Chapter 4

SQUALL-LINE DEVELOPMENT

SECTION A—GENERAL

The term "instability line" and "squall line" are used interchangeably in severe-thunderstorm forecasting. Any line of thunderstorms not readily circumnavigable, regardless of whether it is or is not associated with a front or wind shift, is called a squall line. The term "instability area" does not adequately describe a mass of heavy thunderstorms moving within a general thunderstorm area. The "bubble" is defined as a precipitation-induced mesoanticyclone which may or may not be associated with a frontal system.

SECTION B—CONDITIONS NECESSARY FOR DEVELOPMENT

There are a number of conditions necessary for squall line formation. The most favorable conditions are the following [23, 32, 39, 40, 64].

a. Cold-air advection in the middle and higher levels;

b. Cooling of middle and higher levels;

c. An increase of surface temperature (usually by insolation) to the point where convective currents reach their condensation level and release the latent instability of the air column;

d. Increasing moisture at all levels except that, in the most favorable situation, a dry source is found upwind in the low and/or middle levels;

e. Low-level wind convergence;

f. A mechanism to transfer momentum of strong middle-level winds down to the surface.

A previous section stated that the most favorable air-mass structure for the production of severe local storms occurs when a maritime polar air mass overruns a lower moist layer of maritime tropical air. This statement can be explained in terms of the above conditions. It is clear that condition a. is satisfied for this case; conditions c. and e. may be, depending on the particular synoptic situation. Also, one can describe how conditions b., d., and f. occur in this combination of air masses.

Frequently there is strong low-level moisture advection in the lower levels with maritime polar air aloft approaching the low-level moisture ridge line from a perpendicular direction. The amount of wind shear necessary for optimum conditions has been determined empirically to have a component at 14,000 to 16,000 feet of at least 25 knots perpendicular to the lower moisture ridge. Rain falling from the overrunning layer can evaporate in the dry air above the lower moist layer and cool the dry layer to near the wet-bulb temperature. Also, if condition a. is met, this evaporative process will be accelerated by the presence of the liquid moisture condensed from vertical motions, and the result will be further cooling. This process could eventually result in the formation of a squall LINE as shown in Figure 25.

The importance of the exception noted in condition d. must be emphasized. If there is no significant wind shear, the trajectory of the air above the moisture ridge will be approximately parallel to the ridge. Therefore, the air above the moisture ridge will have nearly the same moisture content as the lower levels and not much evaporation and cooling will take place.

The increased density of the cooled air at upper levels can cause vertical motions which will lend support to condition f. These downdrafts amplify existing convective currents, whose updrafts provide additional moisture for continuous cooling of the inflowing dry air above the lower moist layer. Thus, the mechanism is self-perpetuating, and the end product usually is the formation of a group of thunderstorms. However, after thunderstorms form, squall line movement is unlikely unless two other requirements are fulfilled.

a. The angular shear between low-level and middle-level winds should be at least 30 degrees on the "lee" or forward side of the trough.

b. Sufficient high-level moisture should be available to support the mechanism described. Cold advection in the middle levels is not sufficient by itself to assure squall-line development. Unless there is a low-level trough coupled with the above two factors, no more than a line of heavy rain or rainshowers may be expected.

SECTION C—FAVORED DEVELOPMENT AREAS

If squall line development is probable, the initial formation of the line can usually be forecast in one of a number of favored areas. One of the better known examples is along or in advance of a fast-moving cold front. Other

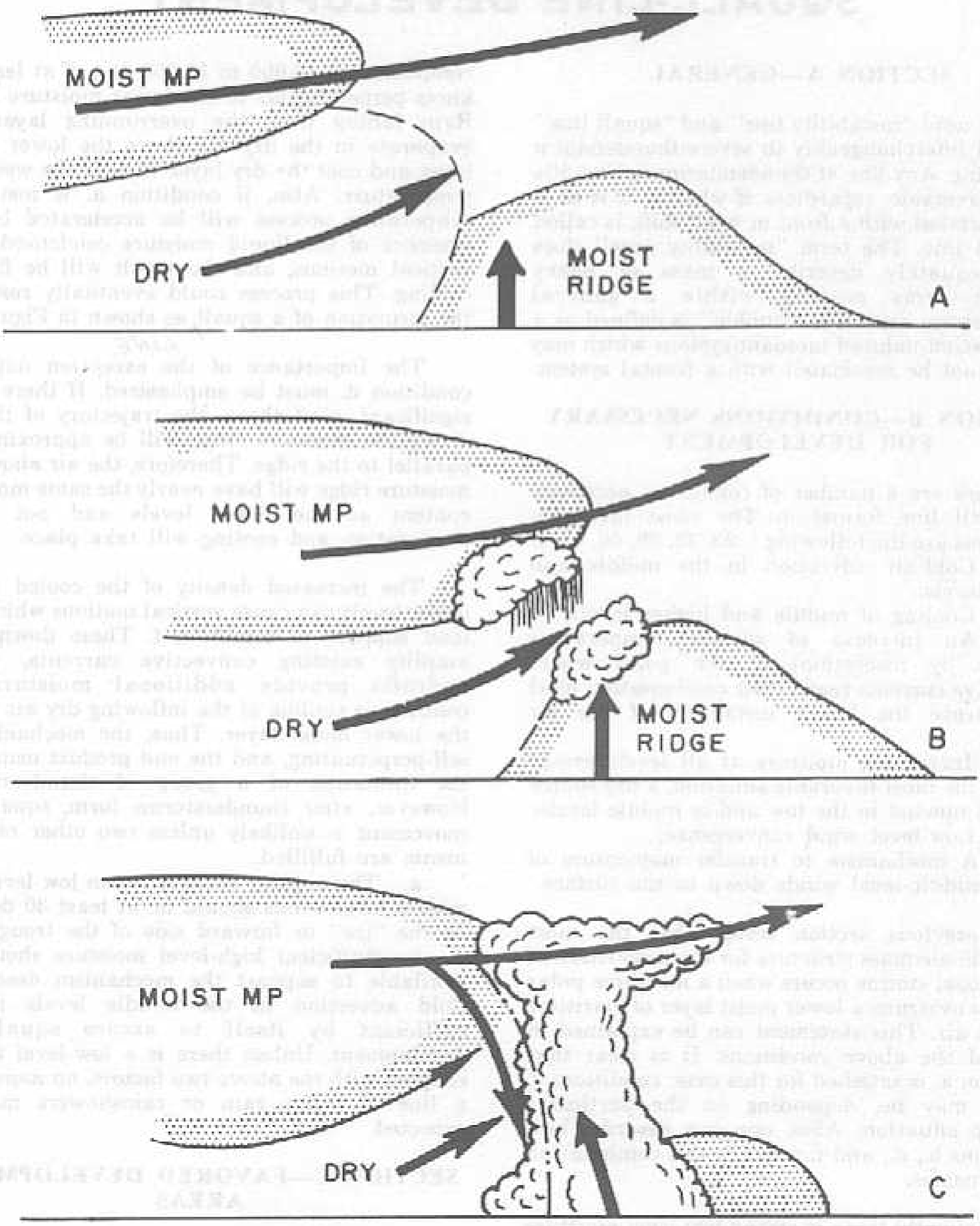


Figure 25. Cross-section of air mass suggesting one way squall lines can develop.

favored locales are in the area of lowest Convective Condensation Levels (these are usually less than 6,000 feet above the ground), and along a low-level trough within or just above the moist layer. Crumrine [14] believes that the position and orientation of the 850/500-mb thickness ridge is an excellent guide to the likely location of squall-line development and severe activity. He states in his paper "If other parameters are favorable for the development of severe thunderstorms, the most intense thunderstorms should be expected about 100 miles behind the 850/500-mb thickness ridge. . . . The instability line should be located in the maximum anticyclonic shear zone of the 850/500-mb shear wind or in areas of marked anticyclonic vorticity of the shear wind."

Chappell listed several useful criteria [12, 13] to aid in the location of a squall line on the surface charts:

a. Squall lines always lie in a surface pressure trough.

b. The location of the showers and thunderstorms, towering cumulus, cumulonimbus and lightning coincide closely with the squall line.

c. The temperature distribution in the immediate vicinity of the squall line may be helpful in determining the exact location.

d. Usually the dew point tends to decrease immediately after squall-line passage.

e. Radar echoes are highly useful in determining the location or the initial development of the squall line and its subsequent movement.

f. Pressure tendencies can be used to determine the location of squall lines, but caution must be exercised. A well-developed squall line has falling pressures ahead of it, rising pressures as it passes a station, and pressure falls immediately behind the rise.

SECTION D—CHARACTERISTICS OF SQUALL LINES

Once developed, the active squall line is usually accompanied by a variety of meteorological phenomena. These include buildups, cumulonimbi, showers, thunderstorms, wind shifts and precipitation; and changes in wind speed, temperature, dew point, pressure and cloud cover. The squall line is somewhat self-perpetuating, but carries the seeds of its own destruction. As the line moves further away from the original source of its development, and as its continued activity cools the lower layers, a line of wind shifts and significant pressure rises eventually moves out ahead of the thunderstorm area. Although this line may regenerate as it moves into a favorable area of instability, the line is more likely to weaken gradually and become effective only as a line of intersection for further redevelopment upstream. A line of discontinuity, after moving away from its associated thunderstorms, often acts as a pseudo-warm front, which if overrun by moist unstable air, causes scattered thunderstorm activity to continue well to the rear of the line. These thunderstorms may produce isolated severe-weather reports dependent upon the degree of instability in the overrunning air. This area of overrunning thunderstorms frequently reintensifies the old bubble high which begins to move as a new squall line within the overrunning air. When this intensification results in the new squall line merging with the old, the system may then move into an area previously undistrubed by activity. Thus, a particular area may be affected by severe weather several times during a period of time. Cold fronts often produce several successive squall lines as they move across the country and the affected region can expect relief only after the passage of the primary cold front or dry line. Also, squall lines are likely to dissipate entirely when they move into an area of dry or stable air.

SECTION E—AIR MASS AND SQUALL LINE RELATIONSHIPS

In addition to reporting a variety of squall-line characteristics, severe-weather meteorologists have observed a number of relationships between the parent air mass and the squall line. The more significant observations are summarized in the following paragraphs.

a. Squall lines which form on or very near a surface cold front are very difficult to distinguish during their early state. The first clue that a squall line has moved away from the cold front is often a report of a wind shift with a speed considerably in excess of that previously reported by any station experiencing the frontal passage.

b. The temperature and dew point will fall after passage, but will level off and even recover somewhat during the next few hours. However, if the cold front itself is carrying the thunderstorm activity along, the temperature and dew point will continue to fall with no tendency to recover.

c. Analysis of the isallobaric field is vitally important since it is an excellent method of determining whether or not, and how fast, changes are taking place in the pressure field. Pressure tendencies are often the first clues to the development and movement of mesoscale lows and bubble highs. Negative tendencies at the surface coupled with areas of low-level convergence will define the more likely areas of vertical motion and positive vorticity advection (PVA) aloft. Also, Chappell [12, 13] has noted a high frequency of severe-weather occurrences along the axis connecting the isallobaric rise and fall centers.

d. Surface temperature changes must be studied since increasing temperatures affect the stability of the air column. Chappell [13], in a selected number of cases which included 21 days in the months of March, April, May, June, and July, computed 3-hourly changes in temperature between noon and 3:00 P.M., and then correlated the occurrence of severe weather with respect to the perpendicular distance from the maximum temperature-change axis. He stated that 75% of all severe-weather reports were within 40 miles of this axis while 89% of all reports were within 60 miles of the axis. The results of this study are most useful for a short-term refinement of an existing forecast area or of a severe-weather warning for a particular point. Rapidly falling pressures are typical prior to formation, but rapidly rising pressures indicate that the bubble has materialized. The combination of rising temperatures, rising dew point and falling pressure indicates a rapid increase in instability, and therefore is an important consideration in refining the forecast for a particular location within a larger forecast area.

e. The use of the altimeter setting for determining the rate of change of surface pressure, has been most ably advocated by B. Magor [47, 48, 49]. Magor believes that the detection of significant surface-pressure behavior is best determined by using the altimeter setting, because the actual change that is obtained from one hour to the next has not been affected by sea-level reductions involving the 12-hour mean temperature. This observation is particularly valuable over the Rocky Mountain area where the hourly pressure variations are more apt to be obscured by reduction techniques.

f. North of an active shallow warm front, bubble squall lines are frequent. The forward edges of the bubble highs form along the axis of lowest Convective Condensation Levels in the frontal zone and are determined approximately at the time when the day's maximum temperatures are reached. Usually, a low-level jet is also in the same vicinity.

g. Bubble highs require the same favorable conditions for development as squall lines, except that frontal lifting aids convection and the triggering of thunderstorms and precipitation.

h. Topography is influential in forming bubble squall lines in the lee of the Rockies over the High Plains. The lower-level winds flow uphill, triggering thunderstorms which result in bubble formation.

i. When the middle-level winds parallel the lower moisture ridge, squall lines seldom develop except over Colorado and northward along the Continental Divide. In this region, if the middle and higher levels are moist a line of high-level thunderstorms may form. Their development causes an increase in the lower wind flow perpendicular to the moisture ridge. If the air structure to the east is favorable, the line of the high-level thunderstorms will continue to develop with the bases lowering into the low-level thermal trough usually present on the lee slopes of the Rockies.

j. In warm-sector situations, where moisture is spread over a wide area rather than confined to a narrow ridge or tongue, a series of bubble squall lines may develop simultaneously along a wide front. In such cases, the strongest bubble will develop on the axis of the low-level jet.

k. In some cases, a bubble squall line will pass through an area and be followed in two or three hours by a more severe one. In these situations, continuous advection of cold, moist air in the higher levels is observed. The first squall line will form in relatively deep moist air, and its passage will be marked by an influx of a drier middle layer. The presence of this drier air aloft requires a higher surface temperature to initiate convection that will reach the condensation level. The later, more vigorous line will form near the time of the day's maximum temperatures.

l. Steering of squall lines is generally in the direction of the 500-mb winds at 40% of the speed. In cases of multiple bubbles, formation is usually under the middle-level jet. Bubbles have a pronounced tendency to move about 30 degrees to the right of the 500-mb wind field, toward lower pressures, and toward the highest temperatures.

m. As stated earlier, squall-line development frequently occurs along the surface dew point front or dry line. Development occurs only if the moist layer is at least 3,000 to 6,000 feet deep and the lapse rate is unstable so that even moderate insolation will cause the convective currents to reach the Convective Condensation Level.

n. Although isolated thunderstorms may develop fairly early in the day, the squall line will usually not become organized and start moving until near the time of the diurnal maximum temperature. It has been observed that the maximum intensity calculated to result from isolation will be fully effective up to six hours after the time of maximum surface temperature.

o. Usually, the point of most intense activity will be located within the area of highest moisture and temperature contrast, and will normally be associated with a small low-pressure cell at the surface. This type of squall line breeds frequent tornadoes when the middle-level winds have a component of at least 25 knots perpendicular to the underlying moisture ridge line.

p. As the activity along a squall line decreases, the designation is changed to one that is frontal in character, or at least is carried as a trough line. The importance of following all weakening discontinuities cannot be overstressed. Any deformation in the synoptic pattern may produce significant weather. For example, an old squall line may become stationary or move northward as a warm front. This system can then be intersected by a new squall line or frontal system providing an axis for the production of a new severe-weather outbreak.

q. If a second bubble forms within one to three hours of the first and moves faster than the original, the two bubbles may merge and the associated squall lines intersect. This intersection is a favored area for tornadic activity.

r. A bubble high will be effective in producing gusts as long as its central pressure is greater than in the environment in which it is embedded. The strength of the associated gusts will be proportional to the strength of the bubble, the pressure gradient, and the temperature differential between the downrush and environmental air.

s. Normally a strong bubble will be effective over a 3- to 6-hour period. An estimate may be made of its probable life span by noting the pressure field downwind along the axis of its probable path. The bubble will be effective until it moves into an area where the strength of the pressure field equals the central pressure of the bubble.

t. The strong downdrafts of the thunderstorms are especially noticeable at the leading edges of the bubbles and cause a somewhat peculiar pressure jump.

u. The intersection of a squall line or active cold front with a warm front is very effective in increasing the severity of thunderstorms. This situation will evolve into a mesocyclone at the point of intersection. Generally the extreme and rapid rises in pressure found in bubble situations are missing in this case as are vigorous wind shifts. The point of formation of the mesocyclone may be forecast by noting the intersection of the front with the axis of the low-level jet below 6,000 feet. Also, very rapidly falling pressures just north of the warm front and in line with the low-level jet precede formation of the mesocyclone. As the squall line approches, the mesocyclone deepens rapidly and the severe-weather phenomena are confined to the immediate vicinity of the warm front. This situation permits forecasting relatively small areas of destructive storms, with widths of perhaps only 50 to 100 miles. Figure 26A is the three-dimensional structure of an intersection of two squall lines, and shows the low- and middle-level jet locations and the formation of a mesocyclone. Figure 26B shows the ideal location for mesolow formation when a squall line intersects a stationary warm front.

Three notable examples of this type of storm were the Arkansas-Tennessee tornadoes of March 21-22, 1952, the severe storms and tornadoes of July 31, 1951 in South Dakota and Minnesota, and the devasting tornadoes on Palm Sunday, 11 April 1965. In the first and third cases few significant thunderstorm gusts were reported at the surface, but intense mesocyclones moving along a warm-frontal boundary produced numerous tornadoes and widespread destruction. Figure 27 is a time cross-section of the development and movement of the mesolows and accompanying tornadoes of 22 March 1952. The abscissa are station locations for Hobart, Oklahoma City, Muskogee, McAlister, Fort Smith, Little Rock, and Jackson, Tennessee, and the ordinate is the hourly reports from each of these stations. In the second case an intense mesolow passed through eastern South Dakota into Minnesota with numerous reports of 80 to 120 knot winds. The storm reached a peak at World-Chamberlin Field in Minneapolis with several tornadoes reported in the area.

The above relationships apply primarily to the Great Plains and adjacent area. In the Gulf and Eastern States, tornado activity is more common on the leading edges of thunderstorm areas that have developed during the early mornings. These areas may or may not be migratory, the wind field is often weak (especially in the middle levels), and damage is limited to widely separated, small, discrete areas. These tornadoes are associated with mesocyclones and occur at the intersection of low-level jets and the general thunderstorms areas.

SECTION F—EXAMPLE OF SQUALL LINE AND BUBBLE DEVELOPMENT

An example of this type situation occurred at Waco, Texas, 11 May 1953. Such a pre-frontal squall line development is described in Figures 28A through 28H.

Figure 28B shows a fully developed squall line with a precipitation-induced bubble high.

