Technical Report 200 (Rev)

AIR WEATHER SERVICE

NOTES ON ANALYSIS AND SEVERE-STORM FORECASTING PROCEDURES OF THE AIR FORCE GLOBAL WEATHER CENTRAL

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AUTHOR'S PREFACE

In March of 1948 at Tinker Air Force Base, the author, working under Lt Col E. J. Fawbush, experienced a tornado that struck the base without warning and caused severe damage. The Commanding General of the Oklahoma City Air Materiel Area asked us to try to find a way to forecast such occurrences. We analyzed many past cases, searched the existing tornado literature and found a report by Showalter and Fulks of the US Weather Bureau most valuable. A week later when synoptic conditions similar to the previous storm appeared we forecast a tornado to hit the base, and fortunately for us, the forecast verified. Since that time Air Weather Service has been in the severe-storm forecasting business and I have been associated with it almost continuously. A number of papers by Fawbush and Miller appeared in the journals during the 1950s which described the methods used, culminating in AWS Manual 105-37 (2d ed 1956). Since then much research on severe storms has been carried out by the Air Weather Service (AWS) and other agencies including major contributions by the Severe Local Storms (SELS) unit of the National Weather Service.

Though better data (radar, more rapid collection, etc.), electronic data processing, and extensive practical experience have benefited the severe-storm forecaster, the original empirical forecast rules described in [22] and based, in part, on earlier work done by those vitally interested in the field [25, 41, 45, 61, 63], are still basically sound, but have under gone modification, refinement, and amplification over the years. Highly significant contributions in the field of operational severe-storm forecasting have been made by many, especially [5, 13, 16, 28, 38, 39, 40, 47, 51, 59], and progress will continue to be made by both the research meteorologist and the forecaster faced with day-to-day operational requirements.

To facilitate the training of forecasters newly assigned to the former AWS Military Weather Warning Center (MWWC) at Kansas City, Missouri, the first AWS Technical Report 200 was compiled in a piecemeal fashion over several years at those times when the elements gave us some respite from the forecast room. After careful consideration, it was published for wider distribution in 1967 since AWSM 105-37 was almost entirely obsolete and long out of print. On 1 February 1970, the MWWC was deactivated and the severe weather responsibility transferred to the AWS Air Force Global Weather Central (AFGWC) at Offutt AFB, Nebraska. This move was made to take advantage of the AFGWC computer complex and the programming talent available. Since this transfer, the AFGWC has continued development and refinement of those forecast techniques described in this report with primary emphasis on the development and use of computerized products. Much curiosity about our automated products and current procedures has been expressed and it is felt that recipients of AFGWC severe weather advisories and point warnings would benefit from this updated report.

This report is not intended in itself to describe all about how to forecast severe storms nor to necessarily equip one to forecast them. The inherent nature of the procedures, with their unavoidable subjective and "experience" element, and the large day-to-day fluctuation in available data, charts, and techniques used, plus the varied types of synoptic situations precludes setting forth a rigidly fixed outline of charts and procedures. In fact, the original manuscript of this report consisted only of a collection of notes for use as collateral reading by our trainees, with considerable overlapping and gaps. Personnel of the Aerospace Services Directorate in HQ AWS kindly selected certain of these materials and carefully arranged them under suitable headings in a reasonable order and coherency.

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It will be obvious that while the procedures used in forecasting severe storms are largely empirical, they are predicated on sound rational or physical bases. There is a high degree of redundancy in the analysis and forecast procedures. This redundancy will undoubtedly often confuse the reader, although it is, we believe, the keystone to such success as has been achieved in our forecasting. Basically, severe storms are mesoscale phenomena which are necessary to treat by the analysis of macroscale observations; this leads us to depend directly on the inferences of mesoscale processes from macroscale patterns. Their relations are so manifold and complex, that for each time and area we have to exploit different parameters or different aspects and combinations of parameters. We now believe that computerization will eventually simplify and quantify these relations.

Because severe-weather forecasters are a small and close-knit unit working in some isolation from other forecasters, a special language or lingo has developed which may be unfamiliar and make communication with others difficult. We have, we hope, defined such special terminology where it first appears and in an appended glossary. Likewise the many special parameters plotted on our charts require special symbols, which for convenient reference are shown on a fold-out sheet in Figure 99.

