A Study of Tornado Proximity Data and an Observationally Derived Model of Tornado Genesis

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Principal investigator: William M. Gray
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ABSTRACT

A STUDY OF TORNADO PROXIMITY DATA AND AN OBSERVATIONALLY DERIVED MODEL OF TORNADO GENESIS

The results of a detailed analysis of 159 tornado proximity rawinsonde soundings are considered in Part I of this study. Soundings were stratified into four different categories, based on mean wind characteristics. The tornado soundings were compared to soundings associated with destructive multiple tornado outbreaks, and to soundings associated with non-tornado producing severe thunderstorms.

It is found that there is no distinct set of "tornado conditions". Tornadoes are associated with a surprisingly large range of synoptic conditions. Sub-synoptic scale phenomena play an important role in tornado production. There are no distinctive differences between general tornado, multiple tornado outbreak, and severe thunderstorm soundings. Situations which may produce severe thunderstorms also have some discrete probability of producing tornadoes. A suggested new manner of issuing severe thunderstorm and tornado watches is presented.

An extensive discussion of tornado features and a hypothesized physical model of tornado genesis is presented in Part II of this paper.

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INTRODUCTION

Although many researchers have studied the tornado, this intense vortex remains one of the least understood of meteorological phenomena. Part I of this paper presents a detailed observational study of tornado proximity soundings. A physical model of tornado genesis is developed in Part II of this study.

Fawbush and Miller (1952 and 1954), Beebe (1958), and Miller (1967) have studied proximity soundings with emphasis on developing and improving tornado forecasting techniques by identifying antecedent conditions. Darkow (1969) and Darkow and Fowler (1971) found subtle differences between proximity soundings and "check" soundings within the same general air mass. Wills (1969) and Novlan (1973) emphasized the vertical wind shear of the tornado environment and tried to relate the sounding data to meso-scale storm/environment interactions. The method of studying tornado proximity soundings has been to define proximity sounding criteria and then average the data meeting these criteria to find a "mean" tornado sounding. Fawbush and Miller (1954) and Miller (1967) have categorized different types of mean tornado soundings based on synoptic situation and geographic location. In this study tornado proximity soundings from the Central United States have been carefully studied and stratified into four different categories. The objective was not merely to arrive at a set of mean tornado conditions but rather 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), some tornadoes occur under conditions which would have to be regarded, according to any of the studies cited, as unfavorable.

Proximity soundings were also gathered for Tornado Outbreak Days and Severe Thunderstorm Outbreak Days. A Tornado Outbreak Day was defined as a day on which an unusually large number (roughly twenty or more) of destructive tornadoes occurred over a contiguous region of radius approximately 200 nautical miles (n.mi.). A Severe Thunderstorm Outbreak Day was defined as a day on which twenty or more severe thunderstorms and no tornadoes occurred over a contiguous region of radius approximately 200 n.mi. These types of soundings are closely compared to the tornado proximity soundings.

Four scales of motion which may play important roles in the tornado formation process are defined as:

1. Synoptic scale - > 150 km.
2. Squall-line scale - 40 to 150 km.
3. Tornado-storm scale - 5 to 40 km.
4. Tornado scale - 0 to 5 km.

The tornado scale is defined to include the tornado and its associated circulation. The four scales of motion, as defined above, will be frequently referred to in this paper.

Previous tornado theories and models are reviewed in Part B, especially those of Fulks (1962), Bates (1970), Ward (1972), and Barnes (1973a). The observational studies of Hoecker (1960 and 1961), Fujita (1960, 1970, 1972), Barnes (1972 and 1973a), and Golden (1973) are examined in addition to those of many other researchers. A new physical model of the early stages of tornado genesis is advanced.

PART I

TORNADO PROXIMITY DATA

1. THE DATA SAMPLE AND ITS GENERAL CLIMATOLOGY

Proximity Sounding Definition. In this study a tornado proximity sounding was defined as a sounding taken within 50 n.mi. of a verified tornado which occurred between 1600 and 1900 Central Standard Time (CST). Only afternoon (1800 CST) soundings were considered. Afternoon radiosonde release is at approximately 1715 CST. A further restriction was that the sounding must have been taken in the air mass ahead of the storm so that the environment which spawned the tornado was that being examined.

Previous studies have not specifically considered the fact that thunderstorms which produce tornadoes are often *moving* at speeds of 30 to 60 knots. A thunderstorm which produced a tornado within 50 n.mi. of a sounding at 1900 CST may have been located *over 100 n.mi. away from the radiosonde site at release time!* To minimize this effect a mean severe storm motion was assumed. The detailed studies of severe storm motion by Marwitz (1972, Part I), Fankhauser (1971), Fujita, *et al.* (1970), Achtemeir (1969), and Harrold, *et al.* (1966) were considered. It was decided to assume a movement of the tornado producing thunderstorm (hereafter referred to as the tornado-storm) of 30 degrees to the right at 75% of the mean wind from the surface to 200 mb. Making the additional assumption that the tornado-storm was in existence at 1715 CST it was possible to position the tornado-storm relative to the radiosonde station at release time.

Data Sources and Processing. The log of severe storm occurrences kept by the National Weather Service's Severe Local Storms Forecast Unit (hereafter referred to as the SELS Log) was the primary data source used to determine which particular soundings might meet the proximity criteria. The SELS Log was examined for proximity soundings during the period 1958 through 1972. The criteria of this study were not as restrictive as those of Darkow (1969) in that, since the primary concern was with wind fields, a sounding was not thrown out if showers had occurred ahead of the tornado-storm. A sounding was accepted if it was complete through 200 mb.

A total of 267 potential proximity soundings were examined. The sounding data was compiled from the Northern Hemispheric Data Tabulations. Post frontal, dry-line, and squall-line soundings were eliminated. For each remaining sounding three things were done:

1. The number of reported tornadoes in the general region (this was considered to be the contiguous area within 200 n.mi. of the sounding station) of each proximity sounding was recorded from the SELS Log. The time period considered was from 1200 to 0000 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:

   (a) a thunderstorm wind gust of $\geq$ 50 knots
   (b) an unmeasured thunderstorm wind gust which produced property damage
   (c) hailstones $\geq$ .75 inch in diameter
   (d) a funnel cloud not touching ground
   (e) 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.

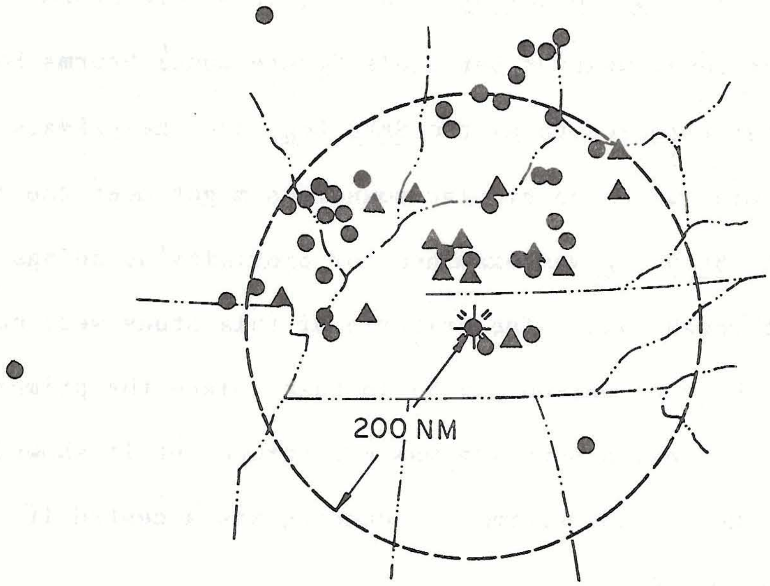

Figure 1

Method Used to Determine Reported Number of Severe Events in the Sounding Region. This Example Shows 14 Tornadoes (Triangles) and 32 Severe Thunderstorms (Circles) for a Total of 46 Reported Severe Events in the Sounding Region.

Figure 1 shows how reported tornadoes and severe thunderstorms were counted in the general region surrounding a possible proximity sounding. If no tornadoes were mentioned in the <u>Climatological Data</u> or <u>Storm Data</u>, or if the tornadoes were listed as "doubtful" or "unconfirmed", then the particular sounding involved was eliminated from the sample. Of the original 267 soundings 159 were retained and studied as tornado proximity soundings.

<u>Data Sample Climatology</u>. Figure 2 shows the area of the study, the location and elevation (in meters) of the radiosonde stations, and the number of proximity soundings obtained at each location. More proximity soundings were obtained at stations located in the region of frequent tornado occurrences from north Texas to south Minnesota. The four stations, North Platte, Dodge City, Amarillo, and Midland were

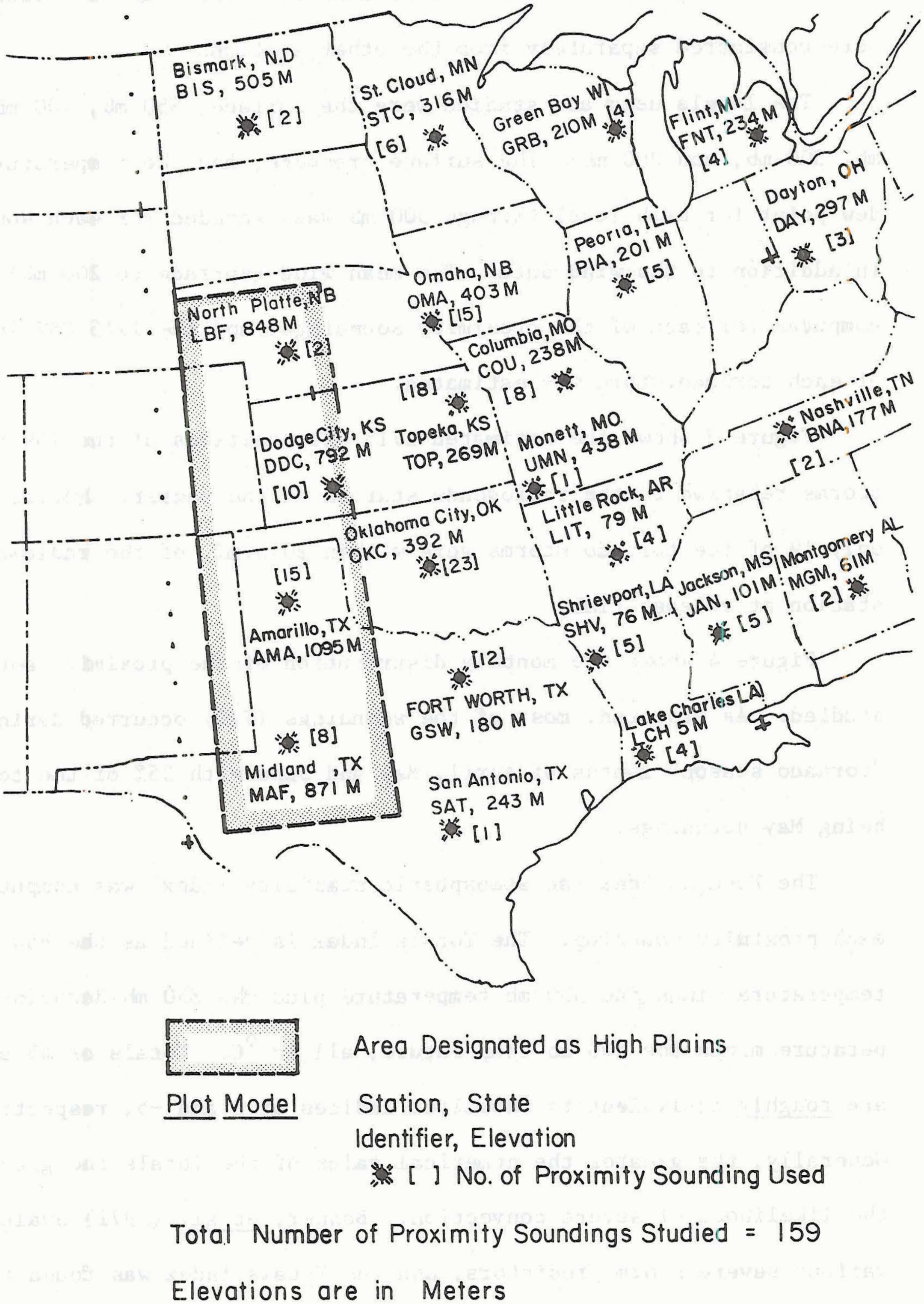

Figure 2

Locations and Numbers of Proximity Soundings.

designated "High Plains" stations because of their high elevations and were considered separately from the other stations.

The levels used and studied were the surface, 850 mb, 700 mb, 500 mb, 300 mb, and 200 mb. The surface pressure, and the temperature, and dew point for each level through 500 mb was recorded for each sounding in addition to the wind data. The mean wind (surface to 200 mb) was computed for each of the proximity soundings, and the 1715 CST location of each tornado storm was estimated.

Figure 3 shows the estimated 1715 CST positions of the 159 tornado storms relative to the radiosonde station at the center. Notice that only 19 of the tornado storms were within 20 n.mi. of the radiosonde station at release time.

Figure 4 shows the monthly distribution of the proximity soundings studied. As expected, most of the soundings (71%) occurred during the "tornado season" months of April, May and June with 35% of the total being May soundings.

The Totals Index (an atmospheric stability index) was computed for each proximity sounding. The Totals Index is defined as the 850 mb temperature minus the 500 mb temperature plus the 850 mb dewpoint temperature minus the 500 mb temperature, all in ^{o}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 the greater the likelihood of severe convection. Bonner, et al. (1971) evaluated various severe storm predictors, and the Totals Index was found to be the one which correlated best with the predictand (the predictand was defined to be radar line echoes of heavy or very heavy thunderstorms).

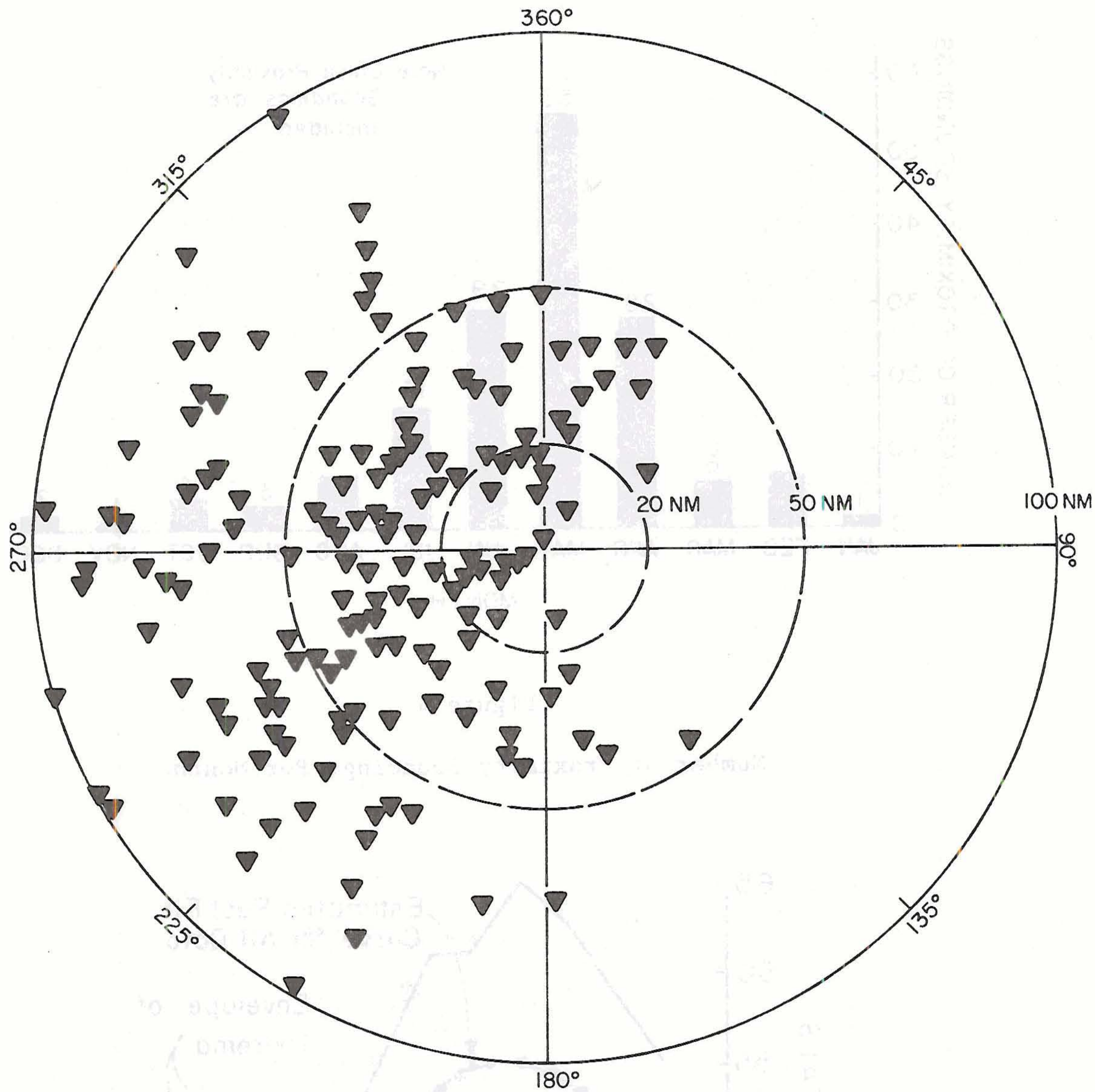

Figure 3

Estimated Positions of the Tornado-Storms at 1715 CST (Radiosonde Station is Center Point).

For a more complete discussion of the Totals Index the reader should refer to Miller (1967).

Scatter diagrams of Totals vs. month and mean wind speed (surface to 200 mb) vs. month were plotted. Figures 5 and 6 show the estimated best fit curves for all data points on these two scatter diagrams plus

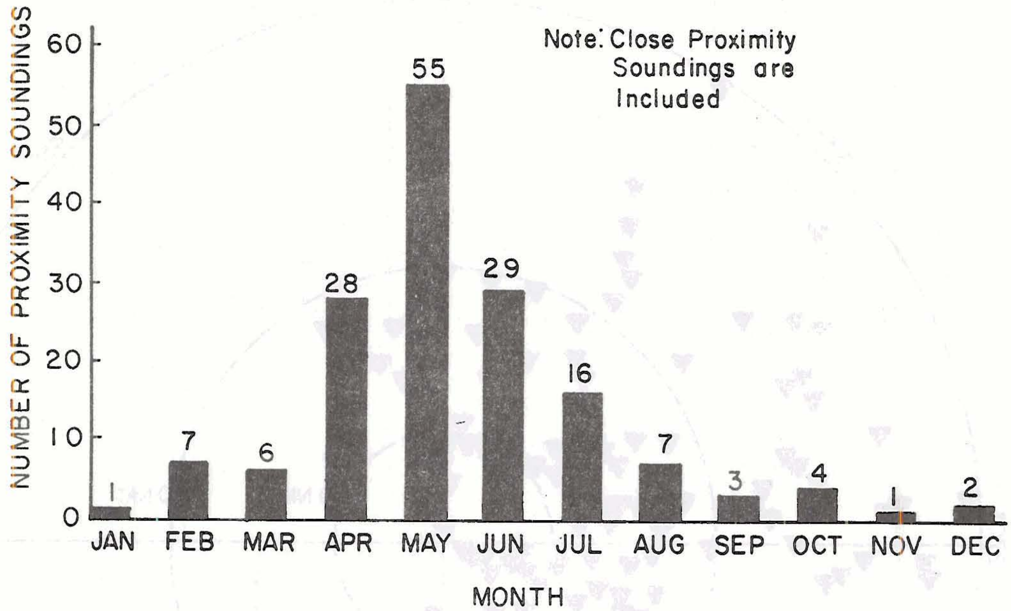

Figure 4

Number of Proximity Soundings Per Month.

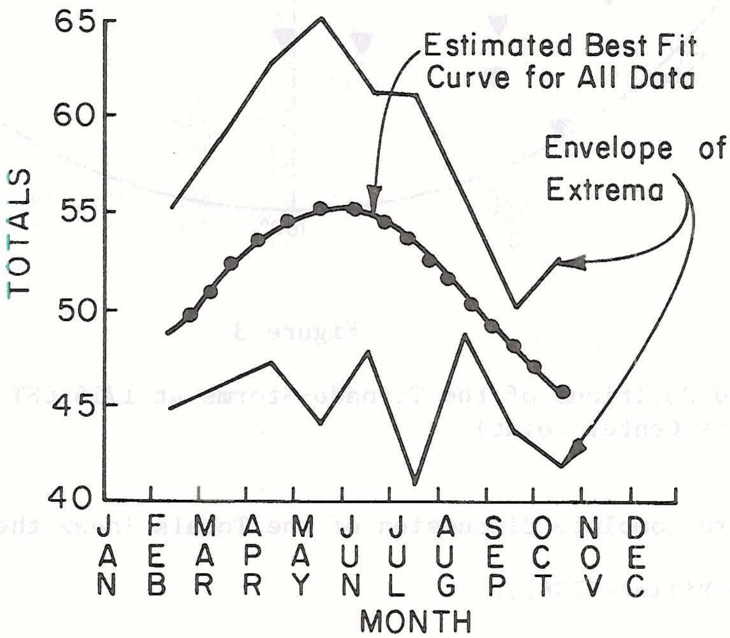

Figure 5

Proximity Sounding's Totals Index Versus Month.

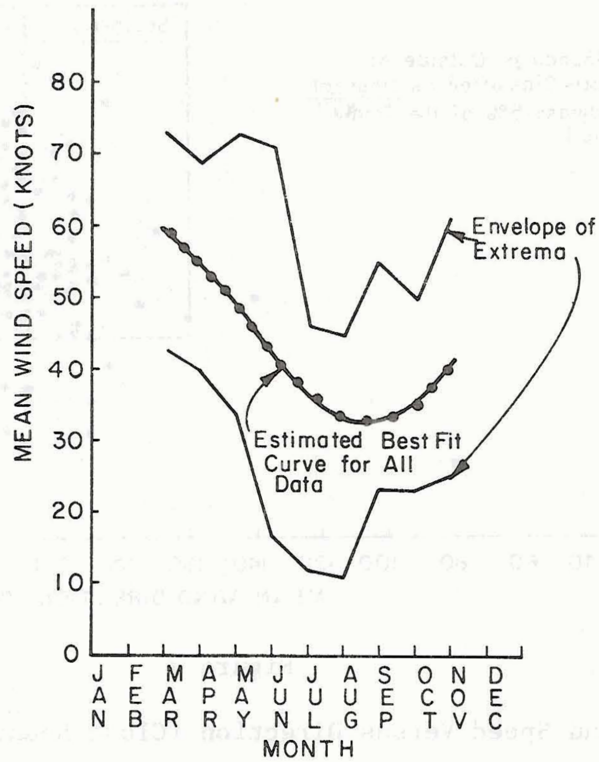

Figure 6

Proximity Sounding Mean Wind Speed (Surface to 200 mb) Versus Month

the envelope of extreme values for each month. The Totals are greatest during April, May, and June, the months of maximum tornado sounding frequency. Mean wind speeds are greatest during the late winter and spring, the time of year when strong synoptic scale storms are common. Not only is May the month of most proximity soundings, but also it is the month of greatest range of both Totals and mean wind speed.

Figure 7 is a scatter diagram of mean wind speed vs. mean wind direction (surface to 200 mb) for all of the proximity soundings. This diagram was used to stratify the soundings into four different categories. Soundings with mean wind speeds of 30 knots or greater and mean directions of 160^{o} to 209^{o}, 210^{o} to 235^{o}, and 236^{o} to 280^{o} were

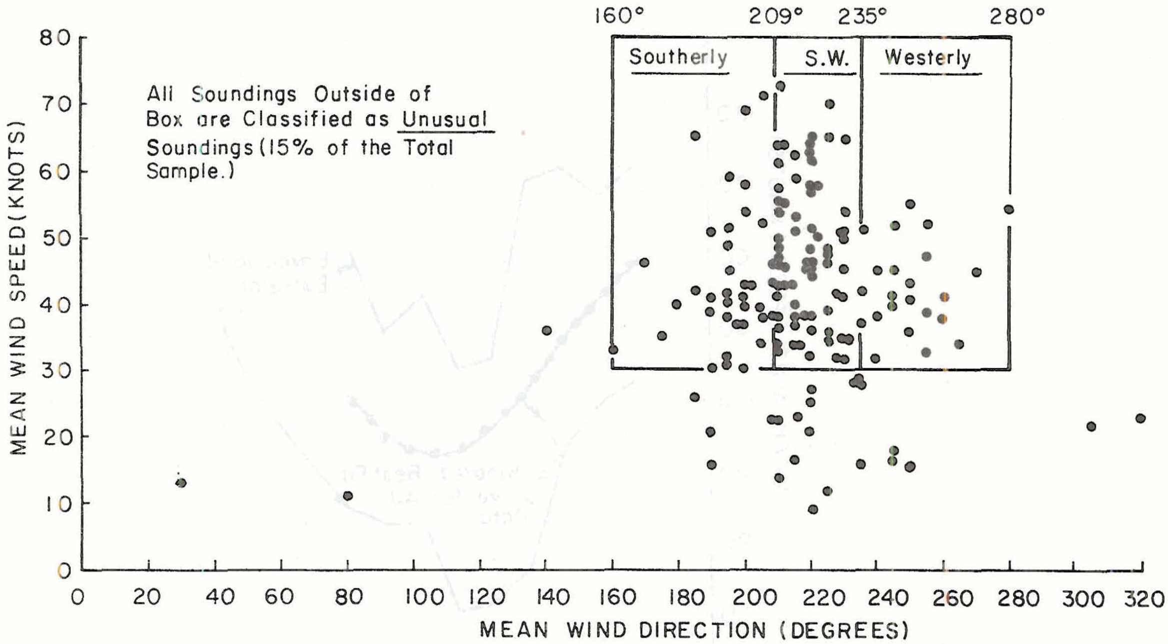

Figure 7

Mean Wind Speed Versus Direction (Close Soundings Included).

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 35 High Plains soundings 13 were SW, 13 were Southerly, 7 were Unusual, and only 2 were Westerly. On the High Plains the Southerly type sounding is much more common than the Westerly type. Of the 19 soundings which were within 20 n.mi. of a tornado storm, 9 were SW, 1 was Westerly, 3 were Southerly, and 6 were Unusual. Of these close soundings 32% were Unusual which indicates that the convection in the area of the radiosonde release was probably modifying the environmental wind fields of most or all of the close soundings. For this reason these 19 close soundings are not considered in the remainder of this study except when they are specifically mentioned.

Data Positioning. It is important to realize that there are many problems which must be considered in positioning the sounding data relative to the tornado-storm. Appendix I contains a complete discussion of these problems. The important conclusion is that the resolution of the data positioning is $\geq$ 50 km. Tornado-storm and tornado scale features cannot be accurately defined using proximity data.

Tornado and Severe Thunderstorm Outbreak Days. One of the objectives of this study was to compare average tornado soundings to soundings associated with intense tornado outbreaks and 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 200 n.mi. of the sounding site (severe events were counted during the period 1200 to 0000 CST). This definition was essentially followed, but the following modifications were added:

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. Only one of these was a High Plains sounding.

A comparison of tornado conditions to severe thunderstorm conditions has not been attempted before. This is a difficult task since:

1. Soundings taken near severe thunderstorms were also quite likely taken within 200 n.mi. of verified tornadoes.
2. Soundings taken in an environment that produced only an isolated severe event can not be considered representative of a severe thunderstorm environment.

In an attempt to distinguish between tornado conditions and severe thunderstorm conditions the following definition was made. A Severe Thunderstorm Outbreak Day is a day on which 20 or more severe thunderstorm events, but no tornadoes, occurred within a contiguous region of 200 n.mi. radius. The following modifications were made as the SELS Log was scanned for days of this type: five days were found and accepted with only 16 to 19 severe events and no reported tornadoes, and six days were accepted with a large number (> 25) of severe events but only 1 or 2 weak, or unconfirmed, tornadoes reported more than 50 n.mi. from the sounding location. Once such a day was identified it was used in the data sample if an 1800 CST sounding was available ahead of the storms in the air mass which supported them. One additional restriction was that the severe thunderstorm outbreak soundings had to be in the same geographical area from which the tornado proximity soundings were taken (see Figure 2). A total of 25 Severe Thunderstorm Outbreak soundings were obtained and studied. It is very significant that in the 15 years considered there were so few days on which numerous severe thunderstorms (16 or more) occurred without also producing tornadoes. It seems that on any day that significant severe thunderstorm activity is likely it is very probable that tornadoes will also occur.

