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FORECASTING TORNADIC VERSUS NON-TORNADIC SEVERE THUNDERSTORMS IN NEW YORK STATE

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1. INTRODUCTION

Identifying the incipient meteorological conditions favorable for the development of tornadoes is the essential initial step the National Weather Service (NWS) takes in the process of warning the nation's citizenry of these hazardous storms. LaPenta and Maglaras (1993) examined atmospheric conditions on 24 days that produced tornadoes in New York State from the period of 1989 to 1992. The analysis performed in this study examined 111 severe weather events that occurred in New York, 37 of which produced tornadoes.

An analysis was carried out to differentiate the atmospheric conditions that produced tornadic and non-tornadic severe thunderstorms. This study also examined the utility of various atmospheric stability and shear indices in tornado forecasting. The analysis performed used data from LaPenta and Maglaras (1993), plus additional data from 13 tornadic days in New York State during 1993. In addition, 74 cases were examined that produced severe thunderstorms in New York State, but did not produce tornadoes.

2. METHODOLOGY

For this study, a day was considered to be non-tornadic if severe thunderstorms were observed in New York State, and tornadoes were not observed anywhere in the northeastern United States (New England States, New York, New Jersey, and Pennsylvania). If severe thunderstorms but no tornadoes were observed in New York, and tornadoes were observed elsewhere in the northeastern United States, the day was not used in the study. The non-tornadic cases were divided into two equal groups. Major severe weather days were categorized as those days that produced 10 or more severe weather events in the northeastern United States. Minor severe weather days were categorized as those days that produced less than 10 events. The data on the tornadic and severe storm events were obtained from Storm Data (U.S. Dept. of Commerce 1989-1993).

For each of the 111 days examined, proximity soundings were constructed and analyzed by using the Skew-T Hodograph Analysis and Research Program (SHARP) Workstation (Hart and Korotky 1991).

Actual atmospheric soundings from across the northeastern United States were examined, and the sounding that was considered to be most representative of the airmass over the location where the tornadoes or severe thunderstorms occurred was selected. This sounding was then modified by using observed surface temperature, dewpoint temperature, and wind from a surface observation site near the location where the severe weather occurred. On a few occasions, additional subjective modifications were made if significant thermal advection aloft was evident, or changes to the vertical wind profile were warranted due to wind speed and/or direction changes aloft. The storm motion was determined primarily from radar observations. However, on the few occasions when radar data were not available, the storm motion was estimated or obtained from the text of NWS warnings and statements.

Various severe weather indices were calculated for each proximity sounding by using the SHARP Workstation (Hart and Korotky 1991). In addition, composite atmospheric soundings were constructed for the tornadic, major severe weather, and minor severe weather day categories.

3. RESULTS

a. Composite Atmospheric Soundings

Table 1 lists the temperature (°C), dewpoint temperature (°C), and equivalent potential temperature (K), at 19 different levels for the composite atmospheric soundings. An analysis of Table 1 reveals that the tornado and minor severe weather composite soundings are surprisingly similar. Although the tornado sounding was slightly cooler, temperatures at each level were generally within 0.5°C. Dewpoint temperatures at or below 850 mb were less than a half degree different, with the tornado sounding being just a bit more moist. From the surface to 300 mb, the composite sounding for the major severe weather day category was warmer, by about 2°C on average, and a bit more moist than the other two categories.

Table 2 shows the wind direction and speed at 15 different levels of the composite atmospheric soundings. Figure 1 illustrates the hodographs for the tornado, major severe, and minor severe composite soundings. The mean 0-6 km above ground level (AGL) wind speed was strongest for the tornado category (27 kt), weakest for the minor severe weather day category (17 kt), and intermediate for the major severe category (22 kt). At higher altitudes, the wind speed in the tornado category was greater than the other categories by an even larger margin. For example, the 9 km mean wind speed was 53, 41, and 35 kt, for the tornado, major severe, and minor severe categories, respectively. The wind direction also showed considerable variation. In the 0-6 km layer, the mean wind for the major severe category exhibited a more westerly direction (270°) than for the other two categories. The tornado category had a mean wind direction of 243°.

It should be mentioned that meteorologists must use caution when examining the composite atmospheric soundings. This is because tornadoes and severe thunderstorms can develop under a variety of different atmospheric conditions. Although there is useful information contained within the composites, the averaging of many soundings together can smooth out potentially important features (e.g., the height and strength of a low-level jet, the presence of temperature inversions, etc.).

