An Evaluation of Tornado Proximity Wind and Stability Data

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ABSTRACT

Over 250 tornado proximity soundings have been closely studied. Emphasis was given to a detailed examination of the wind profiles and stabilities of the soundings. The uncertainties inherent in severe storm reports, and in the positioning of proximity data relative to moving storms, were examined. It was found that the small-scale storm environment cannot be resolved with mean proximity data. On the synoptic scale a very large range of winds and stabilities was found to be associated with confirmed tornadoes. Only slight differences were found between mean tornado proximity soundings, mean soundings associated with destructive tornado outbreaks, and mean soundings associated with outbreaks of non-tornadic severe thunderstorms. Storm relative wind fields were found to be similar for all types of tornado soundings studied. The storm relative flow fields vary dramatically as thunderstorm velocity changes within a given environment.

1. Introduction

One of several techniques which has been used to study tornadoes has been the gathering of "proximity soundings." Proximity soundings are standard sets of upper air data which were taken near (in time and space) confirmed tornadoes. This method allows one to obtain a much larger sample of data than would generally be available if conditions associated with only one tornado, or with one tornado outbreak, were studied.

Fawbush and Miller (1952, 1954), Beebe (1958) and Miller (1967) studied tornado proximity soundings with emphasis on developing and improving tornado forecasting techniques by identifying antecedent conditions. Darkow (1969) and Darkow and Fowler (1971) found differences between proximity soundings and "check" soundings within the same general air mass. Wills (1969) and Novlan and Gray (1974) studied the large vertical wind shear of the tornado environment. The method of studying tornado soundings has generally been to define proximity sounding criteria and then average data which meet these criteria to find a "mean" tornado sounding. Some researchers, such as Wills (1969), have averaged data from specific areas to find mean tornado soundings for geographical regions, e.g., a Gulf Coast mean tornado sounding. Novlan and Gray (1974) studied soundings associated with hurricane produced tornadoes.

Previous studies often have not considered all of the following facts:

1) There is a wide spectrum of tornado intensity, size and duration. This spectrum includes very short-lived, small, rope funnel tornadoes at one extreme and giant, very intense, long-track tornadoes at the other extreme. This fact has been demonstrated by Fujita (1973) who has classified tornadoes according to path length and width, and intensity of damage, and also by Fujita and Pearson (1973) who have shown that a large percentage of tornado damage is caused by infrequent very large and long-lived tornadoes. Conditions which spawn large, destructive tornadoes should probably not be considered in the same category as conditions associated with a "mini-tornado."

2) The times and locations of tornadoes may not be accurately reported, especially in rural or sparsely populated areas.

3) When data are positioned relative to the tornado consideration should be given to the fact that many tornadoes are associated with *rapidly moving* thunderstorms.

The objective of this study was not merely to arrive at another set of mean tornado conditions, but rather to consider the above facts as objectively as possible, and to examine the range of environmental conditions associated with tornadoes. Although most significant tornadoes occur during strong thunderstorm situations as documented by Miller (1967) and Wills (1969), many verified tornadoes occur under conditions which would be regarded as unfavorable for severe storm development.

Soundings were also gathered for Tornado Outbreak days and Severe Thunderstorm days. A Tornado Outbreak day was defined as a day on which an unusually large (20 or more) number of tornadoes occurred within a contiguous region of radius 370 km (200 n mi). A Severe Thunderstorm day was one on which 20 or more

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severe thunderstorms and *no tornadoes* occurred within a contiguous region of radius 370 km. These types of soundings are compared to the tornado proximity soundings.

Four scales of motion which are important on tornado days are referred to in this study as

1. Synoptic scale: >200 km (meso α)
2. Squall-line scale: 20 to 200 km (meso β)
3. Tornado-storm scale: 2 to 20 km (meso γ)
4. Tornado scale: 200 m to 2 km (micro α).

The tornado-storm is defined as the tornado and the thunderstorm it is associated with, and the tornado scale includes the tornado and its immediate circulation. These scale lengths correspond to Orlanski's (1975) definitions of meso α through micro α scales.

2. The data sample and its climatology

In this study a tornado proximity sounding was defined as one taken within 92.5 km of a verified tornado which occurred between 1600 and 1900 (all times CST). Only afternoon soundings (1800) were considered. Afternoon rawinsonde release is at approximately 1715. A sounding was not accepted unless it was taken in the air mass ahead of the tornado storm. The criteria of this study were not as restrictive as those of Darkow (1969), since soundings were not eliminated if showers or rain had occurred in advance of the tornado-storm. However, soundings taken to the rear of fronts, dry lines, and squall lines were eliminated. A sounding was accepted if it was complete through 200 mb.

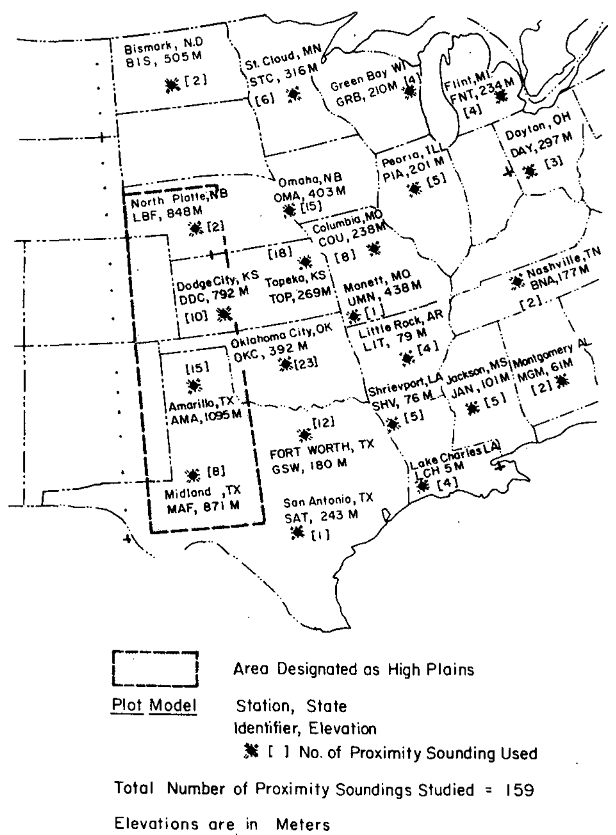

FIG. 1. Rawinsonde locations used in study. The number of proximity soundings obtained at each location and the elevation of each site are shown.