There is no one way to use this report, since the chapters are somewhat independent. The materials are presented in an order used in our training program, but other readers may find it more logical to begin with Chapters 5 then 4, 3, 2, and 1. The later chapters are more specialized. Chapter 11 is intended for AWS base weather stations.

Regarding the "case studies" in Appendices B, C, D, E, F, and G, we wish to state that these situations, while typical for the phenomena, were not chosen on the basis that the forecasting worked especially well. They are representative in all respects except that adequate data were available in each one.

I wish to express my gratitude to Capt A. B. Prewitt, Jr. and Capt Robert A. Maddox for the preparation of the numerous figures in the report. Special recognition must go to Maj Millard F. Page, USAF (Ret) for his overall assistance and for his detailed research on Chapter 7, and to CWO Lewis W. Barlett and CWO Andrew Waters, USAF (Ret) for their assistance with Chapter 8. I also wish to express my appreciation to Lt Col Arthur Bidner for his invaluable assistance on the development of the SWEAT Index and his help in writing Appendix F.

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Chapter 1

THE ANALYSIS ROUTINE

SECTION A—GENERAL

Successful tornado and severe-thunderstorm forecasting is largely dependent upon the forecaster's ability to carefully analyze, coordinate, and assess the relative values of a multitude of meteorological variables, and mentally integrate and project these variables three-dimensionally in space and time. Chart analysis is the standard basis in weather forecasting, but the severe-weather forecaster is concerned with unconventional features on charts, and works with a number of analyses not normally required to make other routine types of weather forecasts. The AFGWC analyses incorporate all available data and care is taken not to ignore, change, or smooth data which may at first appear to be in error. The severe-weather forecaster is primarily concerned with synoptic features smaller than the existing synoptic network, and must pay meticulous attention to transitory features and minor changes in the atmosphere. This attention to detail requires a highly organized approach to the analysis problem.

The analysis rationale of each type of chart prepared at AFGWC is discussed in the following sections and the reasons for concentrating on specific features are given. A detailed analysis of the three-dimensional picture is the goal and no data are disregarded without overwhelming evidence of error. The principles of continuity are followed on all analyses and careful consideration is given to the possibility of persistence of previously noted features.

The collocation of the severe weather function with AFGWC provides many useful and automated products; the benefits from timely receipt of highly accurate surface and upper air prognoses and other specified charts are incalculable. These products and their incorporation into the daily routine of the severe weather forecaster are described in Appendix F.

SECTION B—CONSTANT PRESSURE CHARTS

The analyses on constant pressure charts stress the importance of the wind and temperature fields rather than the height field. The contours are drawn for small intervals to insure the identification of minor features and to avoid the tendency to smooth the analyses. If possible, closed or detached centers are avoided and contours are drawn to imply the air-mass source regions. This approach sometimes results in very long narrow ribbons on the charts, but such ribbons frequently have been observed to exist in the atmosphere [3, 23, 35]. The analyses at 850-mb, 700-mb, and 500-mb are primarily to outline the moisture and temperature distributions, but height contours are drawn to supplement the streamline analyses in the event many winds-aloft reports are missing. Figures 1-7 discussed in the following paragraphs illustrate the analysis techniques for the Palm Sunday tornado situation of April 11, 1965.

The temperature and dew-point fields on the 850-mb chart are analyzed for 2°C intervals, and their respective ridges are located accurately. Areas where dry and moist air lie in juxtaposition are particularly noted. Contours are drawn for 30- or 60-meter intervals, and the wind-field analyses show the maximum-wind band or low-level jets, areas of convergence, and important directional and speed shears. If evident, frontal systems are entered and 12-hour changes in the temperature and dew point noted. Figure 1 is an example of a typical 850-mb analysis. Contours and minor wind-field characteristics have been deleted so that the warm ridging and the moist and dry-air boundaries are clearly visible. Isopleths are isotherms and dew-point lines.