In the sections that follow, the mean value of each atmospheric stability and shear index was calculated by taking the average of the index for the 37 cases in the category. Table 3 presents a summary of these shear and stability indices for the 111 New York State severe weather cases that were examined in this study.

b. Lifted Index

The lifted index (LI) was calculated by lifting the most unstable parcel in the lowest 150 mb of the sounding, dry adiabatically to the Lifting Condensation Level, and from that point moist adiabatically to 500 mb. For the majority of the cases examined, the most unstable low-level parcel was located at the surface. The mean LI to 500 mb (standard deviation[1]) for the tornado, major severe, and minor severe categories was -5, -6, and -4 (1.6, 1.4, 1.7) respectively. Figure 2 (upper left) presents the distribution of LIs for the three severe weather categories.

c. Convective Available Potential Energy (CAPE)

The lifted index estimates instability by comparing the temperature of a lifted parcel to the ambient temperature at a single level. CAPE gives a much better estimate of the instability of a rising parcel, since it incorporates data at all levels of a sounding by vertically integrating the positive buoyancy of the rising parcel. In this study, the most unstable parcel in the lowest 150 mb of the atmosphere was lifted.[2] The mean CAPE was greatest in the major severe category, 2272 J/kg (the standard deviation was 526 J/kg). The mean for the tornado cases was 1856 J/kg (the standard deviation was 687 J/kg). The CAPE was considerably less for the minor severe category, 1421 J/kg (the standard deviation was 635 J/kg). Figure 2 (upper right) presents the distributions of CAPE for the tornado, major, and minor severe weather day categories.

d. Total Totals Index

The Total Totals Index (TT; Miller 1972) considers both the 850 to 500 mb temperature lapse rate, and the moisture at 850 mb to estimate severe weather potential. TT values of 48 or 49 indicate isolated severe thunderstorms. Values of 50 or 51 indicate the possibility of a few severe thunderstorms and isolated tornadoes. TT values from 52 to 55 indicate the possibility of scattered severe thunderstorms and a few tornadoes, while values greater than 55 indicate numerous severe thunderstorms and scattered tornadoes (Miller 1972). The TT showed little difference between the tornadic

1. Standard deviation will refer to the first standard deviation throughout this paper.

2. The parcel lifted in calculating CAPE may be determined a number of ways. For example, the lifted parcel can be assigned the average temperature and dewpoint in the lowest 100 mb, and then be lifted from the mid-point of that layer. The method used in calculating CAPE can significantly alter the calculated CAPE, and values of other indices (i.e., Energy-helicity Index, Bulk Richardson Number) dependent on CAPE. Meteorologists should use caution when comparing CAPE in this and other studies.

and non-tornadic cases. The mean TT for the tornado, major severe, and minor severe categories was 48, 48, and 47, respectively. Not only was the mean TT for the tornado category below the derived tornado threshold of 50, but 23 of the 37 tornado cases (62%) also had TT values below this tornado threshold. This suggests that in the northeastern United States, the commonly used TT threshold for tornadoes that was developed for Great Plains type supercells may be too high. Figure 2 (lower left) presents the distributions of TT.

e. SWEAT Index

The SWEAT Index (SI; Miller 1972) combines the effects of low-level moisture, convective instability, and the wind at 850 mb and 500 mb in determining severe weather potential. SI values between 300 and 400 usually indicate the chance of severe thunderstorms. Values between 400 and 500 indicate a chance of tornadoes. Values between 500 and 600 indicate tornadoes are likely, and values from 600 to 800 point to scattered tornadoes (Miller 1972). In this study, increasing SI values pointed to an increasing threat of severe thunderstorms and tornadoes. The mean (standard deviation) SI for the minor severe category was 235 (77), for the major severe category 250 (68), and for the tornado category 285 (66). The mean value for the tornado cases was well below the 400 SI tornado threshold developed by Miller (1972), suggesting that in the northeastern United States, the commonly used SI threshold for tornadoes that was developed for Great Plains type supercells, may be too high. In fact, in 34 out of 37 tornado cases (92%), the SI was at or below 400. Figure 2 (lower right) presents the distributions of SI.

f. Storm-relative Helicity

Storm-relative helicity (s-rH) is the summation of streamwise vorticity through a storm's inflow layer, which gives a measure of the rotational potential of a thunderstorm updraft. According to Davies-Jones et al. (1990), an empirical rule for mesocyclone formation is that the storm-relative winds should have speeds of at least 20 kt and veer by at least 90° in the lowest 3 km of the atmosphere. This combination produces a threshold s-rH of 150 $(m/s)^2$. Since s-rH is dependent on storm motion, any errors in estimating storm motion could have a significant effect on s-rH, especially if wind fields are strong. In a light wind regime, small errors in storm motion will not have a significant impact on the s-rH.