The log of servere storm occurrences kept by the National Severe Storms Forecast Center (the *SELS Log*) was the primary source used to determine which particular soundings might meet the proximity criteria. The *SELS Log* was examined for the period 1958–72. Two hundred and sixty-seven proximity soundings were examined. Sounding data were compiled from the *Northern Hemispheric Data Tabulations*. Soundings which did not meet all of the proximity criteria were discarded. For the remaining soundings the following types of data were compiled:

1) The number of reported tornadoes in the general region (this was considered to be the contiguous area within 370 km of the sounding station) of each proximity sounding was recorded from the *SELS Log*. The time period considered was from 1200 to 2400 CST.

2) The number of reported severe thunderstorm events in the general region of each proximity sounding was recorded from the *SELS Log*. A severe thunderstorm event was defined as any of the following: (i) a thunderstorm wind gust of $\geqslant 50$ kt, (ii) an unmeasured thunderstorm wind gust which produced property damage, (iii) hailstones $\geqslant 1.9$ cm in diameter, (iv) a funnel cloud, and (v) a tornado.

3) Pertinent statements concerning the size, number, intensity, severity, and property damage of the severe storms and tornadoes in the general region of each proximity sounding were recorded from *Climatological Data National Summary* for 1958 and from *Storm Data* for 1959 through 1972.

4) Temperature, dewpoint temperature, and wind speed and direction were recorded for reported levels from the surface to 200 mb.

5) The mean sounding wind was computed. In this study the mean sounding wind was computed as the mean vector of the observed winds at the surface, and at 850, 700, 500, 300, and 200 mb.

6) The Totals Index was computed for each sounding. The Totals Index is defined as the 850 mb temperature plus the 850 mb dewpoint temperature minus twice the 500 mb temperature, all in °C. Totals of 45 and 55 are roughly equivalent to Showalter indices of 0 and -5, respectively. Generally, the greater the numerical value of the Totals Index the greater the likelihood of severe convection. [For a more complete discussion of the Totals Index, refer to Miller (1967).]

7) The approximate location of the tornado storm at rawindsonde release time was computed. This was done using an estimated storm motion. After considering the studies of severe storm deviate motion by Marwitz (1972), Fankhauser (1971) and Haglund (1969), it was

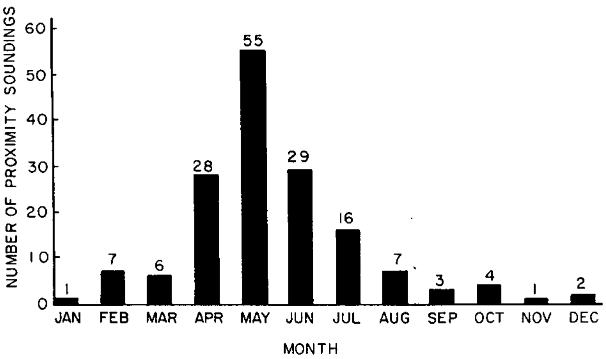

FIG. 2. Number of tornado proximity soundings obtained per month.

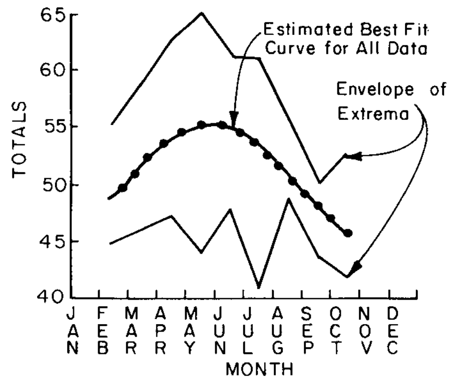

FIG. 4. Monthly variation of Totals Index for proximity soundings.

decided to estimate mean storm motion at 75% of the mean sounding speed and at 30° to the right of the mean sounding wind direction. The data were positioned relative to the *estimated* location of the tornado-storm at rawinsonde release time. A detailed discussion of the errors inherent in positioning proximity data is presented by Maddox (1973).

If no tornadoes were mentioned in the *Climatological Data* or *Storm Data*, or if the tornadoes were reported as "doubtful" or "unconfirmed," then the sounding involved was eliminated from the data sample. Of the original 267 soundings 159 were retained and studied as proximity soundings.

Figure 1 shows the area of the study, the location and elevation of the rawinsonde stations, and the number of tornado proximity soundings obtained at each location. Four western stations were designated as "High Plains" stations and were considered separately from the others because of their elevation. Figure 2 is the monthly distribution of the proximity soundings studied. Most of the soundings (71%) were taken during the "Tornado Season" months of April, May and June. May soundings comprised 35% of the total data sample. Figure 3 shows where the proximity soundings were positioned relative to the rawinsonde station. Only 19 tornado-storms were within 37 km of the rawinsonde station at release time.