The portion of the squall line adjacent to the most intense part of the bubble and under the strongest flow aloft moves rapidly eastward as shown in Figure 28C. This portion of the squall line is in the process of outrunning its own thunderstorm activity which will result in the leading edge degenerating into a line of wind shifts and rain showers. Also, the southern portion of the squall line is lagging westward in the southerly flow ahead of the front.

Figure 28D shows the decayed squall line assuming frontal characteristics. Low-level moist

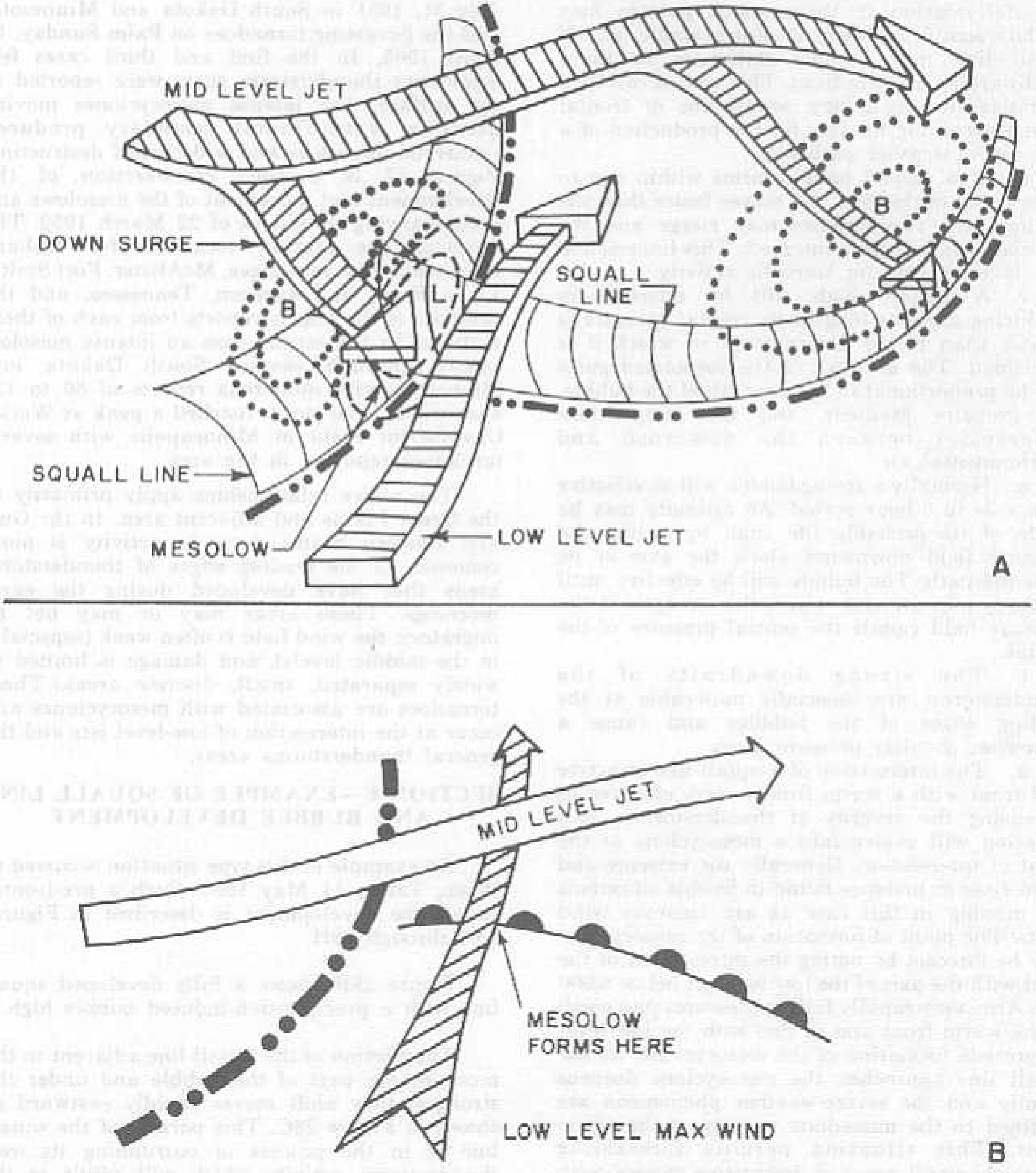


Figure 26. Formation of mesolows and the location of the most intense severe-weather activity. The situation of the Waco, Texas storm of 22 May 1953 is shown in Figure 26B.

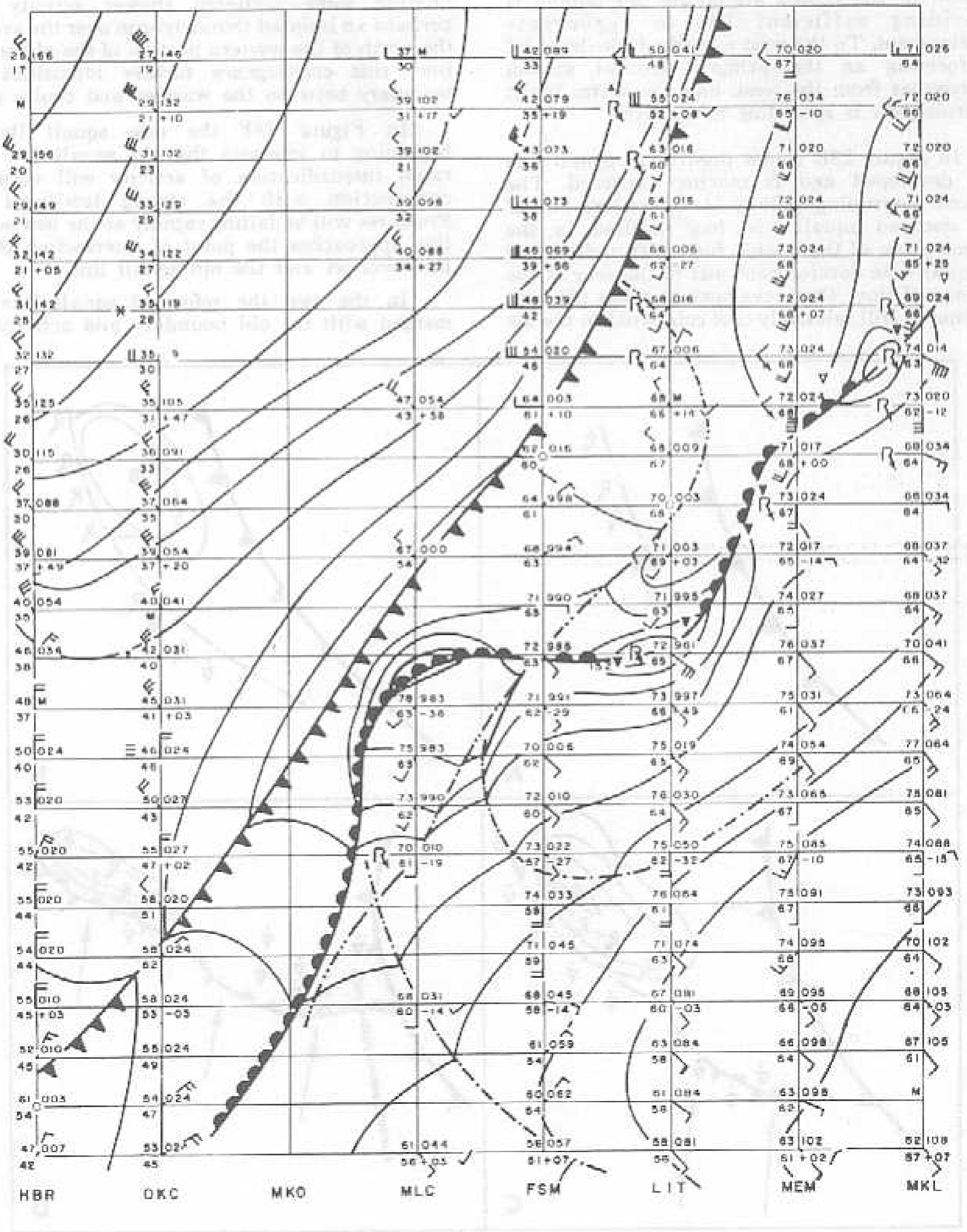


Figure 27. Time cross-section of development and movement of mesolows and accompanying tornadoes of 22 March 1952.

air begins to overrun the old squall line and thunderstorm activity is on the increase where a portion of the cooled air of the old bubble is providing sufficient lift to regenerate development. To the west a marked low-level jet is forming as the primary frontal system approaches from the west, and the warm moist returning air is spreading northward.

In Figure 28E a new pre-frontal squall line has developed and is moving eastward. The intense overruning activity at the eastern end of the decayed squall line has resulted in the regeneration of the bubble high with indications of squall-line development just to the rear of the old squall line. This development takes place in air that is still relatively cool compared to the air south and southeast of the decayed squall line. Convergence in the low levels is beginning to produce some scattered shower activity and perhaps an isolated thunderstorm over the area to the north of the western portion of the old squall line; this convergence further intensifies the boundary between the warmer and cooler air.

In Figure 28F the new squall line is beginning to intersect the old squall line and rapid intensification of activity will occur in conjunction with the strong low-level jet. Pressures will be falling rapidly as the new squall line approaches the point of intersection of the low-level jet and the old squall line.

In the east the reformed squall line has merged with the old boundary and activity has

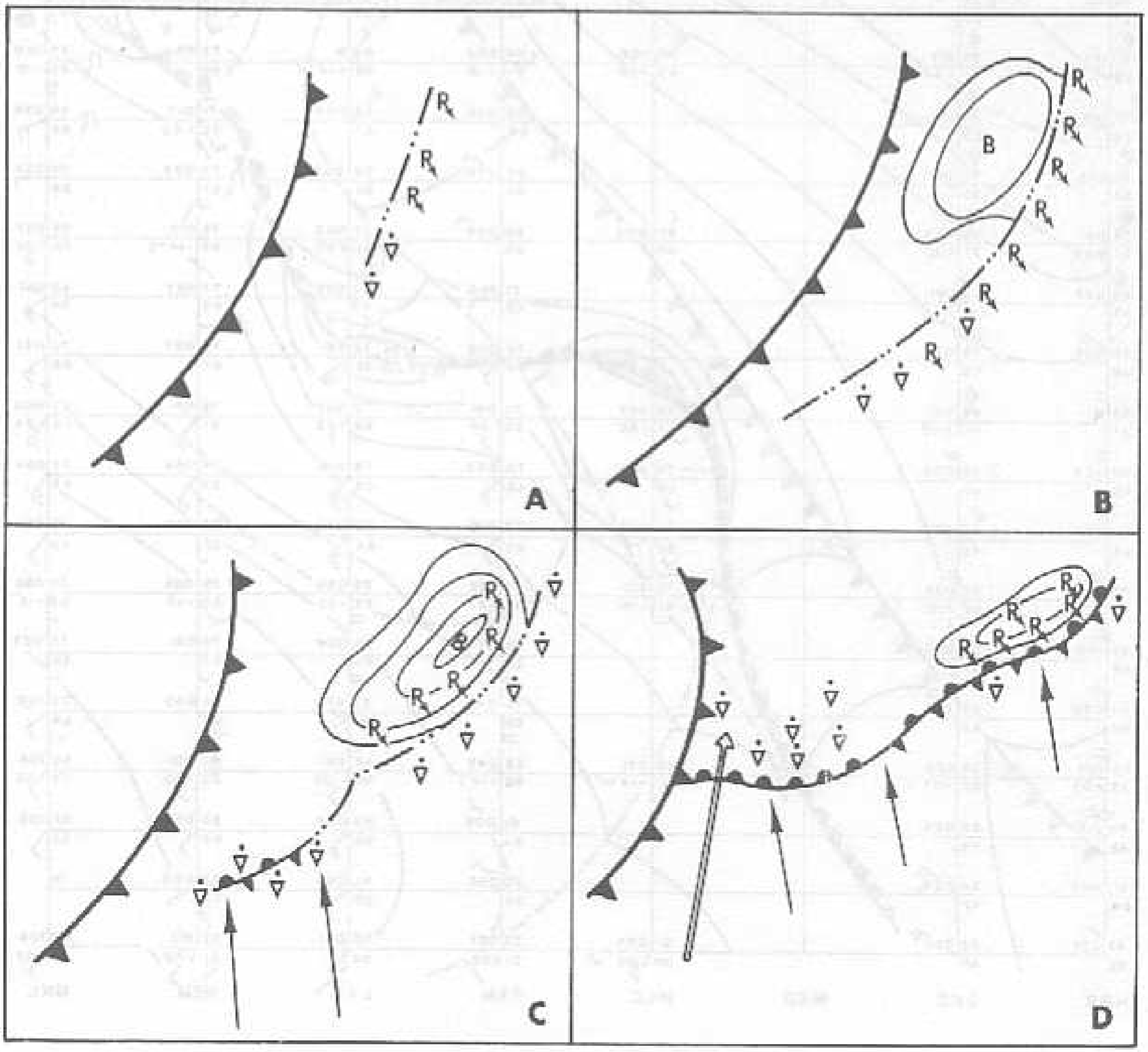


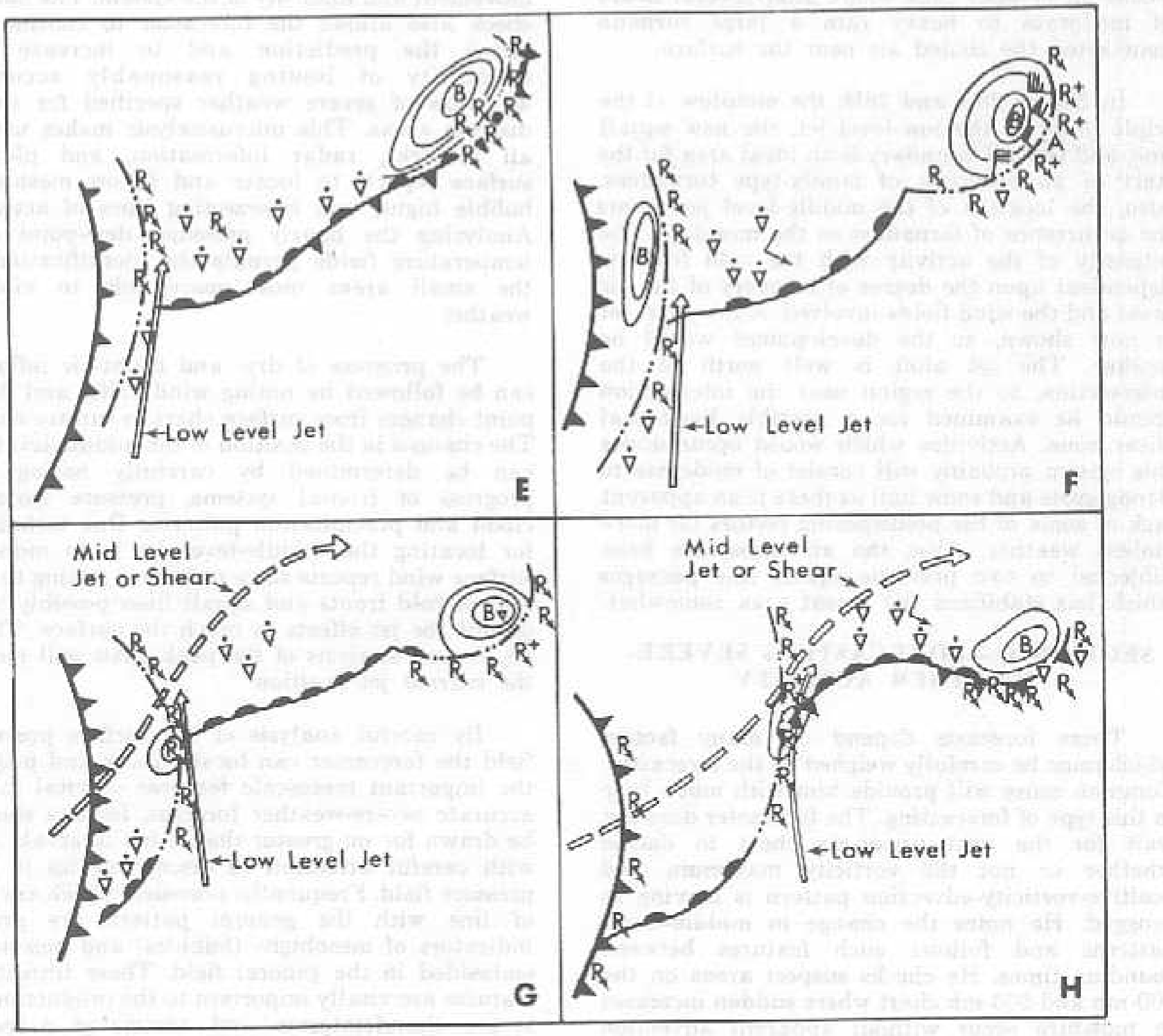
Figure 28. History of the development of squall line and bubble high — Waco, Texas, 11 May 1953.

(Figure 28 continued on the following page)

intensified. In Figure 28G a mesolow has formed at the point of intersection of the second squall line, the old boundary and the low-level jet. Tornadoes or locally damaging winds are highly probable in this area, especially considering the proximity of the middle-level jet or shear. The southern portion of this second squall line is returning northward and the old front will intersect the second squall line shortly.

In Figure 28H the system is fully formed. The cold front has become active and is intersecting the western portion of the second line. The mesolow which formed in the central portion of the old boundary is producing severe activity. In the east the redeveloped squall line continues southeast toward warmer air and lower pressures. Depending on time of day, stability considerations, and wind field, the system may either eventually weaken and degenerate into a relatively broad zone of showers and scattered thunderstorms, or it may continue to move, decay, and regenerate. It should be noted that with the system shown in Figure 28H, the cold front would probably not act as a squall line for a sustained period, but rather the thunderstorms will move out ahead as a pre-frontal line with development possibly renewing along the cold front. One conclusion is certain: areas to the east of the cold front will remain under some threat until either the cold front passes or other marked stabilization of the air mass takes place.

In the Figures shown, some comments may be made on the type of weather to be expected with particular time and space configurations of the system. The first squall line as shown in Figures 28A, 28B, and 28C would not be as likely to produce tornadoes as it would strong straight-line gusts and hail. There is no intersection of



discontinuities and a low-level jet is not present. Gust strength is proportional to the strength of the bubble, the temperature differential between the air mass ahead of and behind the squall line, and the strength of the winds in the opposing air masses. In Figure 28E and 28F the redeveloping eastern bubble is a favored area for very heavy rain and significant hail but with little probability of gusts because of the small temperature differential between the downrush and the environmental air in the cooled bubble. Dependent upon the degree of instability of the overrunning airmass, the strength of the middle-level wind field, the presence of a low-level jet and the degree of coldness and thickness of the very low-level air, tornadoes may occur with this pattern. The tornado funnel must be of sufficient intensity to penetrate the stable cooled layer near the ground, and, if it does would be particularly violent. This type of tornado occurred at Waco, Texas on 11 May 1953 where after several hours of moderate to heavy rain a large tornado penetrated the cooled air near the surface.