The 0-3 km s-rH was significantly larger in the tornadic category than in the non-tornadic categories. The mean [standard deviation] for the tornado cases was 164 $(m/s)^2$ [128 $(m/s)^2$]. The mean [standard deviation] for the major severe cases was 37 $(m/s)^2$ [41 $(m/s)^2$], and for the minor severe cases 25 $(m/s)^2$ [32 $(m/s)^2$]. Figure 3 (upper left) presents the distributions of s-rH. Twenty-three out of the 37 tornado cases (62%) exhibited a s-rH below the 150 $(m/s)^2$ threshold, implying that low s-rH does not rule out tornado formation. Studies by Johns and Doswell (1992); Lazarus and Droegemeier (1990); and, LaPenta (1992), have shown that there is a relationship between s-rH and CAPE that contributes to the development of mesocyclones and tornadoes. Tornadoes are possible with weak instability and large s-rH, if the instability is sufficient to initiate and sustain convection. Likewise, marginal s-rH combined with large CAPE may produce tornadoes.

g. Energy-Helicity Index

The Energy-Helicity Index (EHI) represents potential tornadic intensity as a function of CAPE and s-rH. This index is based on empirical studies of strong (F2 or F3) and violent (F4 or F5) tornadoes. The EHI is defined as:

$$EHI = [+s\text{-}rH * CAPE] / 160{,}000$$

where +s-rH is the positive s-rH in the 0 to 2 km (AGL) layer. The reliability of the EHI is not conclusive, but values between 1 and 5 appear to indicate the potential for F2 or F3 tornadoes. Values greater than 5 indicate the potential for F4 or F5 tornadoes. The EHI must be used with other meteorological information and analyses to have operational value (Hart and Korotky 1991). For example, a sounding may have a high EHI but a capping inversion may prevent convection.

The mean (standard deviation) EHI for the tornado cases was 1.66 (1.33). The EHI was significantly lower in the non-tornadic cases. The mean (standard deviation) for the major severe cases was 0.57 (.53) and for the minor severe weather cases 0.34 (.33). Twenty-eight out of the 37 tornado cases (76%) had EHIs greater than or equal to 1. There were four cases with F2 or stronger tornadoes. Only four out of the 74 non-tornadic cases had EHIs greater than 1. Figure 3 (upper right) presents the distributions of the EHI.

h. Bulk Richardson Number

The Bulk Richardson Number (BRN) is defined as the ratio of positive buoyant energy and wind shear. Weisman and Klemp (1986) showed a general correlation between BRN and storm type. Lazarus and Droegemeier (1990) also found the BRN was correlated with storm type, but that it was less useful in predicting storm rotation. The BRN is not appropriate for assessing storm rotation, because the shear used in its calculation does not address the specific effects of directional and speed shear components (Lazarus and Droegemeier 1990). Weisman and Klemp (1986) indicated that supercell development was favored with a BRN less than 35, with multicell convection likely with a BRN greater than 50. Both supercells and multicells occurred with BRN between 35 and 50. With a BRN below 10, wind shear may be too strong for sustained convection, especially if positive buoyant energy is small. The mean (standard deviation) BRN for the tornado, major severe, and minor severe categories was 45 (35), 108 (120) and 99 (137), respectively. Of the 37 tornado cases, 25 (68%) had a BRN less than or equal to 50. Of the 74 non-tornadic cases, 30 (41%) had a BRN less than or equal to 50. Figure 3 (lower left) presents the distributions of the BRN.

i. Storm-relative Inflow

Lazarus and Droegemeier (1990) noted that storm rotation is dependent not only on helicity, but on the specific combination of velocity (storm-relative) and vorticity in the storm inflow layer, which determined the helicity. They also stated that regardless of the shear, storm-relative low-level turning of the wind alone is not sufficient to produce strongly rotating storms, and that adequate storm-relative, low-level inflow is required. Environments with storm-relative inflow less than 20 kt favor multicellular storms, while storm-relative inflow of greater than 20 kt, with sufficiently high s-rH, favor rotating updrafts and mesocyclones (Lazarus and Droegemeier 1990; Davies-Jones et al. 1990; Hart and Korotky 1991). In this study, the storm-relative inflow was calculated for various layers up to 3 km, and the maximum was determined. The mean storm inflow was greatest in the tornado cases, 32 kt, and was 24 kt for both the major and minor severe weather day categories. The storm inflow was greater than 20 kt in 76% of the tornado cases, and in 32% of the non-tornadic cases. Figure 3 (lower right) presents the distributions of storm-relative inflow.

j. Storm Motion

The mean storm motion for the tornado category was 269° at 30 kt. The mean storm motions for the major severe and minor severe categories were 257° at 25 kt and 268° at 20 kt, respectively. Storms within the tornado category moved most rapidly; and, on average, 26° to the right of the mean 0-6 km wind with a speed slightly faster than the mean wind in that layer. In the non-tornadic categories, the mean storm motion was closer to the direction of the 0-6 km wind. The movement to the right of the mean 0-6 km wind in the tornado category may be the result of the rightward propagation of rotating storms (Weisman and Klemp 1986), or perhaps due to the steering of the storm by winds above the 6 km layer.