Scatter diagrams of the Totals Index vs month and mean wind speed vs month were plotted. Figures 4 and 5 show the estimated best fit curve for all data points on these plots and also the envelope of extreme values for each month. Values of the Totals Index are greatest during April, May and June—the months of maximum proximity sounding frequency. Mean wind speeds are greatest during late winter and spring when intense synoptic-scale storms are common. Not only is May the

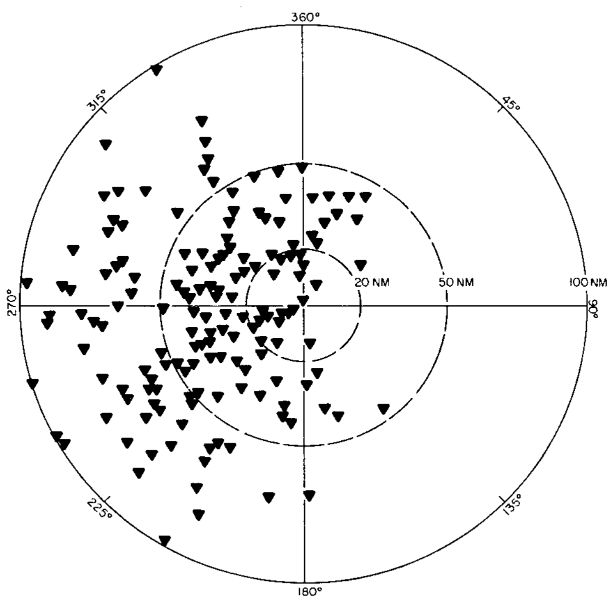

Fig. 3. Estimated locations of tornado-storms at 1715 CST. The rawinsonde station is at the center point. Tornado-storm position was determined using an estimated mean storm velocity.

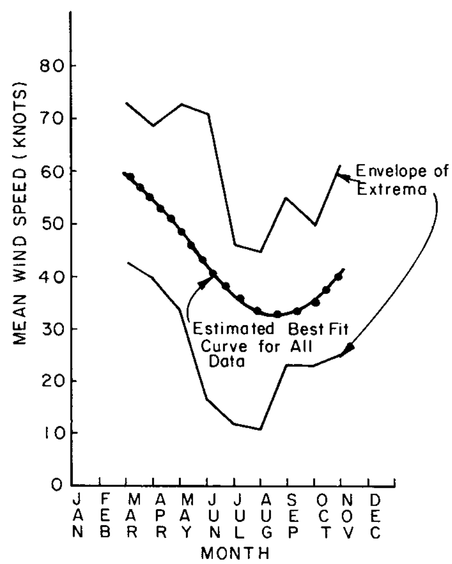

FIG. 5. Monthly variation of mean wind speed (surface to 200 mb) for proximity soundings.

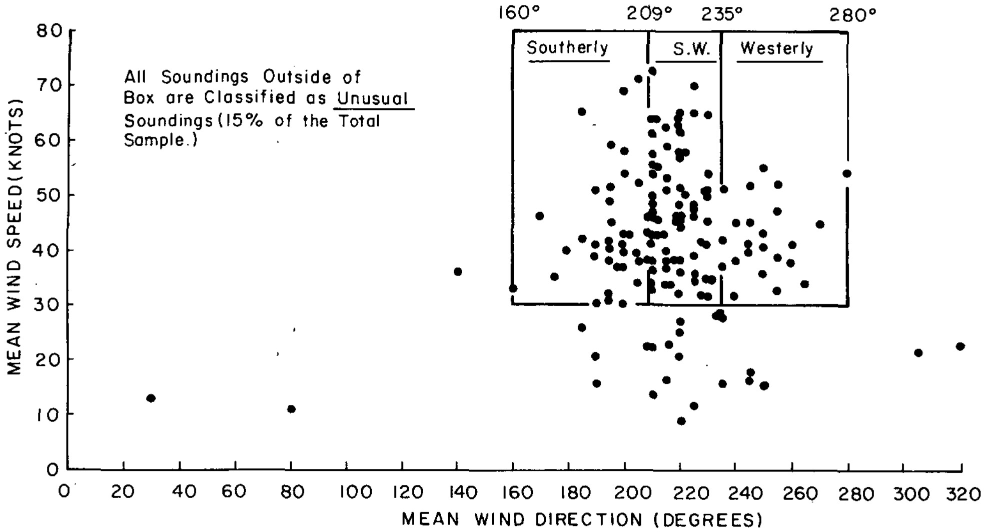

FIG. 6. Scatter diagram of mean wind speed and mean direction for proximity soundings. This diagram was used to classify the soundings as Southerly, Southwesterly (SW), Westerly or Unusual.

month of maximum number of proximity soundings but it also has the largest range of both Totals Index and mean winds. The Totals Index values vary from the low forties to the middle sixties, and the mean wind speeds from less than 15 kt to greater than 70 kt.

Figure 6 is a scatter diagram of mean wind speed vs mean wind direction (surface to 200 mb) for all the proximity soundings. This diagram was used to stratify the sounding sample into four categories. Soundings with mean speeds $\geqslant 30$ kt and mean directions of 160°–209°, 210°–235°, and 236°–280° were classified respectively as Southerly, Southwesterly (hereafter referred to as SW) and Westerly soundings. All other soundings (15% of the data sample) were classified as Unusual soundings. Of the 19 soundings taken within 37 km of a tornado storm 32% were Unusual. Intense convection in the rawinsonde release area was most likely modifying the environmental wind fields of many of the close-in soundings.

3. Tornado and severe thunderstorm outbreaks

One of the objectives of this study was to compare tornado proximity soundings to soundings associated with intense tornado outbreaks and also to soundings associated only with severe thunderstorms. A tornado outbreak sounding was initially defined as a proximity sounding for which there were 20 or more tornadoes reported in the *SELS Log* within 370 km of the sounding site (during the period 1200 to 2400). The following modifications of the definition were added as the data were searched:

1) If the *SELS Log* listed 20 or more tornadoes but *Storm Data* reported less than 20 tornadoes and/or remarked that the tornadoes were generally small or primarily remained aloft, or that little damage occurred, then that particular sounding was rejected.

2) If the *SELS Log* listed less than 20 tornadoes but a check of *Storm Data* showed that intense, very destructive, long-track tornadoes had occurred, then that particular sounding was accepted.

A total of 23 Tornado Outbreak soundings were identified and examined.