The 700-mb chart analysis is similar to the 850-mb analysis, but the moisture field and the location of dry-air tongues are of primary interest at this level. Dry tongues are areas of dew-point spreads greater than 6°C, or relative humidities of less than 50%. Thermal troughs are located along with the 12-hour no-change lines of temperature. In the wind-field analysis, special emphasis is given to the cross-isotherm flow, rates of warm and cold advection, and speed and direction of movement of dry-air intrusions. Height and temperature falls are noted and areas of convergence and diffluence indicated. A typical 700-mb analysis is shown in Figure 2. In this example, one can see that the emphasis was placed on locating the dry and moist areas, max-wind axes, isotherms, and the 12-hr no-change lines of temperature.

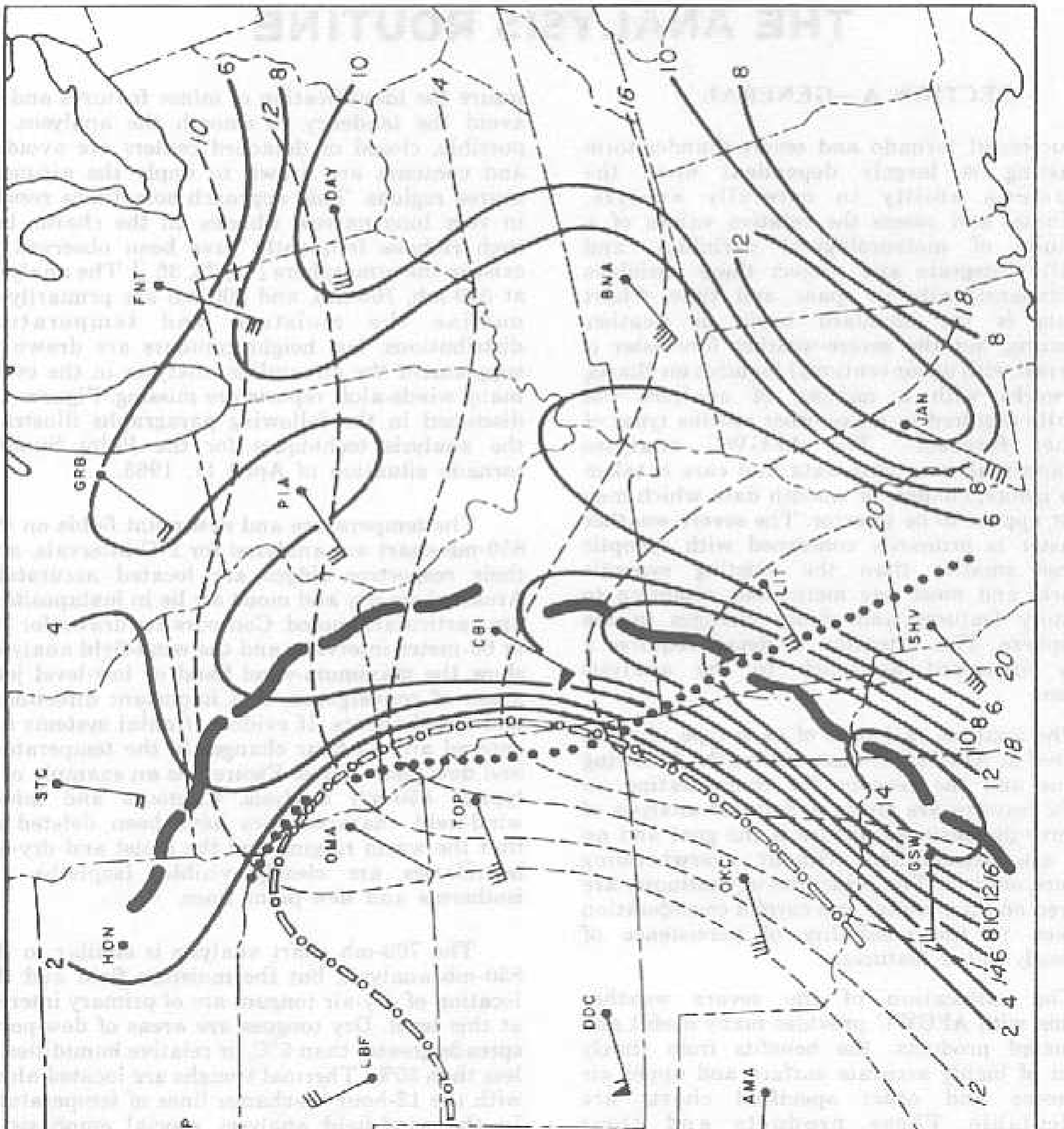

Figure 1. Major features of the 850-mb analysis

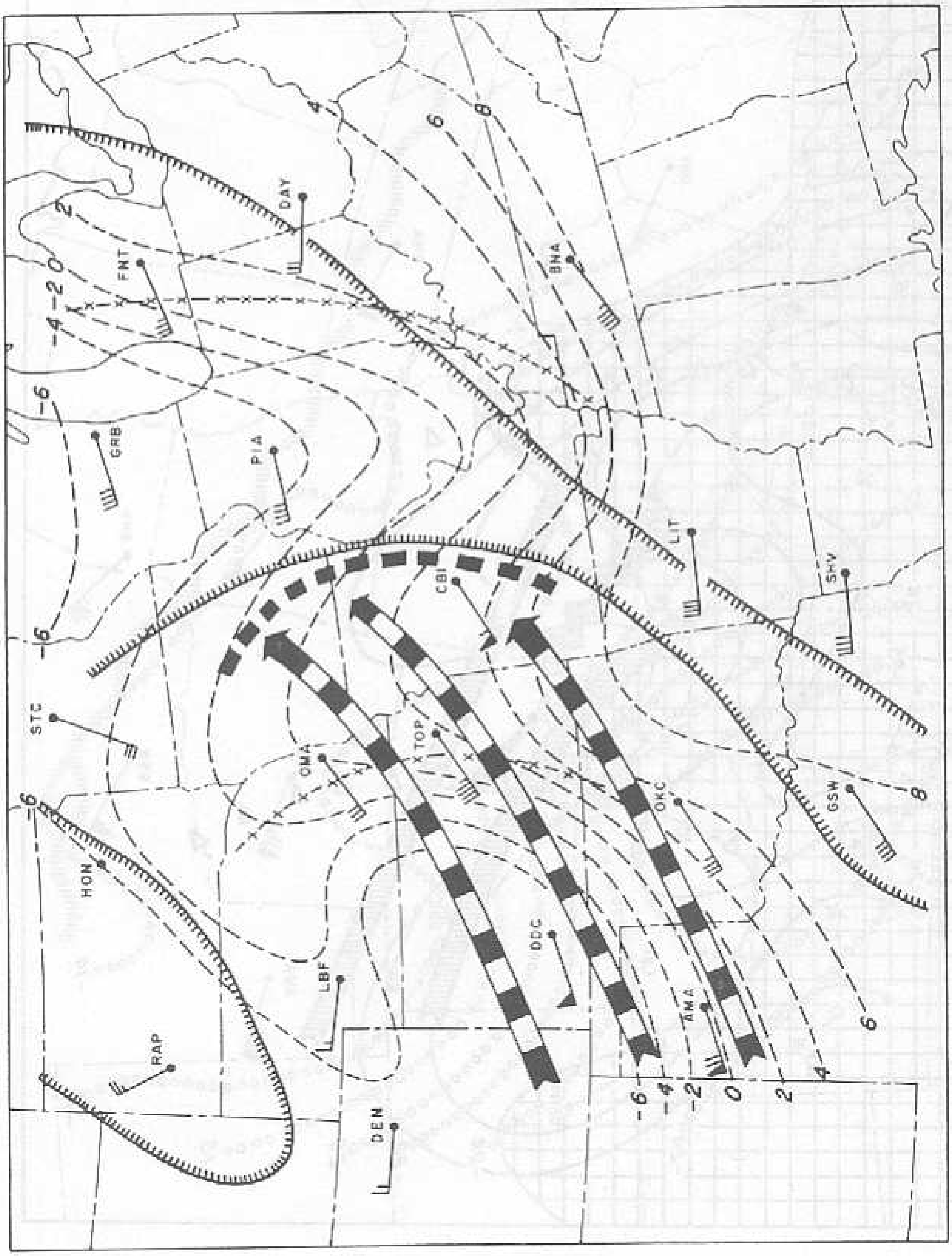

Figure 2. Major features of the 700-mb analysis

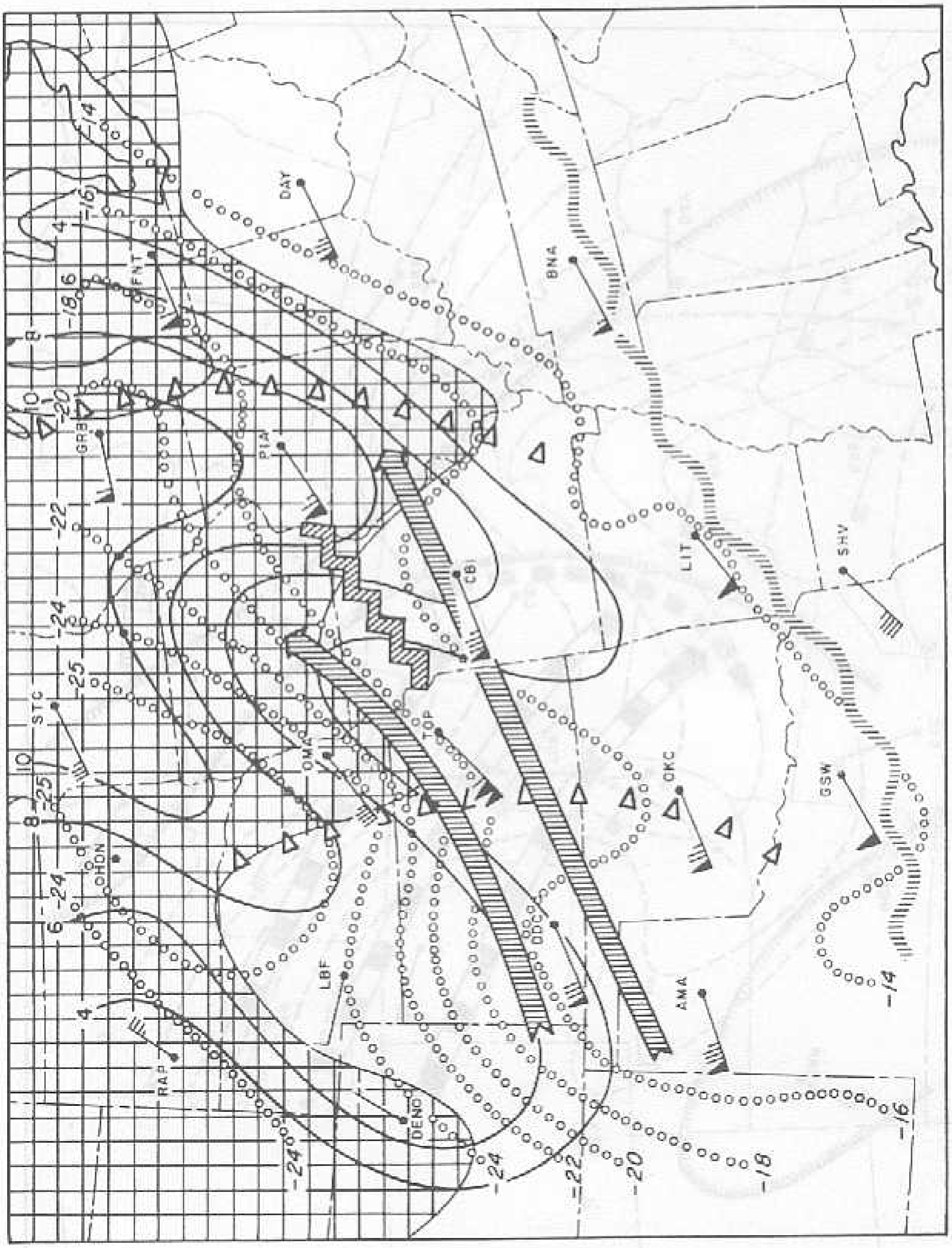

Figure 3. Major features of the 500-mb analysis

The 500-mb chart analysis is similar to the 700-mb and 850-mb analyses, except that height falls are analyzed at 20- or 40-meter intervals. As shown in Figure 3, primary attention is given to the moisture field since the severe-weather forecaster knows that moist and dry regions are often related to the vertical motion fields (e.g., moist areas associated with positive vorticity advection.) Significant moisture at 500 mb is defined