In Figure 28G and 28H, the mesolow at the triple point of the low-level jet, the new squall line, and the old boundary is an ideal area for the start of an outbreak of family-type tornadoes. Also, the location of the middle-level jet favors the occurrence of tornadoes in the mesolow. The intensity of the activity with the cold front is dependent upon the degree of recovery of the air mass and the wind fields involved. A low-level jet is now shown, so the development would be weaker. The jet aloft is well north of the intersection, so the region near the intersection should be examined for a possible horizontal shear zone. Activities which would occur under this system probably will consist of moderate to strong gusts and some hail as there is an apparent lack of some of the predisposing factors for more violent weather. Also, the air mass has been subjected to two previous squall line passages which has stabilized the threat area somewhat.

SECTION G—FORECASTING SEVERE-WEATHER ACTIVITY

These forecasts depend on many factors which must be carefully weighed by the forecaster. Common sense will provide him with much help in this type of forecasting. The forecaster does not wait for the next upper-air chart to decide whether or not the vorticity maximum and positive-vorticity-advection pattern is moving as progged. He notes the change in middle-cloud patterns and follows such features between sounding times. He checks suspect areas on the 700-mb and 500-mb chart where sudden increases in moisture occur without apparent advection from an upwind source. He knows from experience that such changes are often the first indication of increasing vorticity, vertical motion and advection. Finally, monitoring hourly surface pressure changes will provide clues to changes in the large-scale vertical-motion field in the upper atmosphere.

The hourly surface data will nearly always reflect the changes in intensity and position of the low-level jet. Areas of rapidly falling pressure associated with increases in surface wind speed often are the reflection of warm, moist low-level air moving into an area at a more rapid rate than into the surrounding region. Careful analysis of the hourly sequences will provide clues as to the actual beginning development of an expected squall line. These hourly reports coupled with available radar observations enable the forecaster to judge development, speed of movement and intensity of the system. The hourly check also allows the forecaster to continually refine the prediction and to increase the capability of issuing reasonably accurate warnings of severe weather specified for small discrete areas. This microanalysis makes use of all remarks, radar information, and plotted surface reports to locate and follow mesolows, bubble highs, and intersecting lines of activity. Analyzing the hourly pressure, dew-point and temperature fields permits the identification of the small areas most susceptible to violent weather.

The progress of dry- and moist-air influxes can be followed by noting wind shifts and dew-point changes from surface chart to surface chart. The changes in the position of the middle-level jet can be determined by carefully noting the progress of frontal systems, pressure systems, cloud and precipitation patterns. One technique for locating the middle-level jet is to monitor surface wind reports since turbulent mixing to the rear of cold fronts and squall lines possibly may permit the jet effects to reach the surface. Thus, an isotach analysis of the peak gusts will locate the current jet position.

By careful analysis of the surface pressure field the forecaster can locate, track and project the important mesoscale features so vital to an accurate severe-weather forecast. Isobars should be drawn for no greater than 2-mb intervals and with careful attention to discontinuities in the pressure field. Frequently, pressures which are out of line with the general pattern are prime indicators of mesohighs (bubbles) and mesolows embedded in the general field. These transitory features are vitally important to the production of severe thunderstorms and associated activity.

Areas where thunderstorms are, or have recently been occurring, are most likely to reflect these abnormalities. The analysis of frontal systems by severe-weather forecasters are essentially the same for large features as in standard analysis. However, severe-weather analysis concentrates on small-scale features which are vitally important. Therefore, minor differences in temperature and/or moisture within the same airmass are often denoted as "frontal" boundaries. If there is no significant discontinuity in temperature and/or dew point, but there is a line of wind shifts appearing on the surface chart, the convention is to use a trough symbol.

Chapter 5

FORECASTING PARAMETERS

SECTION A—GENERAL

Conditions necessary for the development of tornadoes, severe thunderstorms and their associated destructive phenomena may be summarized under several interdependent headings:

a. *Temperature*—The thermal air structure must be conditionally unstable. The magnitude of the temperature is important in two ways: It controls the ability of the air to hold and transport moisture and it affects the height of the Wet-Bulb-Zero. Also, the most vigorous storms take place in air having a subsidence-type inversion, a characteristic which is observed to be associated with wind shear.

b. *Moisture*—Large quantities of moisture must be available. Usually this requirement is fulfilled by the presence of a low-level tongue of moisture. However, the strongest storms require dryer air above this ridge, or marked dry source to the windward in a position to intrude into or above the ridge (potential instability). It may be possible that the lapse rate is further steepened through evaporative cooling. Such a hypothesis could explain the common effectiveness of a large directional shear between strong and relatively dry low- and middle-level winds and a well-defined ridge of moisture.

c. *Winds*—Strong middle-level winds are required, except in an equatorial-type structure. Sharp horizontal wind shears also favor the development of severe phenomena through instability. Moderate to strong flow in the low level is required for major storm outbreaks of the family type. The intersection of the maximum low-level winds with a warm front or old squall line is a frequent area of development (and a favored area for mesocyclone formation). It is extremely desirable for the middle-level and low-level jets to intersect, since the major axis of tornadic activity is frequently determined by the location and movement of this intersection.

d. *Lifting*—Severe thunderstorms with tornadoes, hail, or destructive winds, do not develop spontaneously, but require the following activating lifting mechanisms:

(1) Cold front.

(2) Pre-frontal squall line.

(3) Warm front.

(4) Upper cold front.

(5) Pseudo-fronts formed at or near the edge of a general thunderstorm area.

(6) Intersection of any two lines of activity such as squall lines, a squall line and a warm front or a bubble or mesocyclone moving along a warm front.

e. *Freezing level*—The height of the Wet-Bulb-Zero above the terrain should be favorable. This height in the environmental air mass is assumed to be the height of the freezing level within the storm column, and is highly correlated with the type and intensity of the severe phenomena which reach the ground. The optimum height of the Wet-Bulb-Zero is about 8,000 feet. When this height is below 5,000 or above 11,000 feet, the incidence of surface hail and thunderstorm gusts is practically negligible, and tornadoes (if any) are relatively weak and short-lived except in a Type 2 airmass.

SECTION B—IMPORTANCE OF KEY PARAMETERS

In deciding whether any, or all of the above conditions may be met in any given situation the severe weather forecaster must consider numerous parameters available from surface and upper-air data. These individual parameters, encompassed by the five conditions of Section A, must be carefully considered both individually and collectively and projected in space and time. It is extremely difficult to weigh these parameters and to assign them an order of relative importance. They are essentially interdependent and vary in relations to each other in different situations.

The Air Weather Service and the National Severe Storms Forecast Center of the Weather Bureau conducted a preliminary computer study of 328 tornado cases [42] from which it was concluded that the 14 parameters shown in Table 1 play a major role in the production of severe thunderstorms and tornadoes. Also, an attempt was made to qualify these listed parameters as weak, moderate or strong. This was a preliminary effort designed to serve as a basic semi-objective forecast checklist for less experienced forecasters. The gathering of more data is planned so that the table can be further refined. The parameters are given in tentative order of importance established by both computer analysis and individual forecasting experience, and are discussed in detail in the paragraphs below.

a. Strong positive vorticity advection (PVA) implies a strong vertical-motion field and indicates the presence of marked low-level convergence with a resultant lifting of the air column. Experience has shown that moderate to strong positive vorticity advection is probably present in all significant severe-weather outbreaks. Since the height and temperature changes at 500 mb are closely associated with the fields of vorticity advection, both are of value in determining type of advection, orientation, and rate of movement of the vorticity pattern. These height and temperature changes at 500 mb supplement the NMC charts and are especially

Table 1 - Summary of Key Parameters

RANK	PARAMETER		WEAK	MODERATE	STRONG
1	500 mb Vorticity		Neutral or Negative Vort Advection	Contours Cross Vort Pattern 30°	Contours Cross at more than 30°
2	Stability	Lifted Index	-2	-3 to -5	-6
		Totals	50	50 to 55	55
3	Middle Level	Jet	35K	35K-50K	50K
		Shear	15K/90 nm	15K-30K/90 nm	30K/90 nm
4	Upper Level	Jet	55K	55 to 85K	85K
		Shear	15K/90 nm	15K - 30K/90 nm	30K/90 nm
5	Low-Level Jet		20K	25K - 34K	35K
6	Low-Level Moisture		8	8 to 12	12
7	850-mb Max-Temp Field		E of Moist Ridge	Over Moist Ridge	W of Moist Ridge
8	700-mb No-Change Line		Winds Cross Line 20°	Winds Cross Line 20° to 40°	Winds Cross Line 40°
9	700-mb Dry-Air Intrusion		Not Available - or Available but weak Wind Field	Winds from Dry to Moist Intrude at an Angle of 10 to 40° are at least 15K	Winds Intrude at an Angle of 40° and are at least 25K
10	12-hr Sfc Pressure Falls			1 to 5 MB	5MB
11	500-mb Height Change		30 m	30 to 60 m	60 m
12	Height of Wet-Bulb-Zero above Sfc		Above 11000 ft Below 5000 ft	9000 to 11000 ft 5000 to 7000 ft	7000 to 9000 ft
13	Surface Pressure over Threat Area		1010 mb	1010 to 1005 mb	1005 mb
14	Sfc Dew Point		55°F	55° to 64°F	65°F

useful in the event the NMC vorticity prognoses are not available. Figure 29 is an example of the initial 500-mb vorticity pattern prepared by NMC. There is significant positive vorticity over a rather large area with the strongest PVA extending from southwest Louisiana into central Tennessee. Since the 500-mb contours cross the vorticity lines at a large angle (a zone of mid-level jet winds), the rate of positive vorticity advective change is the greatest over the stippled threat area. The possibility of severe weather further north must be considered because of the favorable PVA pattern, but the threat also is dependent on the presence or development of the other forecast parameters. The actual numerical value of the vorticity field is probably of some importance with higher values being indicative of a stronger system. However, at this time the presence of cross flow in the vorticity field appears to be more significant in the production of severe storms.

b. The stability of the air column is dependent in large part on the low-level moisture and temperature distribution. The Showalter Index is based on the relationship of the 850-mb temperature and dew point to the 500-mb temperature; the Lifted Index is obtained from the mean moisture in the lower 3,000 ft of the sounding; and the Fawbush-Miller Index utilizes the mean wet-bulb temperature in the lower 3,000 ft. These indexes, which are measures of potential instability, all require examination of the plotted sounding and the use of tables. Also, the Totals Index is based on the 500-mb temperature and the 850-mb temperature and dew point, and may be determined by examination of the raw data. While all four indexes are roughly comparable, each has weaknesses and virtues. The chief weakness of both the Showalter and Totals Index is their dependence of the availability of moisture at the 850-mb level. That is, sufficient low-level moisture could be available but not be as high as the 850-mb level. Thus, the Showalter and Totals Indexes would yield non-representative values. Also, the Showalter Index requires a table for computation. The Lifted Index and the Fawbush-Miller Index use a more representative low-level moisture, but again these require the plotted sounding or a machine analysis. All four indexes give comparable results when the environmental air mass is warm and moist, but the Totals Index gives a more accurate picture of potential instability as the air becomes colder and dryer.

Figure 30 is an analysis of the stability field using the Total Totals Index. It is highly probable that in the primary instability area the Showalter, Fawbush-Miller, and Lifted indexes would overlay the Totals pattern since the low-level moisture seems representative. However, in the unstable area shown over Minnesota and adjacent states, the instability is due primarily to very cold air aloft rather than to low-level heat and moisture. In this area, the Total Totals more reliably indicates the occurrences and the intensity of the thunderstorm activity.

Since relocation of the MWWC to AFGWC, five of the most important parameters have been combined and weighted to provide an index specifically designed to alert the forecaster to tornado and severe thunderstorm potential. The five parameters chosen include: the stability of the air column, the low level jet, the mid-level jet, the low level moisture, and the directional shear between the low level and mid-level winds. These combined parameters result in the Severe Weather Threat Index, referred to as the SWEAT Index, described in detail in Appendix F.

c. and d. The middle-level jet and horizontal-speed-shear zone is commonly used by the AFGWC in preparing severe-weather forecasts. The National Severe Storms Forecast Center (NSSFC) prefers the upper-wind field at or near the axis of the jet stream. This choice is really immaterial since in actual practice the best procedure is a judicious examination of both the middle- and upper-level wind fields. Experience has shown that the vast majority of the most violent and widespread tornado and severe thunderstorm outbreaks occur when the upper-level jet pattern is strong and deep enough to be reflected in the middle levels (10,000 to 20,000 ft MSL). Figure 31 represents the middle-level maximum-wind chart. The strongest wind between 10,000 to 20,000 ft MSL is plotted. This particular max-wind chart is a classic example of well-defined jet axes with marked diffluence aloft, and represents conditions on the morning of the Palm Sunday tornadoes. The unusual strength of these winds in the middle levels is a direct reflection of the intense flow at the jet-core level. Along with other factors, a strong middle-level jet seems to be required for a major severe-weather outbreak.

e. An important ingredient in the production of severe thunderstorms and tornadoes is the low-level jet. The low-level jet is often obvious on the winds-aloft or 850-mb chart, but is just as often not identifiable because of the distance between reporting stations. However, a careful study of the wind field, temperature and contours of the surface, winds aloft and the 850-mb chart will sometimes reveal its probable location. In cases where jet development has not yet occurred, extreme care must be taken in the analysis and short-range prognosis of the features on the charts. During the course of the forecast period the first presence or development of the low-level jet may be ascertained by closely monitoring

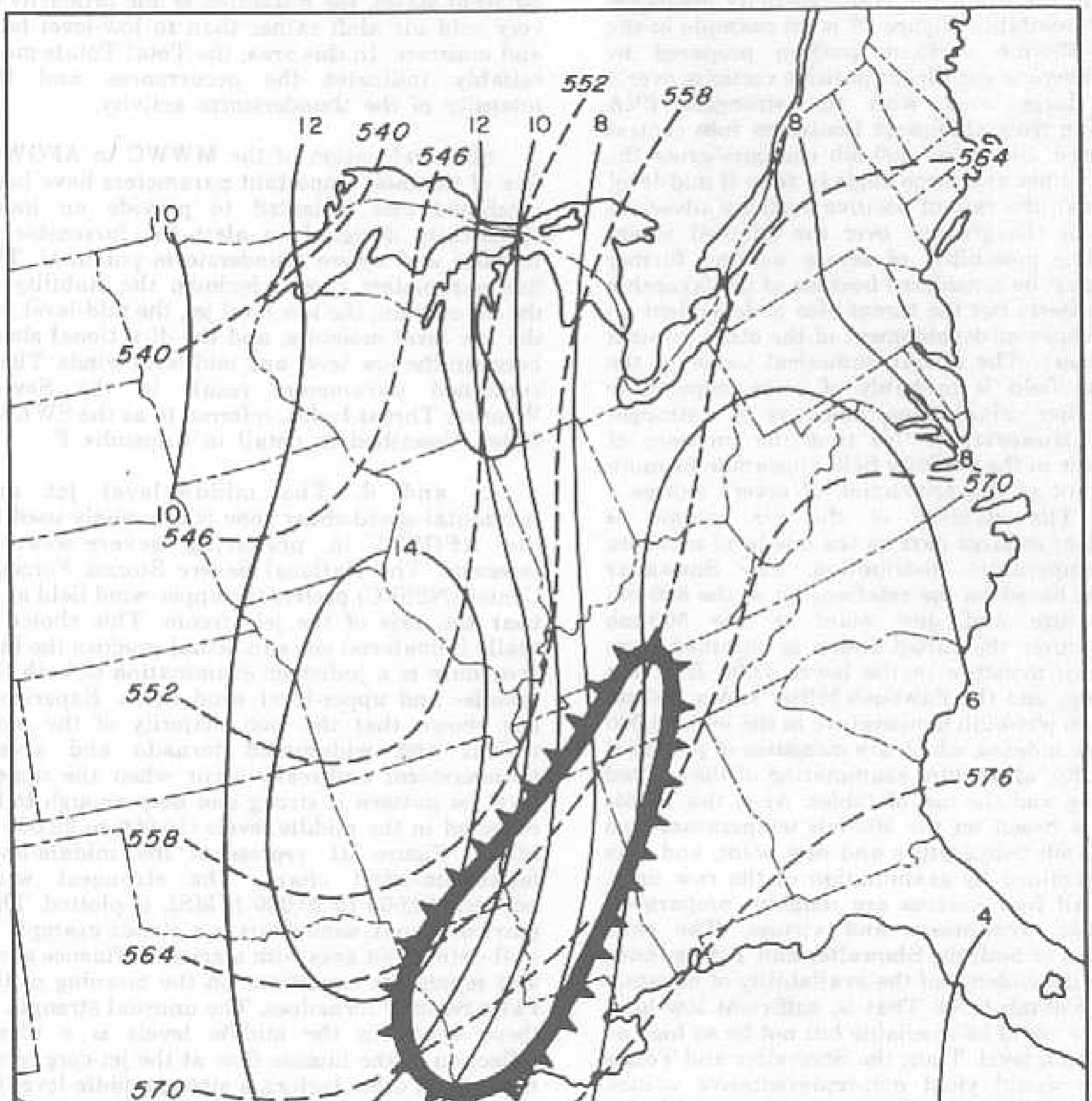


Figure 29. 500-mb contour and vorticity pattern showing strongest PVA.