A comparison of tornado conditions with severe thunderstorm conditions has not been attempted before. This is a difficult task since soundings taken near severe thunderstorms are also quite likely taken within 370 km of verified tornadoes. Soundings taken in an environment which produced only isolated severe storms were not considered representative of a severe thunderstorm situation. In an attempt to distinguish between tornado conditions and severe thunderstorm conditions the following definition was made:

> A Severe Thunderstorm day was one on which 20 or more severe thunderstorm events, but no *tornadoes*, occurred within a contiguous region of 370 km radius.

As the *SELS Log* was scanned for Severe Thunderstorm days, five were found and accepted with only 16–19 severe events and no tornadoes, and six were accepted with a large number (>25) of severe events and 1 or 2 small, or unconfirmed, tornadoes reported more than 92.5 km from the sounding site. Once such a day was indentified it was used in the data sample if an 1800 sounding had been taken in the air mass which produced the storms. A total of 25 Severe Thunderstorm day soundings were obtained and studied. It is significant that during the 15 years considered there were so few days on which numerous severe thunderstorms (16 or more) occurred without also producing tornadoes. On most days in the central United States, when *significant* severe thunderstorm activity is likely, it is very probable that tornadoes will also occur.

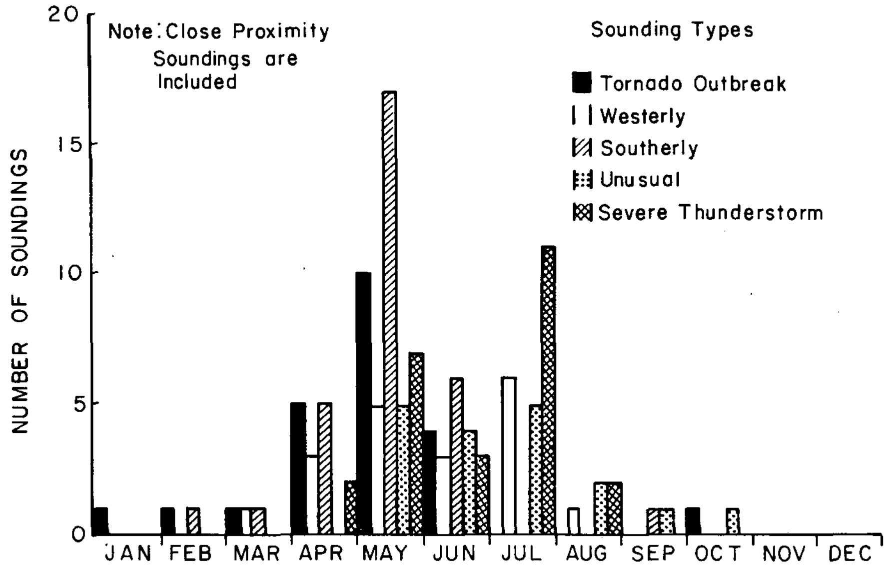

FIG. 7. Number of sounding types per month.

Figure 7 shows the monthly distribution of Westerly, Southerly and Unusual tornado proximity soundings plus the distribution of the Tornado Outbreak and Severe Thunderstorm day soundings. The monthly distribution of SW soundings was similar to that of all tornado proximity soundings shown in Fig. 2 Tornado Outbreak and Southerly soundings are most common during the spring and Unusual, Westerly, and Severe Thunderstorm types are more common during the summer. This is primarily because winds are lighter during the summer and because the flow aloft over the Central United States in summer is often from the northwest favoring the Westerly type of sounding.

4. Proximity sounding hodographs

In this section the wind profiles and the storm relative winds of the various types of proximity soundings are examined. The storm relative wind is defined as the observed wind when a coordinate system moving with the storm is used. The storm relative wind can be computed by vectorially subtracting the storm motion from the environmental wind. *The two important, and surprising, features seen in the wind profiles are the wide range of conditions associated with tornadoes, and the variability of the severity of storm outbreaks in essentially similar air masses.*

Figures 8–11 are the mean hodographs for SW, Southerly, Westerly, and Tornado Outbreak types of soundings. Each figure includes:

- The number of cases in the data sample
- The mean winds and their mean deviations (surface to 200 mb)
- Average Totals Index and its mean deviation
- Average number of reported severe thunderstorms and tornadoes in the general region of the sounding.
- The assumed severe thunderstorm motion for each mean wind profile
- The computed storm relative winds (surface to 200 mb).

The wind profile of the SW proximity soundings (Fig. 8) is similar to those obtained by Darkow and

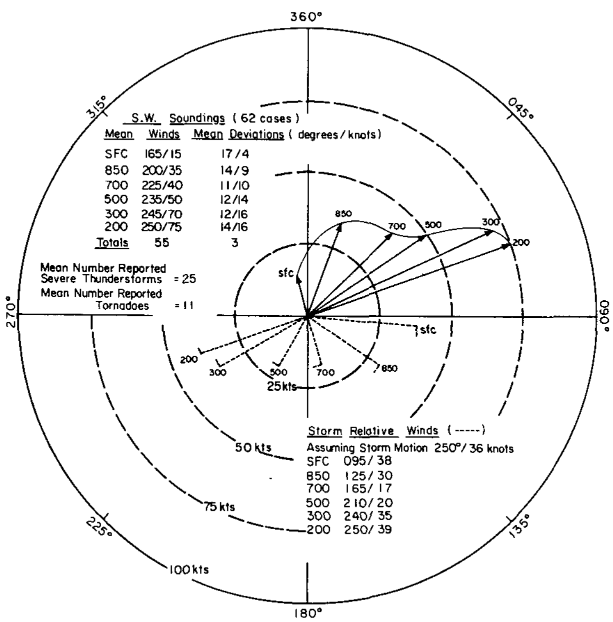

FIG. 8. SW type tornado sounding mean hodograph. SW type has mean direction 210° to 235° and a mean speed ⩾30 kt. Also included are the computed storm relative winds, mean numbers of reported severe events, Totals Index, and mean deviation.