as a dewpoint of -17°C or warmer or temperature dew-point spreads of 6°C or less. Branching in the jet structure is another important feature at 500 mb since branching defines covergent and diffluent areas. On Figure 3 isotherms and isodrosotherms are drawn.

SECTION C—GUIDES TO UPPER-AIR ANALYSES

Severe weather forecasters have developed or adopted a number of rules for guidance in the preparation of constant-pressure analyses. These rules, though very general, in our experience have proven to be right much more often than wrong. Many forecasters probably will recognize most of them as rules they have used in analysis, or for the interpretation of analysis.

a. Divergence associated with an upper cold front at 8,000 to 12,000 feet usually occurs with a south-to-north flow, and careful inspection usually will reveal more 700-mb moisture in the area of the weakest winds than in the area of strongest flow to the east.

b. When a tongue of cold air extends southward from a cold reservoir, or a cold pocket begins to form, careful streamline analysis often will show the existence of a weak trough.

c. Isopleths of temperature, mixing ratio, and height will tend to parallel streamlines, and analyses should indicate this tendency without disregarding data. This concept accentuates minor troughs and ridges and makes the source regions of anomalies more obvious.

d. Tongues, ribbons, or pockets of moisture often indicate the intersection of the constant-pressure surface with frontal surfaces and areas of upward vertical motion.