4. DISCUSSION/CONCLUSION

For the 111 New York State severe weather cases examined in this study, the wind speed was strongest for the tornado category. The 0-6 km AGL mean wind was 27 kt in the tornado category, and 22 kt, and 17 kt in the major severe, and minor severe categories, respectively. The difference in wind speed between the tornadic and non-tornadic categories was even more pronounced at altitudes above 6 km. Storm relative inflow was also significantly greater (32 kt vs. 24 kt) for the tornadic cases. S-rH and the EHI (which is proportional to s-rH) possessed the greatest ability to differentiate between tornadic and non-tornadic severe storms. The average 0-3 km s-rH for the tornado cases was 164 $(m/s)^2$, which was significantly larger than the s-rH in the major severe category [37 $(m/s)^2$] and the minor severe category [25 $(m/s)^2$]. While the CAPE was greatest in the major severe category, the EHI, which combines CAPE and s-rH into a single parameter, was by far greatest in the tornado category. For the tornado cases, the mean EHI was 1.66. The EHI was 0.57 in the major severe category, and 0.34 in the minor severe weather day category. Out of the 74 non-tornadic cases, there were only four cases with an EHI value greater than 1.0, and two cases with an EHI greater than 1.5.

Figures 4a and 4b depict two modified proximity soundings and hodographs on days when the EHI suggested the atmospheric environment was favorable for tornadic development, but tornadoes did not occur. Illustrating these soundings is very important, because they stress the fact that the values for the atmospheric stability and shear indices that were presented in this study, are not applicable to every situation. Figure 4a depicts a modified proximity sounding and hodograph valid at 2300 UTC 4 July 1990. On this date, most of the severe weather was concentrated in northern and western New York, and northern New England, in areas bordering Canada. Severe weather reports from Canada were not used in this study, and there is a possibility that a tornado occurred in Canada. At the time of the sounding, the EHI was 3.6. There was a small, negatively buoyant area between 850 and 700 mb, but it was not substantial enough to inhibit convection. Although the s-rH [188 $(m/s)^2$], CAPE (3265 J/Kg) and EHI (3.16) were quite high, and there were 36 severe weather events reported, tornadoes did not occur.

Figure 4b depicts the modified sounding and hodograph valid at 2300 UTC 16 September 1991. On this day, there were six severe weather events reported across central and western New York and eastern Pennsylvania, but tornadoes did not occur. A CAPE of 2858 J/kg and a s-rH of 47 $(m/s)^2$ produced an EHI of 1.80. The maximum storm-relative inflow was 30 kt. In this case, the low s-rH value and the structure of the sounding, may have indicated a reduced potential for tornadoes. The sounding revealed a substantial warm (but non-capping) layer between 700 and 500 mb. While the CAPE was large, most of the positive buoyant energy was concentrated above 500 mb. Hence, the vertical distribution of the CAPE through the storm environment, could be very important in determining storm characteristics.

This study, and previous research by LaPenta and Maglaras (1993) and Harnack and Quinlan (1988), suggest that in the northeastern United States, commonly used tornado thresholds for some stability indices that were developed for Great Plains type supercells may be too high. In addition, some of these indices showed little or no skill in differentiating between tornadic and non-tornadic cases. For example, the mean TT index for the 37 tornado cases (48), was below the previously established TT tornado threshold (50), with 62% of the cases below the threshold. Also, the TT did not show the ability to differentiate tornadic versus non-tornadic cases. The mean SI was greatest for the tornado category (285), and least for the minor severe category (235). The mean for the tornado category was well below the previously established 400 SI threshold for tornadoes, with 92% of the cases below 400.

While the EHI showed the ability to differentiate between tornadic and non-tornadic events, it appears that the threshold for strong and violent tornadoes in the northeast United States may be different than in other parts of the country. Hart and Korotky (1991) suggested a value of 1.00 as a threshold for strong and violent tornadoes. However, the results of this study suggest that an EHI of 1.00 may be more representative of a threshold for all intensity tornadoes in the Northeastern United States. Seventy-six percent of the tornado cases had an EHI value of greater than 1.00.

A specific atmospheric stability or shear index should not be used alone to assess the potential for tornadoes and severe thunderstorms. This is because these indices do not take into account all atmospheric variables and processes, since they are based on an instantaneous synoptic scale depiction of the atmosphere. Meteorologists must not only be able to accurately assess the current state of the atmosphere (which on the storm scale is very difficult), but they must be able to accurately project the evolution of the storm environment. In addition, indices such as s-rH and the EHI are dependent on an accurate forecast of storm motion. Despite limitations, s-rH and the EHI have demonstrated skill in differentiating tornadic and non-tornadic thunderstorms. The meteorologist should use these indices, in conjunction with other meteorological analyses, model soundings, numerical forecasts, and current observational data (radar, satellite, surface observations, etc.) in assessing the likelihood for severe weather and/or tornadoes.

This study focused on the comparison of tornadic and non-tornadic severe thunderstorms. In the future, the tornado and severe thunderstorm cases will be compared to data from non-severe convective storms, to assess how these various shear and stability indices can be used to identify situations in which tornadoes and severe thunderstorms did not occur.

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Table 1. Composite sounding temperature (T; °C), dewpoint (TD; °C), and equivalent potential temperature (TE; K) for tornado, major, and minor severe weather day categories.