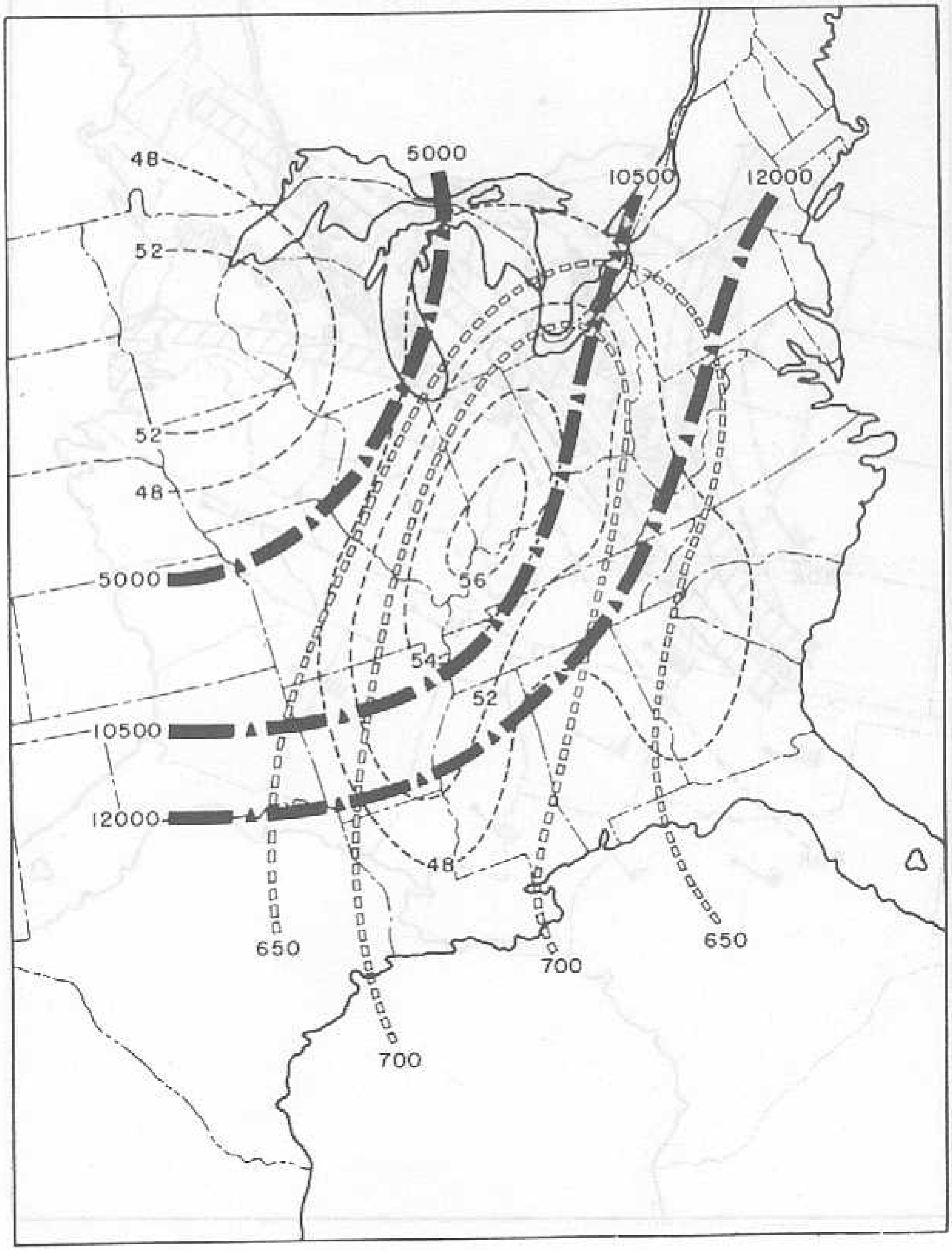


Figure 30. Stability analysis showing Total Totals and Lifted Indexes. Also, isopleths of the height of the Wet-Bulb-Zero and LFC are indicated.

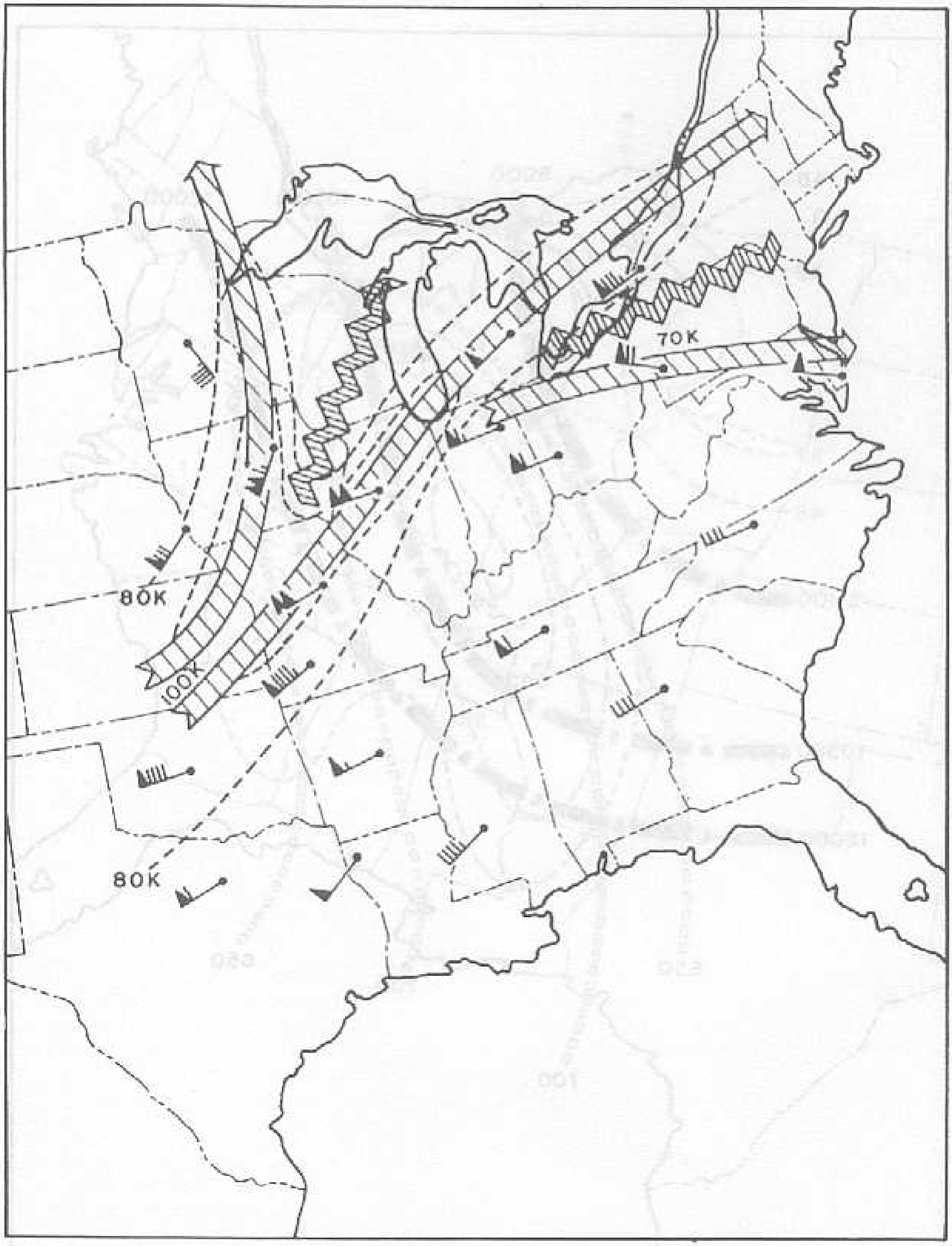


Figure 31. An example of the Maximum-Wind Chart for the Palm Sunday tornadoes of 11 April 1965

hourly changes in the surface pressure, temperature, and wind fields. These analysis procedures will often provide an extremely accurate estimate of the development and movement of the low-level jet through clues to changes in its speed or shape.

Figure 32 is an example of the low-level max-wind chart. The pattern is routine except for the minor jet band in central Alabama. The major feature on the chart is a well-marked and fairly restricted jet around a major low center in the northeastern United States. This particular situation did not produce severe thunderstorms due to the lack of other necessary parameters. However, several thunderstorms with gusts to 35 knots and tops in excess of 40,000 feet did develop over New Jersey, Delaware, and Connecticut in the northeastern portion of the low-level jet and in a small instability area outlined by a 50 Total Totals isopleth.

f. The *low-level moisture* is best determined from the analysis of the lower 3,000 feet of the sounding. Also, the 850-mb chart may be used to determine the moisture field if the low-level moisture is apparent at that level. When the plotted sounding is not available, a third method often used is to take the average of the 850-mb and surface dew-point temperatures. Changes in the orientation and shape of the low-level moisture field between sounding times can be inferred by monitoring the observed changes in the surface dew point, temperature and pressure patterns, and lower-cloud systems.

g. Figure 33 shows the major features at the 850-mb level. The most favorable *850-mb temperature pattern* leading to those family-type tornado outbreaks commonly associated with tornado-producing synoptic patterns Types A and B, occurs when the maximum-temperature ridge is located to the west or southwest (upwind) of the low-level moisture ridge. This pattern places the low-level warmer and dryer air adjacent to the moist air, and, with the proper windflow, provides the strong moisture gradient so essential to this type of storm. In the Type C, D, and E outbreaks the 850-mb temperature pattern will normally be coincident with the low-level moist ridge. However, in the cold-air type outbreaks (Type D) it may occasionally be found to the east of the low-level moist ridge. Since the D pattern is a relatively poor tonado producer and the C and E patterns do not compare with the A and B in numbers of tornadoes produced, one can logically conclude that the temperature ridge coincident with the moist ridge is a moderate tornado-producing situation. (Whereas a temperature ridge east of the moist ridge is weak producer.) As discussed earlier, any changes in the 850-mb temperature field (between sounding times) can be estimated from changes in the surface temperature and dew-point patterns.

h. The *700-mb No-Change Line* is defined as a line connecting points of no advective-temperature change at the 700-mb level. In practice this line separates areas of warm advection from areas of cold advection, and normally is nearly coincident with the 850-mb warm ridge. It has been observed that the advancement of the leading edge of the no-change line into a position ahead of a pronounced middle-level trough is usually associated with deepening or intensification of surface low centers.

i. A *700-mb dry intrusion* appears to be an essential ingredient for any significant outbreak of tornadic storms. Specific values for what is "dry" and what is not are impossible to define since what may be classified as a dry intrusion in one situation may not be so classified in another. In routine operations we consider 50% relative humidity, dew points of less than 0°C, or a temperature-dew-point spread of more than 6°C at 700 mb as "dry." However, it is necessary in each situation to determine whether or not the intruding 700-mb air is significantly dryer than the air over the threat area. Experience dictates that this differential should be at least on the order of 30% or more relative humidity, and, in general the greater the differential and the steeper the gradient from dry to moist air, the more violent will be the activity. This statement must be qualified not only in light of the speed and direction of the winds across the moisture discontinuity, but must also take into account the differential in speed and direction between the low-level winds and the 700-mb flow. The most favorable relationship between the low-level and 700-mb flow is when winds veer with height and increase in speed. Figure 34 shows the major features at the 700-mb level. While the dry-air influx is occurring along a rather broad front, the presence of the strong wind axes across the Midwest into Illinois indicates that the most effective intrusion and greatest rate of advective change will take place across Indiana, southern Michigan and northeastward.

j. The *12-hour pressure falls* reliably indicate major changes or trends in the surface pressure pattern and reflect important changes aloft. The movement and shape of the fall area is vitally important and provides clues to the probable areas of maximum low-level convergence and changes in the low-level wind field. Also the fall area aids in predicting the rate of change of low-level heat and moisture. In the most productive situations it does appear that widespread pressure falls are less desirable than a

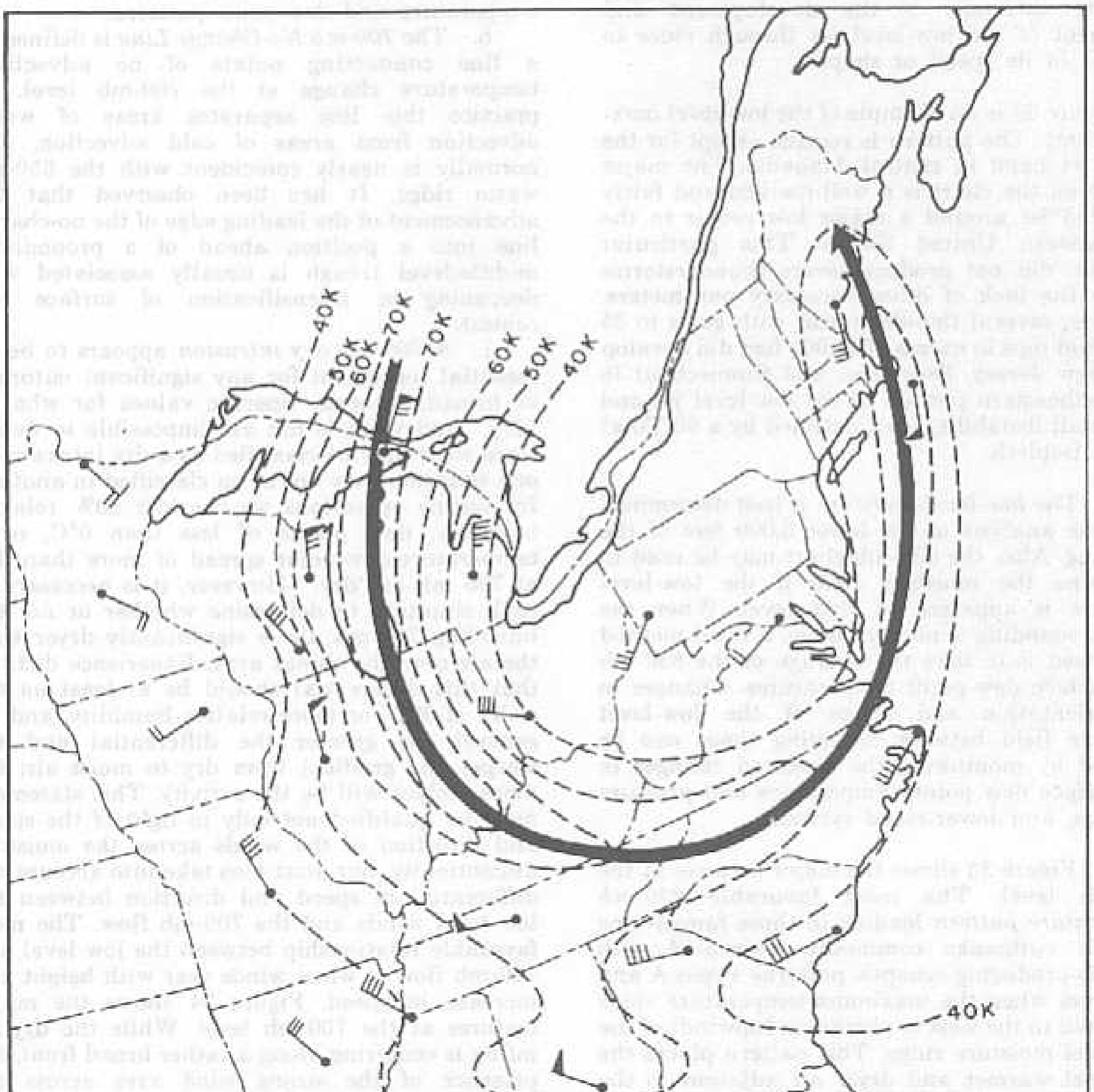


Figure 32. Example of a Low-Level Maximum-Wind Chart.

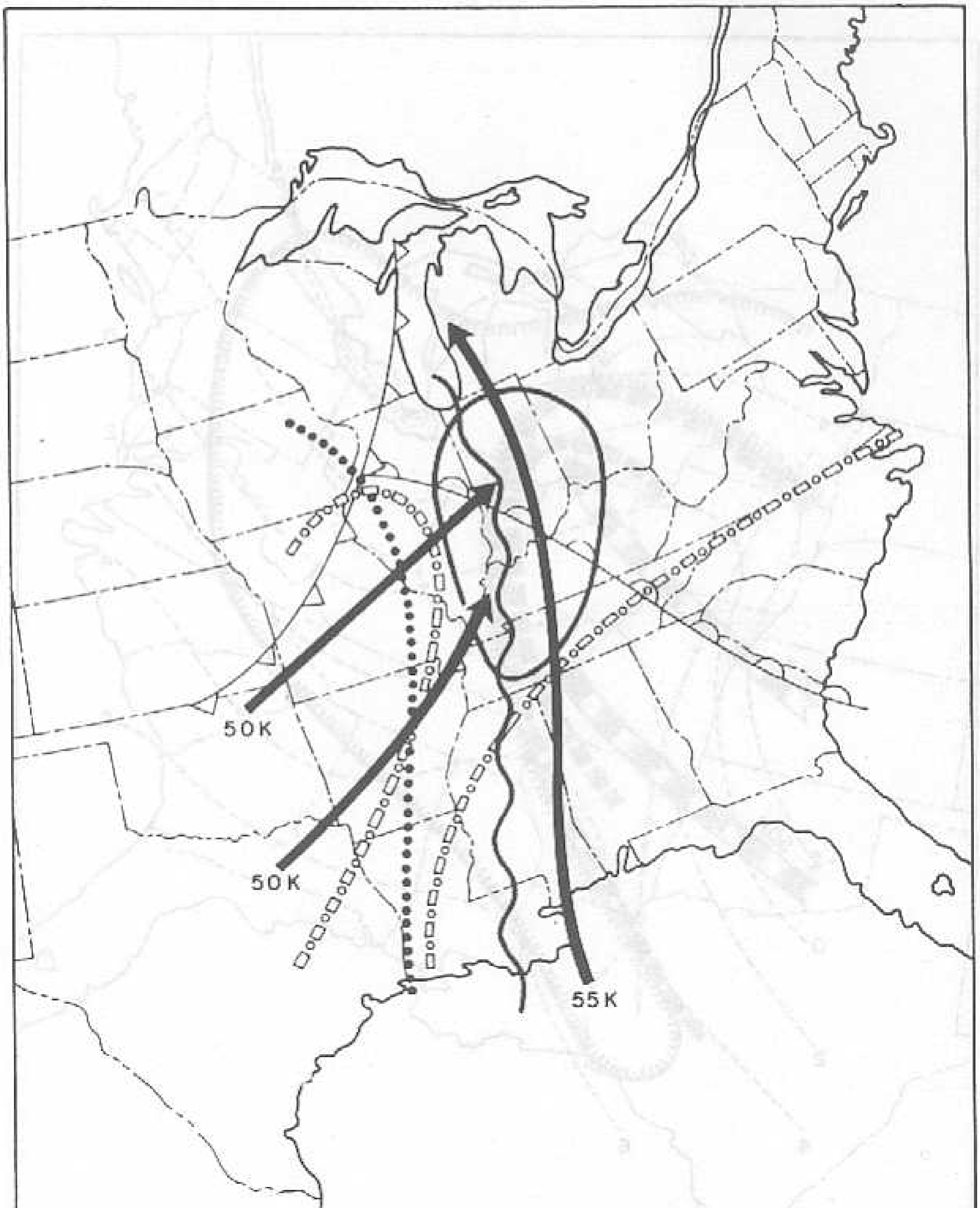


Figure 33. Example of the major features at the 850-mb level showing region of significant moisture and the location of the moisture axis, dry tongues, and low-level jets.