Figure 8 shows the monthly distribution of Westerly, Southerly and Unusual soundings plus the distribution of the previously mentioned Tornado Outbreak and Severe Thunderstorm Outbreak Soundings.

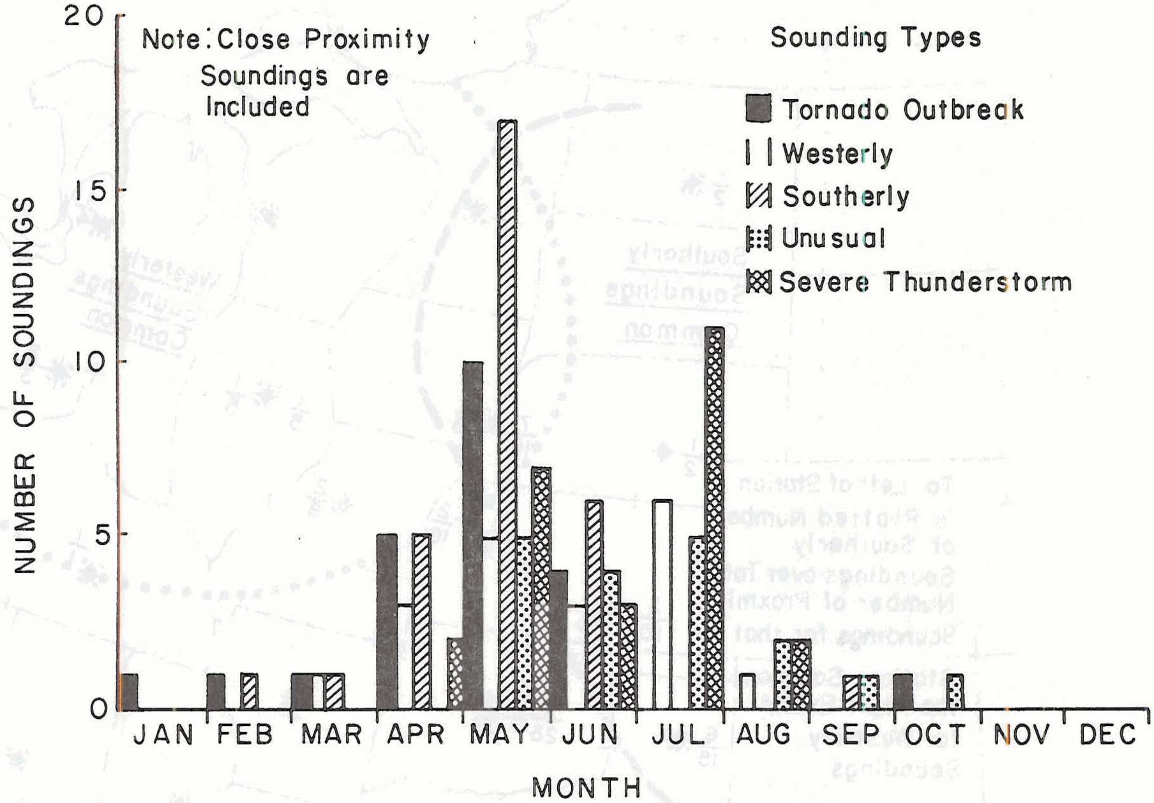

Figure 8

Number of Sounding Types Per Month .

This figure is most meaningful when it is compared with Figure 4. Tornado Outbreak and Southerly soundings are most common during the spring while Unusual, Westerly, and Severe Thunderstorm Outbreak soundings are more common during the summer. This is primarily because winds are lighter during the summer and because the flow aloft over the Central U. S. in summer is often from the northwest which favors the Westerly type sounding.

<u>Geographical Preferences</u>. Figure 9 shows the geographic locations of the Westerly and Southerly soundings. Southerly soundings occurred in the western plains, and Westerly soundings tended to occur in the

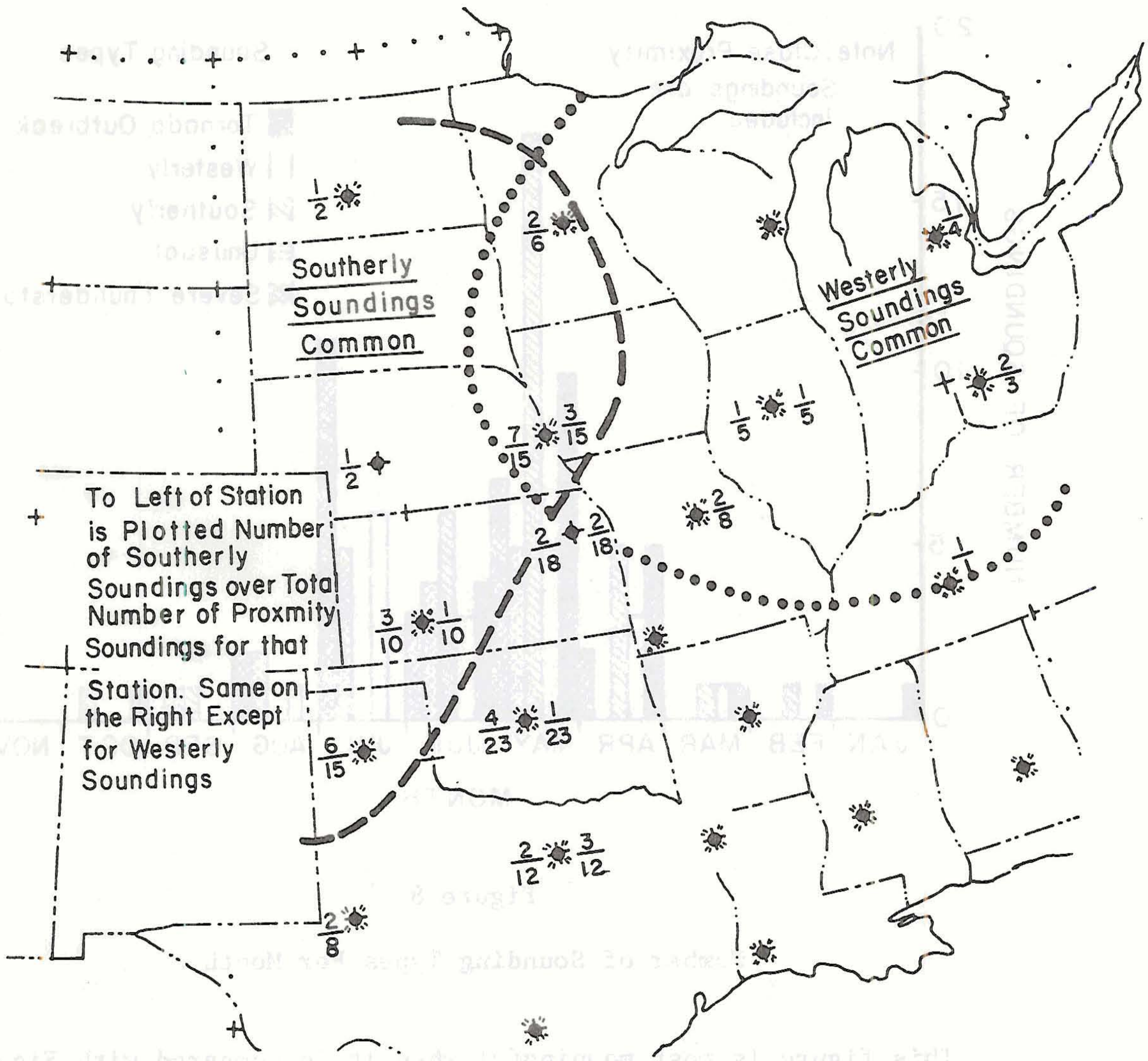

Figure 9

Geographic Locations of Southerly and Westerly Type Soundings .

north central U. S. The postulated reasons for these geographical preferences are:

1. In the spring of the year mid-tropospheric closed lows frequently drop into the Great Basin and then move eastward over the plains. On the first day of the "coming out" process winds are very southerly at all levels. Tornadoes often occur on this first day. This is reflected by the relatively high number of Southerly proximity soundings in the western plains. On the second day of

the "coming out" process the upper low has often become an open trough and/or a dry front has swept far ahead of the upper system so that severe storms occur with a SW type wind profile.

2. In the summer the storm track (and thus stronger winds and strong fronts) has shifted to near the northern border of the U. S. A mid-tropospheric ridge is often present over the Rocky Mountains which produces upper air flow from the west or northwest over the central and north central U. S. Strong outbreaks of thunderstorms, and therefore tornadoes, are most likely where the synoptic scale forcing is strongest. So, in the summer, tornadoes often occur in the north central U. S. where westerly to northwesterly flow prevails, and thus Westerly type proximity soundings are most common in this region.

Many strong severe thunderstorm situations in the spring produce tornadoes under Southerly type conditions on the western plains and then, a day or so later, produce tornadoes under SW conditions in the Mississippi Valley.

2. PROXIMITY WIND PROFILES

Tornado and Tornado Outbreak Hodographs. In this section the wind profiles and the storm relative winds of the various types of tornado proximity soundings are examined. The storm relative wind is defined as the observed wind when a co-ordinate system moving with the storm is used. The co-ordinate system is centered on, and moves with the tornado-storm. The storm relative wind can be computed by vectorially subtracting the storm motion from the environmental wind. The important, and surprising, features of the wind profiles are the large range of conditions associated with tornadoes and the variability of the severity of storm outbreaks under seemingly similar conditions.

Figures 10 through 13 are the mean hodographs for SW, Southerly, Westerly and Tornado Outbreak types of soundings. Each figure includes:

1. The number of cases in the data sample
2. The mean winds and their mean deviations from the surface to 200 mb
3. Average Totals Index and its mean deviation
4. Average number of reported severe thunderstorms and tornadoes
5. The assumed severe thunderstorm motion for each mean wind profile
6. The computed storm relative winds from the surface to 200 mb.

The wind profile of the SW proximity soundings, figure 10, is similar to those obtained by Darkow and Fowler (1971) except that the winds of this study are 5 to 15 knots stronger at all levels. The reason for this difference is that the stratification of soundings into different

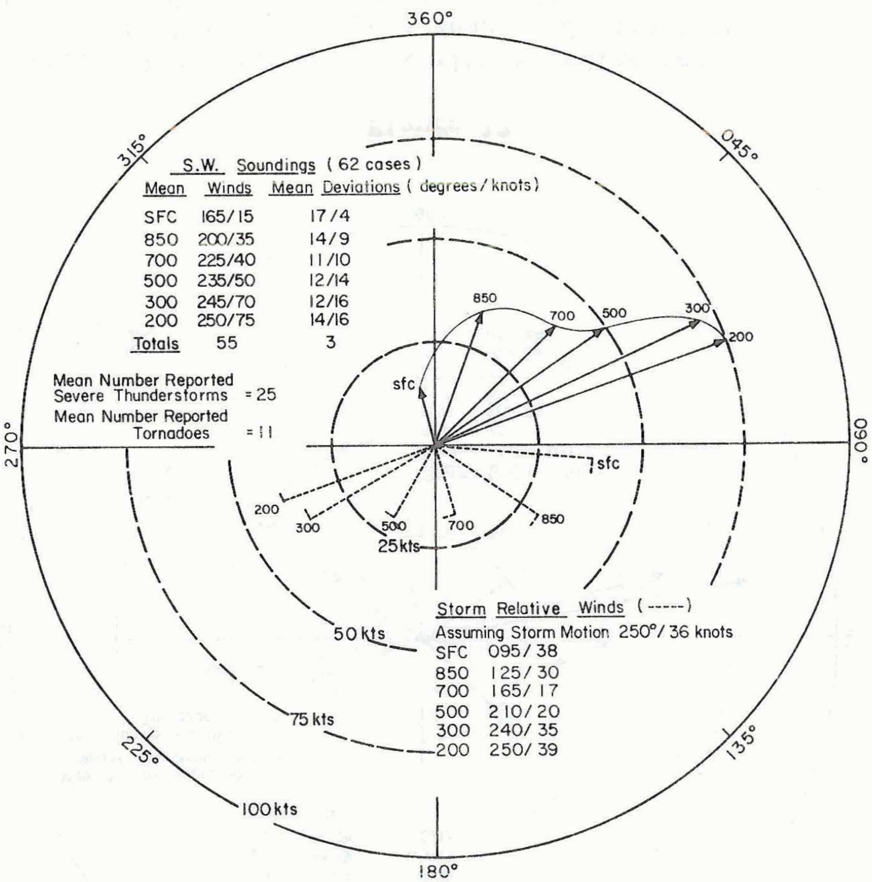

Figure 10

SW Type Tornado Proximity Sounding Mean Hodograph (SW Type = Mean Wind Direction 210° to 235° and Mean Speed ≥ 30 Knots).

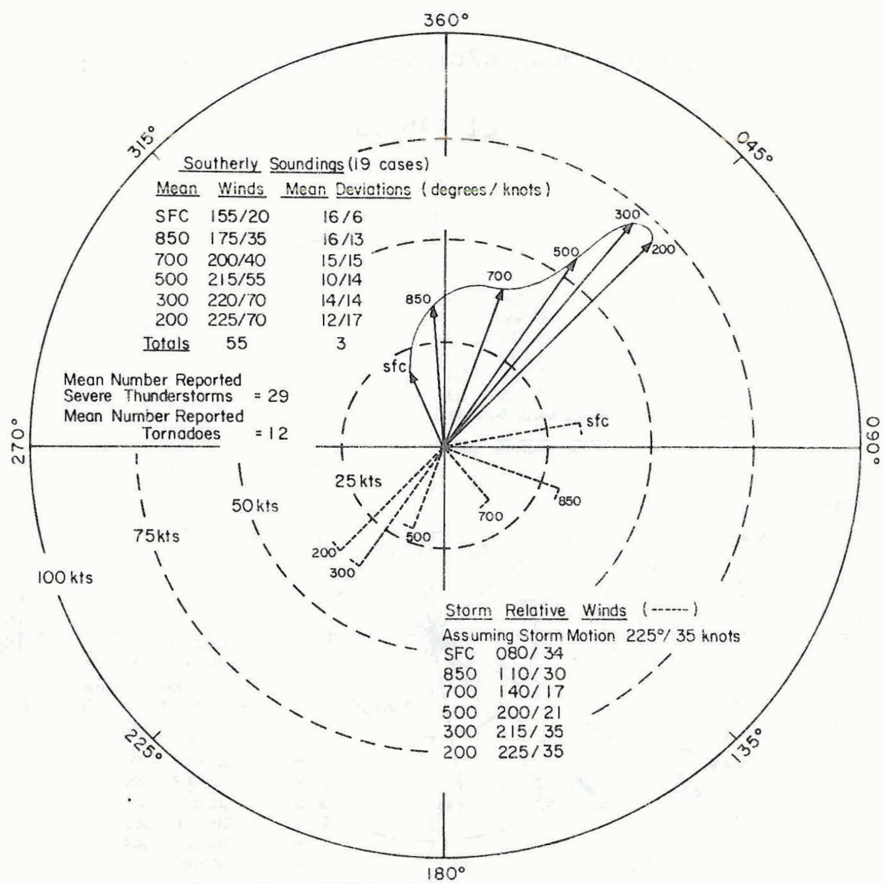

Figure 11

Southerly Type Tornado Proximity Sounding Mean Hodograph (Southerly Type = Mean Wind Direction 160° to 209° and Mean Speed ≥ 30 Knots).

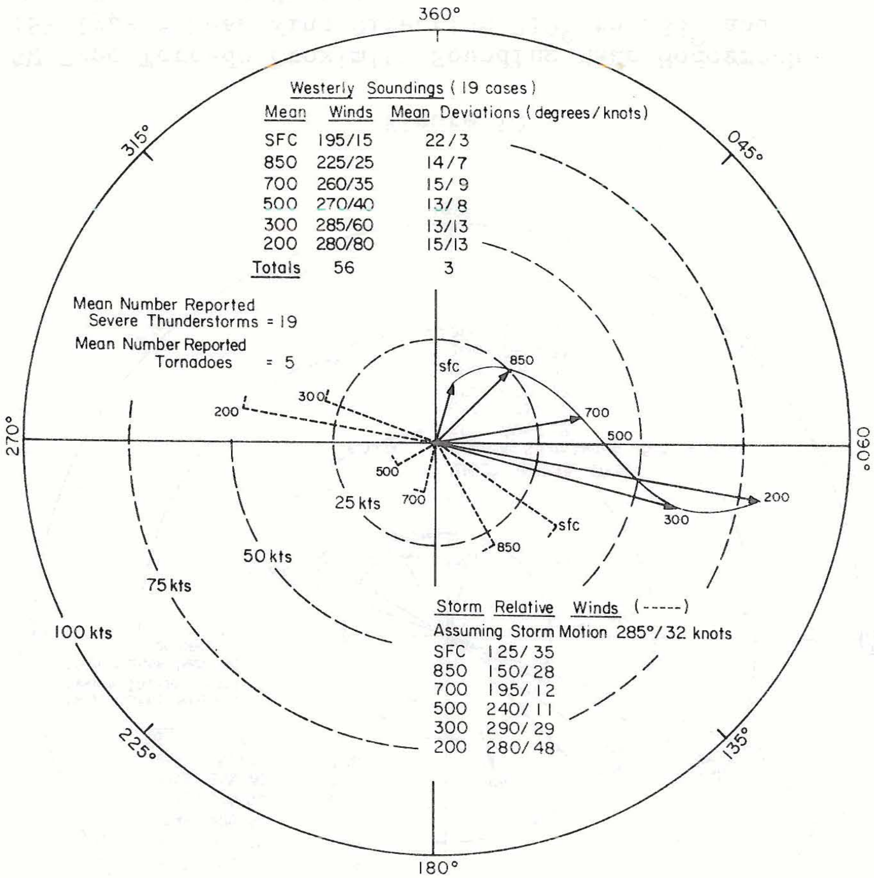

Figure 12

Westerly Type Tornado Proximity Sounding Mean Hodograph (Westerly Type = Mean Wind Direction 236^{o} to 280^{o} and Mean Speed $\geq$ 30 Knots).

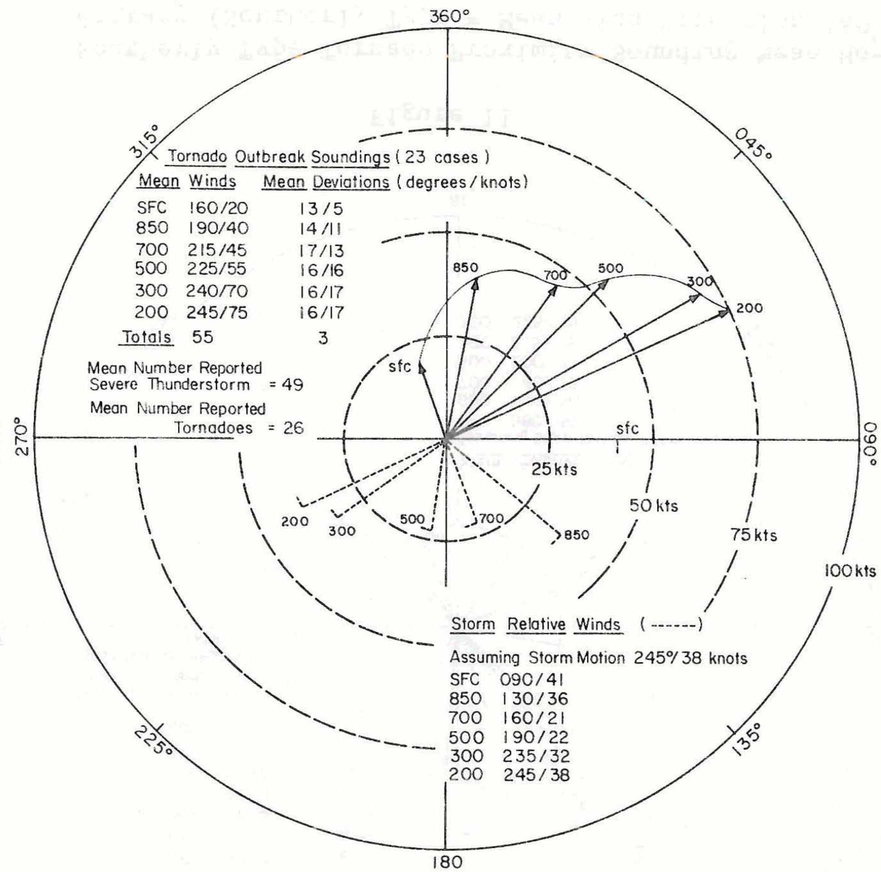

Figure 13

Tornado Outbreak Soundings Mean Hodograph.

categories precludes the averaging of unusual weak wind profiles with stronger, more common, wind profiles.

All of the wind profiles in figures 10 through 13 are basically similar and exhibit only slight differences in speed and veering with height. Although the mean surface winds vary from $155^{o}/20$ knots to $195^{o}/15$ knots the vertical profiles, relative to the surface wind, are very similar. The Tornado Outbreak winds are 5 knots stronger and veer 5 degrees less 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 Totals Index is very uniform for all types of proximity soundings ranging only from 55 to 57. The mean deviation of the Totals is 3 for all sounding categories.

The Westerly type sounding isn't associated with as many tornado occurrences as the SW and Southerly types. The Southerly type sounding tends to be associated with a stronger severe storm outbreak than does the SW type. The differences in number of reported tornadoes become pronounced when it is considered that Southerly situations favor the sparsely populated western portion of the study area, and Westerly situations favor the more densely populated northeastern half of the study area; see figure 9.

The High Plains SW and Southerly hodographs aren't specifically shown since they exhibited no significant differences from the SW and Southerly hodographs. The main differences were lower surface pressures, slightly stronger surface winds and slightly higher Totals. These effects are all a result of the elevation and terrain characteristics of the High Plains.

The mean deviations of the wind directions are approximately 15 degrees for all sounding types at all levels. A 30 degree interval centered on the mean wind direction would include only 58% of the data sample (assuming a normal distribution). This is a remarkable variation, since the soundings were stratified into seemingly similar wind categories before any averaging was done.

<u>Severe Thunderstorm Outbreak Hodographs</u>. Figure 14 is the hodograph of an averaged set of similar Severe Thunderstorm Outbreak wind profiles. The figure includes the same information as do the tornado proximity figures. Figure 15 shows two individual Severe Thunderstorm Outbreak hodographs. Included for each sounding are: wind profile, sounding number, location and month of occurrence, number of reported severe thunderstorms and tornadoes, and the Totals Index.

Figure 14 is the average of the most common type of Severe Thunderstorm Outbreak sounding. This hodograph is similar to that of the Westerly type tornado hodograph except that the 300 and 200 mb winds are respectively 10 and 25 knots stronger for the tornado cases. The mean deviations of both types are large enough that there is considerable overlap between the individual soundings of the two samples. The tornado case is more unstable with a Totals Index of 56 compared to 52 for the severe thunderstorm case. Storm relative winds are much stronger at 300 and 200 mb for the tornado case.

Figure 15 shows individual Severe Thunderstorm Outbreak hodographs for two different cases. These soundings were all taken north of a frontal boundary and are over-running soundings. The low level winds are northerly to easterly while the middle and upper winds are westerly to southwesterly. In this type situation, the warm moist flow feeding

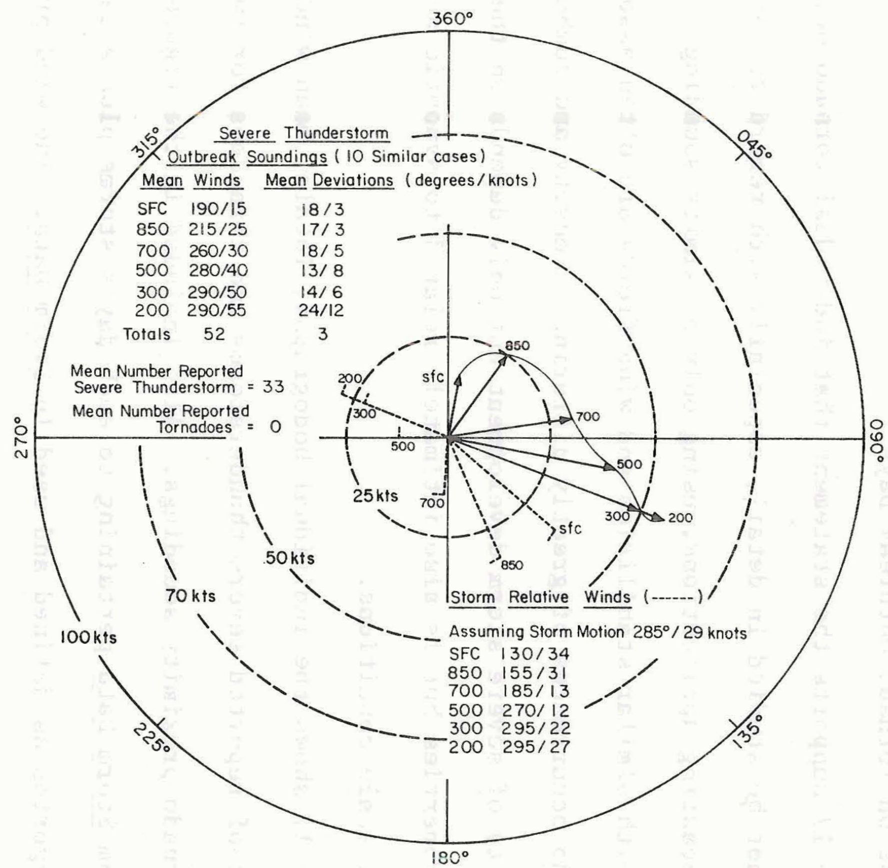

Figure 14

Severe Thunderstorm Outbreak Sounding Mean Hodograph.

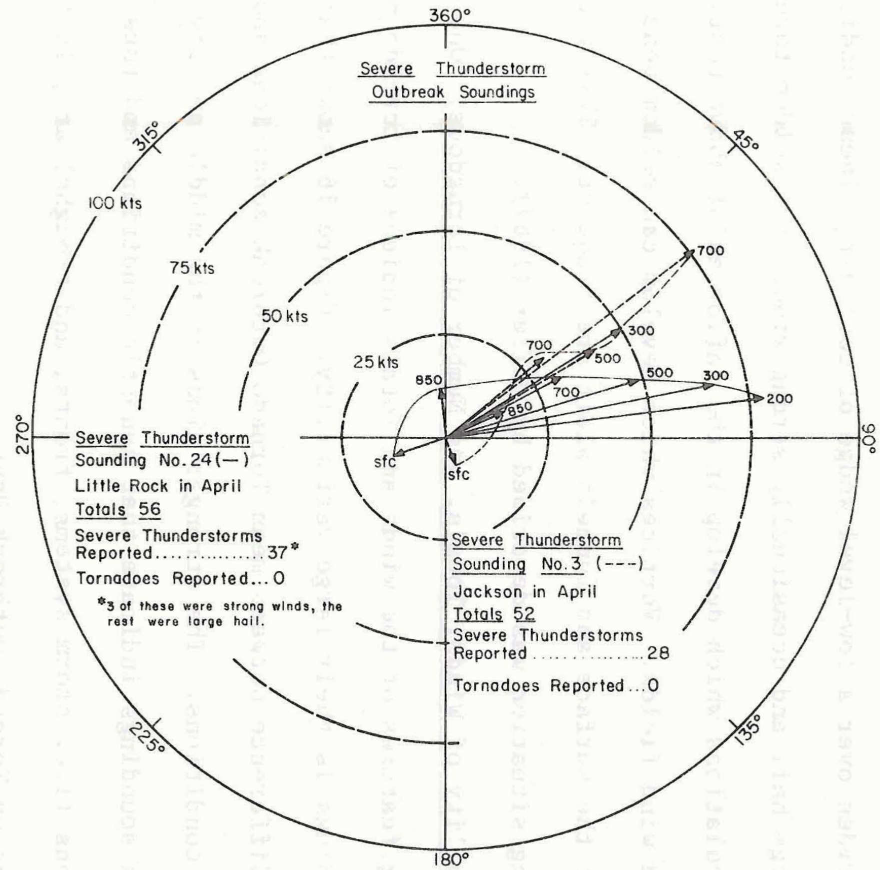

Figure 15

Two Individual Severe Thunderstorm Outbreak Hodographs (LIT on 27 April, 1968 and JAN on 12 April, 1962).

the storm rides over a low-level wedge of cool air. These conditions produce large hail and occasionally strong winds, but seldom tornadoes. Vortex circulations which develop in the inflow exist above hostile thermal and wind fields. Vortices which develop can seldom penetrate downward to the surface and funnels aloft are frequent. This type of over-running situation was described by Miller (1967).