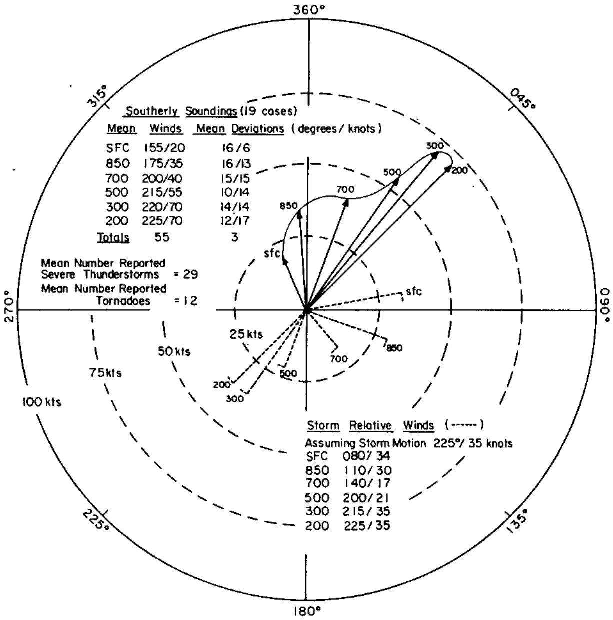

FIG. 9. As in Fig. 8 except for Southerly type tornado sounding mean hodograph with mean direction 160° to 209° and a mean speed ⩾30 kt.

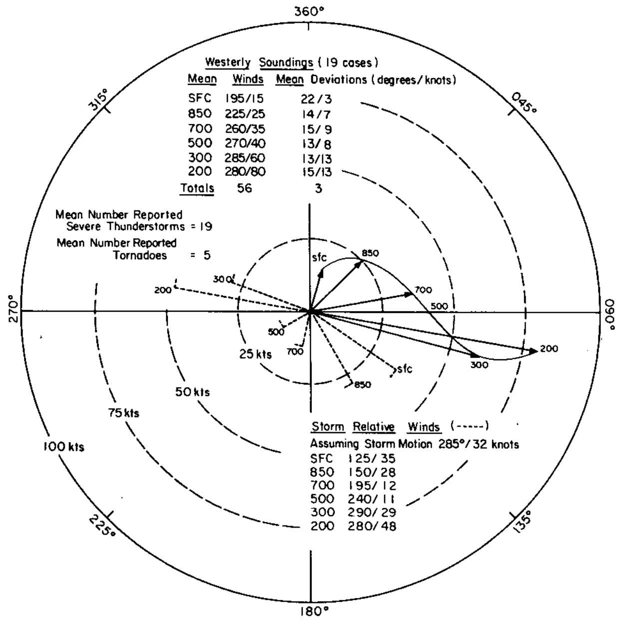

FIG. 10. As in Fig. 8 except for Westerly type tornado sounding mean hodograph with mean direction 236° and 280° to a mean speed ⩾30 kt.

Fowler (1971) except that the winds in this study are 10–15 kt stronger at all levels. The reason for this is that the stratification of the soundings into different categories precludes the averaging of unusual weak wind soundings with stronger, more common, wind fields. All of the wind profiles in Figs. 8–11 are basically similar and exhibit only slight differences in speed and veering with height. Although the mean surface winds vary from 155° at 20 kt to 195° at 15 kt, the vertical profiles, *relative to the surface wind*, are very similar. The Tornado Outbreak winds are 5 kt stronger in the surface to 500 mb layer than the SW proximity winds. The storm relative winds are very similar for all the categories of proximity soundings. The mean Totals Index ranges only from 55 to 57 with a mean deviation of 3 for all sounding categories.

The Westerly type of sounding is not associated with as many tornado occurrences as are the SW and Southerly types. The Southerly type of sounding tends to be associated with a stronger severe storm outbreak than does the SW type. The mean deviations of the wind directions are approximately 15° for all sounding types at all levels. A 30° interval centered on the mean wind direction would include only 58% of the data sample (assuming a normal distribution). This is a significant variation since the soundings were stratified into basically similar wind categories before any averaging was done. The High Plains hodographs are not shown since they were not significantly different from the SW and Southerly hodographs.

Figure 12 is the hodograph of an averaged set of similar Severe Thunderstorm day wind profiles. The figure includes the same information as do the tornado proximity figures. Figure 13 shows two individual Severe Thunderstorm day hodographs. Shown for each of these are wind profile, location and month of occurrence, number of reported severe thunderstorms and tornadoes, and the Totals Index.

Figure 12 is the average of the most common type of Severe Thunderstorm sounding (note that the sample includes only 10 soundings). This hodograph is similar

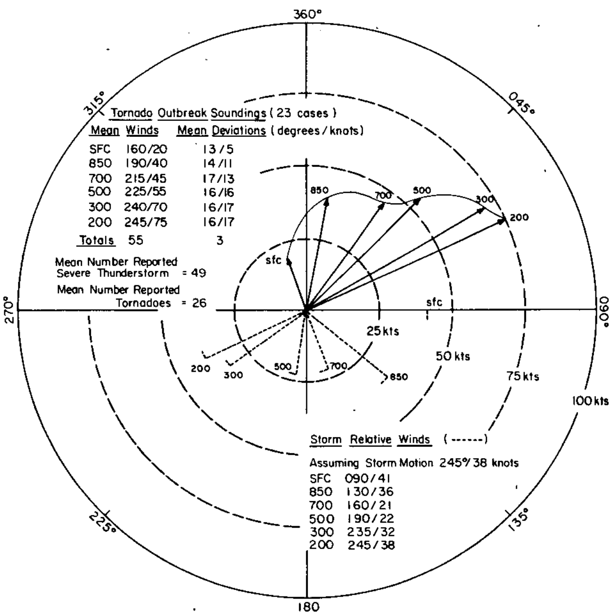

FIG. 11. As in Fig. 8 except for Tornado Outbreak sounding mean hodograph.