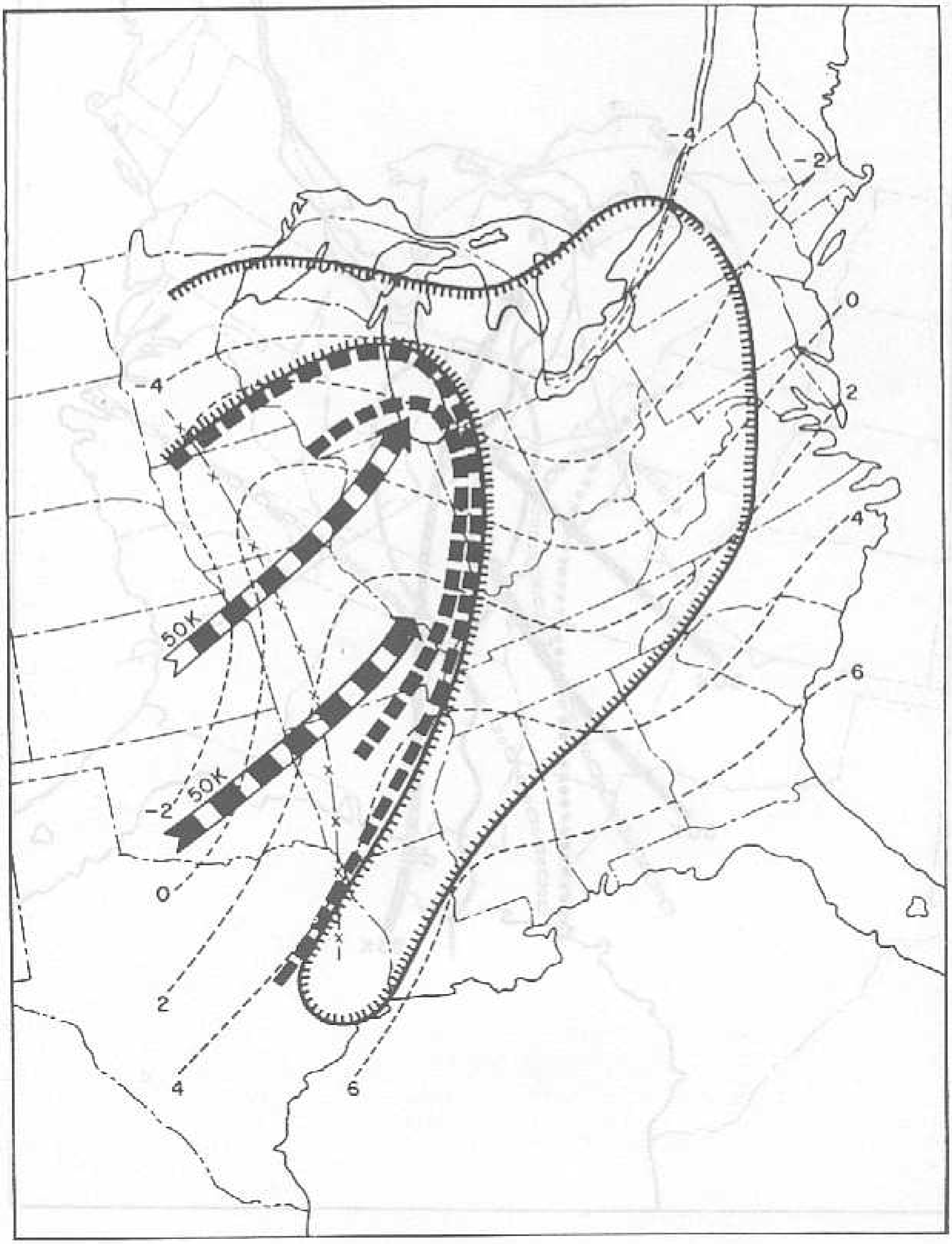


Figure 34. Example of major features at 700-mb level showing jets, dry tongue, and region of significant 700-mb moisture

pattern of more concentrated falls. Also, pressure falls over shorter intervals of time are important in limiting the areal extent of severe activity.

k. The *500-mb height change,* in association with the temperature changes at 500-mb, is closely related to the 500-mb vorticity field. Height falls provide the forecaster with valuable clues as to the location and movement of short- and long-wave troughs in the middle troposphere. Sufficient data is available at this level to locate significant zones of height falls upwind of the threat area, and to assess their movement and the resultant effect reasonably. Figure 35 is a 500-mb chart showing a multiple-branching jet, a marked diffluent area and a strong horizontal shear to the south of the primary jet. Also, the marked thermal trough has a strong temperature-fall pattern moving in behind it. Vertical motion is in progress with considerable moisture evident at this level. If the other parameters are favorable, this 500-mb chart would require close examination in at least three areas:

(1) The area of diffluence associated with the well-defined jet branching.

(2) The area swept by the main jet flow from Missouri into northern Ohio.

(3) The area affected by the horizontal shear south of the main jet.

l. The *height of the Wet-Bulb-Zero* above the earth's surface is well correlated with the incidence of destructive tornadoes, thunderstorms and damaging hail at the surface, and is discussed in greater detail in chapter 7. When this height is below 5,000 feet or above 11,000 feet, the occurence of hail and strong gusts at ground level is rare and tornadoes are infrequent and short-lived. The one exception to this rule is that with a Type II air mass tornadoes will often occur with the Wet-Bulb-Zero above 11,000 feet, although surface hail and strong gusts seldom materialize.

m. The *surface pressure* may be termed a delimiting parameter in the sense that the incidence of tornadoes is sharply reduced as the surface pressure rises above 1013 mb although the interrelated parameters a. through b. may be present in strength and number. Early climatological studies by Joseph G. Galway of the Weather Bureau [34] and later tabulations by both the Air Weather Service and Weather Bureau warning centers, show tornadic occurrence at pressures above 1019 mb to be practically non-existent. The more destructive family-type tornado outbreaks occur in areas where the surface pressure in the threat area is 1005 mb or lower.

n. The *surface dew point* is another limiting parameter, similar to the surface pressure. The incidence of tornadoes is quite infrequent at dew-point temperatures below 55°F, and very rare when surface dew-point temperatures fall below ~~55~~ 50°F. The tornadoes that do occur in these lower dew-point ranges are either connected with a Type III air mass and associated cold pool aloft, or with a Type II air mass which is overrunning a shallow warm front or old mesohigh (bubble). In the latter instance the funnel must have sufficient strength to penetrate the cooled lower levels. Figure 36 is a typical surface pattern associated with major severe weather and tornado outbreaks. The general wind field is shown along with the temperature and dew-point ranges. The 55°F dew-point line is shown by dashed double lines.

SECTION C—OTHER PARAMETERS TO BE CONSIDERED

A number of other parameters must be considered in the study of a potential severe weather system. The following parameters do not correlate with severe weather phenomena as highly as the 14 parameters discussed in Section B above. However, their existence during periods of severe weather activity is of a frequency which demands at least some consideration. It is entirely probable that many other parameters exist that could be useful on a routine basis by experienced severe weather forecasters, but naturally only those parameters readily available in the routine weather reports and analyses are likely to be noticed.

a. The *rates of change of the surface temperature, pressure, and dew point* are usually based on a 3-hourly rate of change or less. Areas of maximum positive dew-point change and positive temperature change assist in decreasing the stability of the air column, while the area of maximum negative pressure change provides information as to the location of the area of most rapidly developing low-level convergence, vertical acceleration and divergence aloft.

b. The *most favorable combined low-level and middle-level wind fields* occur under the following conditions.

(1) Pronounced veering (30° or greater) between the low and middle-level winds is highly desirable for the development of severe storms. It appears that the greater the directional shear between these levels, the more certain the development of severe activity and the more likely its subsequent movement and maintenance of intensity.

(2) Speed differential is also desirable. In cases where the amount of veering between the low- and middle-level flow is less than 30° the middle-level flow must exceed the speed of the low-level winds by at least 30%. Pronounced veering accompanied by significantly stronger winds in the middle levels is the most favorable wind structure for tornado development.

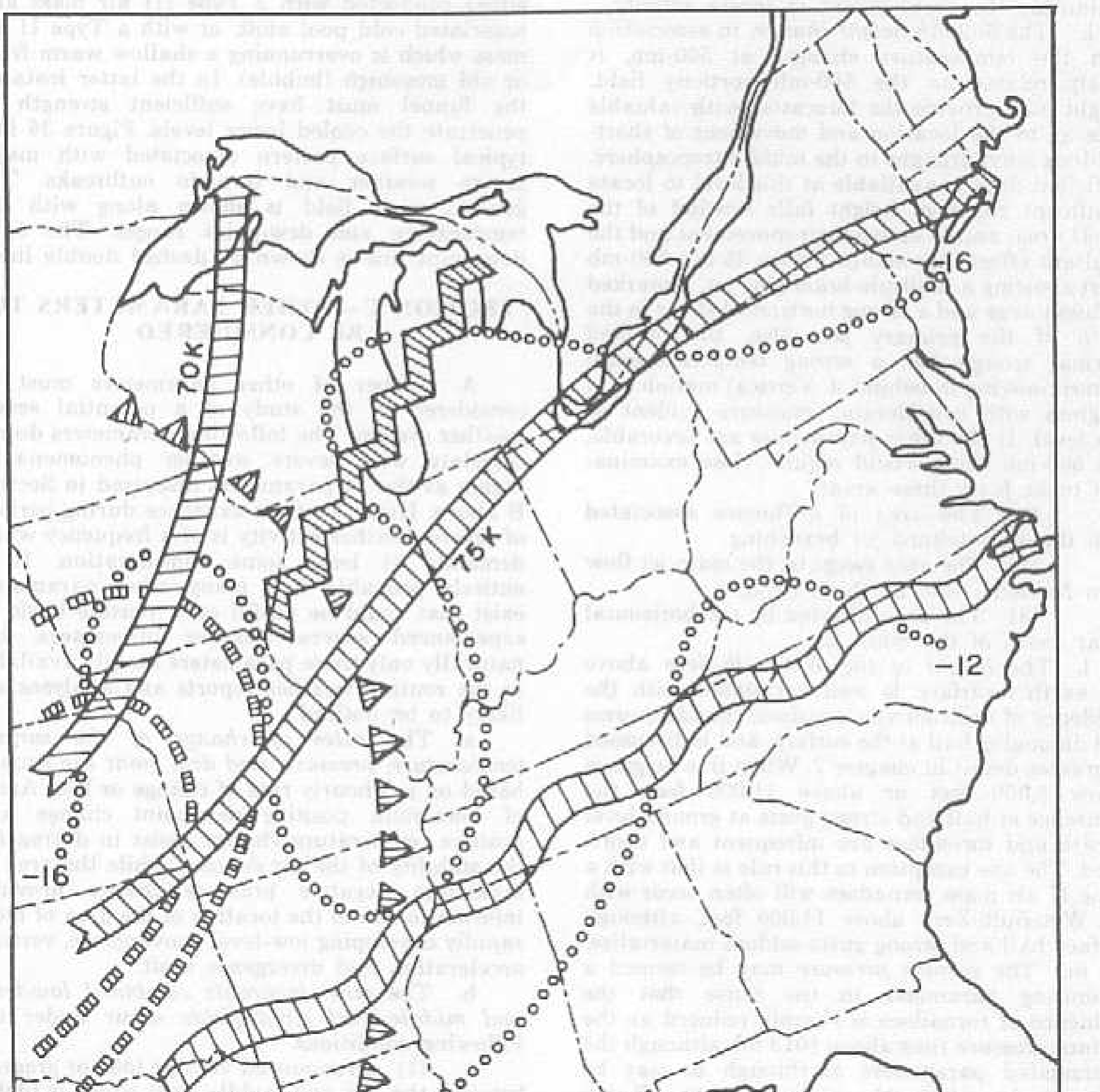


Figure 35. Major features at the 500-mb level

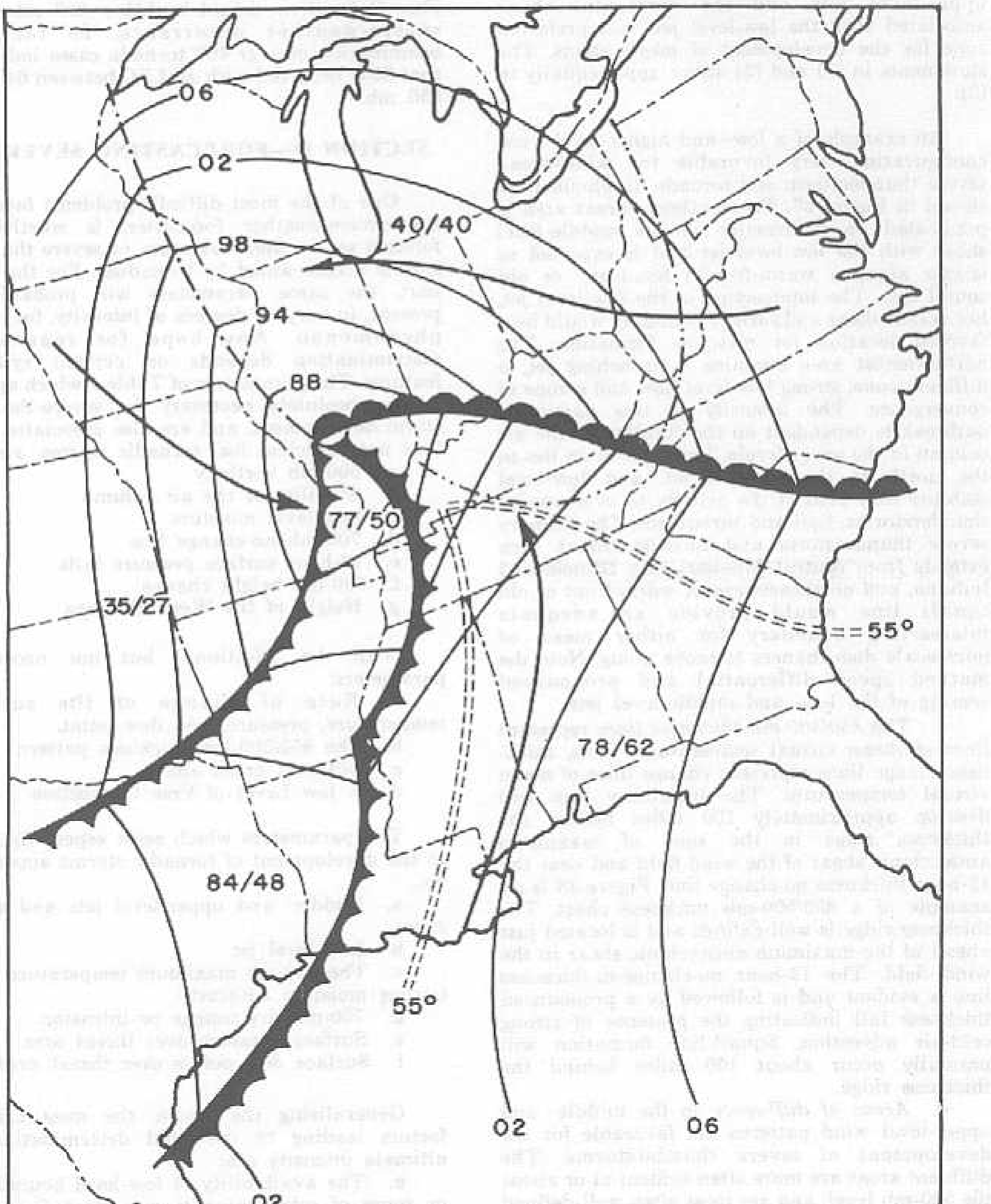


Figure 36. Example of typical surface pattern showing major parameters

(3) The intersection of the middle- or upper-level jets and the horizontal shear associated with the low-level jet, is a preferred zone for the development of mesosystems. The statements in (1) and (2) above apply equally to (3).

An example of a low- and higher-level wind configuration very favorable for widespread severe thunderstorm and tornado development is shown in Figure 37. The southern threat area is predicated on intersection of the middle-level shear with the low-level jet and is expected to trigger along a warm-frontal boundary or old squall line. The intersection of the low-level jet, horizontal shear and surface boundary would be a favored location for mesolow formation. The northernmost area contains a branching jet, a diffluent zone, strong low-level flow and a zone of convergence. The intensity of this particular outbreak is dependent on the stability of the air column in the lower levels. This zone often lies to the north of the warm front, and low-level stability may restrict the activity to overrunning thunderstorms, hail and turbulence. The primary severe thunderstorm and tornado threat area extends from central Missouri into Illinois and Indiana, and northeastward. A warm front or old squall line would provide an adequate intersecting boundary for either meso or microscale disturbances to move along. Note the marked speed differential and pronounced veering of the low- and middle-level jets.

c. The *850/500-mb thickness lines* represent lines of mean virtual temperature. Thus, thickness-change lines represent change lines of mean virtual temperature. The instability line will develop approximately 100 miles behind the thickness ridge in the zone of maximum anticyclonic shear of the wind field and near the 12-hour thickness no-change line. Figure 38 is an example of a 850/500-mb thickness chart. The thickness ridge is well-defined and is located just ahead of the maximum anticyclonic shear in the wind field. The 12-hour no-change-in-thickness line is evident and is followed by a pronounced thickness fall indicating the presence of strong cold-air advection. Squall-line formation will normally occur about 100 miles behind the thickness ridge.

d. *Areas of diffluence* in the middle- and upper-level wind patterns are favorable for the development of severe thunderstorms. The diffluent areas are more often evident at or about the 500-mb level, and are most often well-defined at the 200-mb level (or at the jet level). Since evidence of the presence of an approaching positive-vorticity center aloft is indicated by the existence of a diffluent zone downwind in the middle and upper levels, the importance of this parameter is understandable.

e. Experience has shown that the *Level of Free Convection* should be below 600 mb for a severe-weather occurrence. In fact, an examination of over 400 tornado cases indicated that 80% occurred with an LFC between 640 and 850 mb.

SECTION D—FORECASTING SEVERITY

One of the most difficult problems faced by the severe-weather forecaster, is whether to forecast severe thunderstorms, or severe thunderstorms accompanied by tornadoes. For the most part, the same parameters will probably be present, in varying degrees of intensity, for either phenomenon. Any hope for reasonable discrimination depends on certain synoptic features. The parameters of Table 1 which appear to be absolutely necessary for severe-thunderstorm development, and are also associated with (but not sufficient for) tornadic storms, are:

a. 500-mb vorticity
b. Stability of the air column
c. Low-level moisture
d. 700-mb no-change line
e. 12-hour surface pressure falls
f. 500-mb height change
g. Height of the Wet-Bulb-Zero

With the additional but not necessary parameters:

a. Rate of change of the surface temperature, pressure, and dew point.
b. The 850/500-mb thickness pattern
c. Diffluent areas aloft
d. A low Level of Free Convection

The parameters which seem especially vital to the development of tornadic storms appear to be:

a. Middle- and upper-level jets and shear zones.
b. Low-level jet
c. The 850-mb maximum temperature field (strong moisture contrast)
d. 700-mb dry tongue or intrusion
e. Surface pressure over threat area
f. Surface dew points over threat area

Generalizing the above, the most critical factors leading to the final determination of ultimate intensity are:

a. The availability of low-level boundaries or zones of intersection to provide a favorable environment for the development of intersecting lines, with the resultant development of mesoscale bubble highs and mesocyclones.

b. The proper configuration and strength of the combined lower-zone and higher-level wind fields.