Variability of Winds, Totals, and Number of Tornadoes. One of the outstanding features of the winds and Totals Indices of tornado proximity soundings is their large variability. Figure 16 shows that there is little difference between mean Tornado Outbreak conditions and mean SW tornado conditions. The stronger winds in the middle and low levels of Outbreak soundings indicate that synoptic conditions and thus forcing functions (i.e. storm systems, fronts, and troughs) are, in the mean, more intense on Tornado Outbreak Days.

Figure 17 supports the statement that individual tornado occurrences cannot be studied in detail, especially with regard to operational forecasting applications, using only proximity soundings. Soundings with similar stabilities and wind fields are often associated with tornado occurrences of greatly differing intensity and number. The intensity of severe storm development not only depends on the warm air mass properties but is also intimately related to synoptic and squall-line scale conditions.

Figure 17 shows the individual hodographs, Totals, mean winds, and numbers of reported severe thunderstorms and tornadoes for two similar tornado proximity soundings. Also included in the figure are remarks from Storm Data pertaining to each day's storms plus a table of damage categories as defined and used in Storm Data. The wind profiles,

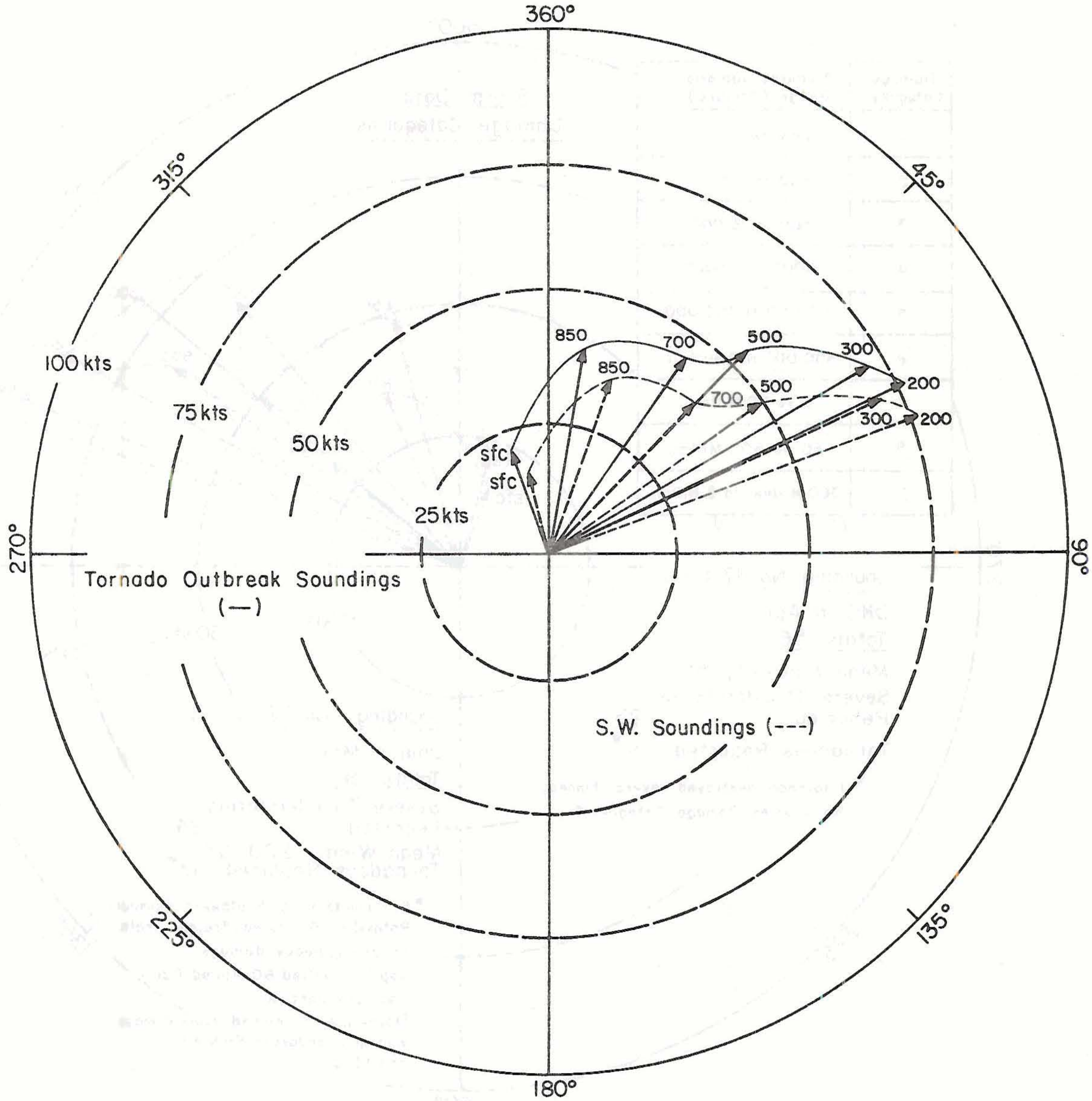

Figure 16

Mean Hodographs for SW Tornado and Tornado Outbreak Proximity Soundings (Mean Totals = 55 for Both Types).

mean winds, and Totals Indices are all similar, but one sounding was associated with several insignificant tornadoes while the other sounding was associated with many more tornadoes, at least two of which were destructive, long-track tornadoes.

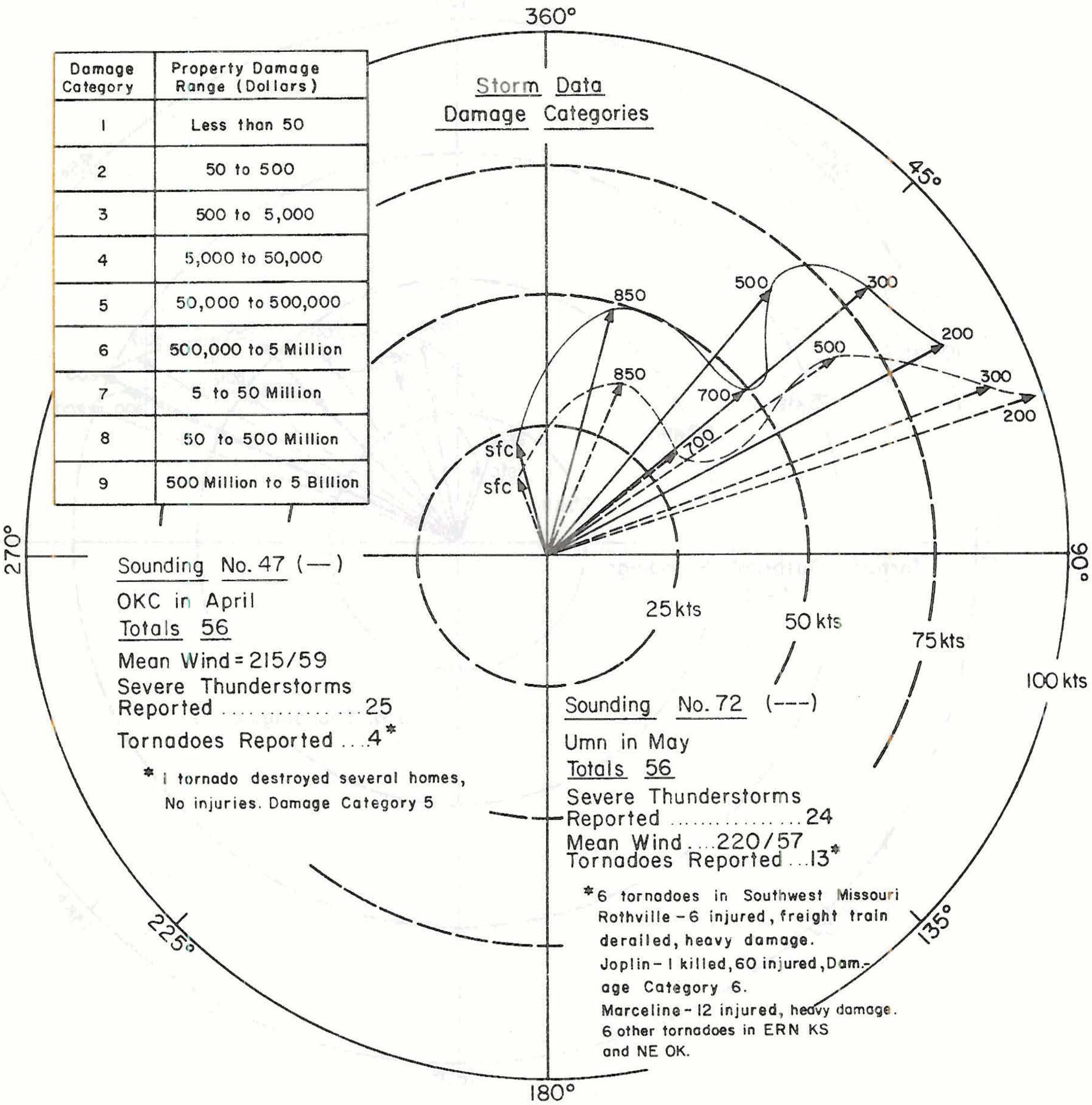

Figure 17

Two Similar Tornado Proximity Hodographs (OKC on 27 April, 1969, and UMN on 6 May, 1971).

The graphs in figures 18 through 21 illustrate the wide range of tornado wind and stability conditions and also the great variability of the number of associated storms.

Figure 18 is a scatter diagram of number of reported tornadoes versus mean wind speed for all proximity soundings and also for Tornado

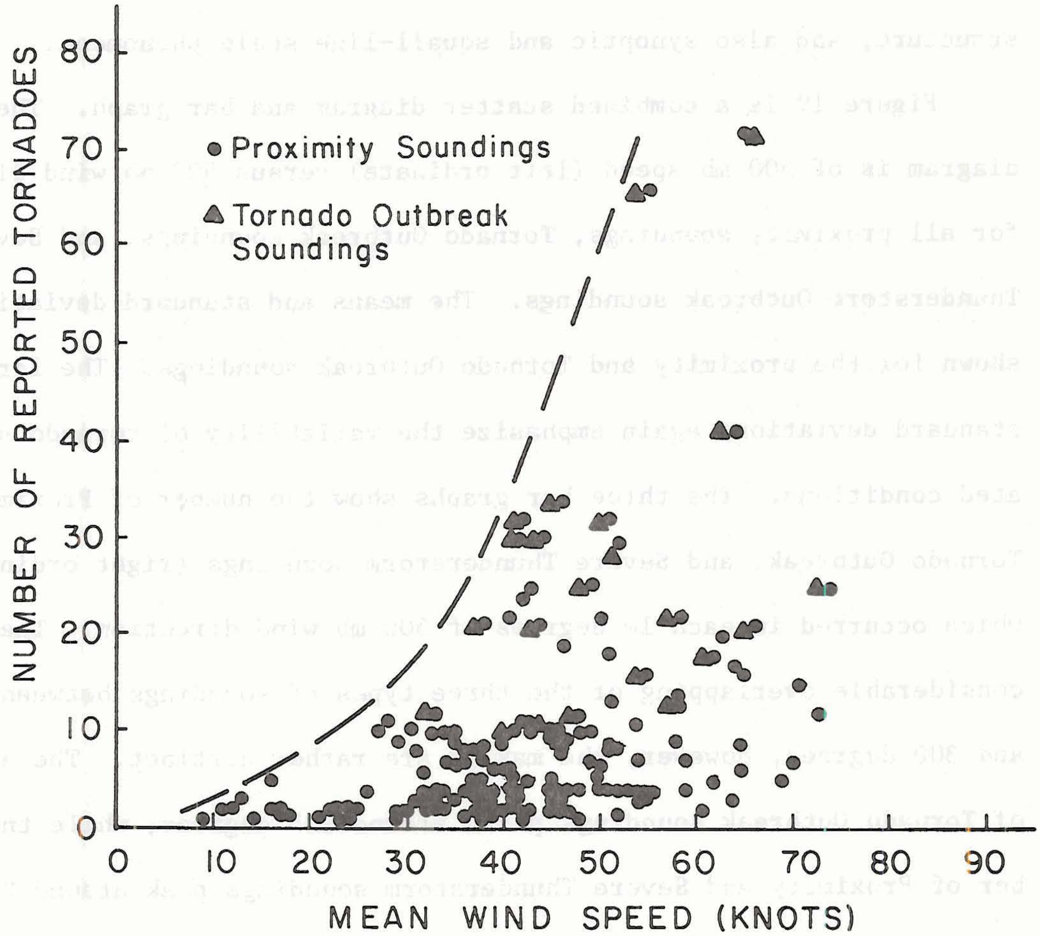

Figure 18

Number of Tornadoes Versus Mean Wind Speed (Surface to 200 mb).

Outbreak soundings. The Tornado Outbreak soundings are a sub-set of the proximity sounding sample so that each plotted Outbreak data point is accompanied by a plotted proximity data point. The number of reported tornadoes generally decreases as mean wind speed decreases, and with a mean wind of less than 30 knots the probability of more than 10 tornadoes occurring becomes quite small. The dashed line depicts this trend. As mean wind speeds become large the range of number of reported tornadoes becomes very large. This demonstrates that tornado events are a result of interactions between the atmospheric wind field and thermal structure, and also synoptic and squall-line scale phenomena.

Figure 19 is a combined scatter diagram and bar graph. The scatter diagram is of 500 mb speed (left ordinate) versus 500 mb wind direction for all proximity soundings, Tornado Outbreak soundings, and Severe Thunderstorm Outbreak soundings. The means and standard deviations are shown for the proximity and Tornado Outbreak soundings. The large standard deviations again emphasize the variability of tornado associated conditions. The three bar graphs show the number of Proximity, Tornado Outbreak, and Severe Thunderstorm soundings (right ordinate) which occurred in each 10 degrees of 500 mb wind direction. There is considerable overlapping of the three types of soundings between 210 and 300 degrees, however, the maxima are rather distinct. The number of Tornado Outbreak soundings peaks around 225 degrees, while the number of Proximity and Severe Thunderstorm soundings peak around 240 and 280 degrees, respectively. Tornado outbreaks are characterized by more southerly flow conditions and Severe Thunderstorm Outbreaks are characterized by westerly flow.

Figure 20 is a scatter diagram of the number of reported tornadoes versus both Totals Index and sounding mean wind speed. This is done by dividing the figure into five separate scatter diagrams of number of tornadoes versus both a mean wind category and a mean wind speed category. The categories are defined in the figure. In each Totals category the number of reported tornadoes tends to increase as the mean wind becomes stronger; however, the range of the number of reported tornadoes becomes very large as the mean speed increases. This is especially true for the three middle stability groups where the data

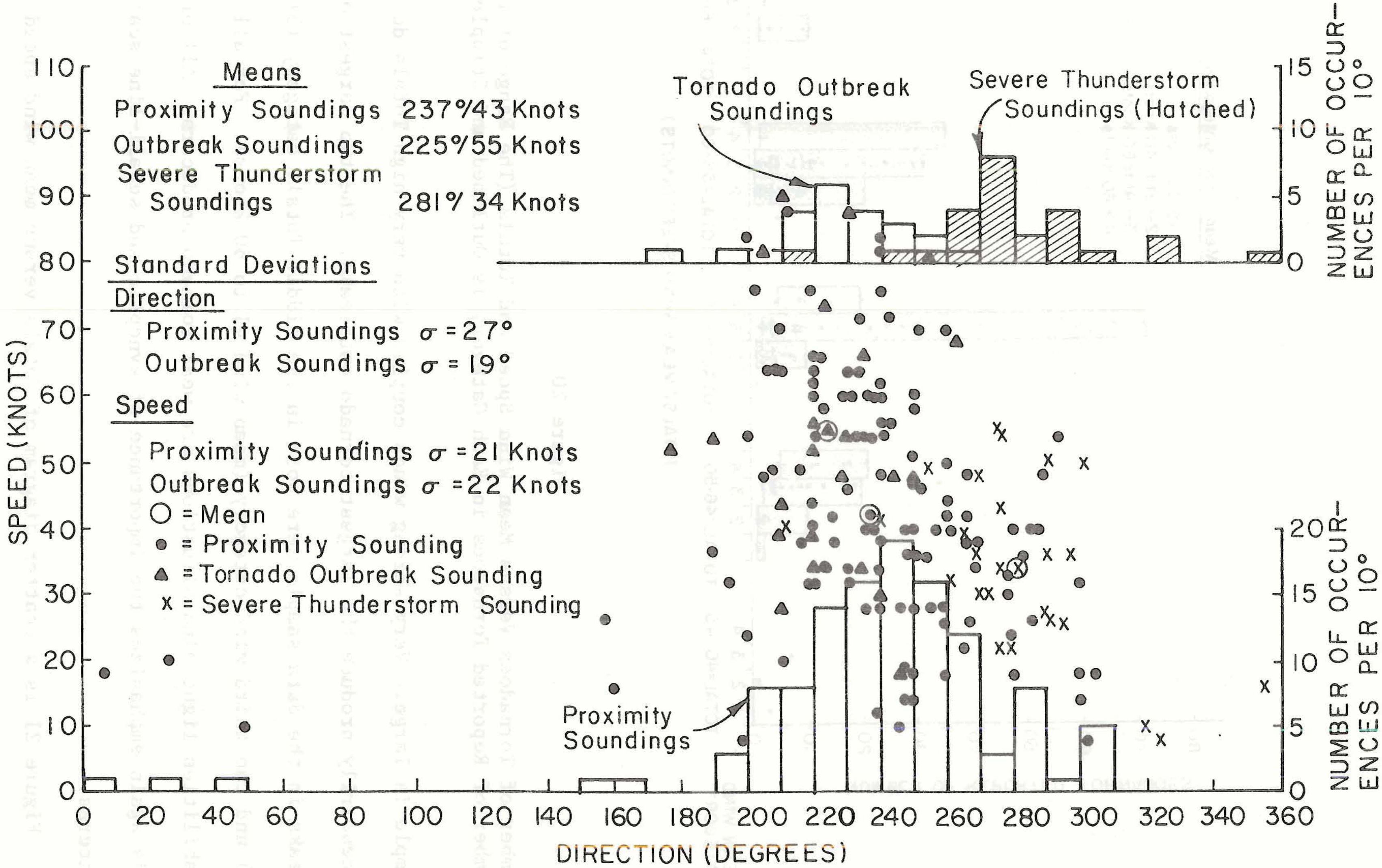

Figure 19

500 mb Wind Speed Versus Wind Direction

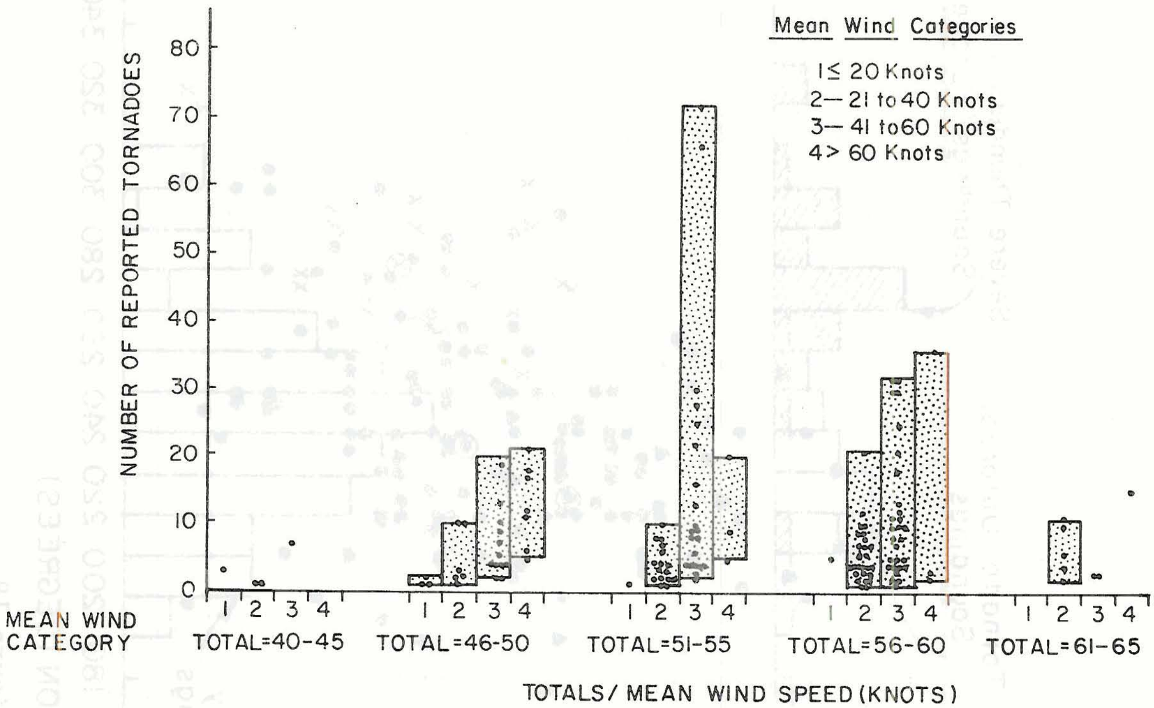

Figure 20

Number of Tornadoes Versus Mean Wind Speed and Totals (The Range of the Number of Reported Tornadoes in Each Category is Outlined and Stippled).

sample is large. Very strong winds coupled with very high Totals do not necessarily produce the largest tornado outbreaks. The two largest outbreaks in the data sample were both in the middle Totals category (51 to 55) and the third wind category (mean wind 41 to 60 knots). For all stabilities light wind situations are weak tornado producers. All of this again emphasizes the importance of synoptic and squall-line scale features.

Figure 21 is a scatter diagram of Totals versus mean wind speed for only the Tornado Outbreak Soundings. This scatter diagram for only

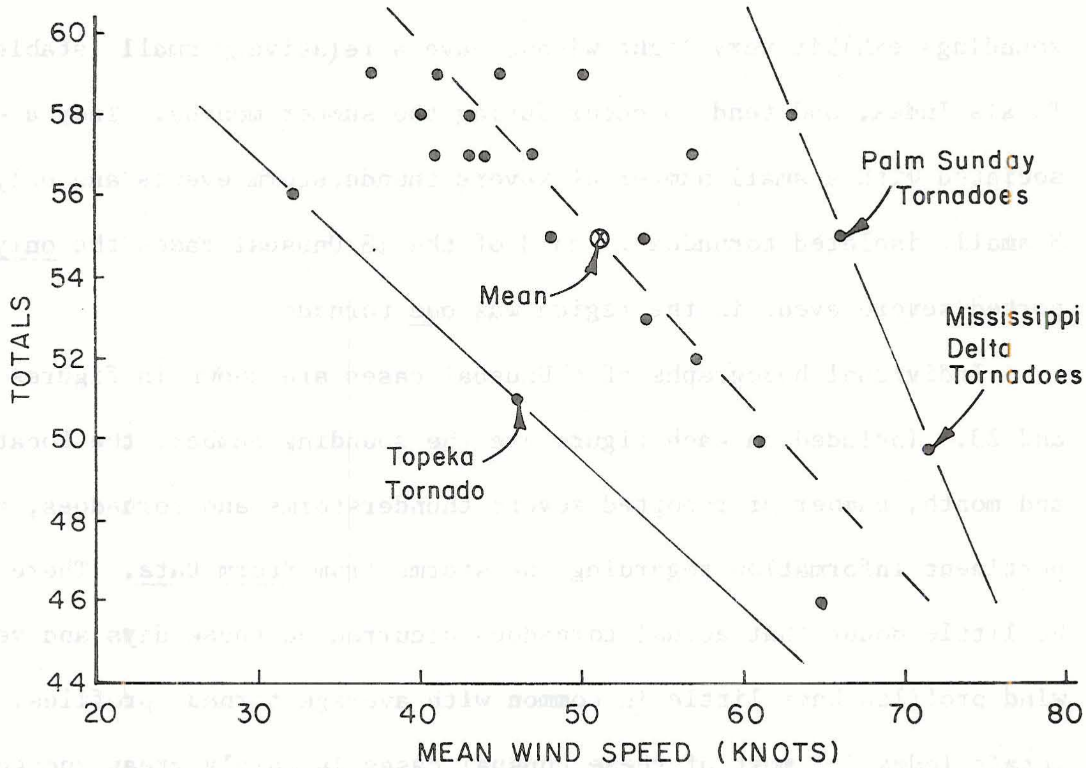

Figure 21

Totals Versus Mean Wind Speed (Surface to 200 mb) for Tornado Outbreaks.

severe tornado days still exhibits a large range of values. In figure 21, the dashed line is an estimated best fit of the data points and the solid lines are the envelope of extreme values. There is a tendency toward stronger winds if the totals are small. Two Tornado Outbreaks occurred with a mean wind of 63 to 65 knots and in one case the Totals were 46 and in the other 58. Four Tornado Outbreaks occurred with Totals 55 to 56 and the mean winds for these four soundings ranged from 34 to 67 knots. The data points for several well known, devastating Tornado Outbreaks are identified.

Unusual Tornado Proximity Soundings. The original sounding categorization listed 18 soundings as being Unusual. Generally, these soundings exhibit very light winds, have a relatively small (stable) Totals Index, and tend to occur during the summer months. They are associated with a small number of severe thunderstorm events and only 1 to 3 small, isolated tornadoes. In 3 of the 18 Unusual cases the only reported severe event in the region was one tornado.

Individual hodographs of 4 Unusual cases are shown in figures 22 and 23. Included on each figure are the sounding number, the location and month, number of reported severe thunderstorms and tornadoes, and pertinent information regarding the storms from Storm Data. There can be little doubt that actual tornadoes occurred on these days and yet the wind profiles have little in common with average tornado profiles. The Totals Index for most of these Unusual cases is barely great enough to indicate that thunderstorms would be likely. Examination of each individual Unusual tornado proximity sounding shows greatly differing wind profiles and stabilities. The only common feature of these soundings is that each one was associated with convective activity. It is highly improbable that Unusual tornado events, such as those presented here, could be successfully forecast.

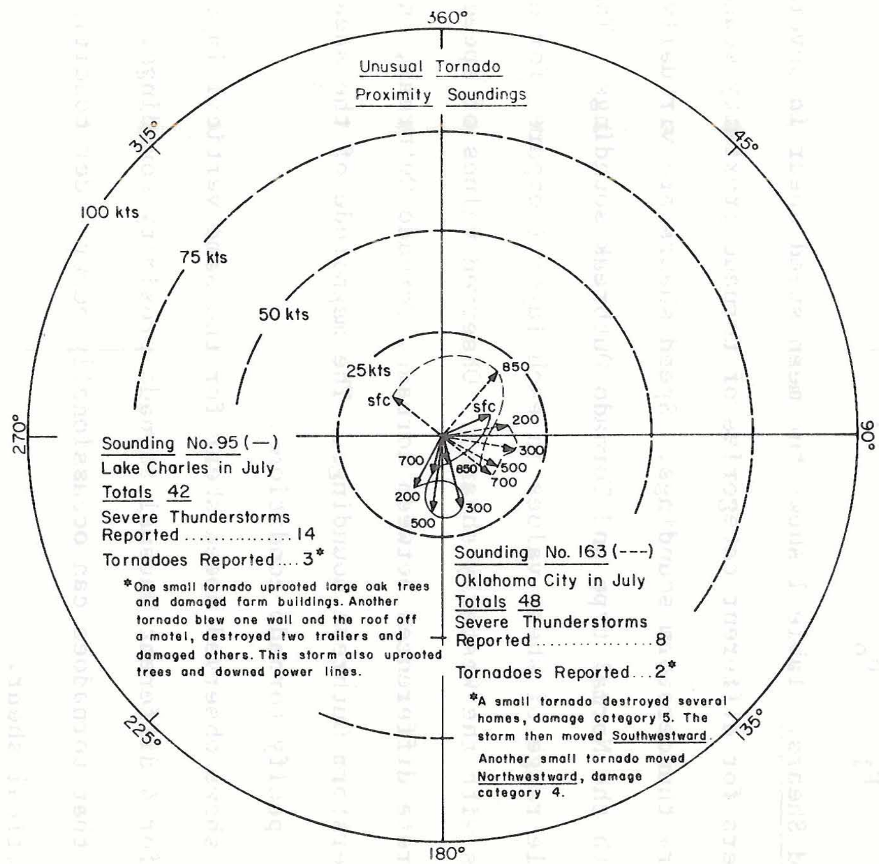

Figure 22

Two Unusual Tornado Proximity Hodographs (LCH on 15 July, 1969 and OKC on 23 July, 1959).