Level (mb)	Tornado			Major			Minor		
	T	TD	TE	T	TD	TE	T	TD	TE
Surface	25.7	18.6	343	29.5	19.8	349	26.5	18.1	342
950	22.3	15.7	338	25.5	17.2	345	22.6	15.5	338
900	18.4	13.5	336	21.3	14.7	342	18.6	12.9	335
850	14.6	10.8	333	17.0	11.8	338	14.7	10.5	333
800	11.1	8.0	331	13.0	8.3	334	11.1	6.7	329
750	7.6	3.5	327	9.6	3.6	330	7.4	1.9	326
700	4.1	-1.9	324	6.0	-0.5	329	3.9	-2.1	329
650	0.5	-6.9	324	2.1	-4.8	328	0.7	-6.5	324
600	-3.2	-12.6	324	-1.5	-10.5	327	-2.6	-12.9	324
550	-7.1	-18.8	324	-5.2	-17.9	327	-6.7	-23.3	325
500	-11.6	-22.5	326	-9.6	-24.3	328	-11.0	-23.3	326
450	-16.9	-29.7	327	-14.7	-29.8	330	-16.0	-31.4	327
400	-22.8			-20.6			-22.1		
350	-29.9			-27.5			-29.3		
300	-37.8			-35.6			-37.3		
250	-47.0			-45.4			-46.4		
200	-55.9			-55.6			-54.4		
150	-59.8			-60.9			-59.8		
100	-61.3			-62.4			-60.9		

Table 2. Composite sounding wind direction (WD), wind speed (WS; kt), and mean 0-6 km wind for tornado, major severe, and minor severe weather day categories.

Height	Tornado		Major		Minor	
(m-AGL)	WD	WS	WD	WS	WD	WS
surface	194	11	238	7	195	6
500	214	17	252	13	229	11
1000	230	23	264	18	246	13
1500	238	26	270	20	254	16
2000	243	28	267	22	259	18
2500	245	30	266	24	261	19
3000	248	31	266	26	262	20
3500	249	32	267	27	262	20
4000	250	33	268	21	264	21
4500	250	34	268	22	262	22
5000	250	37	268	31	263	24
6000	247	39	269	33	266	27
7000	252	42	270	35	262	30
8000	255	46	269	37	258	31
9000	256	53	269	41	259	35
mean 0-6 km	243	27	269	22	257	17

Table 3. Calculated shear and stability indices for the 111 severe weather cases examined for the tornado, major severe, and minor severe weather day categories.

	Tornado	Major	Minor	Units
CAPE	1856	2272	1421	J/kg
BRN	45	108	99	
LI to 500 mb	-5	-6	-4	
Total Totals	48	48	47	
SWEAT Index	285	250	235	
0-6 km Mean Wind	243	269	257	
0-6 km Wind Speed	27	22	17	kt
Storm Motion-Dir.	269	257	268	
Storm Motion Speed	30	25	20	kt
0-2 km s-rH	152	30	25	$(m/s)^2$
0-3 km s-rH	164	37	25	$(m/s)^2$
EHI	1.66	0.57	0.34	
Inflow	32	24	24	kt