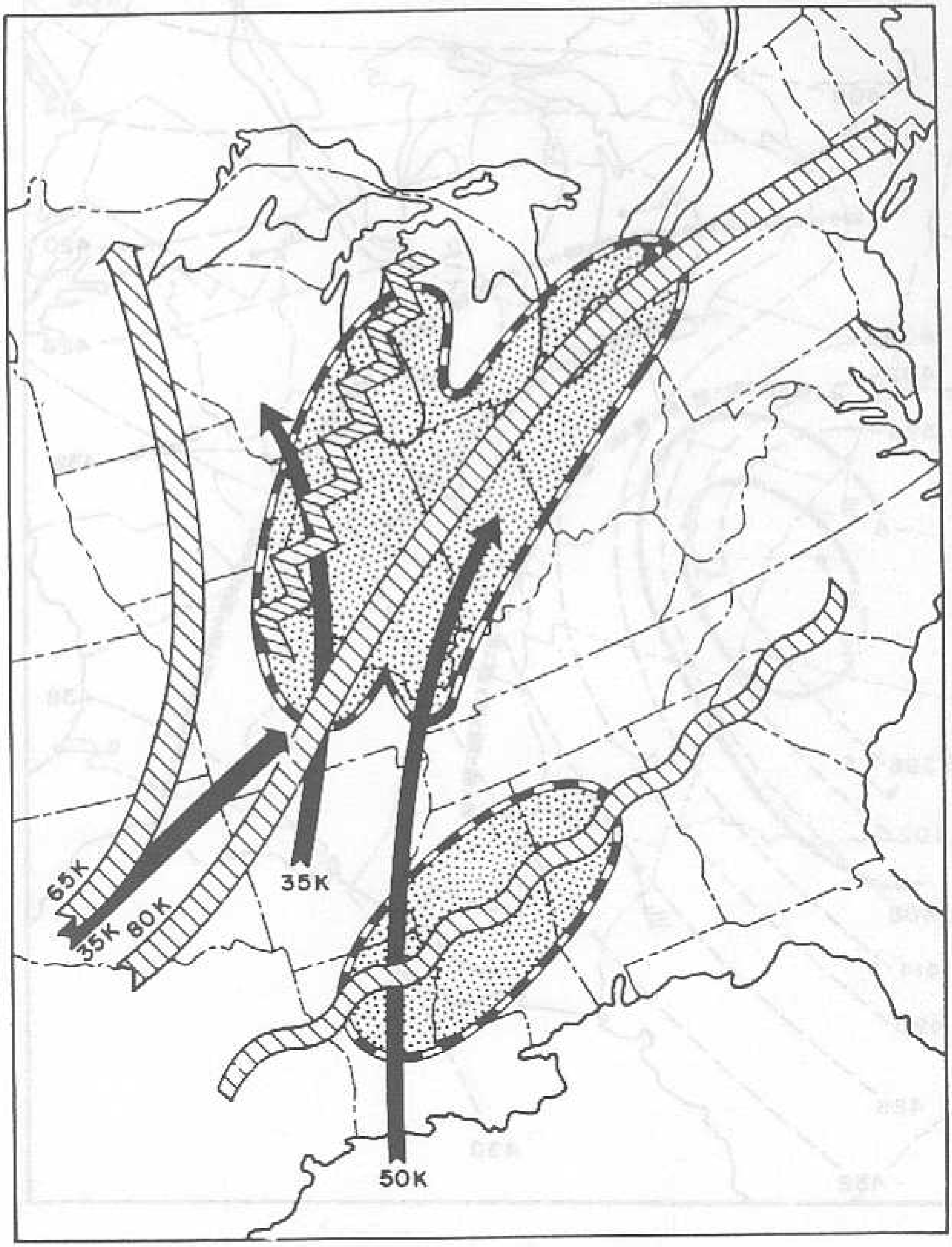


Figure 37. Example of low- and higher-level wind fields. Stippled areas outline regions of severe-weather occurrences.

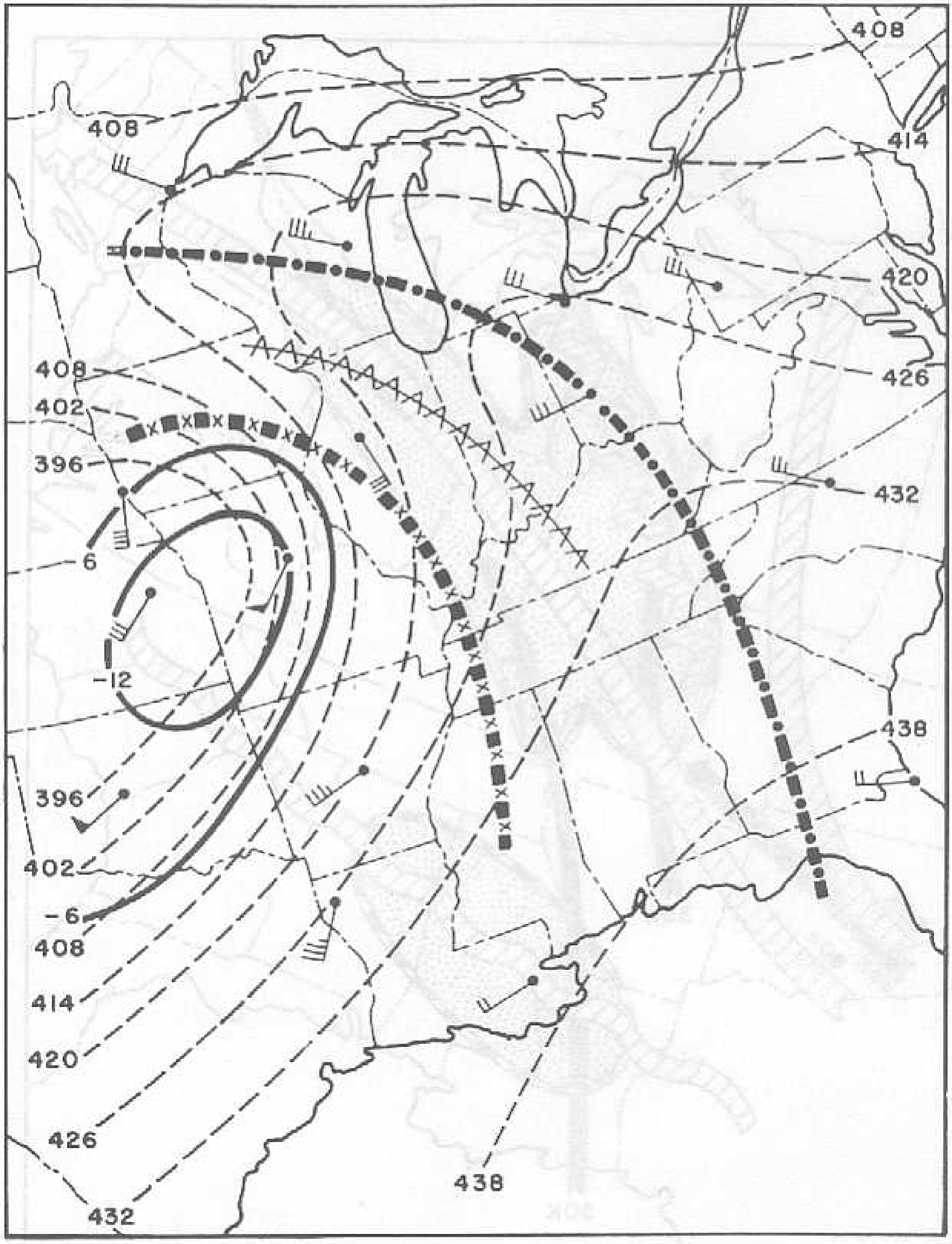


Figure 38. Example of a 850/500-mb Thickness Chart showing max thickness falls, no-change thickness line, thickness ridge and max anticyclonic shear zone.

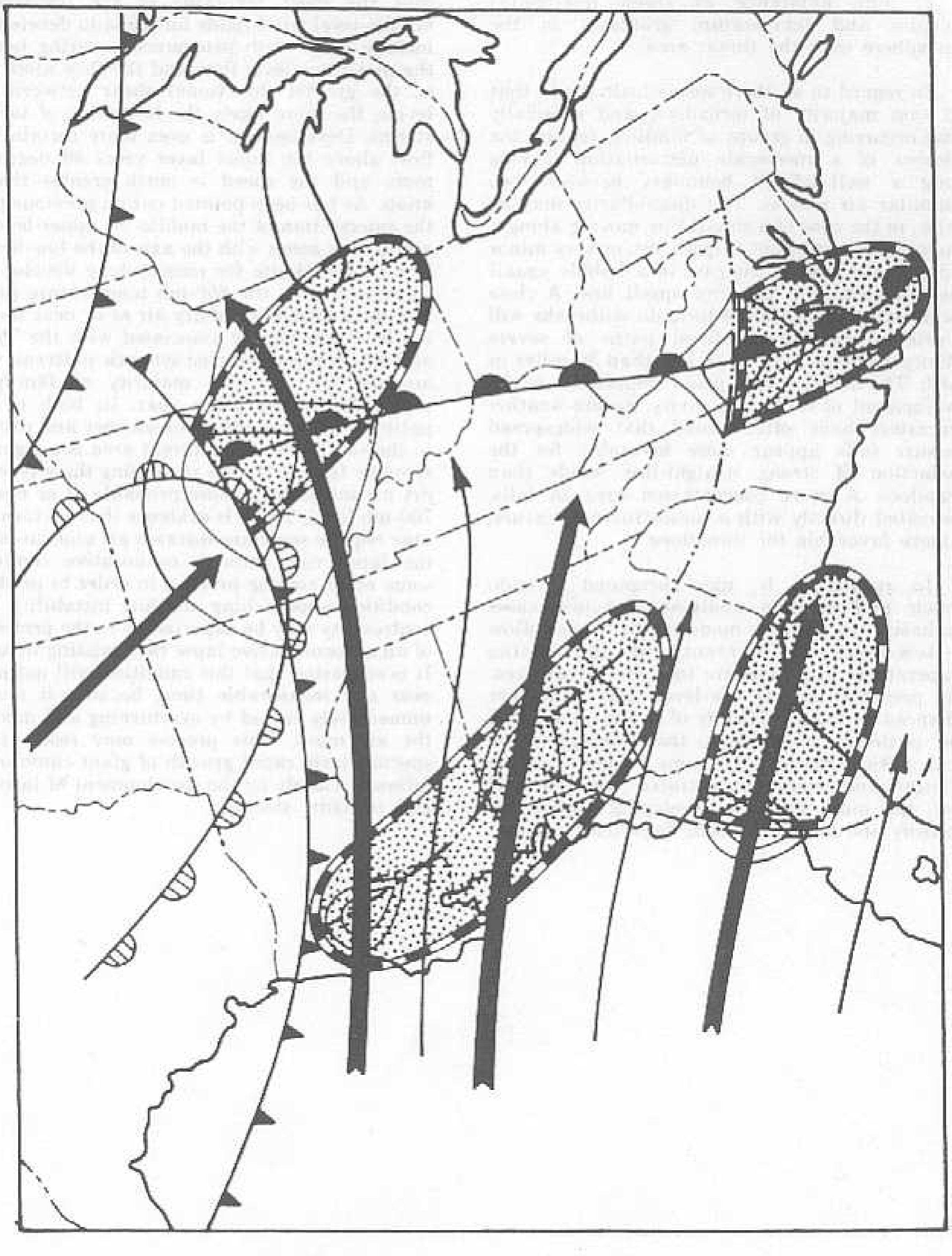


Figure 39. Examples of persistent (warm front) and transitory (squall line) features (and old squall line) in the surface and low-level circulation.

c. The existence of steep horizontal moisture and temperature gradients in the atmosphere over the threat area.

In regard to a., there seems little doubt that the vast majority of tornadoes, and especially those occurring in groups or families, require the presence of a mesoscale perturbation moving along a well-defined boundary between two dissimilar air masses. The dissimilarity may be major, in the case of a squall line moving along a macroscale warm front (Figure 39), or very minor and transitory as in the case of a bubble squall line intersecting a decaying squall line. A close examination of signficant tornado outbreaks will invariably show well-defined paths of severe activity, perhaps only 10 to less than 30 miles in width. The mesolow is of prime importance in the development of tornadic activity. Severe-weather forecasters have often noted that widespread pressure falls appear more favorable for the production of strong straight-line winds than tornadoes. A more concentrated area of falls, associated directly with a mesostructure feature, is more favorable for tornadoes.

In regard to b., most proposed tornado models and detailed analyses of actual cases emphasize the need for moderate to strong inflow of low-level air currents of contrasting temperatures and moisture into the threat area. The presence of this low-level flow is further enhanced by the availability of strong upper-level flow patterns conducive to the development of local vertical motions. It seems evident that the stronger and more concentrated the low-level flow, the more likely a developing vortex can intensify and maintain itself. Experience dictates that the most favorable of the low-level or middle-level wind fields for tornado development include those with pronounced veering between the moist low-level flow and the flow aloft. That is, the greater directional shear between these levels, the more likely the formation of tornadic storms. Development is even more certain if the flow above the moist layer veers 30 degrees or more and the speed is much greater than 25 knots. As has been pointed out on previous pages, the intersection of the middle- or upper-level jets and shears zones with the axis of the low-level jet is a preferred site for mesocyclone development. In regard to c., the 850-mb temperature pattern and the availability of dry air at or near the 700-mb level are closely associated with the Type A and B tornado-producing synoptic patterns, which account for the vast majority of family-type outbreaks in any given year. In both of these patterns the availability of warmer and dryer air to the southwest of the threat area is a signficant synoptic feature. In the remaining three types, the dry-air intrusion is more probable at or near the 700-mb level. There is evidence that all tornadoes may require some unsaturated air aloft to steepen the lapse rate through evaporative cooling or some other cooling process, in order to produce a condition approaching absolute instability. Some controversy may be expected as to the probability of an autoconvective lapse rate existing in nature. It is suggested that this condition will not persist over any measurable time, because it must be immediately erased by overturning and mixing of the air mass. This process may result in the spectacularly rapid growth of giant cumulonimbi followed closely by the development of large hail and tornadic storms.

Chapter 6

FORECASTING IN THE SUMMER MONTHS

SECTION A—GENERAL

The summer months (July, August, and September) present a special problem to the severe-weather forecaster. Major systems are weak, continuity of moving features erratic, wind and temperature fields poorly defined, and thunderstorm occurrences widespread. Since instability is high over most of the country during this period, the forecaster must be vigilant and carefully analyze and monitor all available information to isolate features which might generate a sustained thunderstorm impulse.

Almost any summer thunderstorm can produce violent winds over a localized area and even damaging hail if the Wet-Bulb-Zero height is favorable. The surface temperatures are usually high, so the downrush air has the potential to produce very strong local gusts. The threat of summer storms increases dramatically when some macro or mesoscale feature permits a zone, area or line of these storms to develop and move for a considerable period of time. However, these storms are usually isolated and short-lived, and the area affected is on the order of 1 to 5 square miles. Thus, these storms usually do not present a frequent hazard to specific bases or locations.

Since the wind and temperature fields are normally weak and the Wet-Bulb-Zero is high in a summer air mass, the number of tornado occurrences is quite small, but the frequency of straight-line damaging windstorms increases proportionally. Hail is infrequent over the country, but the incidence of large hail in certain geographical areas* increases in major outbreaks because of the abundant supply of low-level moisture and heat. Severe thunderstorms are more frequent during these months over the northern plains including Montana and Wyoming, because significant cool-air intrusions still frequently penetrate into the north central and northeastern portions of the United States. Although there are more hours of low-level heating available during the summer, especially over the northern portions of the country, stabilization due to nocturnal cooling in the lower layers is slight. This results in a more frequent severe activity during the nighttime hours than is normal for the rest of the year. The occurrence of severe thunderstorms after midnight in the summer months is not rare and even common during a major outbreak.

SECTION B—SOURCE REGIONS FOR SUMMERTIME OUTBREAKS

A major source region for summertime severe-weather outbreaks lies over the High Plains along *the eastern slopes of the Rockies* from New Mexico northward. In this region the formation of middle-level thunderstorms is common during the late afternoon and evening and is primarily dependent on the availability of 700- and 500-mb moisture and a weak middle-level convergence field. These storms show little inclination to drift eastward when the upper winds are light and variable. However, it has been observed that if several cells develop in a fairly restricted area and there is local cooling due to heavy precipitation, the result is the formation of bubble (mesohigh). Even without the drag of middle-level winds, a bubble of a central pressure of 2- to 4-mb higher than the surrounding air-mass pressure will move downslope because of the density difference. This movement initiates more thunderstorms with potentiality for severe activity. The thunderstorm bubble is not likely to persist for more than 2 to 4 hours and usually weakens rapidly after moving east of a general line from Amarillo, Texas to Mobridge, South Dakota. The normal movement is toward lower pressure and higher temperature, and is usually at 30 degrees to the right of any significant prevailing middle-level flow.

The lee-slope bubble squall line is far more dangerous when the middle-level convergence becomes better defined, along with an increase in the westerly component of the middle-level winds. Middle-level flow of 20 knots or greater is highly correlated with the movement of a strong bubble, or series of bubbles, and with the movement of a major squall line off the mountains eastward into the plains. A wind component from south of west will cause a line to move east or northeast at about the speed of the middle-level flow, and any activity that develops usually will degenerate into

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*These areas are along the Continental Divide eastward into the High Plains to Iowa, Minnesota, northern Missouri, Wisconsin, Michigan, and most of Illinois. Damaging hailstorms are also frequent over the Carolinas and southern Virginia during the summer months.

mere showers around 1200Z. This south-of-west wind component will keep the activity north of the Kansas-Nebraska border, the most intense storms being associated with the strongest middle- and low-level winds. These storms undergo sharp intensification as they move into the western plains and entrain air of higher surface dew points. The intensity and persistence of these mountain squall lines is proportional to the strength of the wind fields and to the number of the standard forecast parameters that are favorable.