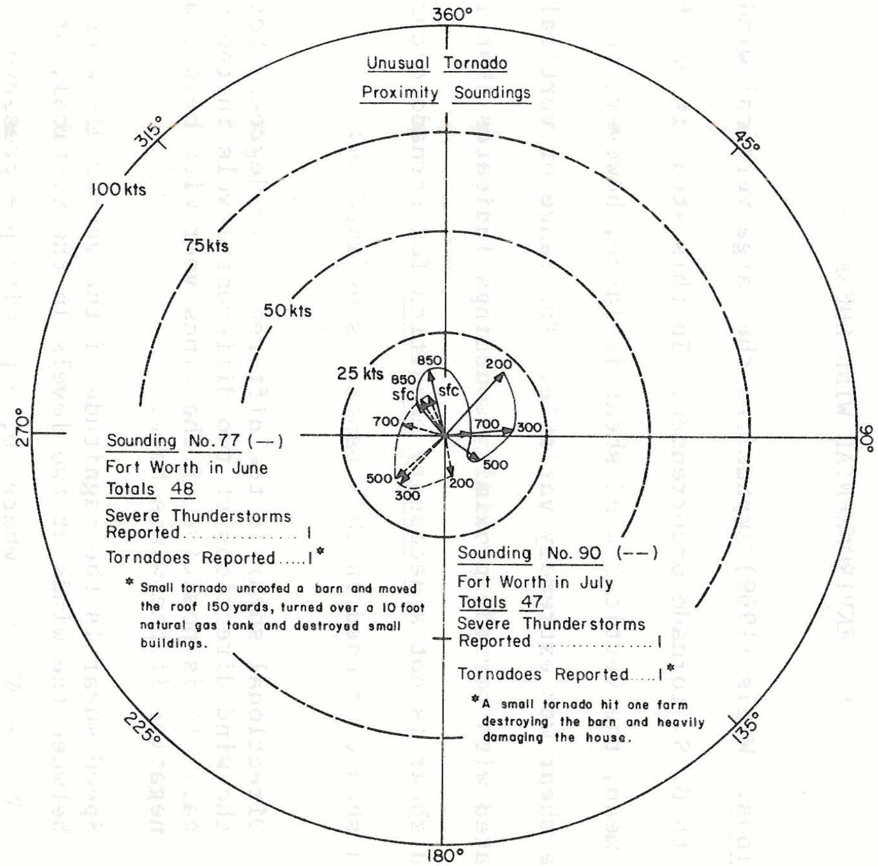

Figure 23

Two Unusual Tornado Proximity Hodographs (GSW on 29 June, 1962 and on 30 July, 1964).

3. ENVIRONMENTAL WIND SHEAR

Definitions. Wills (1969) emphasized the large vertical wind shear associated with U. S. tornado occurrences. In this study it was found that, in the mean, the vertical wind shear is large, however, the magnitude of the shear was extremely variable. The range of vertical wind shear associated with tornado proximity soundings indicates that large vertical wind shear is not a necessary condition for tornado occurrence. Vertical wind shear, as used in this paper, is defined as:

1. Directional shear is the difference, in degrees, between the wind directions at two different levels in the vertical. It is positive if the winds veer with height and negative if the winds back.

2. Speed shear is the magnitude of the vector difference between the winds at two levels in the vertical, or

$$|\mathbb{V}_{p_1} - \mathbb{V}_{p_o}| \quad \text{where } p_1 < p_o \text{ with } p = \text{pressure}$$

Observed Shears. Table 1 shows the mean speed shear in several vertical layers for different categories of tornado proximity soundings and for severe thunderstorm soundings. Speed shears are virtually identical for both the Normal type and Tornado Outbreak soundings. There is a considerable range of shear values in each layer (compare, for example, the SW shears with the Westerly shears). Observed values of speed shear show no discrete differences between tornado, Tornado Outbreak, and Severe Thunderstorm Outbreak soundings. The magnitude of the shear does not directly specify tornado conditions.

Table 2 shows observed speed shear for the same vertical layers as Table 1 but for 4 different Unusual tornado proximity soundings. This demonstrates that tornadoes can occassionally occur under conditions of very weak vertical shear.

Table 1

Speed Shear (Knots) For Different Types of Tornado Proximity Soundings

Sounding Type	sfc to 850 mb	850 mb to 700 mb	700 mb to 500 mb	500 mb to 300 mb	300 mb to 200 mb	sfc to 200 mb	sfc to 600 mb	600 mb to 200 mb
S.W. (62 Cases)	24	17	13	23	9	76	40	38
Tornado Outbreak (23 Cases)	24	19	13	23	8	76	43	38
Westerly (19 Cases)	15	21	9	24	21	81	36	45
Southerly (19 Cases)	18	17	19	16	6	67	39	30
Severe Thunderstorm (10 Cases)	15	22	16	13	5	63	36	27

Table 2

Speed Shear (Knots) For Unusual Tornado Soundings

Sounding Number	sfc to 850 mb	850 mb to 700 mb	700 mb to 500 mb	500 mb to 300 mb	300 mb to 200 mb	sfc to 200 mb	sfc to 600 mb	600 mb to 200 mb
77	8	19	7	11	14	22	16	20
90	3	8	14	2	12	19	16	15
84	6	16	21	24	13	41	20	20
162	4	23	13	7	9	38	25	22

Figure 24 is a scatter diagram of speed shear versus directional shear for SW, Tornado Outbreak, and Severe Thunderstorm Outbreak soundings. The winds used to compute the shears were the mean wind, surface to 850 mb, and the 500 mb wind. This is felt to approximate the shear between storm inflow and middle level flow. There is a large range of values of both speed and directional shear. For the SW soundings speed shear ranges from 8 to 80 knots and directional shear ranges from -15 to 98 degrees. Standard deviations are shown about each mean. Their large values indicate great sample variability for all three types of soundings. Notice that only Severe Thunderstorm Outbreak soundings exhibited a directional shear of more than 98 degrees. It appears that severe thunderstorms, without attendent tornadoes, are more likely in an environment which displays very large veering. The physical implications of this will be discussed in Part II. Vertical wind shear is large in the vicinity of frontal boundaries. Most tornado proximity soundings were obtained during April, May and June (refer to figure 4). It is not surprising then, that in the mean, proximity soundings exhibit strong shear, since the majority of them occur during the time of the year when convection is primarily triggered along and ahead of strong fronts.

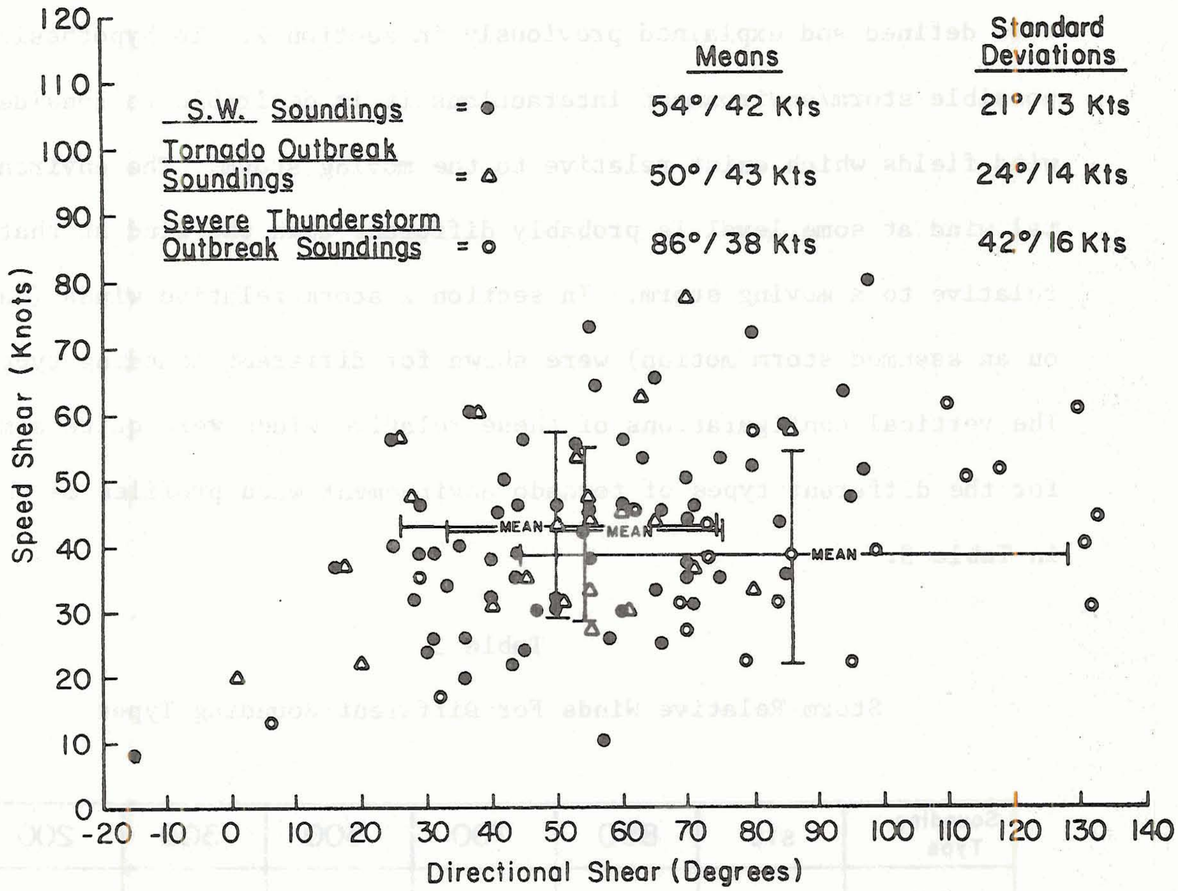

Figure 24

Shears For Different Sounding Types
(Inflow Layer to 500 mb)

4. STORM RELATIVE WIND FIELDS

Relative Winds for Different Sounding Types. Storm relative winds were defined and explained previously in section 2. To hypothesize on possible storm/environment interactions it is desirable to consider the wind fields which exist relative to the moving storm. The environmental wind at some level is probably different than the wind at that level relative to a moving storm. In section 2 storm relative winds (based on an assumed storm motion) were shown for different sounding types. The vertical configurations of these relative winds were quite similar for the different types of tornado environment wind profiles as shown in Table 3.

Table 3

Storm Relative Winds For Different Sounding Types

Sounding Type	sfc	850	700	500	300	200
S.W. (62 Cases)	095/38	125/30	165/17	210/20	240/35	250/39
Tornado Outbreak (23 Cases)	090/41	130/36	160/21	190/22	235/32	245/38
Westerly (19 Cases)	125/35	150/28	195/12	240/11	290/29	280/48
Southerly (19 Cases)	080/34	110/30	140/17	200/21	215/35	225/35
High Plains S.W. (10 Cases)	100/34	115/36	145/18	245/12	260/27	245/42
High Plains Southerly (12 Cases)	080/35	095/36	115/16	180/16	235/28	225/38
Severe Thunderstorm (10 Cases)	130/34	155/31	185/13	270/12	295/22	295/27

All sets of relative winds show strong flow at the surface and 850 mb, light flow at 700 and 500 mb, and strong flow again at 300 and 200 mb. Westerly tornado and Severe Thunderstorm Outbreak soundings have similar storm relative wind profiles except for weaker flow in the upper levels of the severe thunderstorm case.

To determine just how similar a set of relative winds are the storm motion must also be considered. To do this, a relative flow angle (θ) is defined as the angle between the storm's motion and the relative wind. See figure 25 for an example of this.

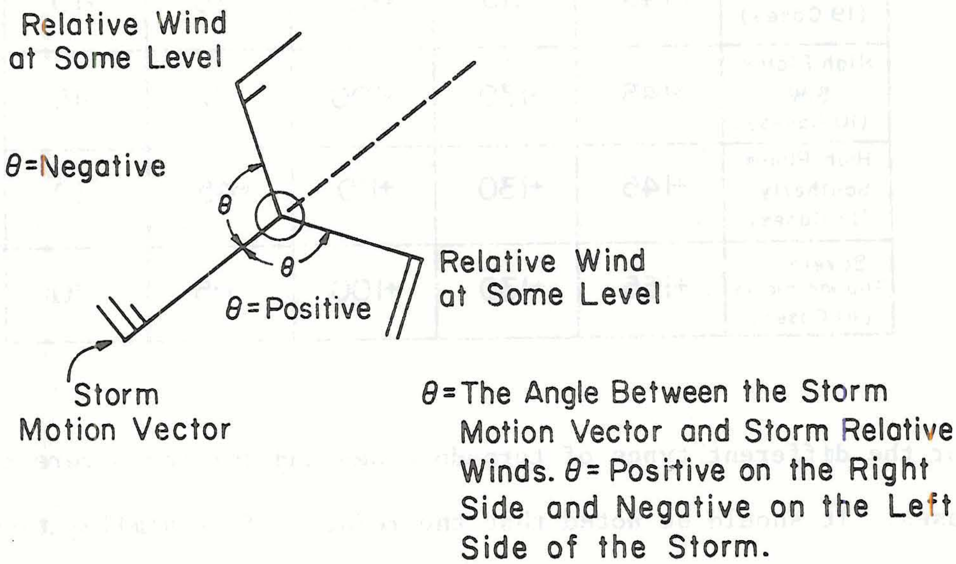

Figure 25

Definition of Relative Flow Angle (θ).

A relative flow angle of -45 degrees indicates that relative flow approaches the left rear of the storm and an angle of +90 degrees indicates that relative flow approaches the right flank of the storm. Table 4 shows the computed relative flow angle for different types of soundings. This clearly demonstrates how similar the relative winds are

Table 4

Relative Flow Angle For Different Sounding Types

Sounding Type	sfc	850	700	500	300	200
S.W. (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
High Plains S.W. (10 Cases)	+145	+130	+100	0	-15	0
High Plains Southerly (12 Cases)	+145	+130	+110	+45	-10	0
Severe Thunderstorm (10 Cases)	+155	+130	+100	+15	-10	-10

for the different types of tornado cases <u>and</u> for the severe thunderstorm cases. It should be noted that the relative flow similarities of the Westerly tornado and Severe Thunderstorm Outbreak soundings are partially a result of making the assumption that individual storms move similarly in both cases. This is probably not a valid assumption. The relative flow angles of Table 4 show the surface and 850 mb flow approaching the right front of the storm. The relative flow at 700 and 500 mb approaches the right or right rear flank of the storm. The upper relative winds approach the rear of the storm. It must be remembered that the observed environmental wind profiles, which were used as a base for the storm relative computations, do not have sufficient resolution to imply that they are representative of near storm winds. The winds in the immediate storm region may differ significantly from the squall-line scale winds.

Relative Winds for Varying Storm Motion. The storm relative wind fields were derived for the mean sounding types based on an assumed storm motion. An interesting question is: How does the storm relative wind field vary if differing storm motions are assumed? To answer this question the SW type (largest data sample) wind profile was used and storm relative winds were computed for different possible storm motions. The different storm motions used were:

1. 30 degrees left at 75% of the mean wind.
2. With the mean wind.
3. 15 degrees right at 85% of the mean wind.
4. 30 degrees right at 75% of the mean wind.
5. 45 degrees right at 60% of the mean wind.
6. 60 degrees right at 50% of the mean wind.

Storm movement number 1 has been designated as left moving, number 2 as mean wind, number 4 as right moving, and number 6 as extreme right moving.

Table 5 lists the computed relative winds for these different assumed storm motions. The relative flow changes dramatically, in the fixed environment, as the storm motion changes from left moving to extreme right moving. Figure 26 shows the difference in relative winds for two of the assumed storm motions.

Table 6 shows the relative flow angles for the various different assumed storm motions. As the storm motion changes from left moving to extreme right moving the following changes occur (see also table 5):

Table 5

Storm Relative Winds (SW Sounding) For Different Storm Motions

Assumed Storm Motion	sfc	850	700	500	300	200	
190/36	027/23	282/24	288/24	282/36	277/58	278/66	Left Moving
220/48	067/37	094/20	003/7	297/15	280/35	280/43	Mean Wind
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	Right Moving
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	Extreme Right Moving

Table 6

Relative Flow Angles (SW Soundings) For Different Storm Motions

Assumed Storm Motion	sfc	850	700	500	300	200	
190/36	+163	-92	-98	-92	-87	-88	Left Moving
220/48	+153	+126	-37	-77	-60	-60	Mean Wind
235/40	+157	+118	+96	-8	-26	-32	
250/36	+155	+125	+85	+40	+8	0	Right Moving
265/30	+155	+117	+87	+50	+33	+24	
280/25	+155	+121	+93	+72	+50	+43	Extreme Right Moving

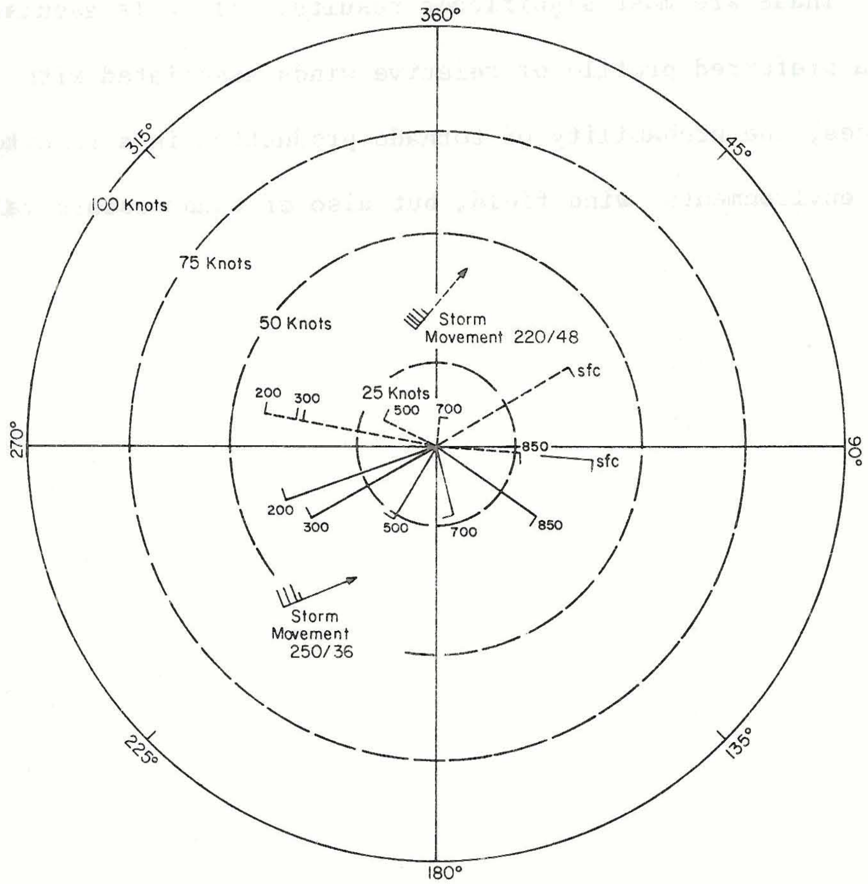

Figure 26

Storm Relative Winds (For the SW Type Wind Profile) for Two Different Assumed Storm Velocities.

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 storm's 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).

These are most significant results. If it is assumed that there is a preferred profile of relative winds associated with tornado occurrences, the probability of tornado production is a function not only of the environmental wind field, but also of thunderstorm velocity.

5. TEMPERATURE AND MOISTURE FIELDS

Temperature and moisture (dewpoint and relative humidity) values were studied at the surface, 850, 700 and 500 mb. This was done for SW type soundings because of their large sample size and for Tornado Outbreak soundings. The temperature and moisture fields exhibit large variability just as the winds and Totals do. The most extreme variability is found in the moisture fields.

Figure 27 is a scatter diagram of 850 mb temperature versus surface temperature for SW, Tornado Outbreak, and Severe Thunderstorm Outbreak soundings. For SW soundings the temperature range at the surface was 27°C and at 850 mb it was 22°C. The only distinction between the three sounding types is that Tornado Outbreak temperatures cluster in the cooler region of the diagram and Severe Thunderstorm temperatures cluster in the warmer region. This is because of their respective occurrence maxima in spring and summer (see figure 8). The solid line in the figure represents a dry adiabatic lapse rate from the surface to 850 mb, with a surface pressure of 980 mb. Some of the large scatter of figure 27 is caused by seasonal differences. While most of the soundings occurred in spring and early summer, 29% of the data sample occurred in late summer, fall, and winter. Figure 28 is identical to 27 except it is for <u>only</u> May and June data. The range of values is not quite as great, but it is still large. The range of both surface and 850 mb temperature for SW soundings was 20°C. There is no thermal distinction between SW proximity soundings and the other two types.

The SW soundings showed several different distributions of moisture in the vertical. Many of the soundings were very moist or very dry at

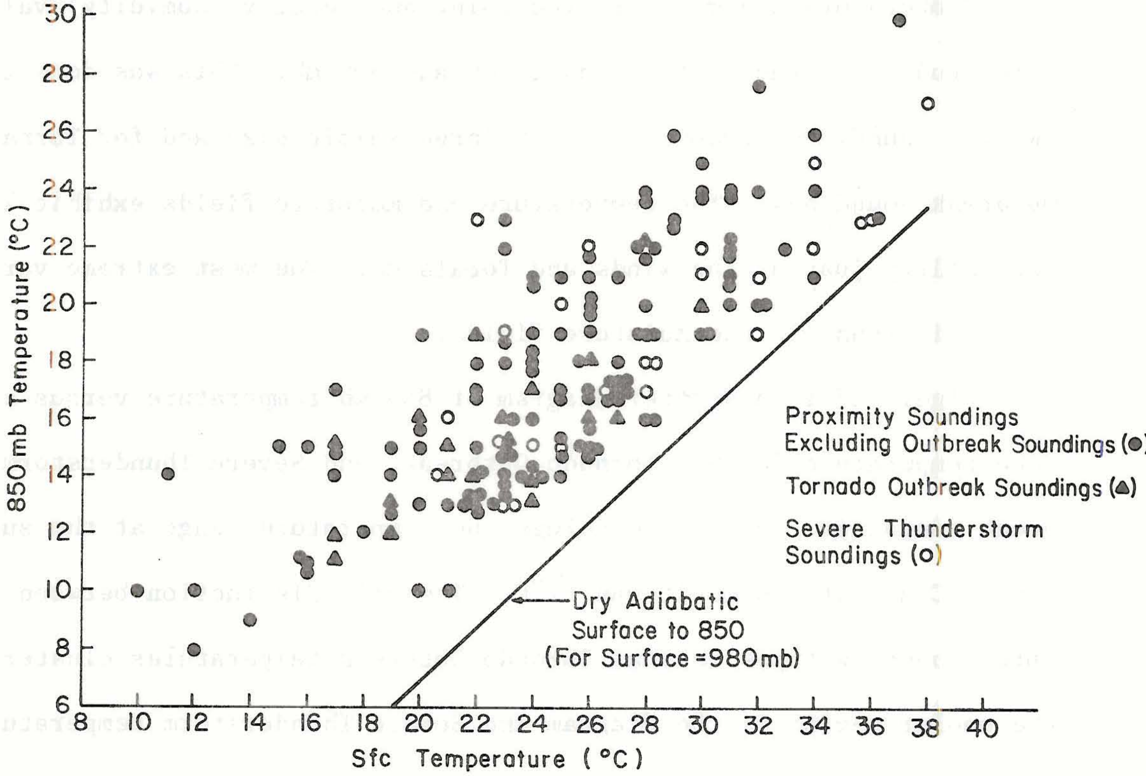

Figure 27

850 mb Temperature Versus Surface Temperature For All Soundings.

both 700 and 500 mb. All soundings had a high ($T_d > 10^{o}C$) moisture content below 850 mb. The soundings were categorized as moist, dry or indeterminate according to these criteria:

1. A sounding with relative humidity 60% or more at both 700 and 500 mb was a moist sounding.

2. A sounding with relative humidity 30% or less at both 700 and 500 mb was a dry sounding.

3. All others were indeterminate soundings.

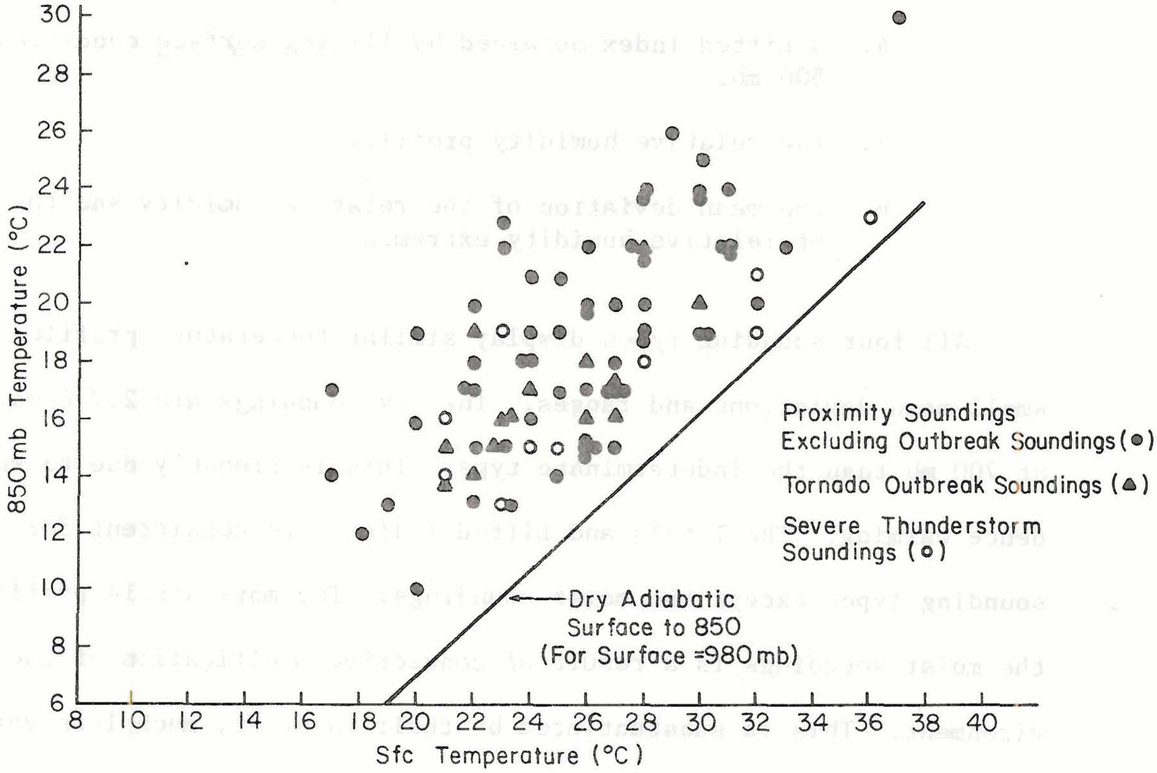

Figure 28

850 mb Temperature Versus Surface Temperature For May and June Soundings.

The close SW soundings were included in the data sample. The number of soundings obtained in each category were: 16 moist cases, 15 dry cases, and 40 indeterminate cases. Of 71 soundings, 44% were either very dry or very moist.