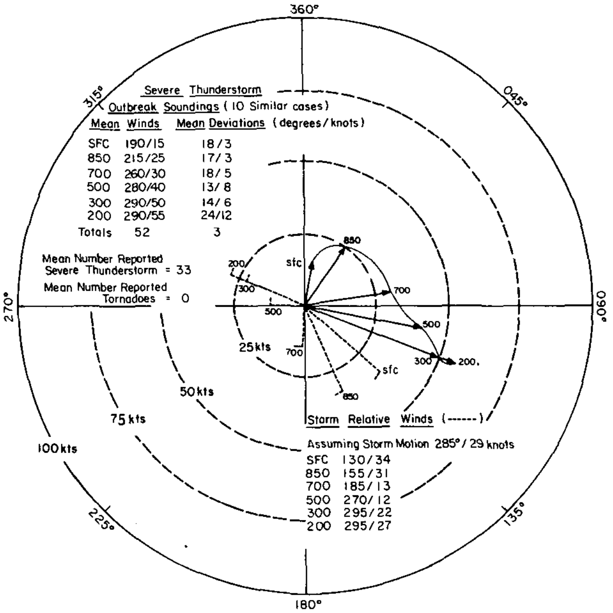

FIG. 12. As in Fig. 8 except for Severe Thunderstorm day sounding mean hodograph.

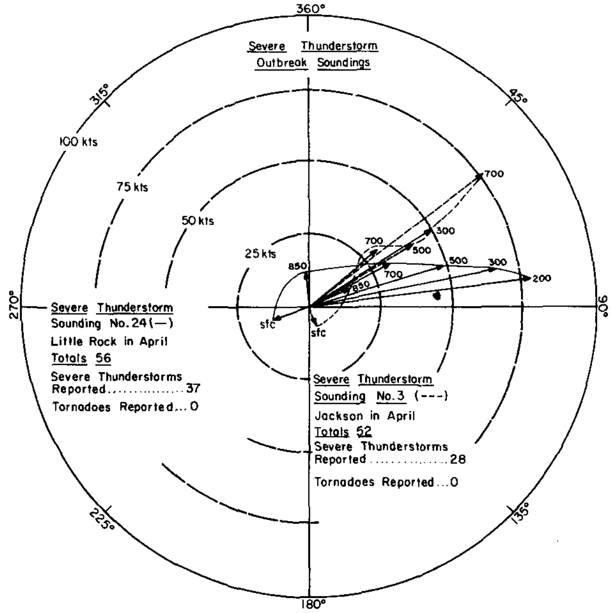

FIG. 13. Two individual Severe Thunderstorm day hodographs: Little Rock (LIT) on 27 April 1968 and Jackson (JAN) on 12 April 1962. Included is the number of reported severe events on each day.

to that of the Westerly type of tornado hodograph except that the 300 and 200 mb winds are, respectively, 10 and 25 kt stronger for the tornado case, and the tornado case is more unstable with a mean Totals Index of 56 compared to 52 for Severe Thunderstorm days. The mean deviations are large for both types so that there is considerable overlap between the individual soundings of the two samples. There is not such a distinctive difference between the two types of soundings that, given an individual sounding, one could confidently predict that tornadoes would or would not be expected. Figure 13 shows individual Severe Thunderstorm day hodographs for two cases. These soundings were taken north of a frontal boundary. In this situation the warm, moist flow feeding the storm rides over a low-level wedge of cool air. These conditions can produce large hail and occasionally strong surface winds, but tornadoes are rare. Vortices which develop exist above hostile thermal and wind fields and can seldom penetrate downward to the surface. Funnels aloft are frequent. This type of overrunning situation was described by Miller (1967).

5. Variability of soundings

One of the outstanding features of individual tornado proximity soundings is the large variability in their winds, Totals Index, and the number of reported tornadoes. Tornado occurrences cannot be studied in detail using only proximity soundings. Proximity soundings with similar characteristics are often associated with tornado occurrences of greatly differing intensity and number. The intensity of severe storm development not only depends on air mass properties but is also a function of the synoptic situation and of many smaller scale features and conditions.

The graphs in Figs. 14 and 15 illustrate the variability of number of reported tornadoes, and the wide range of 500 mb wind velocities found in the proximity soundings. The number of reported tornadoes generally decreases as the mean wind speed decreases. The dashed line in Fig. 14 depicts this trend. The range of number of reported tornadoes becomes very large as mean wind speed increases. The probability of more than five

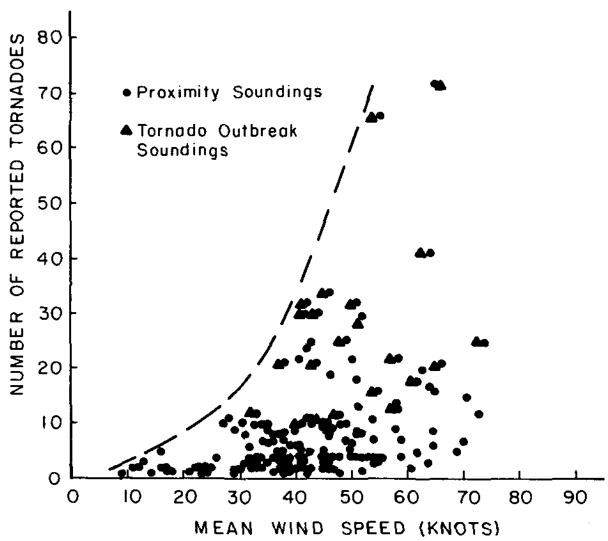

FIG. 14. Scatter diagram of number of reported tornadoes and proximity sounding mean wind speed (surface to 200 mb).