When the surface and low-level winds are easterly in the lee of the Rocky Mountains, the situation is more favorable for the production of widespread numerous heavy thunderstorms with severe-storm development in the inception area.

When the middle-level flow is west or north of west, the major outbreaks will move more southeasterly and the activity will persist until 1200Z. The squall lines usually degenerate once they pass a line from Wichita Falls, Texas to Des Moines, Iowa, but this degeneration is dependent on the source region and length of the squall line. These squall lines are likely to recur on successive nights during a stagnant synoptic situation. This same type of activity occurs along *the Continental Divide over portions of western Montana and western Wyoming.*

The *Appalachian Mountain Chain and the Eastern Coastal Plain* are geographically favorable for the development of signficant summer thunderstorm activity. The formation and movement of the storms are governed by the same factors that control development along the Rocky Mountains, but the incidence of severe thunderstorms is more concentrated in the afternoon and early evening hours. This afternoon preference is due to the low-level heating and high dew point of the tropical air mass.

SECTION C—FRONTAL INFLUENCES

There is little doubt that the most destructive severe-weather outbreaks in the summer are associated with southeastward moving surface cold fronts or a west-northwest or northwest flow in the mid-troposphere. Positive vorticity advection is necessary but may not be apparent due to the weak thermal fields aloft and smoothing of the data. The stronger the system the more likelihood there will be widespread and long-lived activity if sufficient instability is present. These outbreaks develop most frequently after 0200Z in the Dakotas or Minnesota and move east or southeast into Iowa, Wisconsin, Illinois, Indiana, and western Ohio. Along the Appalachians the systems are most frequent and active between 2000Z and 0200Z, and are usually associated with a persistent westerly middle-level flow. Also, the activity will continue through the night and the storms are likely to repeat on several successive nights. Once developed by the front the squall line will more southeastward, usually confined to the north of a weak warm-frontal boundary. The activity of the squall line and the precipitation cooling of the air below the front has been observed to reinforce this frontal surface. Given favorable low-level winds such a reinforced boundary may experience late afternoon and evening overrunning, usually resulting in an outbreak of hail-producing thunderstorms downwind of where the next evening squall line might otherwise have been expected. This synoptic pattern produces a multiple squall-line situation which increases the future chances for squall-line intersections and the development of mesostructures. Depending on the extent and strength of the upper-wind flow, the southeast or leading edge of these old squall lines occasionally will reactivate during the next afternoon and move south or southeastward into the Gulf Coastal States.

SECTION D—ANALYSIS

The key to successful summertime severe-thunderstorm forecasting is, as always, meticulous attention to detail. During this period of widespread unstable air any organization of the normally scattered convective cells must be detected and monitored. The surface chart must be carefully analyzed for persistent and transitory features, lows, fronts, convergence zones, mesohighs, mesolows, old squall lines and changes in the pressure field. The National Radar Chart and local radar are useful for locating areas where lines seem to be forming or thunderstorms collecting. Also, close examination of the hourly sequences (including the remarks) may provide a clue to the areas where thunderstorms are apparently becoming more numerous or organized.

The 850-mb chart is analyzed for many of the same features as the surface chart, and for the sources of dry and very hot intrusions. The apex of hot intrusions is a favored area for the development of summer severe storms. The low-level wind field provides a look in depth at low-level convergence and may indicate development of a low-level jet.

The 700-mb chart is analyzed for minor troughs, convergent zones, horizontal shears and the availability of moisture. Cold-air advection is looked for and the location of dry hot intrusions

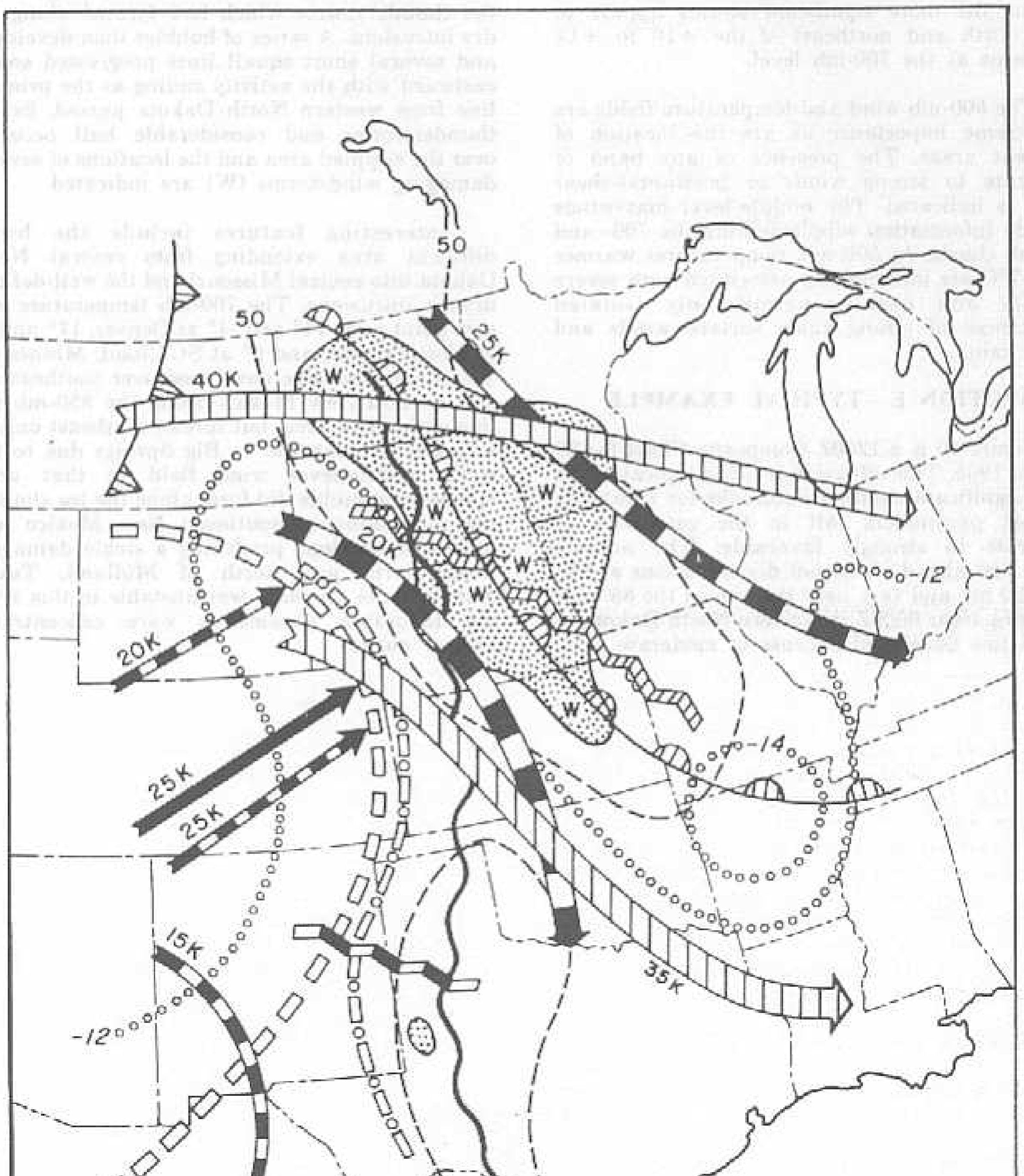

Figure 40. Composite Chart for 1200Z 26 August 1965 is a typical summertime severe-weather pattern

indicated as on the 850-mb chart. During summer months the more significant storms appear to form north and northeast of the +10 to +14 isotherms at the 700-mb level.

The 500-mb wind and temperature fields are of extreme importance as are the location of diffluent areas. The presence of any band of moderate to strong winds or horizontal-shear zones is indicated. The middle-level max-winds provide information supplementing the 700- and 500-mb charts. At 500 mb, temperatures warmer than -7°C are infrequently associated with severe activity and usually permit only isolated occurrences of strong gusty surface winds and heavy rain.

SECTION E—TYPICAL EXAMPLE

Figure 40 is a 1200Z Composite Chart for 26 August 1965. This situation is fairly typical of the more significant summer outbreaks for which the forecast parameters fall in the categories of moderate to strongly favorable: The activity began just ahead of the hot dry intrusions at 850 and 700 mb and very near the axis of the 850-mb moisture. Near 0000Z in western North Dakota, a squall line developed because of moderate cold-air advection, moved southeast, and merged with the thunderstorms which had formed along the dry intrusions. A series of bubbles then developed and several short squall lines progressed southeastward with the activity ending as the primary line from western North Dakota passed. Severe thunderstorms and considerable hail occurred over the stippled area and the locations of several damaging windstorms (W) are indicated.

Interesting features include the broad diffluent area extending from central North Dakota into central Missouri and the well-defined dry-air intrusions. The 700-mb temperature and dew point were 14° and -4° at Denver, 11° and 4° at North Platte, and 6° at St. Cloud, Minnesota. Thunderstorms also developed over southeastern and eastern New Mexico along the 850-mb dry line within this area, but spread southeast only to a line from Amarillo to Big Springs due to the weak middle-level wind field in that area. However, a bubble did form along the lee slope of the mountains in southeast New Mexico and moved down slope producing a single damaging wind storm just north of Midland, Texas. Although the air mass was unstable in this area, the favorable parameters were concentrated further north.

Chapter 7

THE WET-BULB-ZERO HEIGHT

SECTION A—GENERAL

In many instances when severe activity including tornadoes, hail and surface gusts are predicted and severe thunderstorms form, the damaging phenomena fail to reach the surface. Careful examination of many of these situations indicates that the Wet-Bulb-Zero (WBZ) height above the earth's surface may be the best single index for discriminating the cases in which the damaging phenomena affect the ground. Figures 41, 42, 43, exemplify how well the severe-weather activity at the surface is limited to regions where the WBZ height is greater than 10,500 feet above the terrain. The areas north of the 10,500-foot WBZ contour are of lower WBZ heights and only therein are the severe storms prevalent. These and many other examples suggest that the 10,500-foot WBZ isoline provides an effective separation of areas where severe phenomena reach the surface from areas where they do not. Thus, this line offers the severe-weather forecaster an exceedingly useful tool for determining the most probable extent of severe-weather phenomena at the earth's surface, when other criteria predict they are likely to occur. Of course not all areas with above 10,500-foot WBZ heights necessarily have severe storms.

SECTION B—RELATIONSHIP OF HAIL SIZE TO THE WET-BULB-ZERO HEIGHT

Studies of hail storms disclosed that over 90% of reported surface hail occurred where the WBZ ~~WMZ~~ height was between 5,000 and 12,000 feet above the terrain. In situations where the larger sizes were reported, the WBZ heights were clustered around an average height of about 9,000 feet above the terrain. When WBZ heights were above 11,000 feet or below 7,000 feet, the frequency and size of hail diminished rapidly. Also, when the WBZ heights were above 12,000 feet or below 5,000 feet, the hail size at the surface was reported no larger than 1/4-inch in diameter regardless of the instability of the air mass. Based on an extensive list of reported hailstorms and the associated soundings, Figure 44 shows the distribution of cases by increments of the WBZ heights. This histogram (revised from an earlier study) emphasizes the concentration of large hail in the 7,000 to 11,000-foot range of WBZ heights, and the sharp cut-off of hail occurrence above 11,000 and below 7,000 feet.

SECTION C—RELATIONSHIP OF TORNADOES TO THE WET-BULB-ZERO HEIGHT

Tornadoes are not confined to the same WBZ height ranges as hail, except for the Type I or family-type tornadoes which have a maximum WBZ height about 8,000 feet above the terrain. Figure 45 presents the distribution of Type I air-mass situations [17] which produced one or more tornadoes. Increments of WBZ height above the terrain are denoted on the ordinate. The Figure shows the 68% of the total cases occurred with WBZ heights in the range from 7,000 to 9,000 feet. Figure 46 shows the number of reported cases of Type I tornado situations which produced families of five or more tornadoes. Increments of WBZ height are defined on the ordinate, and Figure 46 shows that total of 42 or 70% of the cases occurred when the WBZ height was between 7,000 and 9,000 feet.

The Type II Gulf Coast air mass does not fit the WBZ height category for Type I air-mass convection in nature and the moisture extends to great heights producing a higher WBZ height. In this particular air type, thunderstorms rarely produce surface hail or strong surface gusts outside the immediate vicinity of the tornado.

Generally Type II tornadoes occur singly, and reports of more than two or three tornadoes are rare. A histogram of 73 Type II tornado situations with WBZ heights is presented in Figure 47. The majority of Type II tornadoes occurred with WBZ heights in the 11,000 to 14,000-foot range. Two or three tornadoes were reported in 26 of the above 73 situations, and more than three tornadoes occured in four cases. Thunderstorms wind gusts of fifty knots or greater were reported at the surface in six of the 73 situations, and 1/4- to 1/2-inch hail was reported at the surface in 11 cases. Situations with both wind gusts of fifty knots or greater and 1/4- to 1/2-inch hail were reported in four cases. No hail sizes above 1/2-inch were reported.

SECTION D—RELATIONSHIP OF SURFACE WIND STORMS TO THE WET-BULB-ZERO HEIGHT

Destructive winds in squall lines and air-mass thunderstorms are dependent on the

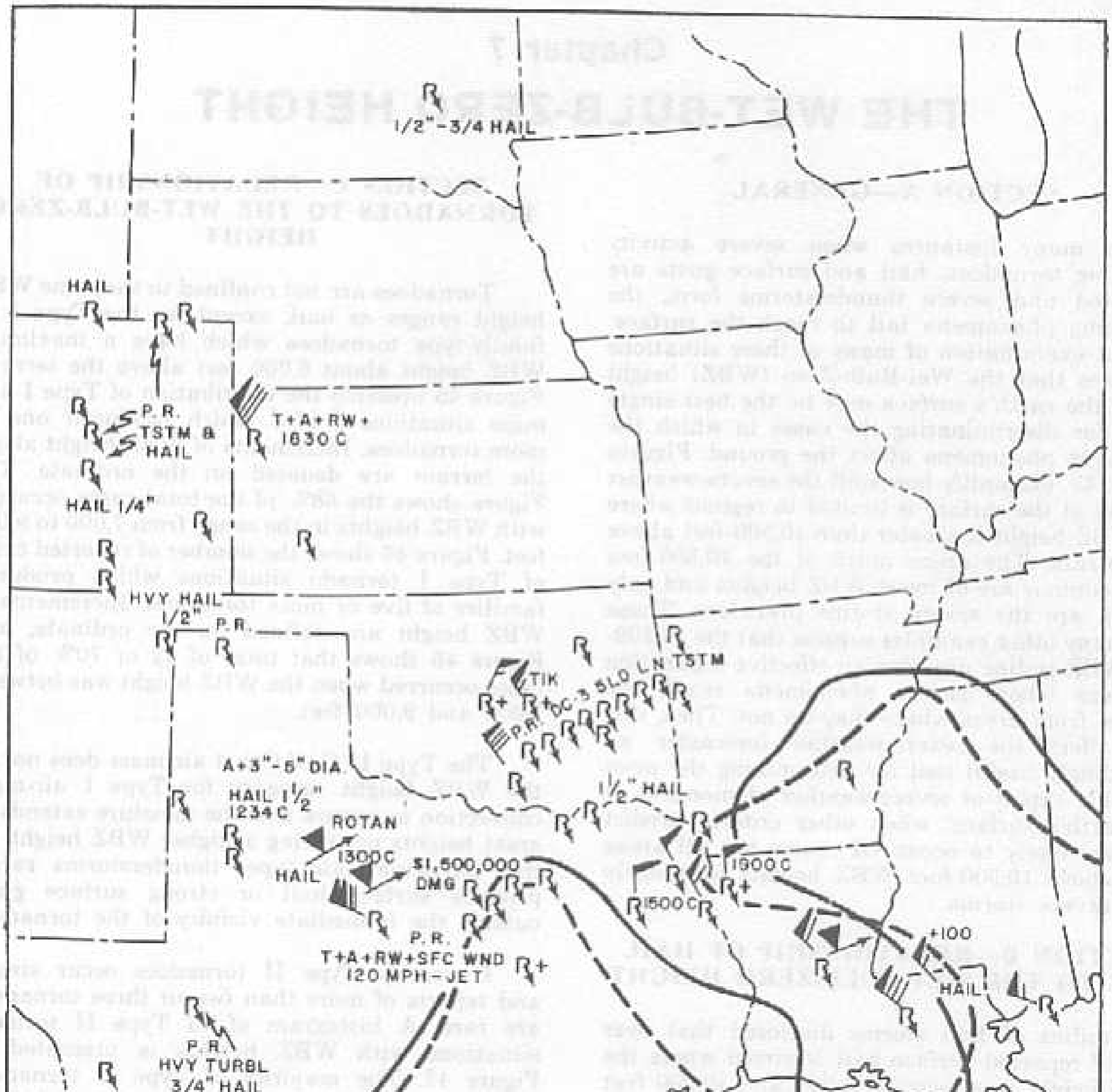

Figure 41. Location of 10,500-foot Wet-Bulb-Zero isopleth and areas of severe-weather activity from 1500Z 10 June to 0300Z 11 June 1951

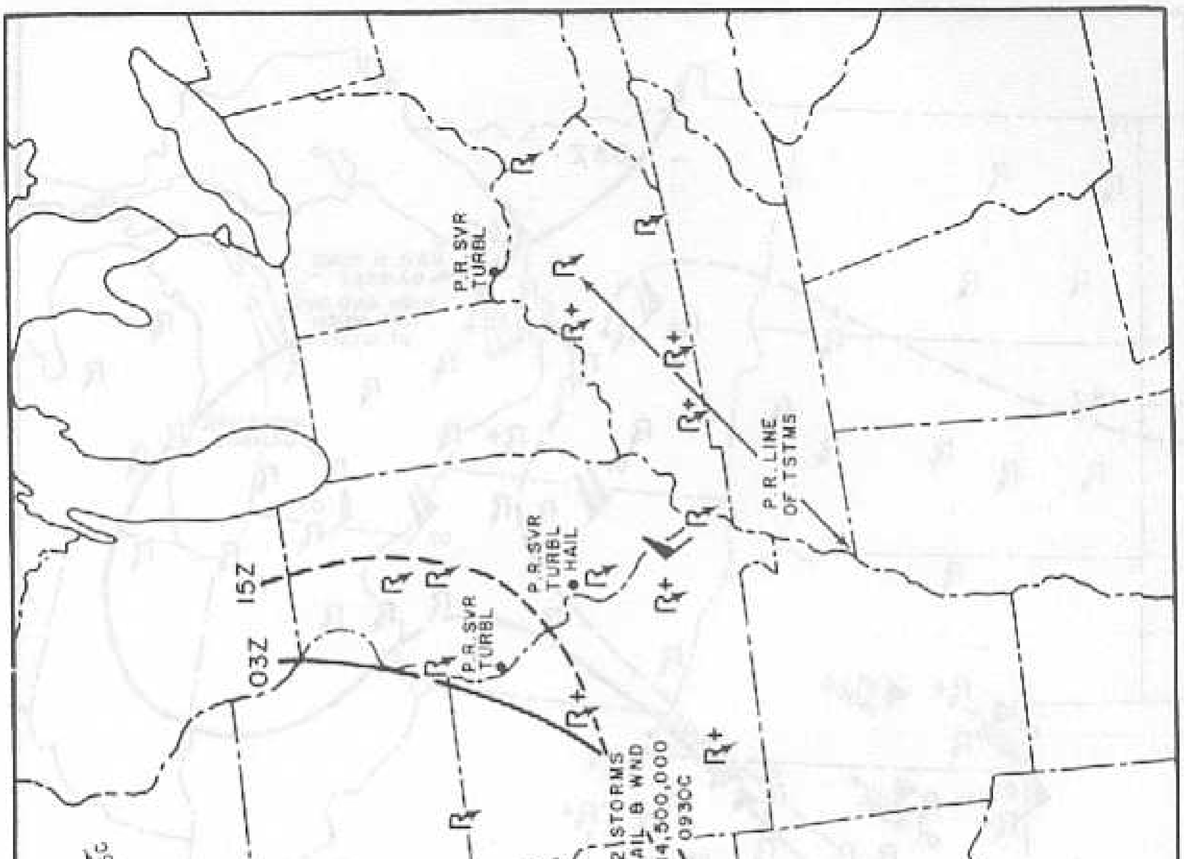

Figure 42. Location of 10,500-foot isopleth and areas of severe-weather activity from 1500Z 23 June to 0300Z 24 June 1951.