Figures 29 through 32 are vertical plots of temperature and moisture for these three sounding types and also for Tornado Outbreak soundings. Each figure includes:

1. The mean temperature and dewpoint profile.

2. The mean deviation of the temperature and the range of temperature extremes.

3. The Totals Index.

4. A Lifted Index obtained by lifting surface conditions to 500 mb.

5. The relative humidity profile.

6. The mean deviation of the relative humidity and the range of relative humidity extremes.

All four sounding types display similar temperature profiles with small mean deviations and ranges. The dry soundings are 2.7^{o}C warmer at 700 mb than the indeterminate type. This is probably due to subsidence warming. The Totals and Lifted Indices are consistent for all sounding types except the moist soundings. The more stable profile of the moist soundings is a result of convective modification of the environment. This is substantiated by their constant, much less variable, moisture profile. The relative humidity profiles show large variability for the indeterminate and Tornado Outbreak soundings and for dry soundings at 850 mb and the surface. This large variability is not surprising when it is realized that these soundings are sampling a wide range of convective conditions.

The mean temperature and dewpoint profile of figure 29, the indeterminate cases, is very similar to Darkow's (1969) average tornado proximity sounding. This indicates that averaging produces similar results whether or not the very moist and very dry cases are included in the sample. In averaging a large data sample one smoothes away the very interesting, unusual soundings. These "lost" soundings might provide a better insight into associated events. To further investigate this point of view the locations of moist and dry soundings were

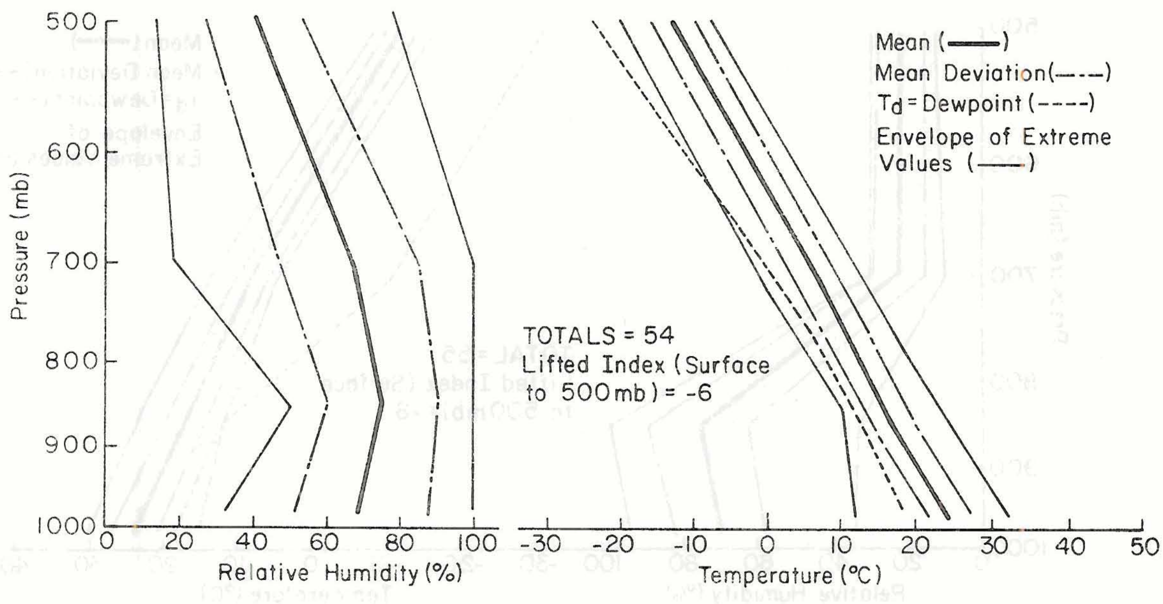

Figure 29

Temperature and Moisture Profiles for Indeterminate Soundings (40 cases).

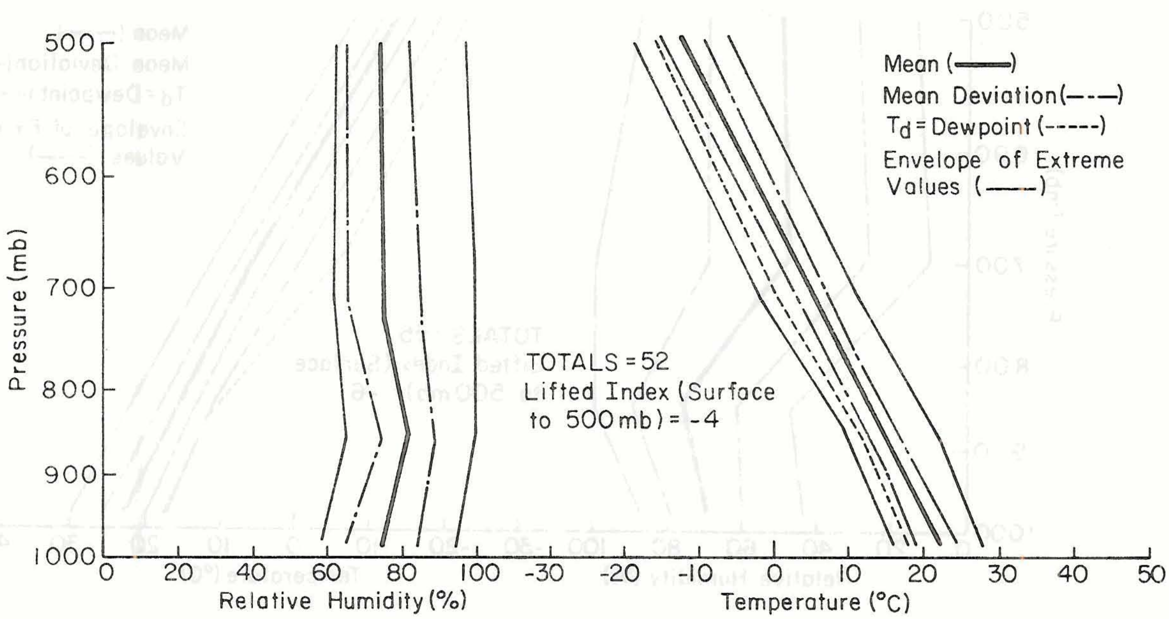

Figure 30

Temperature and Moisture Profiles for Moist Soundings (16 Cases).

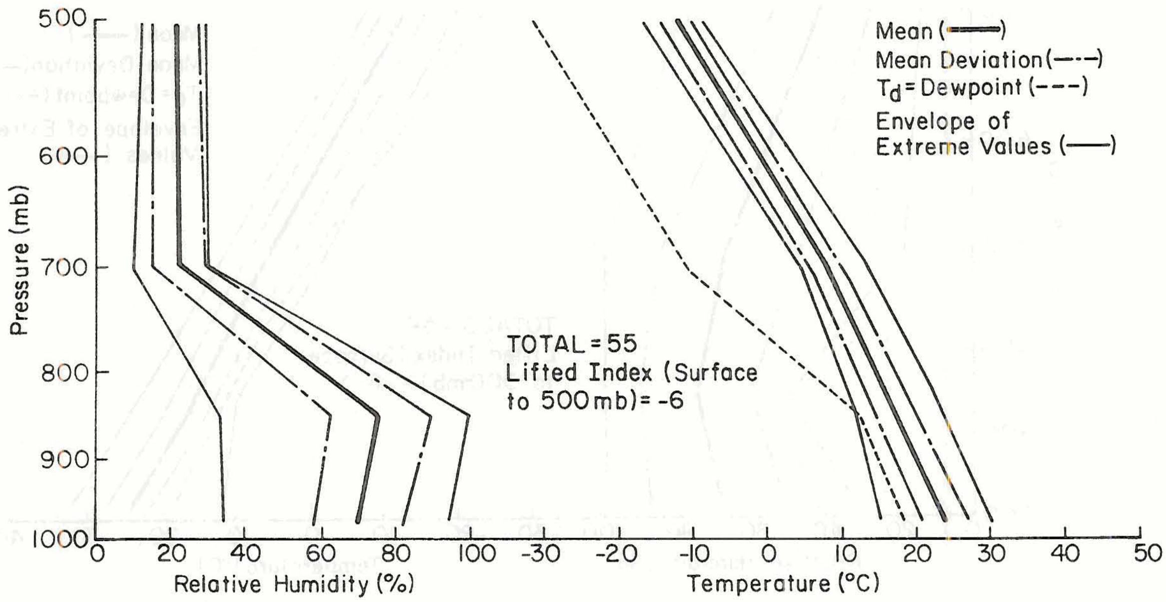

Figure 31

Temperature and Moisture Profiles for Dry Soundings (15 Cases).

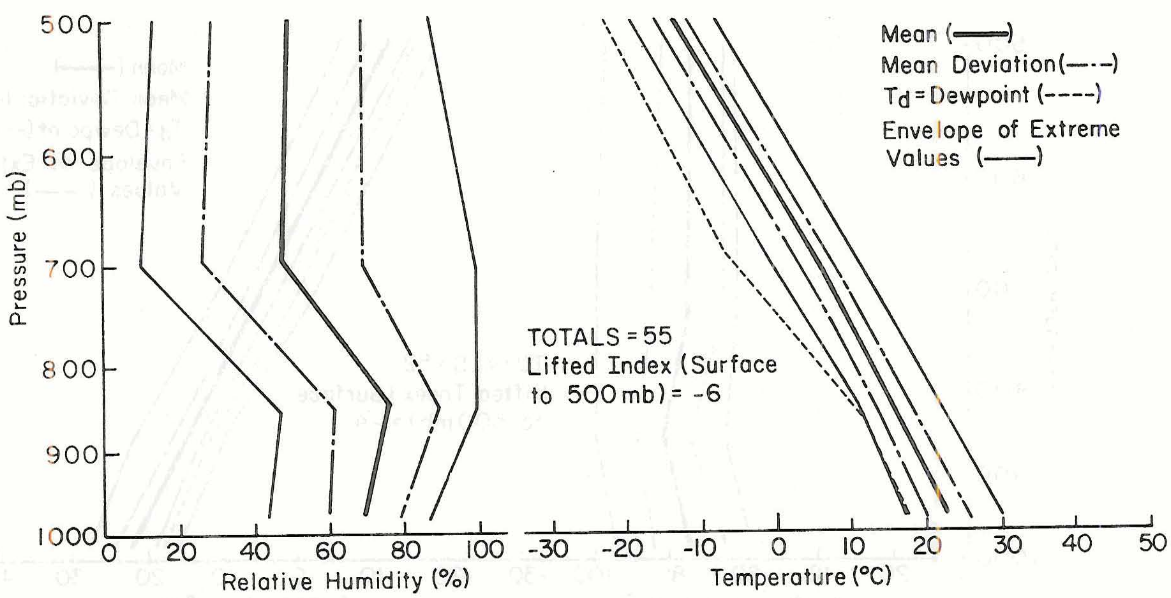

Figure 32

Temperature and Moisture Profiles for Tornado Outbreak Soundings (23 Cases).

plotted. Plotted first were the positions of all the moist and dry soundings at 700 mb relative to the location of the tornado storm. The results are shown in figure 33. The moist soundings tend to be within 50 n.mi. of the tornado storm indicating vertical motion and convective mixing in the immediate storm area. The dry soundings tend to be well ahead of the storm in a region of little vertical mixing and/or subsidence.

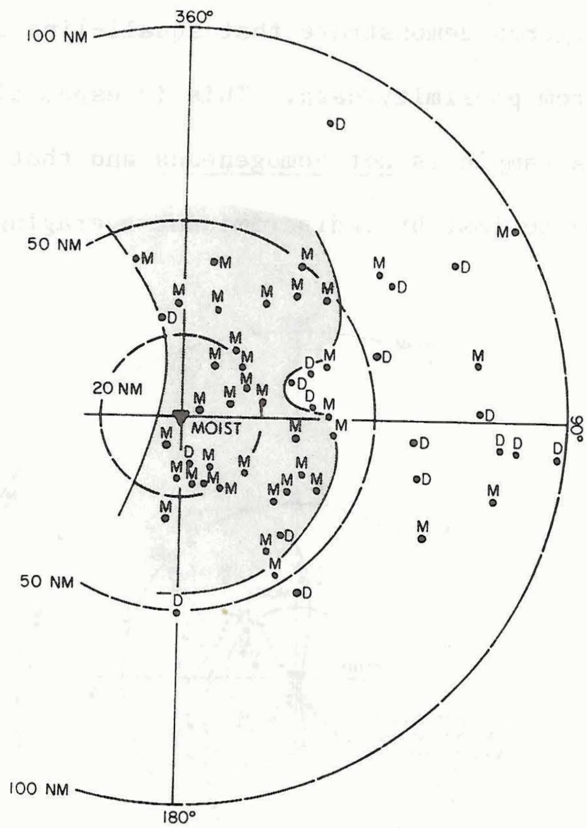

Figure 33

Locations of Moist (M) and Dry (D) Soundings at 700 mb. Tornado-Storm is at Center.

Figure 34 shows the position of soundings which were either dry or moist at <u>both</u> 700 and 500 mb. The moist area near the storms and the very dry region ahead of them are both well defined. Since the time of all soundings is late afternoon, it is most likely that the dry region ahead of the storms is a result of storm induced subsidence. Also shown on this figure is a region where very dry conditions at 500 mb exist above a surface to 700 mb moist layer. This region, where upward motion and mixing in the lower troposphere is likely capped by upper tropospheric subsidence, tends to exist immediately ahead of and to the right of the tornado storm.

These figures demonstrate that squall-line scale features can be identified from proximity data. This is especially so when one realizes that the data sample is not homogeneous and that important individual soundings can be lost by indiscriminant averaging.

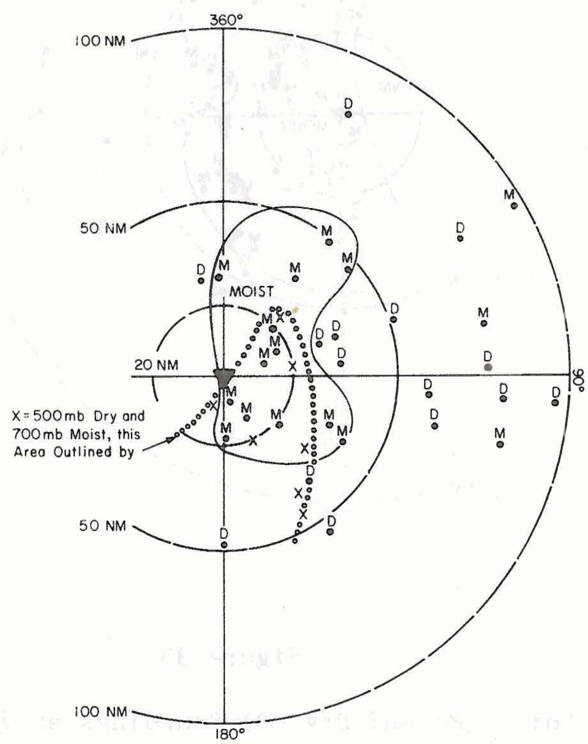

Figure 34

Locations of Moist (M) and Dry (D) Soundings at Both 700 and 500 mb. Tornado-Storm is at Center.

6. NORMALIZED WIND FIELDS

Definitions and Procedures. Wills (1969) derived a tornado wind field by averaging data in sixteen different sectors around the tornado. The most serious problems of this approach are poor resolution in data positioning, and the averaging together of different type soundings. In this study an attempt was made to examine near tornado wind fields at two levels, 850 and 300 mb, using methods which maximize data compatibility. The term "normalize" is used to describe the methods used to derive comparable sets of wind data. The data considered were the SW and close SW proximity soundings. This gave a large and basically comparable data sample.

The winds at 850 and 300 mb were normalized in the following manner:

1. Each wind was expressed as a deviation in degrees from its individual sounding's mean wind direction and as a percent of the mean speed.
2. The deviation and percentage were then applied to the mean sounding wind of the SW data sample (220^{o}/48 knots) to obtain a normalized wind.

For example, consider a proximity sounding with a mean wind 195^{o}/80 knots and an 850 mb wind 155^{o}/60 knots. Its 850 mb direction deviation is then -40 degrees (a direction backed from the mean was considered negative) and its speed percentage is 75%. When -40 degrees and 75% are applied to the mean SW wind of 220^{o}/48 knots a normalized wind of 180^{o}/36 knots is obtained.

In this manner the winds of both unusually strong and light wind soundings are reduced or increased to be more comparable to the bulk of the data sample. This normalizing procedure was applied to a basically similar set of data and the corrections applied were not generally large. At 850 mb 52% of all speed corrections were 10 knots or less, and they ranged from 0 to 28 knots. The direction corrections ranged from 0 to 50 degrees and 55% of the corrections were 20 degrees or less. The normalization example given above is an extreme case. Each normalized wind was plotted at its estimated location relative to the tornado-storm. No averaging of resultant winds was done, instead the two plotted fields of normalized winds were examined for general characteristics.

Tornado Wind Fields. Figure 35 is the 850 mb normalized wind field. Winds of 40 knots or greater are enclosed by a dotted boundary. The zone of strong winds covers a large region from south to northeast of the tornado-storm. No distinct jet maxima can be identified. The more westerly winds near and to the north of the tornado-storm are possibly a storm produced effect. A general zone of confluence is apparent along a line from southwest to northeast through the tornado-storm. These normalized winds around the tornado-storm are generally 50 to 100 percent stronger than the composited tornado proximity wind field obtained by Wills (1969).

Figure 36 is the 300 mb normalized wind field. The area labeled MIN and bordered by a dashed line is the general region in which winds of less than 60 knots occurred (note that this is not a region of only less than 60 knot winds and that it depicts a trend for lighter winds to occur in the outlined area). The area labeled MAX and bordered by a dotted line is the general region in which winds of 75 knots or greater occurred (note again that this is not a region of only very strong winds but rather a region where the trend is toward stronger winds). A broad zone of diffluence is apparent from east to north-northeast of the tornado-storm. These general features might be expected if it were hypothesized that a cluster, or line, of thunderstorms existed along a slightly curved line from north-northeast to southwest of the tornado-storm. There is a tendency for a zone of maximum wind speeds to exist 25 to 75 n.mi. south to east of the tornado-storm. This could position the storm in a region of cyclonic speed shear. Once again the winds are significantly stronger than those of Wills.

These normalized wind fields demonstrate again that it is possible to investigate the squall-line scale environment surrounding tornadoes using a large sample of proximity soundings. The important consideration is that extreme care must be taken to obtain a comparable set of data before any data processing or averaging is done.

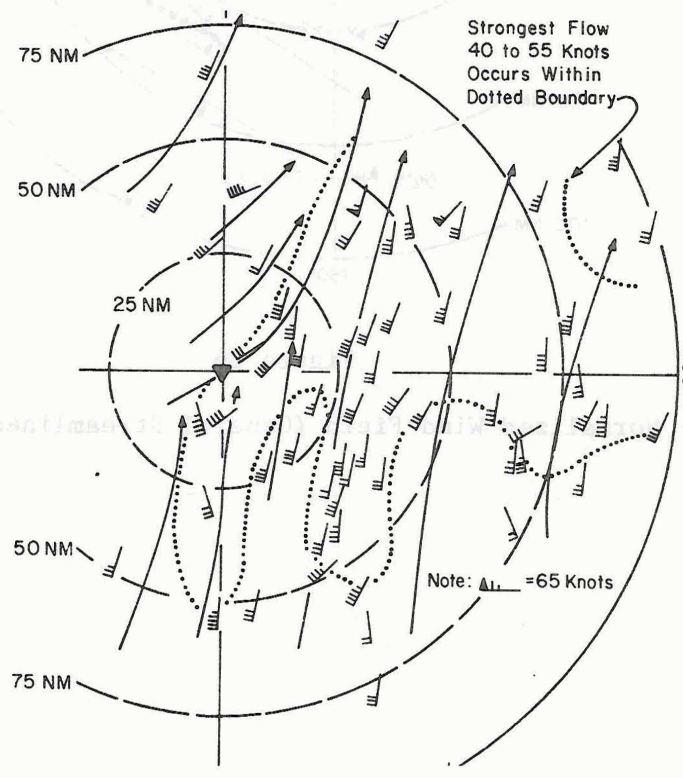

Figure 35

850 mb Normalized Wind Field (General Streamlines are Shown).

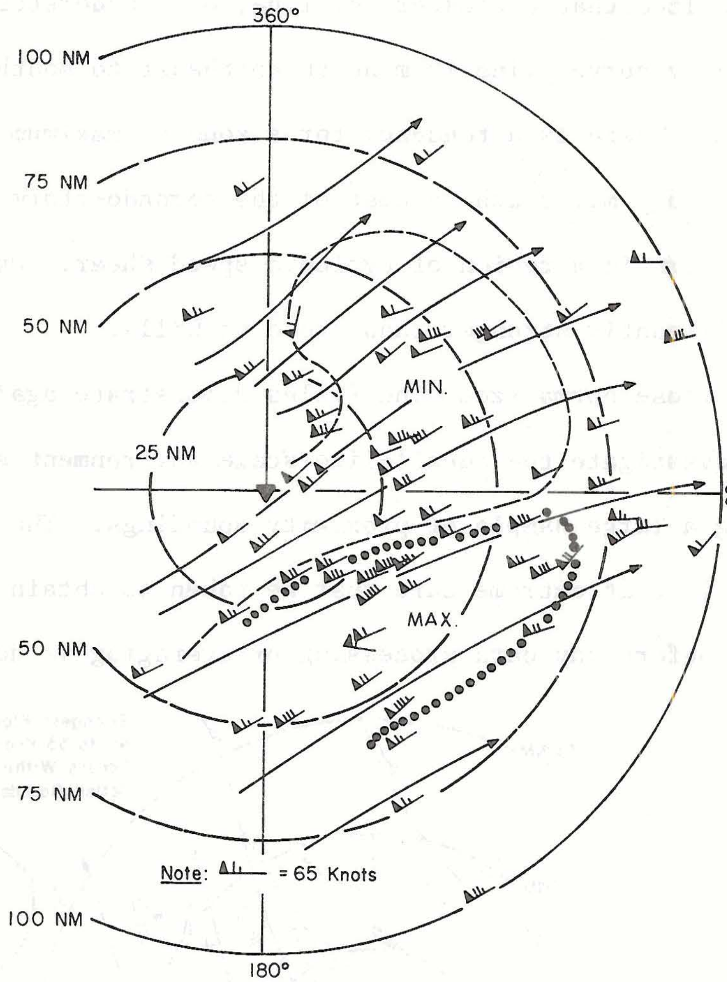

Figure 36

300 mb Normalized Wind Field (General Streamlines are Shown).

7. RESEARCH AND PREDICTION IMPLICATIONS

Research Methodology. Many researchers have used compositing or averaging techniques to study the "tornado environment". The results of this data study indicate that compositing techniques are not accurate enough to resolve the near tornado or tornado-storm environment. In addition to this, the ranges of various parameters associated with tornado occurrence is so large that averaging processes smooth away any unusual data; this unusual data could well be that which was actually obtained very near the tornado-storm. The assumption that average proximity data is representative of the near tornado environment is tenuous and conclusions based on this assumption may not be valid. The research methods of the National Severe Storms Laboratory (NSSL) are those most likely to specify the near tornado environment. The combination of dense observational data in the horizontal, vertical, and in time, precise radar data (conventional and dual doppler), and a field operation to track, photograph, and accurately locate tornadoes is the only way to document the actual tornado and tornado-storm scale environment. Descriptions of the precise data processing methods of NSSL are contained in Barnes (1973b) and Barnes, et al. (1971). An interesting explanation and description of the tornado intercept field operation is given by Golden and Morgan (1972).

It has been shown that there is a wide range of synoptic and squall-line scale environmental conditions associated with tornadoes and that similar sets of conditions may be associated with a large range of number, size and intensity of tornadoes. The range of tornado associated synoptic and squall-line scale parameters is so great that the only necessary condition, on these larger scales, for there to be a probability of tornado occurrence is that convection must occur. The probability is quite small under all but strong severe thunderstorm conditions. The set of Unusual proximity soundings examined in section 2 does verify that occasionally phenomena on the different scales of motion interact to produce a tornado under very weak thunderstorm conditions.

Forecasting Implications. The fact that air mass thermal and wind structure does not specify either tornado likelihood or number and intensity substantiates many of the severe storm and tornado forecast procedures of the Air Force Global Weather Central (Miller, 1972). These procedures stress the importance of the interaction of air mass type with synoptic and squall-line scale features. The proximity data of this study verifies the usefullness of a severe storm predictor which includes not only air mass stability but also incorporates important synoptic features such as winds aloft and directional shear in the vertical; the reader should refer to Miller, et al. (1971) for a description of such a predictor, the SWEAT Index. The importance of subsynoptic scale phenomena indicates that an index composed of important hourly surface parameters (used to monitor synoptic and squall-line scale conditions as closely as possible) should be very useful, especially when used in conjunction with a predictor such as SWEAT; see Maddox (1973) for the description of such an index.

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

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

2. Sets of conditions which produce significant severe thunderstorms, without attendent tornadoes, also occur infrequently.

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

Fujita and Pearson (1973) have shown that a small number of large, intense tornadoes are responsible for the major portion of tornado damage, and that most tornadoes are relatively weak and have a short, narrow path. This agrees well with the data of figure 20, which shows that most of the proximity soundings were associated with fewer than 10 reported tornadoes, and also with the fact that so few Tornado Outbreak soundings were found. However, Fujita and Pearson are apparently presenting a case for either:

1. Redefining the term "tornado" to apply to only large, very dangerous tornadoes, or

2. Changing forecast procedures so that the public is alerted only when large, very dangerous tornadoes are likely.

This study supports the contention that, rather than redefining "tornado" or the meaning of a "tornado watch", only severe thunderstorms should be forecast as such. The relative strength or weakness of each severe thunderstorm situation could be assessed and a "probability statement" that some of the severe thunderstorms may be accompanied by tornadoes would be included in the forecast. The individual whose farm or home is destroyed by a small, isolated tornado can hardly be consoled by the fact that, in a statistical sense, the tornado which destroyed his property was insignificant. The tornado which did 135 million dollars damage in Lubbock, Texas was one of three reported tornadoes in West Texas on 11 May, 1970. Consider also that on 19 April, 1968, there were four reported tornadoes in Arkansas. One of these formed on the outskirts of, and then moved through, the small town of Greenwood. This tornado had an observed lifetime of four minutes; yet it resulted in 14 deaths, 270 injuries, and damage in category 6 (see figure 17).

The proposed new type of severe thunderstorm watch could be worded similarily to these two examples:

1. Isolated severe thunderstorms are likely in a specified area during a specified time period. The possibility exists that one or two of these storms may produce funnel clouds or small tornadoes. This could be the forecast for a northwest wind or an over-running situation.

2. Numerous severe thunderstorms are likely in a specified area during a specified time period. Some of these storms will likely be accompanied by large, potentially destructive tornadoes. This could be the forecast for a strong, southerly type situation.

8. SUMMARY PART I

The results of a detailed study of tornado proximity soundings were presented in Part I. This work differed from previous studies in several important ways. The data was positioned relative to a moving tornado-storm. The various proximity soundings were stratified into distinct categories before any averaging was done. The general, or usual, type of tornado proximity soundings were compared to tornado outbreak and severe thunderstorm proximity soundings. Four scales of motion, important in tornado formation, were defined. Careful consideration was given to inherent errors of the data sample.

The most outstanding characteristic of the proximity data was the extremely large range of parameters associated with tornadoes. The storm relative wind configuration was found to be very 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 in a given environment. It has been shown that there is little difference between tornado outbreak and more general tornado conditions. This indicates that synoptic, squall-line, and tornado-storm scale phenomena are very important, in addition to general air mass features.

It was shown that data positioning errors of this study, and also of past studies, are great enough that tornado and tornado-storm scale features cannot be resolved by compositing techniques. Proximity soundings can be used to study squall-line and synoptic scale features associated with tornadoes. There are several different types of moisture profiles common in the vicinity of severe storms, and it was shown that squall-line scale vertical motion can be deduced from careful study of moist and dry type soundings. General features of the tornado associated, squall-line scale, wind field were identified using a normalization technique.

Several important conclusions have been made concerning research and forecast techniques. A detailed study of individual situations, the approach used at NSSL, is the best way to investigate tornado and tornado-storm scale features. Several severe storm forecasting techniques of the Air Force Global Weather Central have been given additional substantiation. There was little distinction between tornado conditions and severe thunderstorm conditions, and there have been relatively few times in the past 15 years when a significant number of severe thunderstorms occurred without isolated tornadoes also occurring. Since there is little observational basis for differentiating "tornado watches" from "severe thunderstorm watches" a new manner of wording severe storm forecasts has been suggested.