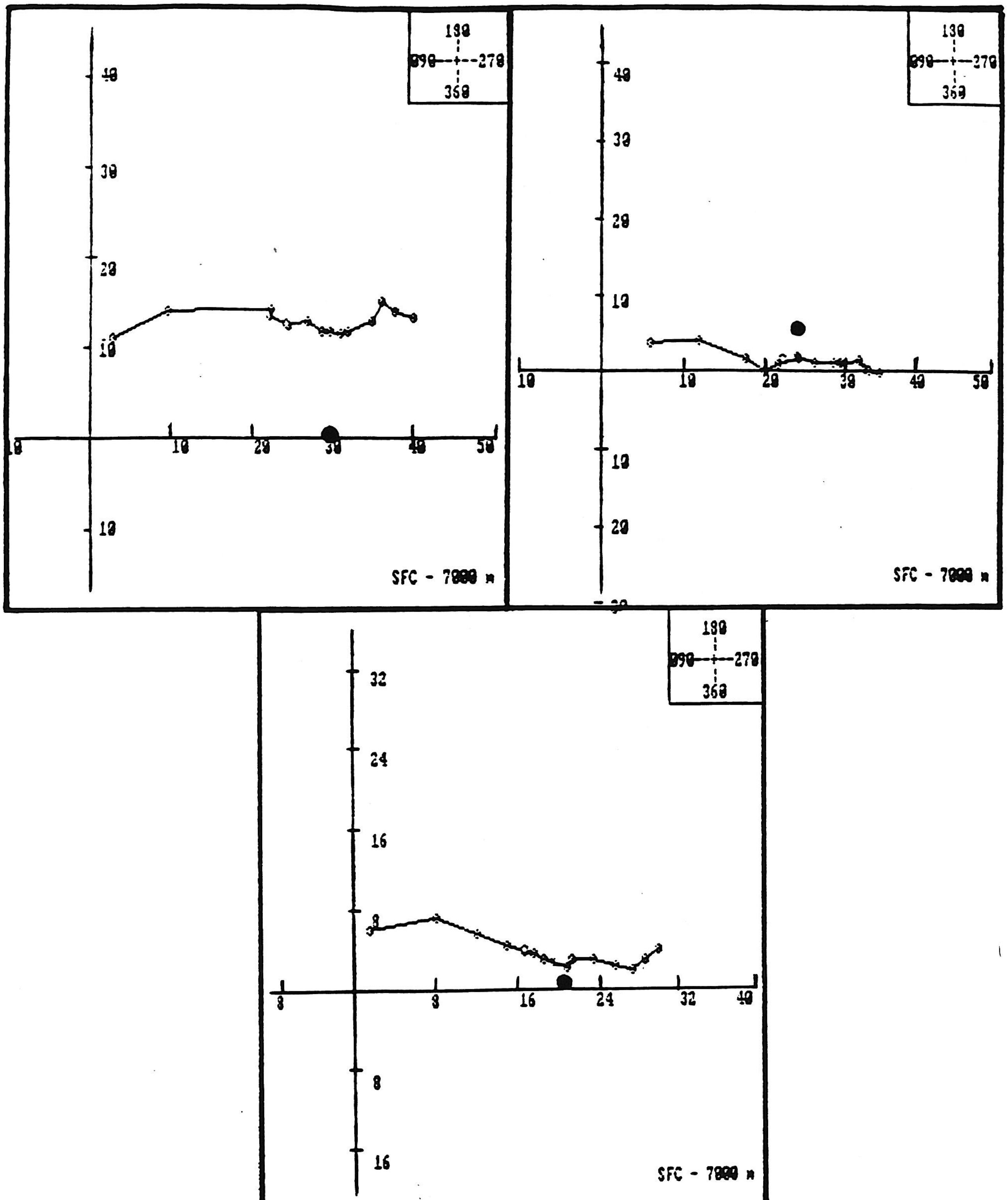

Figure 1. Composite hodographs for the 37 New York State tornado cases (upper left), the 37 major severe weather day cases (upper right), and the 37 minor severe weather day cases (lower). The storm motions for the three categories were 269° at 30 kt (tornado), 257° at 25 kt (major severe), and 268° at 20 kt (minor severe). The large solid dots indicate the end of the storm motion vectors.