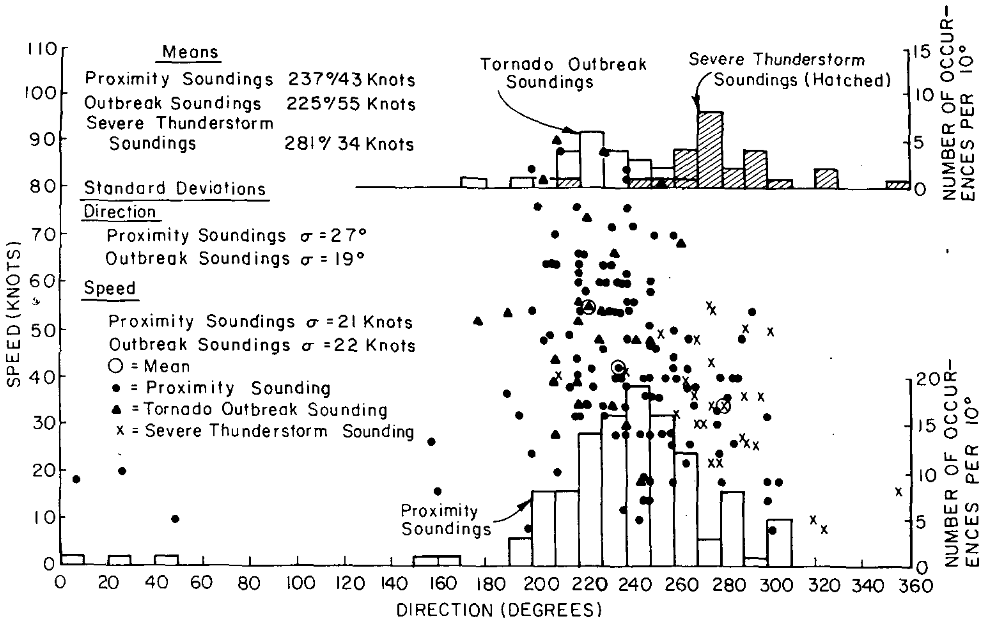

FIG. 15. Scatter diagram of 500 mb wind speed (left ordinate) and 500 mb wind direction for tornado proximity soundings, Tornado Outbreak soundings, and Severe Thunderstorm soundings. The bar graphs show the number of occurrences (right ordinate) per each 10° of 500 mb direction for the three types of soundings. Also shown are standard deviations for tornado proximity soundings and Tornado Outbreak soundings.

tornadoes occurring with a mean 500 mb wind speed of less than 30 kt is small.

Figure 15 is a combined scatter diagram and bar graph. The scatter diagram is of 500 mb speed (left ordinate) vs 50 mb direction for all of the proximity soundings, Tornado Outbreak soundings, and Severe Thunderstorm soundings. The means and standard deviations are shown for the proximity and Tornado Outbreak soundings. The large standard deviations emphasize the variability of tornado-associated conditions. The two bar graphs show the number of proximity, Tornado Outbreak, and Severe Thunderstorm soundings (right ordinate) which occurred in each 10° of 500 mb wind direction. There is considerable overlap of the three types of soundings between 210° and 300°; however, the maxima are distinct. The number of tornado Outbreak soundings peaks around 225°, while the number of proximity and Severe Thunderstorm soundings peaks around 240° and 280°, respectively. Tornado outbreaks are generally characterized by southerly flow and Severe Thunderstorm days by westerly flow at 500 mb.

Fifteen percent of the original proximity soundings were classified as Unusual soundings. Generally these soundings exhibit very light winds, have a relatively small (stable) Totals Index, and tend to occur during the summer months. They were associated with a small number of severe thunderstorm events and only 1–3 small, isolated tornadoes. In three of these Unusual cases the *only* reported severe event in the region was one tornado. Individual hodographs of two Unusual cases are shown in Fig. 16. Included on the figure are the location and month of the sounding, and the number of reported tornadoes and severe thunderstorms. There can be little doubt that tornadoes occurred on these days, yet the wind profiles have little in common with the proximity soundings examined in the previous sec-

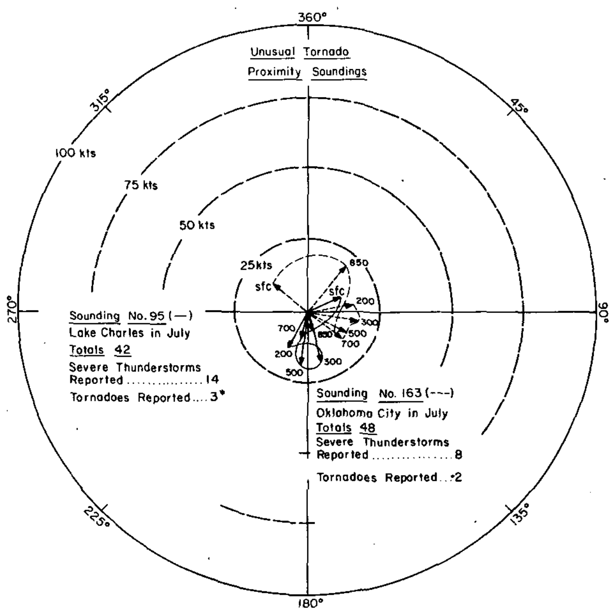

FIG. 16. Two Unusual tornado sounding hodographs: Lake Charles (LCH) on 15 July 1969 and Oklahoma City on 23 July 1959. Also included are numbers of reported severe events and the Totals Index.

TABLE 1. Computed relative flow angles (deg) for the mean sounding types. The flow angle θ is the angle between the storm's mean velocity vector and the computed storm relative wind.

Sounding type	Surface	850	700	500	300	200
	Pressure heights (mb)					
SW (62 cases)	+155	+125	+85	+40	+8	0
Tornado Outbreak (23 cases)	+155	+115	+85	+55	+10	0
Westerly (19 cases)	+155	+130	+85	+40	+10	0
Southerly (19 cases)	+145	+115	+85	+25	+10	0
Severe Thunderstorm (10 cases)	+155	+130	+100	+15	−10	−10

tion. The Totals Index for these Unusual soundings is barely great enough to indicate that thunderstorms would be likely. Each Unusual tornado proximity sounding has greatly differing wind profiles. The only common feature of these soundings is that each was associated with *convective activity*.