PART II

AN OBSERVATIONALLY DERIVED MODEL OF TORNADO GENESIS

1. OBSERVED FEATURES AND CHARACTERISTICS OF THE TORNADO AND TORNADO-STORM ENVIRONMENT

The most important prerequisite of any tornado theory or model is that it must be compatible with documented features of the tornado-storm environment. These observed features are reviewed in this section.

Synoptic Features. Miller (1967), Wills (1969), Darkow and Fowler (1971), and Novlan (1973) have all shown that most tornadoes form under conditions when strong convective updrafts exist in lower tropospheric layers of large vertical wind shear. Tornadoes are usually associated with high instability, strong wind fields, and severe convection. However, it was shown in Part I that tornadoes can be associated with a very large range of synoptic conditions. The reader should refer to Miller (1972) for a comprehensive review of synoptic scale features most commonly associated with tornado occurrences.

Tornado-storm Features. The preferred location for tornado development is on the right flank of a large, severe thunderstorm. Bates (1961) emphasized this favored location. Purdom's (1971) work with satellite imagery clearly demonstrates that tornadoes associated with the severe storms he studied were on their right flanks.

The core of heavy precipitation is usually 2 to 5 km N to NNE of the tornado. This feature is referred to many times in Storm Data reports. It has been documented by Snider (1971) in his study of precipitation rates and amounts associated with tornado producing thunderstorms. Tornado photographs, and numerous accounts in Storm Data, indicate that precipitation in the immediate tornado vicinity, if any, is usually very light. Large hail frequently occurs just to the left of the tornado's track.

Tornadoes usually develop beneath a lower based, rotating collar cloud. Tornadoes often are located beneath the first (in relation to the main thunderstorm) towering cumulus of a line of flanking cumulus clouds extending southwestward from the main thunderstorm (see Bates, 1961 and 1970).

Size and Intensity. A wide range of sizes and intensities is associated with verified tornadoes (Pearson and Fujita, 1973). There is a spectrum of dust devil and tornado intensity with some overlap between small tornadoes and large dust devils. There are many reports in Storm Data that demonstrate the existence of this intensity spectrum. For example:

1. 18 May, 1967, Omaha, Nebraska. A large whirlwind 100 feet in diameter and several thousand feet high formed under clear skies. It destroyed garages, toppled trees and downed power lines.

2. 21 April, 1971, Western Tennessee. A large whirl did considerable property damage several minutes before a thunderstorm began.

3. 16 May, 1971, Lubbock, Texas. A funnel cloud was spawned by a small shower with a radar top of 22,000 feet. The funnel was observed by thousands of persons and produced no damage.

4. 6 October, 1969, Conway, Arkansas. A small, white, rope funnel damaged four houses. It was 20 feet wide at the ground.

5. 19 May, 1960, Eastern Kansas. A large tornado produced heavy damage, 1 fatality, and 91 injuries along a 80 mile path. The storm was not well defined as a funnel but was described as a rolling, black mass of cloud accompanied

> by a dreadful roar. The damage path was exceptionally wide, 1/4 to 3 miles, but the debris showed a definite center line along the track.

Kraus (1973) studied a storm in Connecticut and Massachusetts that produced a verified tornado which remained on the ground for three minutes. The storm's radar top at the time of tornado occurrence was only 35,000 feet. No hail and only one lightning stroke was reported by people in the storm path.

Duration. A relatively few large tornadoes exist for several hours and produce a long damage track. These destructive storms have been studied by Darkow (1971), Wilson and Morgan (1971), and Pearson and Fujita (1973). However, descriptions in Storm Data indicate that most tornadoes have a short duration of 15 minutes or less. In fact many tornadoes had an observed duration of only 1 to 3 minutes. Reber (1954) observed a series of tornadoes and funnel clouds in Northeastern Colorado and Western Nebraska, and none of them had a life time of more than 3 minutes.

Pressure Profiles. Few pressure measurements have been made in the actual damage track of a tornado. Fujita (1960 and 1970) reported in depth on the Fargo, North Dakota, and Lubbock, Texas tornadoes. The pressure traces associated with these tornadoes and also those obtained at Topeka, Kansas, 1966: Newton, Kansas, 1962: and Dyersburg, Tennessee, 1952, have all recorded pressure drops of 35 mb or less. These measurements may, however, be subject to significant errors. One of the most important factors would be the instrument's response to the rapid pressure changes. The intensity and stage of development of the tornado could also affect the measured pressure deficit. For example, the Lubbock tornado was dissipating when it passed over the instrument site.

The visible edge of the condensation funnel has been said to roughly represent the condensation pressure surface. The exactness of this approximation depends upon many factors such as the precise temperature and moisture distributions in the sub-cloud layer. However, the height of the cloud base from which tornadoes often descend, 2,000 to 5,000 feet above ground level, implies a significant surface pressure reduction. An approximate pressure profile can be obtained by using measured winds and applying cyclostrophic balance:

$$-\frac{1}{\rho}\frac{\partial p}{\partial R} = \frac{V^2}{R}, \quad \text{where}$$

ρ = density
p = pressure
R = radius
V = velocity

Hoecker (1961) and other researchers have used this method to deduce central pressure deficits of 60 to 80 mb.

Wind Profiles. Few wind measurements have been taken very near a tornado funnel. Most "measured" velocities are determined by photogrammetrically tracking debris and cloud features in tornado photographs and movies. Studies of this type, in particular those of Fujita (1960) and Hoecker (1961), have found maximum speeds on the order of 100 meters per second. An annemometer near Tecumseh, Michigan, measured a wind gust of 151 miles per hour as a tornado was passing by on Palm Sunday, 1965 (see Fujita, et al. 1970). This agrees well with inferred velocities. The velocity profile near the tornado funnel is considered to be similar to that of a combined Rankine vortex. The velocity increases exponentially with decreasing radius until a velocity maximum is reached. The velocity then decreases linearly to zero at the vortex center.

Appendix II is a discussion of a series of photographs of tornado genesis. Many of the important features of the tornado environment, as discussed in this section, are clearly visible and are reviewed.

2. TORNADO THEORIES AND MODELS

Brief Review of Tornado Theories. Many theories of tornado genesis have been advanced. Vonnegut (1960), among others, advanced the theory that electrical discharge heating was an energy source for initiating tornado circulations. The electrical heating would produce lowered pressure and increased wind flow. Many tornadoes are associated with unusual electrical phenomena. However, only about 75 percent of tornado producing thunderstorms can be identified as being unusually electrically active (see Taylor, 1973). Since tornadoes tend to develop on the right flank of a thunderstorm away from the electrically active region, it is doubtful that electrical discharges are directly related to tornado genesis.

Fulks (1962) hypothesized that a middle and lower tropospheric vortex could develop and intensify beneath a region of strong upper tropospheric divergence. The upper divergence field would be produced by flow around the intense thunderstorm and the vortex circulation would strengthen as it built downward into the warm, moist sub-cloud layer. Some of the important requirements of his theory are:

1. A wind field that veers strongly with height.
2. A stable inversion at the top of the tornado associated towering cumulus.
3. A basically hydrostatic pressure drop at the vortex center.
4. Frictionally induced convergence into the vortex to produce a central core of rapidly rising air.

Bates (1961) felt that the tornado was produced by the subsidence of a rotating, "wet" cloud layer. The middle level, wet cloud layer was produced by a dying storm cell, and because of its relative coolness should be sinking. If it interacted with the cyclonic, wake vortex on the right side of an active thunderstorm, rotation would be induced. The rotation would produce a centrifugal redistribution of mass toward the outer regions resulting in a doughnut shaped region of strong subsidence and eventually a converging flow, with conserved angular momentum, toward the center of the doughnut. The eventual production of a tornado would occur at the doughnut center.

As more observational data became available Bates (1970) modified his ideas and advanced a different theory of tornado formation. He considered that a flanking line of developing cumulus-congestus was a necessary prerequiste. The discrete updrafts of these developing cumuli could, under favorable flow conditions, be sheared into the large, rotating updraft of the parent thunderstorm. The mass demands of the large updraft upon the interacting smaller updraft, and conservation of angular momentum, could eventually produce a tornado beneath one of the flanking cumuli. Bates also felt that large, long-lived thunderstorm updrafts would inevitably rotate because of the convergence of weak angular momentum from the environmental flow into the updraft region.

Gray (1969 and 1971) hypothesized that the impulsive blocking of a strongly sheared vertical wind field by a new updraft would produce a cyclonic, wake vortex necessary for circulation initiation. Gray, like Fulks, advanced the idea that the overall approximate hydrostatic balance of the central pressure drop must be considered when dealing with the energetics of the tornado vortex. This idea requires subsidence of upper tropospheric air down the vortex center.

Fujita (1973) proposes that the mechanism of tornado formation is the production of a twisting downdraft on the right flank of a large rotating thunderstorm. When this downdraft interacts with the mesocyclone in lower levels a region of very strong cyclonic vorticity (on the order of 10^{-2}/sec or greater) is produced. He also points out (Fujita, et al. 1971) that intense tornadoes tend to occur in the evening when a more stable lapse rate near the surface forces stronger inflow into the vortex center because of less outer radius vertical motion.

Maddox and Gray (1973) have emphasized the development of the initial vortex on the thunderstorm produced gust front. Once the vortex is formed, frictional convergence toward the circulation center and suppressed vertical motion in outer portions of the circulation appear to play an important role during initial intensification.

Barnes (1972 and 1973a) made a precise study of the tornado occurrences in the NSSL data network on 30 April, 1970. He found that the tornado circulations (hook echoes) were on the leading edge of the thunderstorm gust front and that the echo configuration of two coexistent hook echoes along the gust front resembled gravity waves. The thunderstorm associated pressure field produced a strong west to east acceleration of the downdraft air. Barnes suggests that the density interface of the gust front may be unstable and that components of gravity and wind shear normal to the interface may act to intensify vortical perturbations upon it. These vortices could be entrained into the main updraft enhancing its rotation. Once updraft rotation becomes large smaller vortices moving into the updraft region may intensify about their own axes.

It is of interest that Golden (1973) has found that Florida Keys waterspouts form on a cloud-line produced wind discontinuity. In fact he occassionally observed several circulations existing along such a discontinuity line, one or two of which might intensify into waterspouts. The waterspouts he observed rapidly dissipated when a flow of much cooler, precipitation associated air (the "density surge") entered the waterspout circulation.

<u>Laboratory Models</u>. Many investigators have studied the tornado by creating tornado-like vortices in the laboratory. Ryan and Vonnegut (1969) created a vortex about a vertical axis by electrical discharge heating. Many other researchers, in particular Chang (1969), Wan and Chang (1971), Ward (1972), Fujita (1972), Hsu (1973), and Chang and Park (1973), have produced laboratory vortices by imposing both vorticity and vertical velocity on the air flowing into their models. Since many of the results obtained studying these various models are similar, and since the primary difference between the various models is their actual physical and mechanical features only the model of Ward will be considered in detail.

Ward's model consisted of an exhaust fan which produced an upward flow (considered analogous to convection) through a cylinder. Angular momentum was imparted to the inflowing air by a cylindrical mesh screen rotating around the edge of the inflow layer. The depth of the inflow layer and the diameter of the updraft could be varied. Photography was used in conjunction with smoke tracers to determine the flow fields. The inflow angle was determined at the outer edge of the inflow layer by using a small direction vane. Ward defined the ratio of the width of the updraft cylinder to the depth of the inflow layer as the "configuration ratio". The surface pressure profile was measured with a static pressure port connected to an electronic manometer. The pressure sensor could be moved in an arc across the bottom surface of the model.

The measured pressure profiles are qualitatively very similar to actual tornado pressure traces. The magnitude of the measured pressure drop was proportional to the ratio of vortex height divided by vortex diameter. Of considerable interest is the fact that these pressure reductions are maintained solely by the "convective updraft". More than one vortex can be produced when the "configuration ratio" is greater than unity. The number of vorticies which form depends strongly on the inflow angle and the "configuration ratio". With a fixed "configuration ratio" the greater the inflow angle the greater the number of small, intense vortices which rotate about a common center.

A brief summary of the findings of the previously mentioned laboratory modelers is presented in the following list:

1. Chang (1969) and Wan and Chang (1971) - boundary layer effects very important, vortex inflow occurs in a very shallow surface layer.

2. Ward (1972) - frictional induced inflow important, tornado-like pressure profile duplicated, pressure reduction proportional to ratio of vortex height to vortex diameter, number and intensity of vortices produced strongly dependent upon inflow angle, updraft diameter and depth of inflow layer.

3. Fujita (1972) - updraft strength and rotation speed affect intensity of resultant vortex, most intense vortex produced by a combination of strong rotation and a weak to moderate updraft.

4. Chang and Park (1973) - frictionally induced low-level convergence and bouyancy drive the air upward as it spirals inward.

5. Hsu (1973) - frictional retardation of tangential motion near the ground results in an excessive radial pressure gradient which produces convergence and the updraft near the earth's surface.

The work of these modelers has demonstrated the importance of frictionally induced radial inflow and of boundary layer effects.

3. A QUALITATIVE MODEL OF TORNADO GENESIS

Vortex Initiation. The initial formation of a vortex circulation probably occurs on the leading edge of the thunderstorm gust front. This could be the result of perturbations on the gust front producing intense shear zones and perhaps even unstable vortex sheets (Maddox and Gray, 1973) or it could be the result of the shear across the gust front density interface becoming so great that the interface becomes unstable (Barnes, 1973a).

Figures 37, 38 and 39 show a hypothetical series of events which could produce a vortex circulation 1 to 5 km in diameter. In figure 37 the gust front curves from downwind of the precipitation core around the weak echo region (WER), or updraft inflow region (Marwitz, 1971 Part I), and then trails off to the SSW. The occassional presence of a cyclonic wave on the gust front, in the updraft region, is verified by the case studies of Barnes (1972) and Lemon (1970). The portion of the gust front extending SSW from the updraft region is considered to be the discontinuity line along which vortices are likely to form. The tornado storm relative wind profiles examined in section 4 of Part I, show that, typically, strong inflow with a large easterly component is occurring in the region labeled WER. Strong upper level flow is impinging against and around the rear, or southwest flank of the storm (refer to tables 3 and 4 in section 4). It is important that Marwitz (1973) and Grandia (1973) have found low level winds in the WER inflow that are significantly stronger than winds measured in nearby environmental soundings. This implies that the storm-relative low level winds may be considerably stronger than those derived in section 4 using environmental

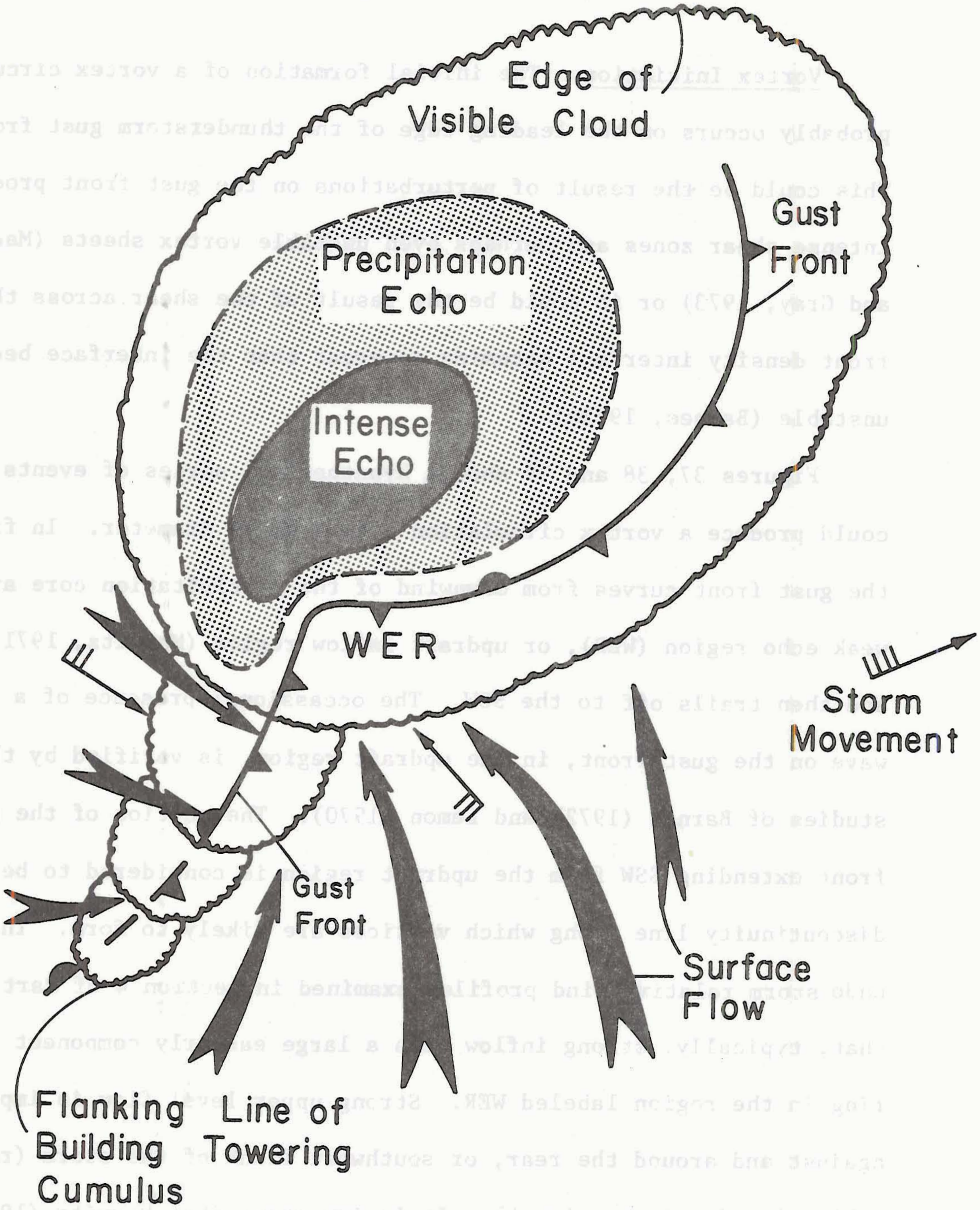

Figure 37

Simplified Model of a Single Severe Thunderstorm With a Flanking Line of Cumuli (View is Looking Down From Above).

soundings. Since the intense echo portion of the storm normally slopes toward the inflow with height, or out over the area labeled WER, the strong flow around the <u>upper portion</u> of the storm creates a convergent region, and a dynamic pressure excess, over the area immediately south of the precipitation echo (as depicted in figure 37) and west of the gust front. Barnes' studies (1972 and 1973a) indicate that the region of lowest surface pressure (or meso-low) exists, at least in some cases, SE of the cyclonic wave on the gust front. This location of the meso-low and higher pressures west of the gust front combine to produce a strong pressure gradient across the SW portion of the gust front. Subsidence produced by blocked upper winds, precipitation and cloud particles evaporating into dry, middle level air, and a strong west to east pressure acceleration all act together to produce a strong westerly flow behind the gust front, especially just south of the precipitation echo (note that this refers to the low elevation angle precipitation echo).

Figure 38 shows how localized strong flow could perturb the gust front configuration of figure 37 and cause an intrusion of westerly winds into the right (moving with the storm) side of the updraft region. If the strong, horizontal, cyclonic shear zone produced by this intrusion is unstable, a vortex could be produced on the right flank of the storm. This is depicted in figure 39.

Charba and Sasaki (1971) did a detailed analysis of a squall-line gust front. They found that the wind shift line preceded a strong density surge, and temperature minimum, by almost 4 km and that there was actually a weak temperature maximum between the wind shift line and density surge. Through the lower 500 meters the gust front was very steep, actually exhibiting a slight forward tilt. These findings are

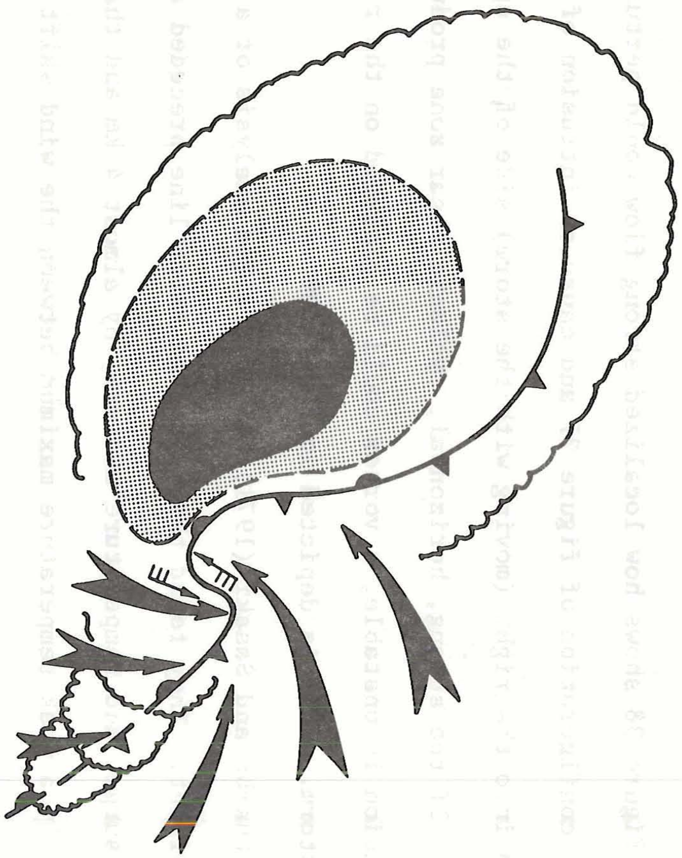

Figure 38

Perturbation on the Gust Front South of the Precipitation Echo (Features are Identical to Those of Figure 37).

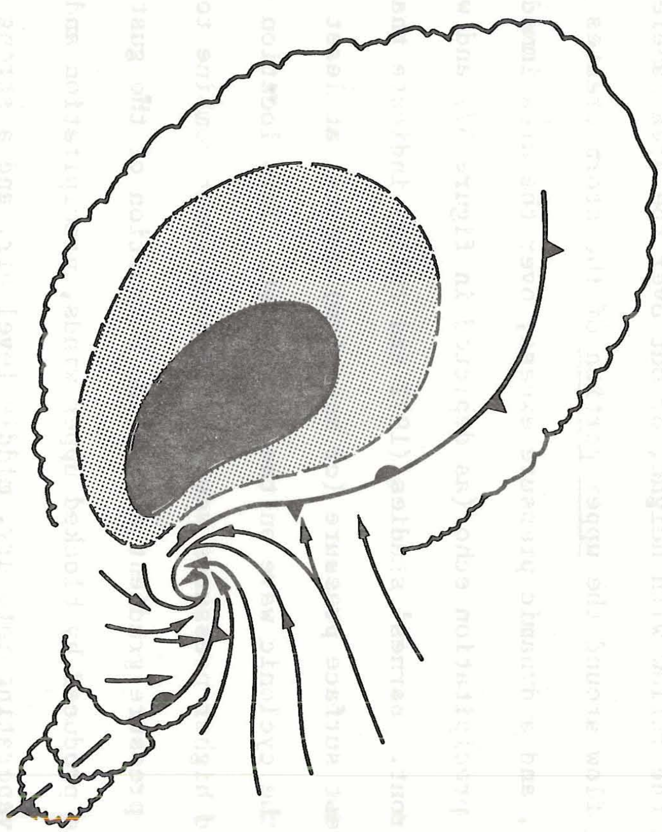

Figure 39

Perturbation Develops into Vortex Circulation on Right Flank of Storm (Features are Identical to Those of Figure 37).

important because they show that cold, stable air (air which would probably destroy the vortex if it became involved in the circulation) can be far to the west of the gust front. The nearly vertical slope of the gust front means that any perturbation of it, as shown in figure 38, could produce a nearly vertical surface across which there would be a directional wind shear of approximately 180 degrees. This meets the definition of a vortex sheet, an unstable phenomena which tends to wrap itself into a vortex circulation (Milne-Thomson, 1955).

In section 2, Part I, it was shown that wind fields which were characterized by a large veering between low and upper levels, or by northwesterly flow at middle and upper levels were poor tornado producers. It was also shown that most of the Severe Thunderstorm Outbreak soundings had west to northwest middle and upper level winds. It is hypothesized that in these type situations, with strong upper flow impinging on the left rear of the storm, the thunderstorm produces a strong northwest to southeast pressure gradient. This pressure gradient could cause the gust front to be accelerated southeastward across the inflow region. This would either cut off the inflow or, more likely, lift the inflow aloft. A tornado-storm scale overrunning situation would thus be created. As already discussed in detail this is an unfavorable situation for vortex circulations to reach the ground. Crawford and Browns' (1972) doppler study of a squall-line thunderstorm revealed a circulation aloft over a shallow dome of outflow. The environmental wind field was characterized by middle and upper level northwesterly winds.

Vortex Intensification. Once a vortex forms it may intensify rapidly for a brief period of time because of strong frictional convergence toward its center. The importance of frictional drag near the surface in allowing a strong radial inflow has been discussed by Kuo (1971), Wan and Chang (1971), Ward (1972), Chang and Park (1973), and Hsu (1973). This is considered to be similar to the CISK type of frictional convergence associated with tropical storm development as discussed by Charney and Eliassen (1964), and Gray (1968).

The possible effects of frictionally induced radial inflow were examined by studying individual parcel accelerations from a lagrangian point of view. Figure 40 depicts the basic symbology used in this study. Individual parcel accelerations were computed and parcels were tracked in time for different sets of conditions. The horizontal momentum equation may be expanded into the following two equations in the natural coordinate system:

1		2	3
$\frac{\partial V}{\partial t}$	=	$-\frac{1}{\rho}\frac{\partial p}{\partial s}$	$-F_s$
Parcel Rate of Change of Speed		Pressure Gradient Acceleration in the Direction of the Motion	Frictional Retardation

4		5	6
$\frac{V^2}{R}$	=	$-\frac{1}{\rho}\frac{\partial p}{\partial n}$	$-fV$
Centrifugal Acceleration		Pressure Gradient Acceleration Normal to the Direction of Motion	Coriolis Acceleration

V = speed
t = time
ρ = density
p = pressure
F_s = frictional acceleration

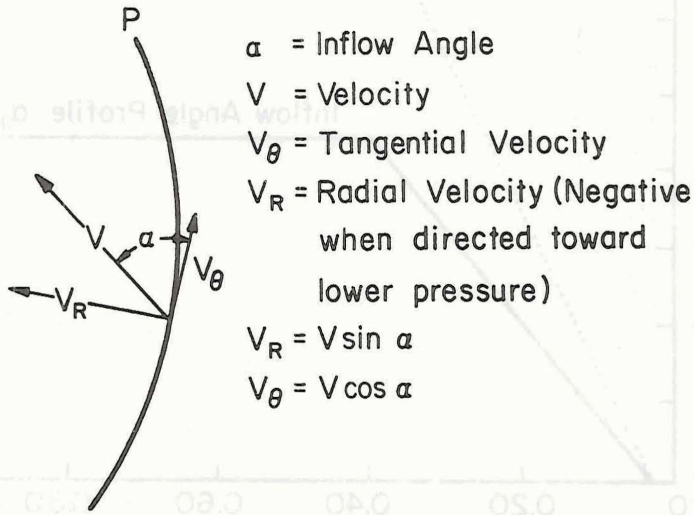

Figure 40

Vortex Symbology (P = an Arc of a Circular Isobar with Center at the Vortex Center).

R	=	radius of curvature
f	=	coriolis parameter
s		denotes along the direction of motion
n		denotes normal to the direction of motion.

Terms 2 and 3 can act to change the speed of a parcel and terms 4, 5, and 6 can act to change the parcel's direction of movement. The coriolis term (fV) is assumed to be negligibly small. If an inflow angle profile is assumed and left constant then terms 4 and 5 need not be considered and the effects of terms 2 and 3 can be studied. Two sets of inflow angles were assumed and left constant. These assumed inflow angle profiles are shown in figure 41. The data of Fujita (1960) and Hoecker (1960) both indicate that the inflow angles around actual tornadoes are quite large (65^{o} to 80^{o}) except at very small radii.

Before the effects of accelerations 2 and 3 are specifically discussed the assumptions involved will be listed and considered.