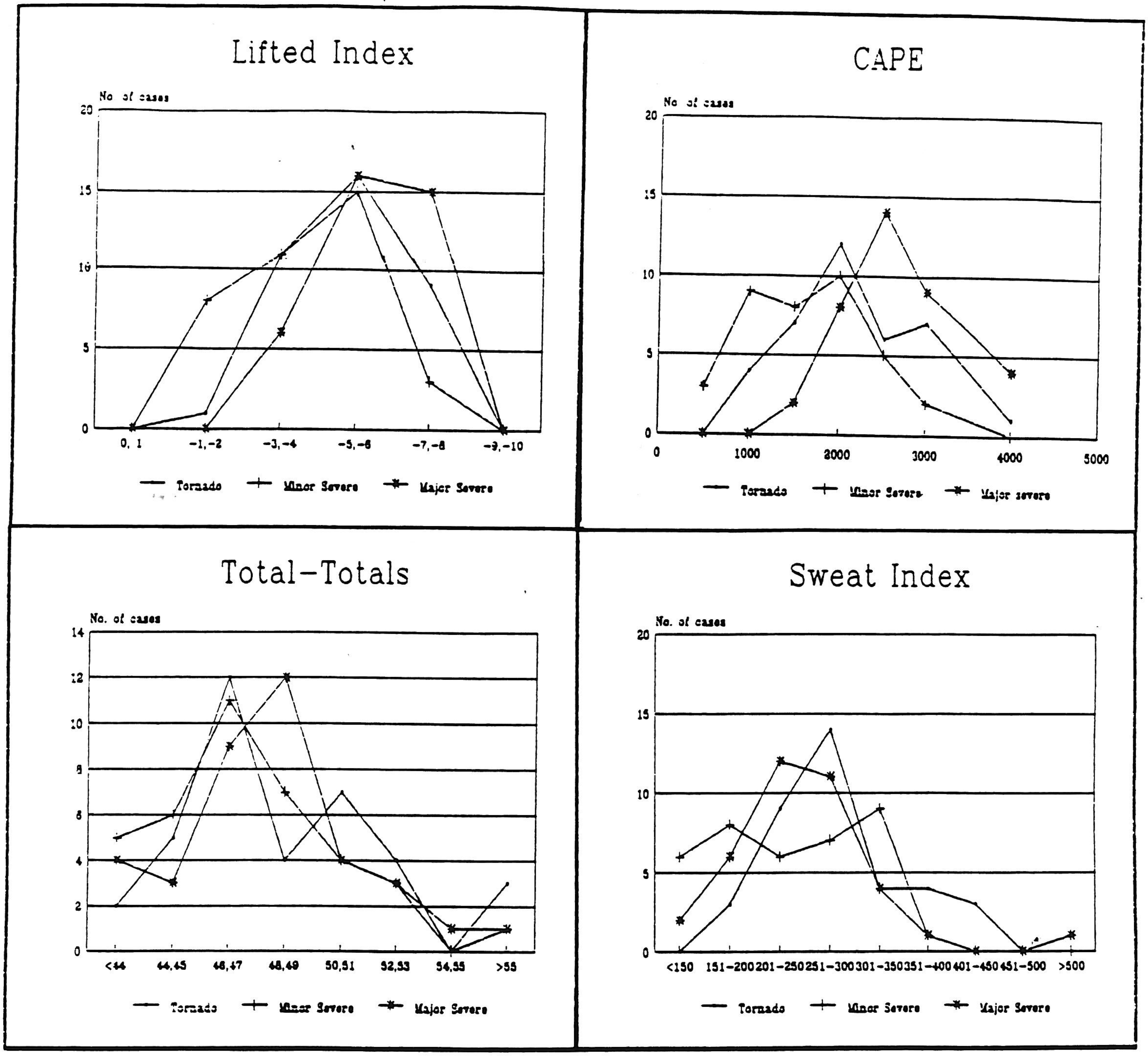

Figure 2. The distribution of Lifted Index (upper left), CAPE (upper right), Total-Totals (lower left), and the SWEAT Index (lower right), for the New York State tornado, major severe, and minor severe weather day categories.

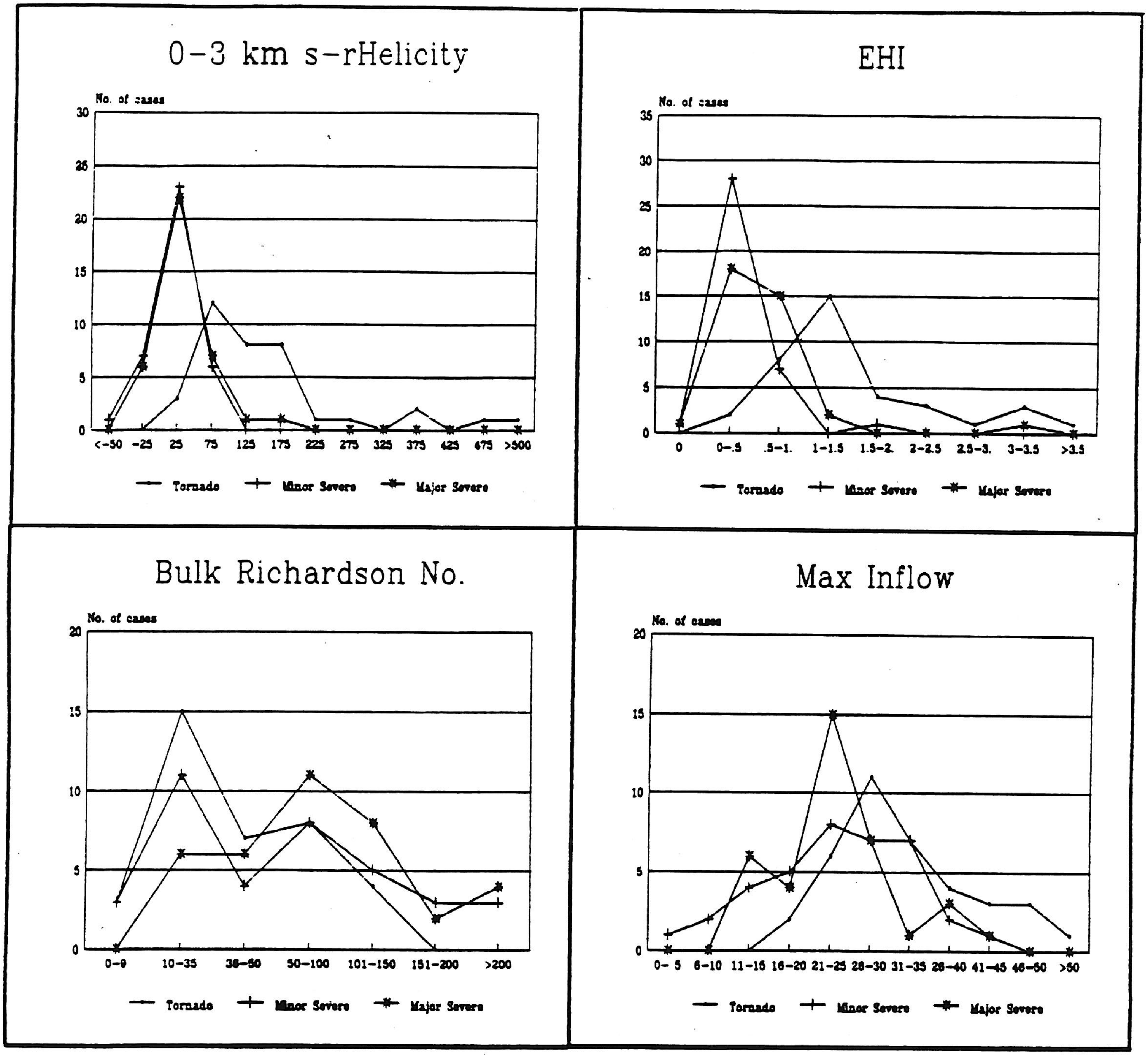

Figure 3. The distribution of Storm-relative Helicity (upper left), Energy-Helicity Index (upper right), Bulk Richardson Number (lower left), and the Maximum Storm-relative Inflow (lower right), for the New York State tornado, major severe, and minor severe weather day categories.