6. Storm relative winds

Storm relative winds were defined and explained in Section 3. The environmental wind at some level is different from the flow at that level relative to a moving storm. The storm relative winds were shown for different sounding types in Figs. 8–12. The vertical configurations of these relative winds were very similar for the different types of tornado proximity wind profiles. They demonstrate strong relative flow at low levels, light flow in the middle levels, and strong relative flow again in the upper levels.

To determine the similarities of relative winds, thunderstorm motion should also be considered. To do this, a relative flow angle (θ) was defined as the angle between the storm's velocity vector and the relative wind. A relative flow angle of −45° indicates that, relative to the storm, flow approaches the left rear of the storm, and an angle of +90° indicates that flow approaches the right flank of the storm. Table 1 shows the computed relative flow angles for different sounding types. The relative flow is very similar for all sounding types. The similarities of the Westerly tornado and the Severe Thunderstorm soundings are partially a result of assuming that individual storms move similarly in both cases. This is probably not a valid assumption. The relative flow angles of Table 1 show that the surface and 850 mb flow approaches the right front of the storm. Relative flow at 700 and 500 mb approaches the right or right rear flank of the storm. Upper relative winds approach the rear of the storm. It should be remembered that these relative wind fields were derived using the mean winds for the various sounding types and that the actual winds near the peripheries of individual storms may differ significantly from the environmental winds.

An interesting question is: How does the storm relative wind field vary if differing storm motions are assumed? To answer this, differing storm motions were assumed, and the resulting storm relative winds were computed, using the mean wind field of the SW type tornado soundings. These are shown in Table 2 for storm motions of 30° left at 75% of the mean wind, with the mean wind, 15° right at 85% of the mean wind, 30° right at 75% of the mean wind, 45° right at 60% of the mean wind, and 60° right at 50% of the mean wind. Table 3 shows the computed relative flow angles for these different storm motions. As storm motion changes from left-moving to extreme right-moving the following changes occur (refer to Tables 2 and 3):

1) At the surface little change occurs with strong inflow toward the right front of the storm in all cases.
2) At 850 mb flow approaching the storm varies all the way from the left flank to the right flank and remains strong for all but the left mover.
3) At 700 and 500 mb flow approaching the storm varies from the left to the right flank and becomes weak for storms moving with or near to the mean wind.
4) At 300 and 200 mb flow approaching the storm varies all the way from left flank to right flank.
5) As the storms deviate motion becomes greater (with respect to the mean environmental wind), the magnitude of the storm relative winds substantially increase (by as much as a factor of 5 at 700 mb).

TABLE 2. Storm relative winds (degrees/knots) computed using the mean SW type tornado sounding for varying storm motions.

Assumed storm motion	Surface	850	700	500	300	200
	Pressure heights (mb)					
190/36	027/23	282/24	288/24	282/36	277/58	278/66
220/48	067/37	094/20	003/17	297/15	280/35	280/43
235/40	078/37	117/25	139/6	243/10	261/31	267/39
250/36	095/38	125/30	165/17	210/20	242/35	250/39
265/30	110/36	148/38	178/25	215/29	232/42	241/49
280/25	125/35	159/43	187/33	208/37	230/52	237/55

TABLE 3. Relative flow angles (deg) for the storm relative winds computed using the mean SW type tornado sounding for varying storm motions.

Assumed storm motion	Surface	Pressure heights (mb) 850	700	500	300	200
190/36	+163	−92	−98	−92	−87	−88
220/48	+153	+126	−37	−77	−60	−60
235/40	+157	+118	+96	−8	−26	−32
250/36	+155	+125	+85	+40	+8	0
265/30	+155	+117	+87	+50	+33	+24
280/25	+155	+121	+93	+72	+50	+43

These are most significant results. If there is a preferred profile of relative winds associated with tornadoes, the probability of tornado occurrence is a function of both the environmental wind field and of thunderstorm velocity. As a storm begins to deviate to the right of the mean flow *the rapid changing of the relative flow field may feedback to help intensify the storm and also to increase its deviate motion.*

7. Summary and conclusions

This study of tornado proximity soundings differed from previous studies in several ways. The data were positioned relative to a moving storm; the proximity soundings were stratified into distinct categories before any averaging was done; and tornado proximity soundings were compared to Tornado Outbreak and Severe Thunderstorm soundings.

The most outstanding characteristic of the tornado proximity data was the wide range of the parameters considered. The storm relative wind configuration was similar for all types of mean tornado wind profiles. An important finding was that the storm relative wind configuration changes dramatically as the storm's velocity varies within a given environment. Little difference was found between Tornado Outbreak and more general tornado soundings. There is a wide range of synoptic conditions associated with a large range of number, size and intensity of tornadoes. The range of tornado-associated synoptic-scale parameters is so great that the only *necessary condition,* on this scale, for there to be a probability of tornado occurrence is that convection must occur. This probability is naturally very, very small under all but strong severe thunderstorm situations. The Unusual tornado proximity soundings demonstrated that small tornadoes sometimes occur during weak thunderstorm situations. These results indicate that the interaction of synoptic, squall line, and tornado-storm features—in addition to air mass properties—is very important in determining tornado likelihood.

The small size of the Tornado Outbreak and Severe Thunderstorm data samples indicates that:

Sets of conditions which produce many large, destructive tornadoes occur infrequently.

Sets of conditions which produce many severe thunderstorms, without attendant tornadoes, also occur infrequently.

The soundings associated with only severe thunderstorms, even though their upper winds tend to be more westerly, are not distinctly different from certain tornado proximity soundings. This, along with the small number of pure severe thunderstorm days, indicates that there is little synoptic-scale data available which can be used to delineate a pure severe thunderstorm situation from one that may produce an isolated tornado.

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