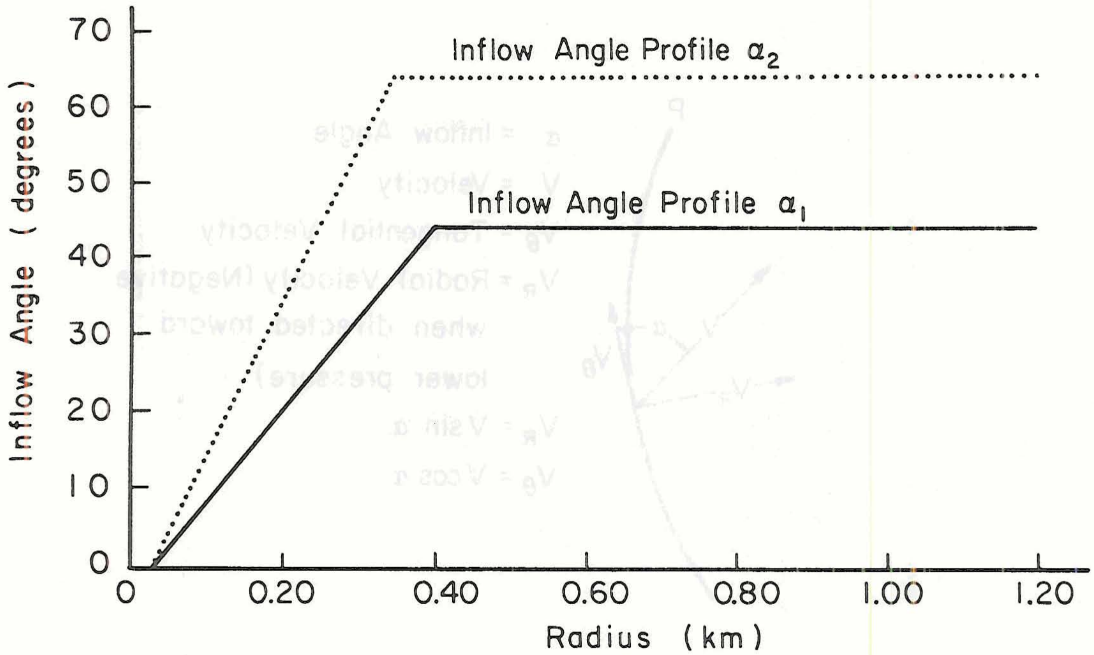

Figure 41

Assumed Inflow Angle Profiles.

The assumptions which were made in calculating accelerations were:

1. An initial circulation and velocity profile were assumed.
2. Frictionally forced inflow angles were assumed and held constant in time but allowed to decrease with radius.
3. A pressure decrease was assumed to be occurring near the center of the circulation.
4. Two dimensional flow. Any vertical motions considered were those necessary to maintain mass continuity of the two dimensional flow field.
5. A symmetric vortex was considered.
6. Density constant.
7. f negligibly small.
8. Frictional accelerations were approximated by

   $$-C_D/\Delta Z\ V^2 \quad \text{where}$$

   C_D = drag coefficient which was assumed to be 5×10^{-3}, and

   ΔZ = depth of dissipational layer which was assumed to be 250 meters.
9. All calculations involved <u>mean values</u> for the layer surface to 250 meters.

Such a restrictive set of assumptions precludes one from drawing direct or precise analogies with actual processes. However, the results can be used to help speculate on what might be occurring in the atmosphere.

The initial vortex was assumed to have a radius of 1.2 km with a weak velocity maximum of 10 m/sec at radius 0.6 km. The flow in the undisturbed environment was set at 7.5 m/sec. Accelerations were computed and individual parcels were followed in 10 second time intervals for four different cases. Little will occur, except a slow decay, if a drop in central pressure is not assumed to be occurring during the time steps. The assumed initial conditions were considered for two fixed inflow angle profiles and for two sets of pressure profiles.

The pressure profiles were determined as follows: At each 10 second time step the pressure gradient acceleration, along R, was assumed to be either $-V_\theta^2/2R$ or $-2V_\theta^2/R$ where R = radius. The assumed pressure drop was either half or twice what cyclostrophic balance would require. It should be emphasized that the initial wind profiles, inflow angle profiles, and rates of pressure drop were not meant to duplicate any specifically observed features of actual tornadoes. Figures 42 through 45 show the initial and final velocity profiles, the inflow profile, and the assumed pressure gradient for the four cases. In all four cases the final velocity maximum occurred at a decreased radii and was more pronounced. Two cases (I and III) intensified only slightly because of the assumed weak pressure gradient. Case II with the stronger pressure gradient and smaller inflow angle profile showed a marked increase in intensity. In this example the velocity maximum has almost doubled in intensity. The most spectacular intensification was in Case

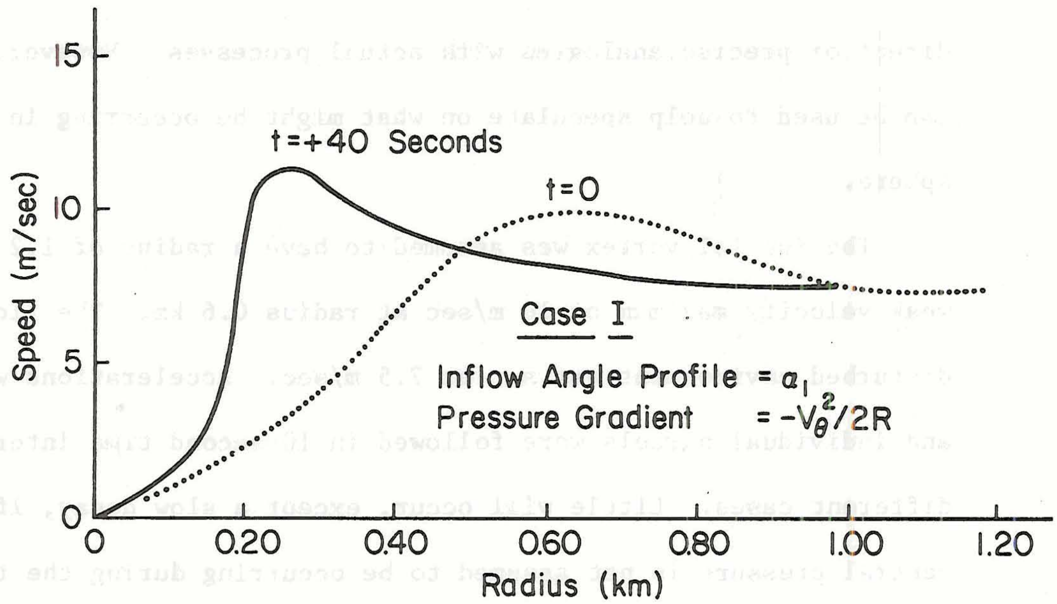

Figure 42

Case I Initial and Final Velocity (V) Profiles.

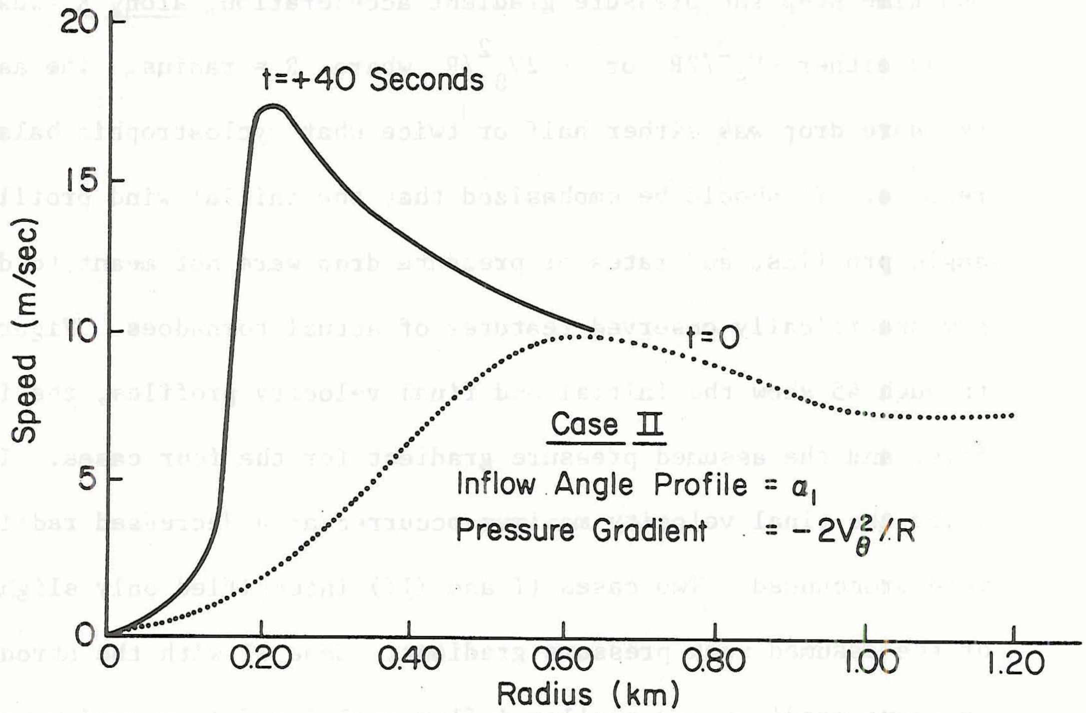

Figure 43

Case II Initial and Final Velocity (V) Profiles.

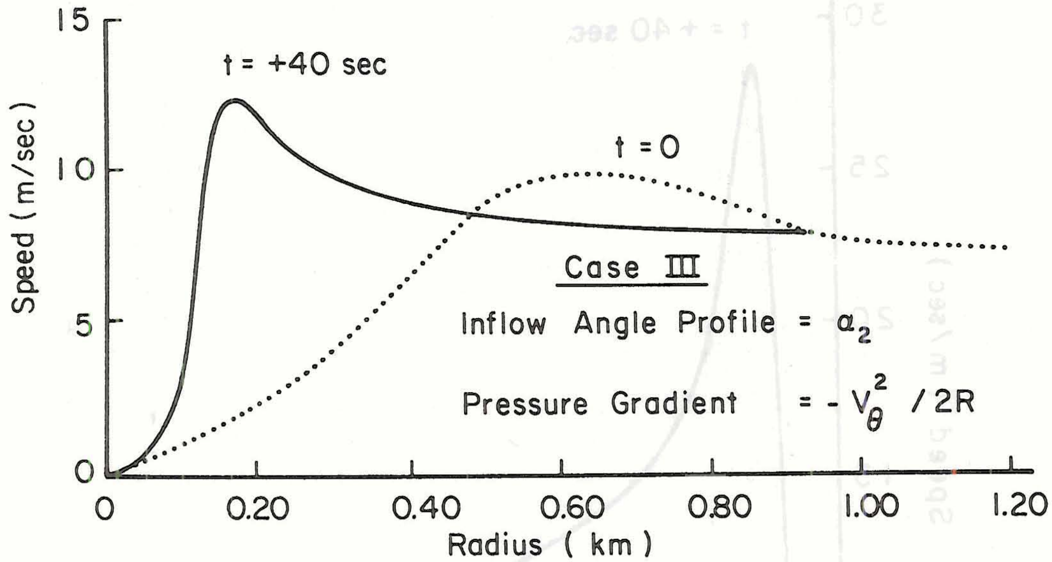

Figure 44

Case III Initial and Final Velocity (V) Profiles.

IV where the large inflow profile (α_2) and stronger pressure gradients ($-2V_\theta^2/R$) were assumed. The broad 10 m/sec maximum rapidly becomes a sharp velocity peak almost three times more intense. The calculations were not carried beyond 40 seconds because in that short time frame the pressure gradient and advective terms had acted to intensify the velocity maximum to its peak and also to decrease the radius of this maximum to inner radii where the inflow angle is very small. Beyond about 40 seconds all the resultant circulations considered decay rapidly as the advective and frictional terms act to destroy the velocity peak.

It is of interest that the central pressure drop required in case IV, the case of dramatic intensification, is only 1.8 mb. This certainly doesn't seem to be an unrealistically large pressure fall. However, an important point is that for this circulation to intensify further a continued drop of central pressure must occur. In nature it seems likely that the further intensification of the vortex must be the

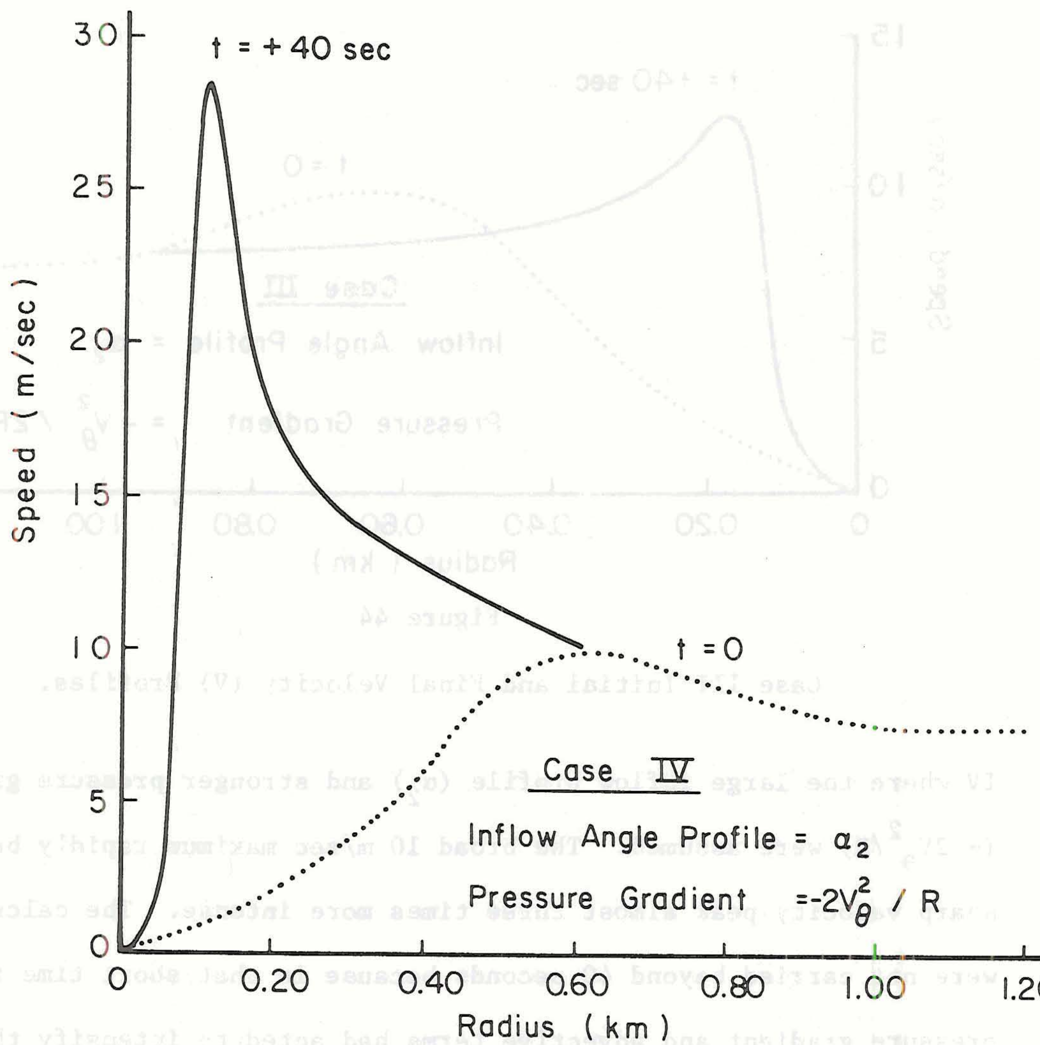

Figure 45

Case IV Initial and Final Velocity (V) Profiles

result of an unspecified interaction between the motion fields of the vortex and those of the attendent thunderstorm.

The vertical velocities required by mass continuity at the top of the 250 meter layer were computed for the initial circulation and for case IV. These vertical velocity profiles are shown in figure 46. The broad area of upward motion in central portions of the initial circulation rapidly shrinks to a small annulus of <u>intense vertical motion</u>.

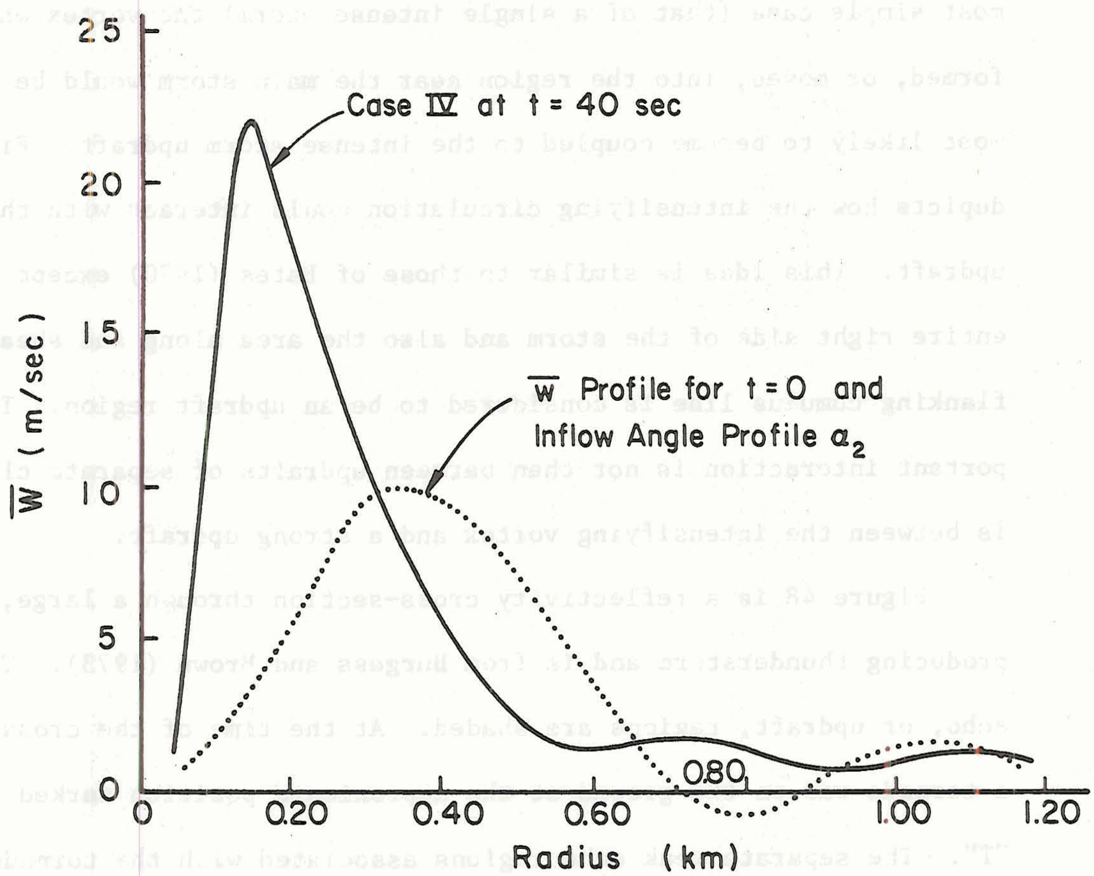

Figure 46

Required Vertical Velocity ($\overline{W}$) Profiles.

The vertical motion is weakly up or down in outer portions of the circulation and must become downward at larger radii where inflow angles of near zero increase to the large values assumed near the circulation. The circulation tends to isolate itself as a separate flow feature as it begins to intensify. It becomes characterized by subsidence at outer radii (a result of the divergence of mass produced by increasing radial velocities) and an annulus of intense vertical motion near its center. If the circulation exists in, or under, the right portion of the main thunderstorm's updraft it may develop in vertical extent to a point where it becomes coupled or interacts with the storm updraft. In the most simple case (that of a single intense storm) the vortex which formed, or moved, into the region near the main storm would be the one most likely to become coupled to the intense storm updraft. Figure 47 depicts how the intensifying circulation could interact with the primary updraft. This idea is similar to those of Bates (1970) except that the entire right side of the storm and also the area along and ahead of the flanking cumulus line is considered to be an updraft region. The important interaction is not then between updrafts of separate clouds but is between the intensifying vortex and a strong updraft.

Figure 48 is a reflectivity cross-section through a large, tornado producing thunderstorm and is from Burgess and Brown (1973). The weak echo, or updraft, regions are shaded. At the time of the cross-section a tornado was on the ground at the approximate position marked by the "T". The separate weak echo regions associated with the tornado and the thunderstorm could be interpretted as indicating that the vortex circulation is indeed isolated from the thunderstorm updraft at low levels. The frequently observed fact that tornadoes tend to form beneath the first cumulus of the flanking line seems to verify the importance of an interaction occurring between the thunderstorm and the intensifying updraft. The importance of this interaction is also substantiated by the studies of Golden (1973) and Henz (1973). Golden found that circulations which intensified into waterspouts were usually associated with a rapidly growing cumulus. Henz found that tornado occurrences on Colorado's plains were usually associated with rapidly intensifying thunderstorms.

The vortex considered in cases I through IV was a symmetric cylinder by assumption. Frictional convergence is strongest nearer the

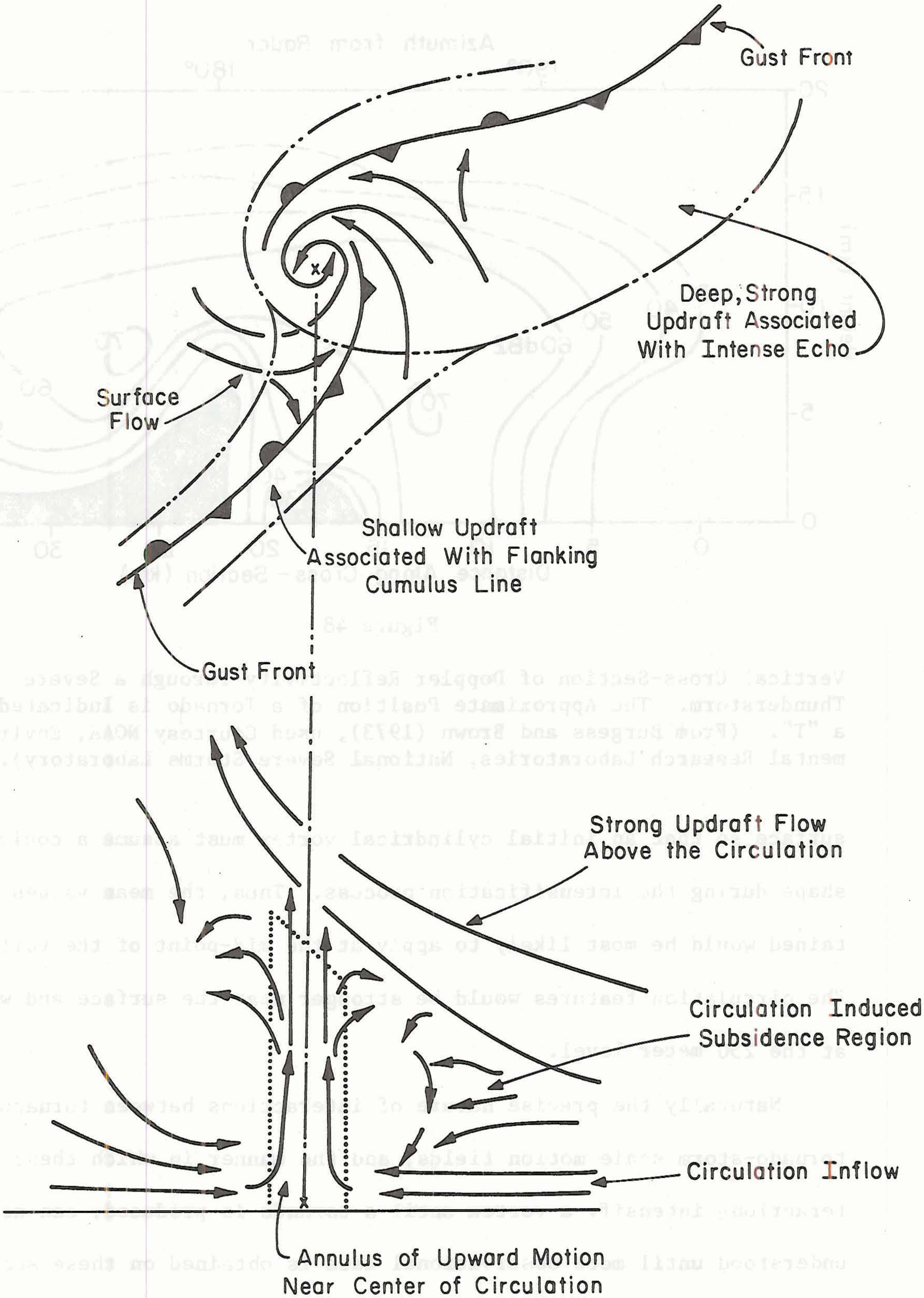

Figure 47

Hypothesized Interaction Between the Intensifying Vortex Circulation and the Strong Thunderstorm Updraft.

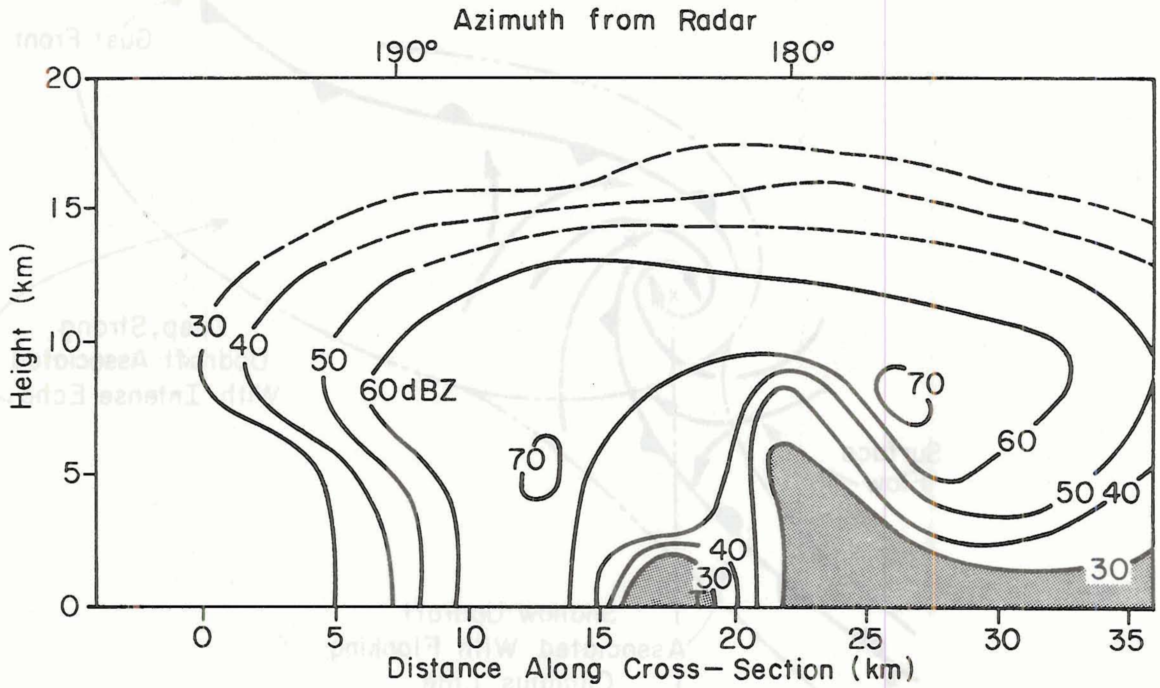

Figure 48

Vertical Cross-Section of Doppler Reflectivity Through a Severe Thunderstorm. The Approximate Position of a Tornado is Indicated With a "T". (From Burgess and Brown (1973), used Courtesy NOAA, Environmental Research Laboratories, National Severe Storms Laboratory).

surface so that an initial cylindrical vortex must assume a conical shape during the intensification process. Thus, the mean values obtained would be most likely to apply at the mid-point of the vortex. The circulation features would be stronger near the surface and weaker at the 250 meter level.

Naturally the precise nature of interactions between tornado and tornado-storm scale motion fields, and the manner in which these interactions intensify a vortex until a tornado is produced, can not be understood until more observational data is obtained on these scales. The fact that most tornadoes form, intensify, and dissipate in a very short period indicates that there may be substantial differences, at least quantitatively, between the processes and interactions which produce the short lived "average" tornado and those which produce the occassional intense long-lived tornado.