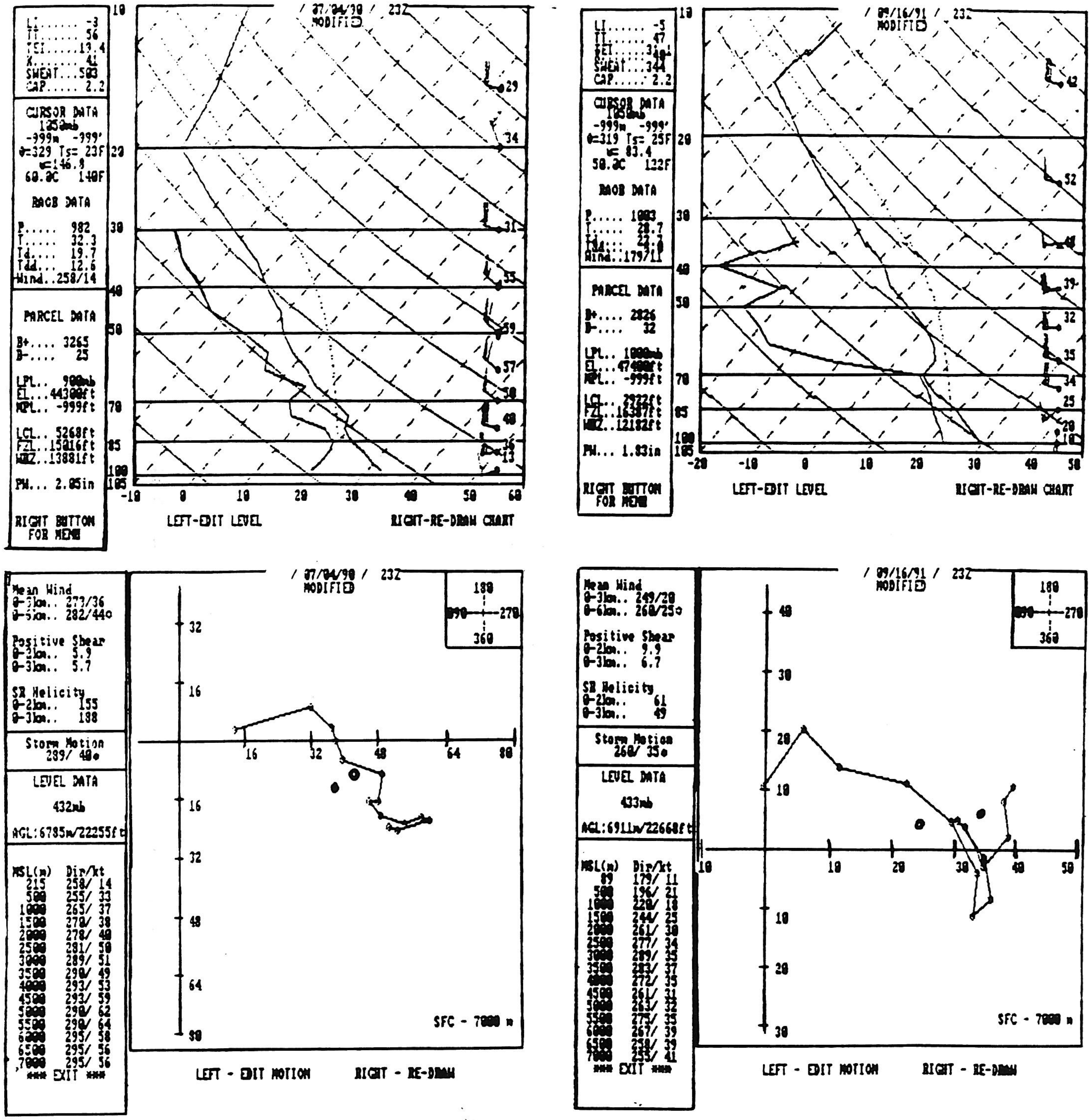

Figure 4. Modified proximity soundings and hodographs for a) northern and western New York/northern New England valid at 2300 UTC, 4 July 1990, and b) western and central New York/eastern Pennsylvania valid at 2300 UTC, 9 September 1991. Severe weather was reported on these dates, but tornadoes did not occur.