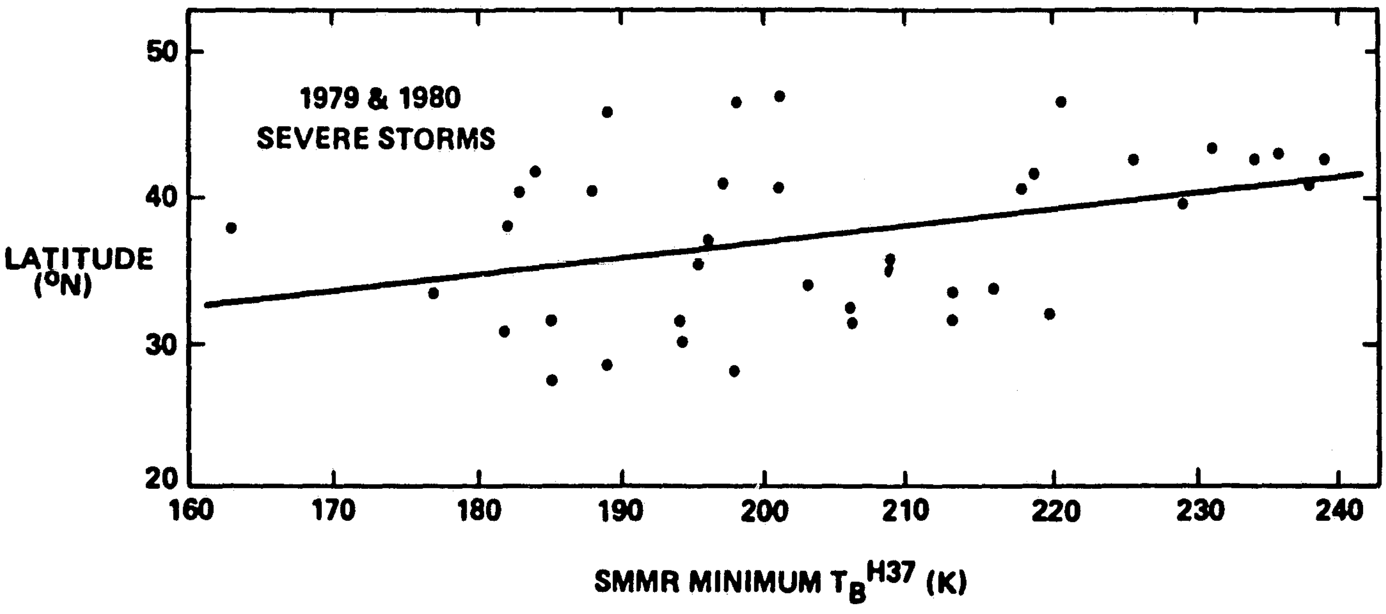

Figure 4 The minimum SMMR 37 GHz T_B of the 1979 and 1980 severe storms as a function of latitude, with a least squares regression fit.