4. SUMMARY PART II

The important features of the tornado and tornado-storm scale environments have been considered. Tornado theories and laboratory models have been reviewed and considered. The modeling work of Ward was discussed in detail because the vortex features observed in his experiments duplicate many features actually observed, in and near tornadoes. One of the very basic features of any tornado theory must be its compatibility with observationally documented tornado characteristics.

A qualitative model of tornado genesis on the right flank of a single, intense thunderstorm has been developed. The important features of this model are:

1. The initial vortex develops on an unstable perturbation of the thunderstorm gust front.

2. Frictional convergence in lower layers allows the initial vortex to intensify rapidly for some discrete time period.

3. The vertical motion field established by the intensifying circulation establishes the vortex as a distinct flow feature. It is characterized by a large outer region of subsidence, or weak vertical motion, and a small inner annulus of intense upward motion.

4. The interaction of the vortex and thunderstorm motion fields provides the unspecified mechanism for increasing the pressure drop at the vortex center which is needed for continued intensification.

The hypothetical examples of frictional induced intensification were very simplified and were done to achieve an insight into processes which might occur in the atmosphere. Actual measurements of wind, temperature, and moisture fields around tornadoes are needed so that the manner in which the thunderstorm updraft and a boundary layer circulation interact to produce an intense vortex can be understood.

BIBLIOGRAPHY

Achtemeir, G. L., 1969: Some observations of splitting thunderstorms over Iowa on August 25-26, 1965. Preprints of Papers, Sixth Conf. on Severe Local Storms, Chicago, 89-94.

Barnes, S. L., 1972: Morphology of two tornadic storms: An analysis of NSSL data on April 30, 1970. Preprints of Papers, Fifteenth Radar Meteor. Conf., Champaign, 69-76.

____________, 1973a: Radar-observed merger of twin hook echoes. Preprints of Papers, Eighth Conf. on Severe Local Storms, Denver, 161-164.

____________, 1973b: Mesoscale objective map analysis using weighted time-series observations. NOAA Tech. Memo. ERL NSSL-62, 60pp.

____________, J. H. Henderson, and R. J. Ketchum, 1971: Rawinsonde observation and processing techniques at the National Severe Storms Laboratory. NOAA Tech. Memo. ERL NSSL-53, 246pp.

Bates, F. C., 1961: The Great-Plains squall-line thunderstorm - a model. Ph.D. Dissertation, St. Louis University, 164pp.

____________, 1970: Refer to Severe Storms Research Group of St. Louis University.

Beebe, R. G., 1958: Tornado proximity soundings. Bull. Amer. Meteor. Soc., 39, 195-201.

Bonner, W. D., R. M. Reap, and J. E. Kemper, 1971: Preliminary results on severe storm prediction by screening regression using forecast predictors. Preprints of Papers, Seventh Conf. on Severe Local Storms, Kansas City, 36-41.

Burgess, D. W., and R. A. Brown, 1973: The structure of a severe right-moving thunderstorm: New single doppler radar evidence. Preprints of Papers, Eighth Conf. on Severe Local Storms, Denver, 40-43.

Chang, C. C., 1969: Recent laboratory model study of tornadoes. Preprints of Papers, Sixth Conf. on Severe Local Storms, Chicago, 244-252.

____________, and C. Park, 1973: New laboratory model of a tornado-like vortex. Preprints of Papers, Eighth Conf. on Severe Local Storms, Denver, 197-198.

Charba, J., and Y. Sasaki, 1971: Gravity current model applied to analysis of squall-line gust-front. Preprints of Papers, Seventh Conf. on Severe Local Storms, Kansas City, 277-283.

BIBLIOGRAPHY (cont'd)

Charney, J. G., and A. Eliassen, 1964: On the growth of the hurricane depression. J. Atmos. Sci., 21, 68-75.

Crawford, K. C., and R. A. Brown, 1972: Doppler velocity measurements in an approaching squall-line. Preprints of Papers, Fifteenth Radar Meteor. Conf., Champaign, 27-34.

Darkow, G. L., 1969: An analysis of over sixty tornado proximity soundings. Preprints of Papers, Sixth Conf. on Severe Local Storms, Chicago, 218-221.

____________, 1971: Periodic tornado production by long-lived parent thunderstorms. Preprints of Papers, Seventh Conf. on Severe Local Storms, Kansas City, 214-217.

____________, and M. G. Fowler, 1971: Tornado proximity sounding wind analysis. Preprints of Papers, Seventh Conference on Severe Local Storms, Kansas City, 148-151.

Fankhauser, J. C., 1971: Thunderstorm-environment interactions determined from aircraft and radar observations. Mon. Wea. Rev., 99, 171-192.

Fawbush, E. J., and R. C. Miller, 1952: A mean sounding representative of the tornadic airmass environment. Bull. Amer. Meteor. Soc., 33, 303-307.

____________, and ____________, 1954: The types of airmasses in which North American tornadoes form. Bull. Amer. Meteor. Soc., 35, 154-165.

Fujita, T. T., 1960: A detailed analysis of the Fargo tornadoes of June 20, 1957. U. S. Weather Bureau Research Paper No. 42, 67pp.

____________, 1970: The Lubbock tornadoes: Study of suction spots. Weatherwise, 23, 160-173.

____________, 1972: Tornado occurrences related to overshooting cloud-top heights as determined from ATS pictures. SMRP Paper No. 97, Univ. of Chicago, 33pp.

____________, 1973: Proposed mechanism of tornado formation from rotating thunderstorm. Preprints of Papers, Eighth Conf. on Severe Local Storms, Denver, 191-196.

____________, D. L. Bradbury, and C. F. Van Thullemar, 1970: Palm Sunday tornadoes of April 11, 1965. Mon. Wea. Rev., 98, 29-69.

____________, J. J. Tecson, and L. A. Schall, 1971: Preliminary results of tornado watch experiment 1971. Preprints of Papers, Seventh Conf. on Severe Local Storms, Kansas City, 255-261.

BIBLIOGRAPHY (cont'd)

Fujita, T. T., and A. D. Pearson, 1973: Results of FPP classification of 1971 and 1972 tornadoes. Preprints of Papers, Eighth Conf. on Severe Local Storms, Denver, 142-145.

Fulks, J. R., 1962: On the mechanics of the tornado. NSSP Report No. 4, 33pp.

Golden, J. H., 1973: The life cycle of the Florida Keys waterspout as the result of five interacting scales of motion. Ph.D. Dissertation, Florida State University, Tallahassee, 370pp.

__________, and B. J. Morgan, 1972: The NSSL-Notre Dame tornado intercept program, Spring 1972. Bull. Amer. Meteor. Soc., 53, 1178-1880.

Grandia, K. L., 1973: Aircraft observations in the weak echo region of a thunderstorm. Preprints of Papers, Eighth Conf. on Severe Local Storms, Denver, 6-9.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. Mon. Wea. Rev., 96, 669-700.

__________, 1969: Hypothesized importance of vertical wind shear in tornado genesis. Preprints of Papers, Sixth Conf. on Severe Local Storms, Chicago, 230-237.

__________, 1971: Research methodology, observations and ideas on tornado genesis. Preprints of Papers, Seventh Conf. on Severe Local Storms, Kansas City, 292-297.

Haglund, G. T., 1969: A study of a severe local storm of 16 April 1967. ESSA Tech. Memo. ERLTM-NSSL-44, 54pp.

Harrold, T. W., W. T. Roach, and K. E. Wilk, 1966: Notes on thunderstorm motions, heights, and circulations. ESSA Tech. Memo. IERTM-NSSL-29, 51pp.

Henderson, J. H., 1972: A detailed description of the internal structure of a thunderstorm. Preprints of Papers, Fifteenth Radar Meteor. Conf., Champaign, 61-68.

Henz, J. F., 1973: Characteristics of Colorado High Plains convective systems. M.S. Thesis, Colorado State University, Ft. Collins, CO, 125 pp.

BIBLIOGRAPHY (cont'd)

Hoecker, W. H., 1960: Wind speed and air flow patterns in the Dallas tornado of April 2, 1957. Mon. Wea. Rev., 88, 167-180.

_____________, 1961: Three-dimensional pressure pattern of the Dallas tornado and some resultant implications. Mon. Wea. Rev., 89, 533-542.

Hsu, C. T., 1973: Laboratory modelling of the tornado suction mechanism. Preprints of Papers, Eighth Conf. on Severe Local Storms, Denver, 199-202.

Kraus, M. J., 1973: Doppler radar observations of the Brookline, Massachusetts tornado of 9 August 1972. Bull. Amer. Meteor. Soc., 54, 519-524.

Kuo, H. L., 1971: Axisymmetric flows in the boundary layer of a maintained vortex. J. Atmos. Sci., 28, 20-41.

Lemon, L. R., 1970: Formation and emergence of an anticyclonic eddy within a severe thunderstorm as revealed by radar and surface data. Preprints of Papers, Fourteenth Radar Meteor. Conf., Tucson, 323-328.

Maddox, R. A., 1973: A severe thunderstorm surface potential index (SPOT). Preprints of Papers, Eighth Conf. on Severe Local Storms, Denver, 252-256.

_____________, and W. M. Gray, 1973: A frictionally driven model for tornado genesis with similarities to hurricane genesis. Preprints of Papers, Eighth Conf. on Severe Local Storms, Denver, 203-206.

Marwitz, J. D., 1972: The structure and motion of severe hailstorms. Parts I, II, III: Supercell storms. Multi-cell storms. Severely sheared storms. J. Appl. Meteor., 11, 166-201.

_____________, 1973: Non-hydrostatic pressures in severe thunderstorms. Preprints of Papers, Eighth Conf. on Severe Local Storms, Denver, 14-17.

_____________, A. H. Auer, Jr., and D. L. Veal, 1972: Locating the organized updraft on severe thunderstorms. J. Appl. Meteor., 11, 236-238.

Miller, R. C., 1967: Notes on analysis and severe-storm forecasting procedures of the Military Weather Warning Center. AWS Tech. Report 200, 94pp.

_____________, 1972: Notes on analysis and severe-storm forecasting procedures of the Air Force Global Weather Central. AWS Tech. Report 200 (Rev.), 102pp.

BIBLIOGRAPHY (cont'd)

__________, A. Bidner, and R. A. Maddox, 1972: The use of computer products in severe weather forecasting (the SWEAT index). Aerospace Sciences Review, 72-1, 2-9.

Milne-Thomson, L. M., 1955: Theoretical Hydrodynamics. The Macmillan Company, New York, 632pp.

Novlan, D. J., 1973: Hurricane spawned tornadoes. Atmos. Sci. Paper No. 200, Colorado State University, Ft. Collins, 57pp.

Purdom, J. F. W., 1971: Satellite imagery and severe weather warnings. Preprints of Papers, Seventh Conf. on Severe Local Storms, Kansas City, 120-127.

Reber, C. M., 1954: The South Platte Valley tornadoes of June 7, 1953. Bull. Amer. Meteor. Soc., 35, 191-197.

Ryan, R., and B. Vonnegut, 1969: Generation of a vortex by electrical heating. Preprints of Papers, Sixth Conf. on Severe Local Storms, Chicago, 253-256.

Severe Storms Research Group of St. Louis University, 1970: F. C. Bates' conceptual thoughts on severe thunderstorms. Bull. Amer. Meteor. Soc., 51, 481-487.

Snider, C. R., 1971: One hour rainfall amounts near tornadoes. Preprints of Papers, Seventh Conf. on Severe Local Storms, Kansas City, 244-249.

Taylor, W. L., 1973: Evaluation of an electromagnetic tornado-detection technique. Preprints of Papers, Eighth Conf. on Severe Local Storms, Denver, 165-168.

Vonnegut, B., 1960: Electrical theory of tornadoes. J. Geophys. Res., 65, 203-212.

Wan, C. C., and C. C. Chang, 1971: Flow patterns of the Dallas Tornado and the laboratory tornado-like vortex - An Exploratory comparison. Preprints of Papers, Seventh Conf. on Severe Local Storms, Kansas City, 271-276.

Ward, N. B., 1972: The exploration of certain features of tornado dynamics using a laboratory model. J. Atmos. Sci., 29, 1194-1204.

Wills, T. G., 1969: Characteristics of the tornado environment as deduced from proximity soundings. Atmos. Sci., Paper No. 140, Colorado State University, Ft. Collins, 55pp.

Wilson, J. W., and G. M. Morgan, Jr., 1971: Long-track tornadoes and their significance. Preprints of Papers, Seventh Conf. on Severe Local Storms, Kansas City, 183-186.

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APPENDIX I

DATA RELIABILITY AND ACCURACY

Severe Storm Reports. There are many inherent problems in studying severe storm/tornado proximity soundings. A general summary and discussion of these problems is made here.

The SELS Log, while it is certainly the most comprehensive and accurate listing of severe storm occurrences, undoubtably contains discrepancies and inaccuracies. This is immediately obvious if one compares storm reports in the SELS Log and in Storm Data. Unfortunately, many of the discrepancies could be resolved only by detailed post-storm damage and radar analysis; this is done only after very significant severe storm/tornado outbreaks. Although the SELS Log was accepted as the definitive listing of severe storm/tornado occurrences it must be remembered that:

1. Many severe storms and tornadoes which occur in remote areas are never reported.
2. A long-track tornado may be reported as several different tornadoes, or several tornadoes occurring in rapid sequence may be assumed to be one single tornado.
3. Some damaging windstorms may be reported and recorded as tornadoes, or vice versa.

These inaccuracies have been partially resolved by the cross-check process of determining proximity soundings described in section I, Part I.

Data Positioning. Once a sample of proximity soundings has been gathered the problem of positioning the tornado-storm relative to the data must be solved. Facts which must be considered in positioning the data are:

1. The tornado-storm is generally moving rapidly from west to east.

2. Discrepancies of 5 to 15 minutes in the reported time of tornado occurrence are probably common, especially for rural storms.

3. Radiosonde release may not occur at precisely 1715 CST.

4. Once the radiosonde is released the data sampled varies in both time and space.

It is realized that severe thunderstorms rarely travel in perfectly straight lines. The path followed is often similar to a backward, flattened S, i.e.  . The storm moves with the mean flow, veers to the right during its most severe period, and then again follows the mean flow. The reader should refer to Marwitz (1972), Fankhauser (1971), and Haglund (1967) for examples of severe storm deviate motion. A further complication is that the storm's speed is likely varying during its lifetime. These problems were partially resolved by assuming a probable mean storm motion for each individual proximity sounding.

Problem number 2 above can be avoided by using only proximity soundings near large, very well documented and time positioned tornadoes. However, this would reduce the data sample to only a few soundings. In this study the time of occurrence has been accepted as listed in the SELS Log, even though it is realized that there are errors involved.

Problems 3 and 4 can be solved by precise positioning of the sounding instrument in time and space, as is done at the National Severe Storms Laboratory, see Barnes, et al. (1971). During a typical tornado proximity sounding the instrument is likely to be displaced 30 to 40 n.mi. from the release site by the time that 200 mb is reached. For an example of balloon positions relative to the release site see Henderson (1972). However, since the storm and the balloon are both moving, in the mean, at roughly similar velocities, the errors introduced by not considering balloon movement are relatively small.

Figure 49 is an example of the complexities of placing data relative to the storm. A set of upper air data from Barnes, et al. (1971) has been used to depict an actual x,y balloon trajectory. The trajectory is shown from release, assumed to be 1715 CST, to 1742 CST (300 mb). If it is postulated that a tornado occurs at 1815 CST 30 km west of the release point it is possible to estimate the errors involved in:

1. Positioning the data 30 km east of the 1830 CST tornado-storm (the method of previous proximity studies).
2. Positioning the data at 068/100 km from the tornado-storm (this position is determined by taking the mean wind of the actual sounding and assuming an average tornado-storm motion of 30° to the right at 75% of the mean wind and also by assuming that the tornado storm existed at 1715 CST).

If the balloon is precisely located relative to the tornado-storm it is found that at 1715 CST the storm is 248/100 km from the data point and that at 1742 CST (300 mb) the storm is located at 246/98 km, a horizontal discrepancy of only 4 km. A 15 minute error in either release time or time of tornado occurrence amounts to a horizontal discrepancy of 18 km in the estimated tornado storms position (this possible error is depicted by an 18 km circle around the assumed 1815 CST storm position). The error introduced by not keeping precise track of the balloon (data point) position is insignificant when compared to the unresolvable errors of not knowing the exact time of tornado occurrence or balloon release. The combined uncertainties of not knowing the precise balloon

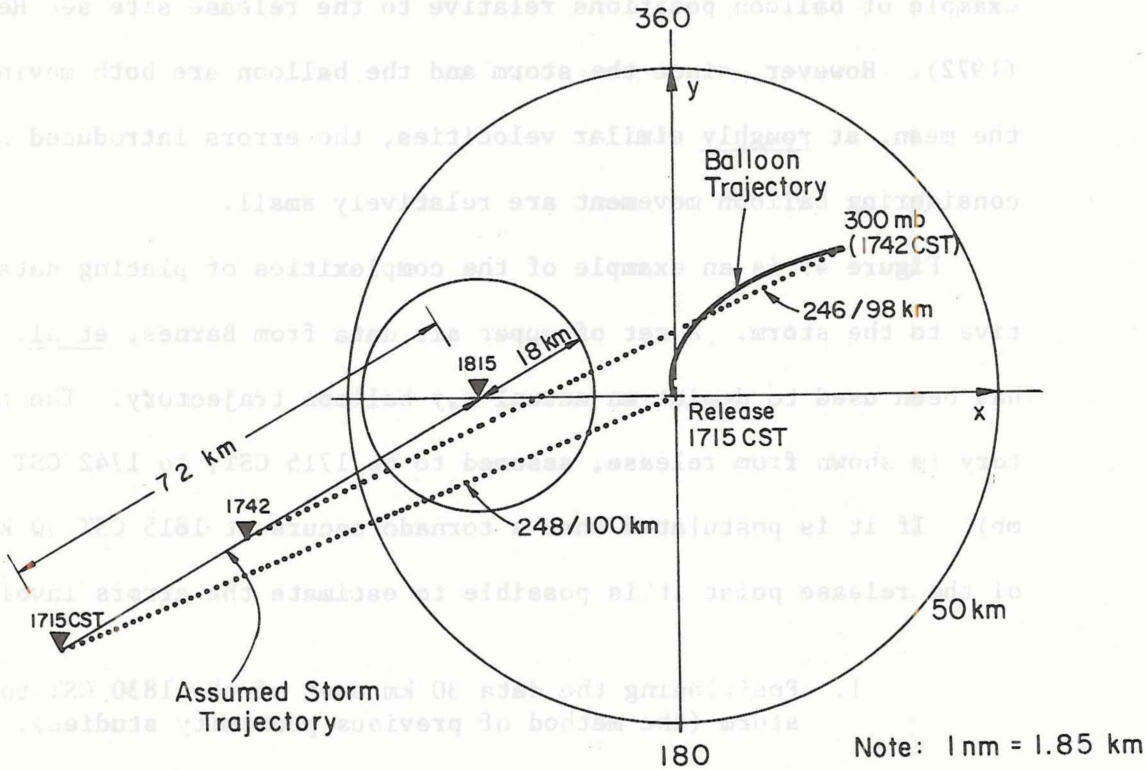

Figure 49

Data Positioning Relative to Tornado Storm.

location and the exact storm path may introduce a positioning error on the order of 10 km. The timing inaccuracies could easily cause a positioning error of 50 km.

It is interesting to note that the method of placing the data relative to the reported tornado, rather than relative to a moving storm, results in a positioning difference of 72 km in this example. Both methods are subject to the same timing uncertainties. It seems reasonable to assume that the data positioning methods of this study, even though still subject to considerable error, give an improved location of data relative to the tornado-storm.

Most significant is the fact that past studies may have been well over 100 km off in data positioning, and that this study may be as much as 50 km in error. The size scale of the phenomena being studied, the tornado thunderstorm, is only 5 to 40 km, while that of the actual tornado circulation is less than 5 km. The scale of the phenomena is less than the resolution of data positioning. Any study attempting to use proximity soundings to define tornado-storm scale features or storm/environment interactions must consider only precisely documented tornado-storms. A study of a large number of proximity soundings can examine the sub-synoptic scale environment associated with tornadoes but only implications can be drawn concerning the actual tornado-storm scale environment.

APPENDIX II

PHOTOGRAPHS OF TORNADO GENESIS

Figure 50 is a series of photographs taken by A1c Cecil W. Nichols, 3 April 1964, at Sheppard AFB, Texas. The series runs from upper left to right and from lower left to right. In the first photograph the lower based collar cloud is apparent in the center. To the left (moving with the storm) of the collar cloud is a heavy shower. A line of flanking clouds trails off to the right of the collar cloud. The smooth-based, very dark cloud across all of the upper right portion of the photograph indicates the presence of an updraft in this region (see Marwitz, et al. 1972). At this stage an intensifying vortex probably exists from cloud base to the surface beneath the collar cloud. In photograph two the vortex is becoming intense and the downward bulging cloud base indicates lowering pressures. Condensate, or dust, is appearing in the lower portion of the circulation. By photograph three the heavy shower has moved out of view to the right. An intense subcloud circulation is present and the condensation funnel extends half way to the ground. By the last photograph an intense tornado has developed. The sky is lighter to the west of the flanking line. The tornado developed at the right rear of a strong updraft associated with the heavy shower which moved across the right edge of the photographs. The total time period covered in the photographs is approximately ten minutes.

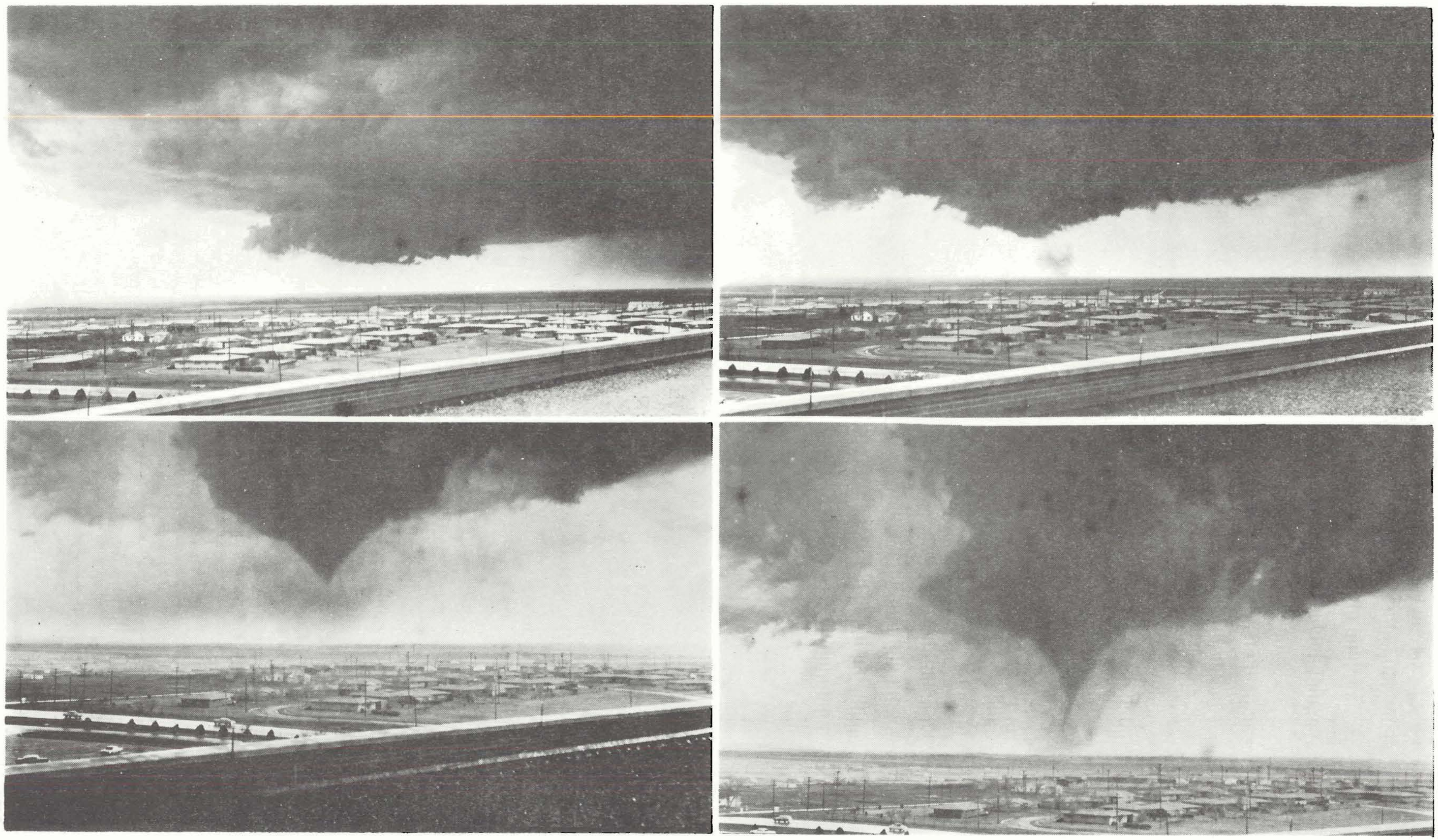

Figure 50

Photograph Series Showing the Development of the Witchita Falls, Texas, Tornado of 3 April, 1964. (USAF Photographs Taken by Alc Cecil W. Nichols and Used With Permission of Air Weather Service.)

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4. Title and Subtitle A STUDY OF TORNADO PROXIMITY DATA AND AN OBSERVATIONALLY DERIVED MODEL OF TORNADO GENESIS			5. Report Date November, 1973
			6.
7. Author(s) Robert A. Maddox			8. Performing Organization Rept. No. CSU-ATSP-212
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12. Sponsoring Organization Name and Address National Oceanic and Atmospheric Administration, Rockville, Maryland 20852			13. Type of Report & Period Covered Project Report
			14.

15. Supplementary Notes

16. Abstracts

The results of a detailed analysis of 159 tornado proximity rawinsonde soundings are considered in Part I of this study. Soundings were stratified into four different categories, based on mean wind characteristics. The tornado soundings were compared to soundings associated with destructive multiple tornado outbreaks, and to soundings associated with non-tornado producing severe thunderstorms. It is found that there is no distinct set of "tornado conditions". Tornadoes are associated with a surprisingly large range of synoptic conditions. Sub-synoptic scale phenomena play an important role in tornado production. There are no distinctive differences between general tornado, multiple tornado outbreak, and severe thunderstorm soundings. Situations which may produce severe thunderstorms also have some discrete probability of producing tornadoes. A suggested new manner of issuing severe thunderstorm and tornado watches is presented. An extensive discussion of tornado features and a hypothesized physical model of tornado genesis is presented in Part II of this paper.

17. Key Words and Document Analysis. 17a. Descriptors

Tornado Genesis
Tornado Observations
Tornado Forecasting
Severe Thunderstorms

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

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A STUDY OF TORNADO PROXIMITY DATA AND AN OBSERVATIONALLY DERIVED MODEL OF TORNADO GENESIS

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Department of Atmospheric Science

National Oceanic and Atmospheric Administration
Grant 04-3-158-51

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<u>Subject Headings:</u>
Severe Thunderstorms
Tornado Forecasting
Tornado Genesis
Tornado Observations

The results of a detailed analysis of 159 tornado proximity rawinsonde soundings are considered in Part I of this study. Soundings were stratified into four different categories, based on mean wind characteristics. The tornado soundings were compared to soundings associated with destructive multiple tornado outbreaks, and to soundings associated with non-tornado producing severe thunderstorms. It is found that there is no distinct set of "tornado conditions". Tornadoes are associated with a surprisingly large range of synoptic conditions. Sub-synoptic scale phenomena play an important role in tornado production. There are no distinctive differences between general tornado, multiple tornado outbreak, and severe thunderstorm soundings. Situations which may produce severe thunderstorms also have some discrete probability of producing tornadoes. A suggested new manner of issuing severe thunderstorm and tornado watches is presented. An extensive discussion of tornado features and a hypothesized physical model of tornado genesis is presented in Part II of this paper.

Author: Robert A. Maddox

A STUDY OF TORNADO PROXIMITY DATA AND AN OBSERVATIONALLY DERIVED MODEL OF TORNADO GENESIS

Colorado State University
Department of Atmospheric Science

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