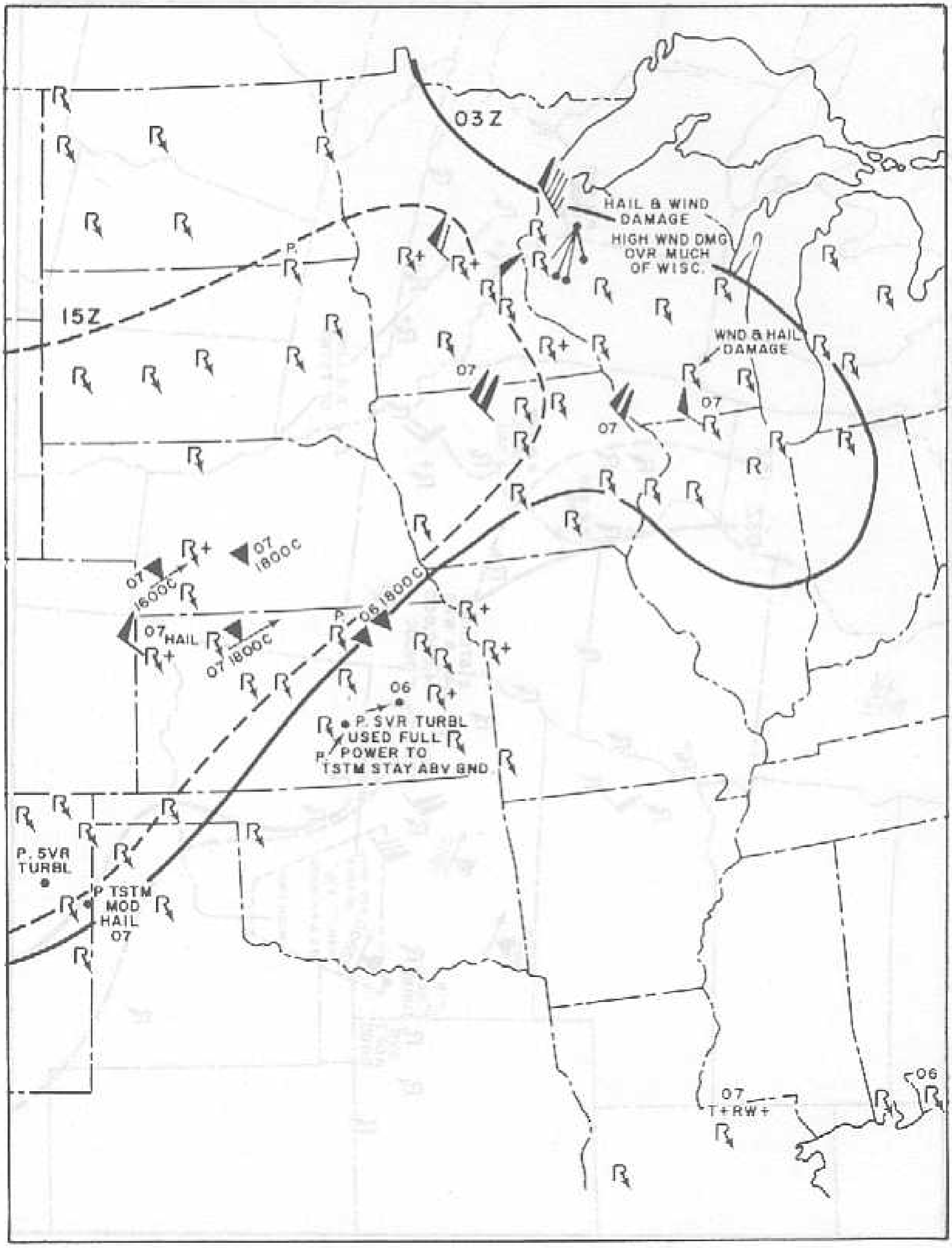

Figure 43. Location of 10,500-foot isopleth and areas of severe activity from 1500Z 7 July to 0300Z 8 July 1951.

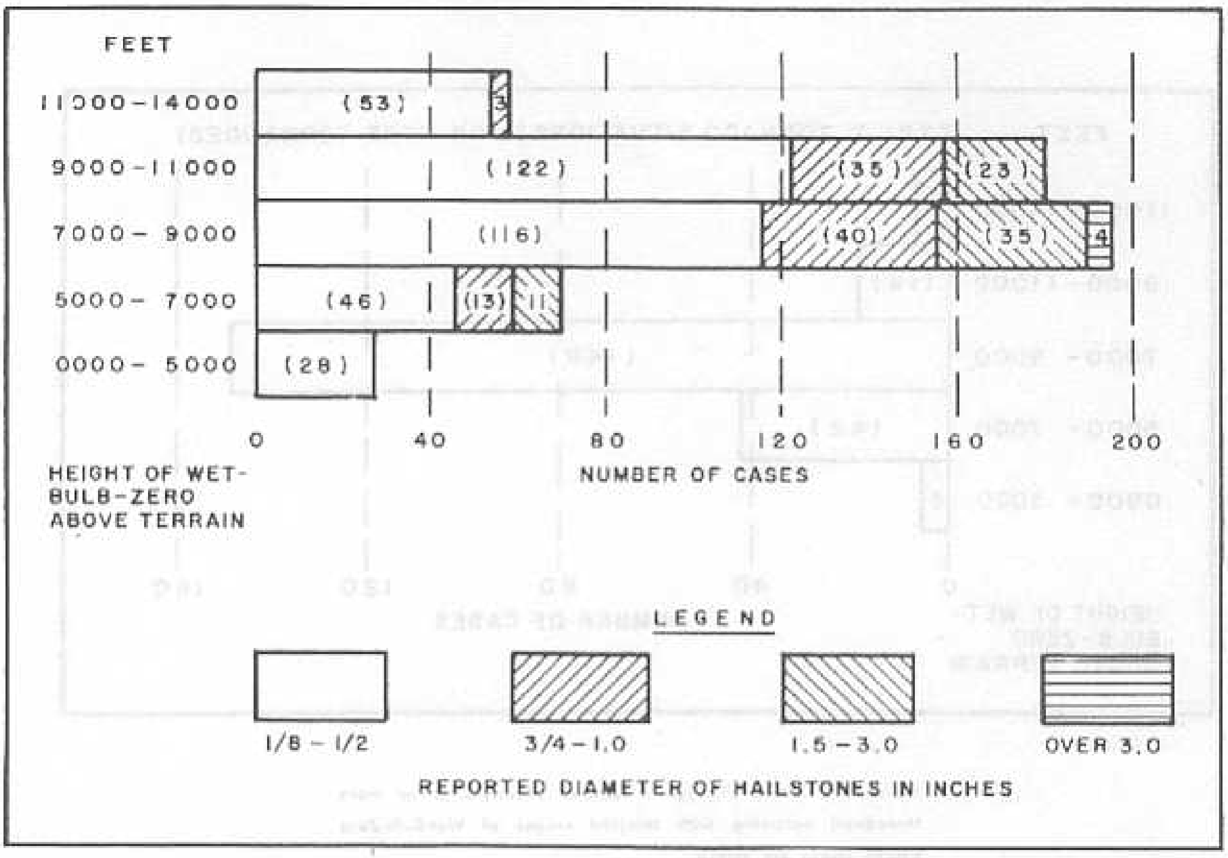

Figure 44. Cases of hail of various sizes by selected ranges of Wet-Bulb-Zero height above the terrain (529 Reports).

downward surge of a strong wind current aloft, the temperature difference between the downdraft and environmental air, and the forward component of the storm. A preliminary examination of over 500 cases of thunderstorm winds of 50 knots or greater shows much the same distribution on the WBZ histogram as for the occurrence of all the hail cases.

SECTION E—USE OF THE WET-BULB-ZERO HEIGHT IN THE FORECAST PROCEDURE

The WBZ height is determined as an integral part of the analysis routine. These heights are entered on a chart in hundreds of feet above the earth's surface and are analyzed for 500-foot intervals between 12,500 feet and 5,000 feet. The 10,500 and 7,000-foot isopleths are shaded to indicate the most probable limits of severe-weather phenomena at the surface. The analyst must evaluate carefully the atmospheric soundings and avoid use of unrepresentative values of WBZ heights. Possible WBZ height changes due to dry or moist advection and to changes in other parameters are considered. However, it has been observed that the height values vary little from chart to chart, and most major height changes occur with the outbreak of the severe weather. The judicious use of the WBZ height can assist the forecaster in determining the general areal limit of the severe-weather phenomena at the surface, and in many instances delineate the axis of maximum activity. Also, the WBZ height may be used to forecast the development of squall lines, since there is a definite tendency for squall lines to develop along the ridge of warmer WBZ heights if the middle-level wind flow is approximately normal to this ridge. Experience suggests that the WBZ height is an indicator of whether or not damaging phenomena will reach the surface. Pilot reports may frequently indicate damaging phenomena aloft in a region of an unfavorable WBZ height, while in an adjacent region of a more favorable height these phenomena will reach the surface. The Wet-Bulb-Zero height chart has proven to be extremely useful for monitoring the location of given WBZ height-contour values.

SECTION F—CONCLUSION

In forecasting severe local storms, the experience gained over the years indicates that

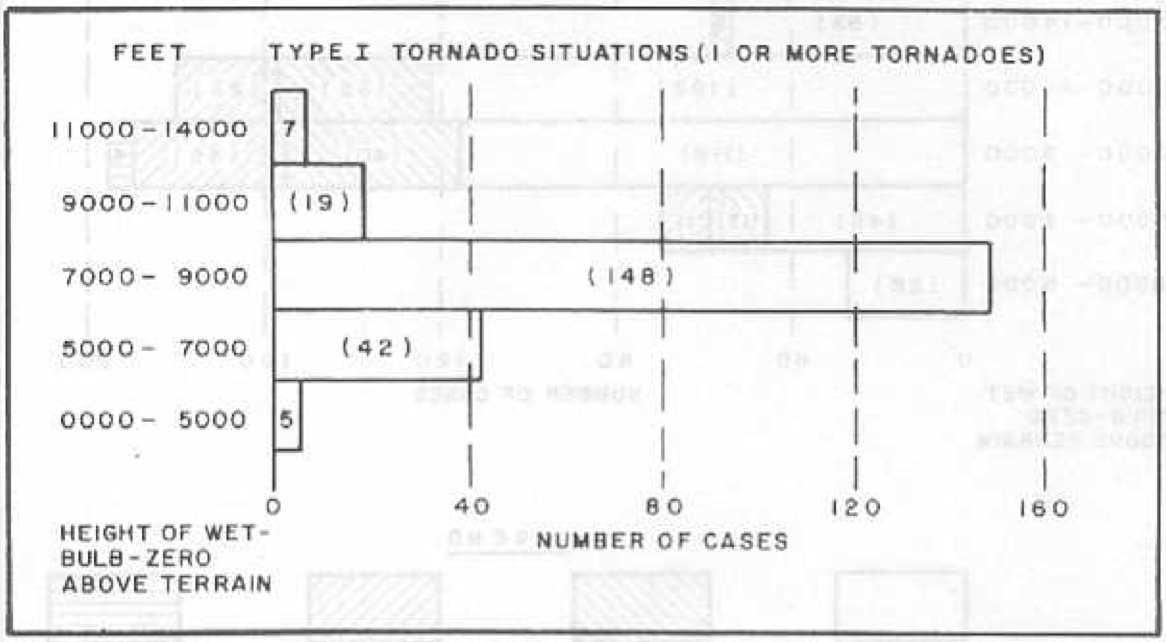

Figure 45. Cases of Type I tornado situations (1 or more tornadoes) occurring with selected ranges of Wet-Bulb-Zero height above the terrain.

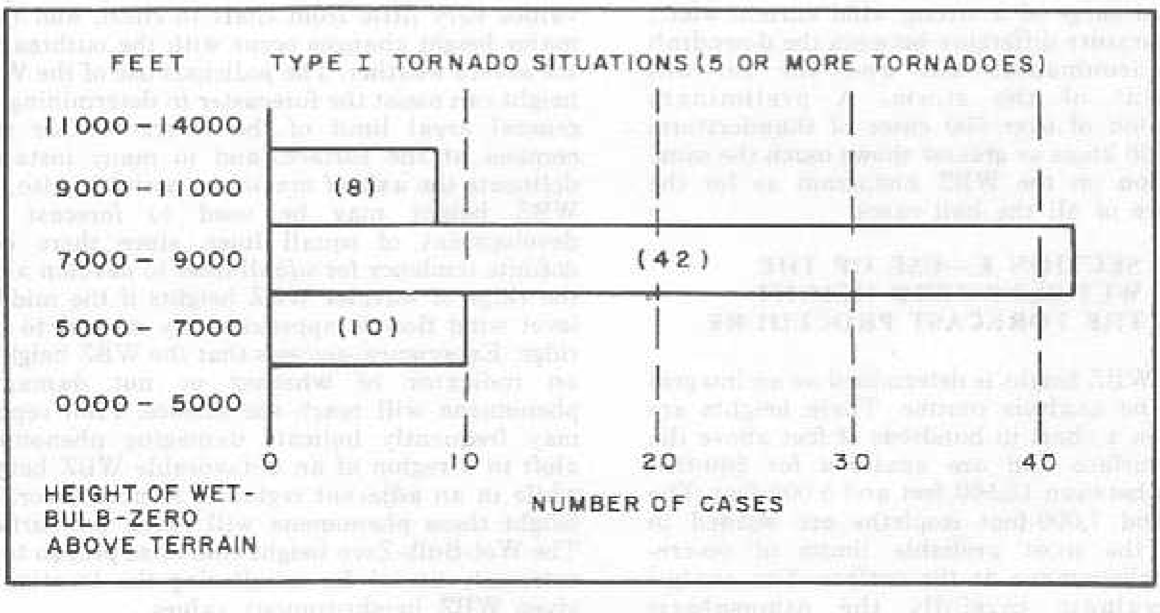

Figure 46. Cases of Type I tornado situations (5 or more tornadoes) occurring with selected ranges of Wet-Bulb-Zero height above the terrain.

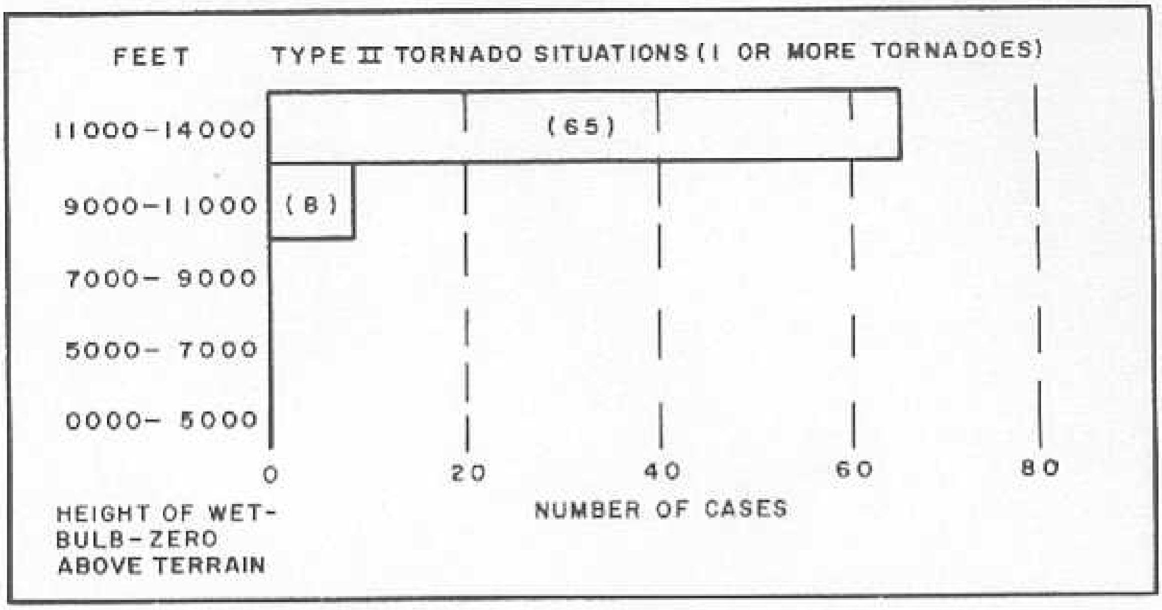

Figure 47. Type II tornado cases (one or more tornadoes) occurring with selected ranges of Wet-Bulb-Zero height above the terrain.

only the most careful attention to detail in making and interrelating the analyses of the atmospheric fields can produce a successful forecast, and the WBZ height alone cannot be used as a unique predictor. The histograms discussed in the previous sections show a statistical distribution for the appropriate air-structure type, but regardless of whether or not thunderstorms form in the air structure, the distribution of WBZ heights, may be the same. Therefore, one cannot conclude that since damaging phenomena reach the surface more frequently for some ranges of WBZ heights than others, that occurrences are dependent only on the WBZ height.