e. Wind shifts have been found to precede advection of temperature and moisture up to six hours, but the advection rate is dependent on the contour gradient.

f. Minor temperature troughs and ridges are frequently reflected in corresponding streamline troughs and ridges in the wind field.

g. Some warm areas on the lee side of the Rocky Mountains are the result of katabatic flow.

h. Some moist areas on the 700-mb chart over the region west of the Continental Divide are due to orographic lift of a lower moist layer. However, these moist areas will not continue eastward at this level unless the lower air is extremely cold.

i. If a moisture ridge aloft is parallel to the streamlines, and no other discontinuity appears, an old warm front may be responsible for the moisture ridge.

j. Severe-weather forecasters have noted that the subsidence of a warm frontal surface often is revealed by a decrease in the dew point with time without a corresponding significant change in the free-air temperature.

k. A moisture ridge more or less perpendicular to the streamlines may be the result of moisture being carried up a warm frontal surface. The rate of advection of this moisture ridge is normally about one-half the mean wind speed in that layer.

l. Warm and cold pockets at the 500-mb level are usually associated with the large-scale features. These pockets are carefully tracked since cold-air advection causes wind to back and increase, and warm-air advection causes winds to veer and decrease.

m. The sudden appearance of moisture at the 700-mb and/or 500-mb levels, that cannot be explained by pure advection from a moisture source, is probably the result of vertical motion. Such areas may be related to regions of positive vorticity advection and may be observed by the development and movement of middle-level clouds. Monitoring the movement of this cloudiness will help provide continuity on the vorticity centers between radiosonde reports, and will assist in estimating the accuracy of the forecast fields of vertical motion on the facsimile charts.

n. A well-defined region of significant positive vorticity advection is almost always present in major severe-weather outbreaks and, is undoubtedly present, but not necessarily observed, in minor outbreaks. Therefore, meticulous use of the more dense and readily available surface data is required to locate small, migratory areas of middle cloudiness.

o. The 850-mb chart is valuable in defining and evaluating the three-dimensional picture. The analysis is very useful for estimating changes in stability, and in locating fronts, temperature tongues and moisture ridges.

p. A minor trough in the wind field at 850-mb is sometimes the first indication that advection of moisture from a source region will occur; or, if a moist layer is already present, the appearance of this trough is ususally followed by an increase in the depth of the moist layer.

q. The appearance of a trough in a previous westerly flow may indicate strong advection of warm air to the west of the trough.

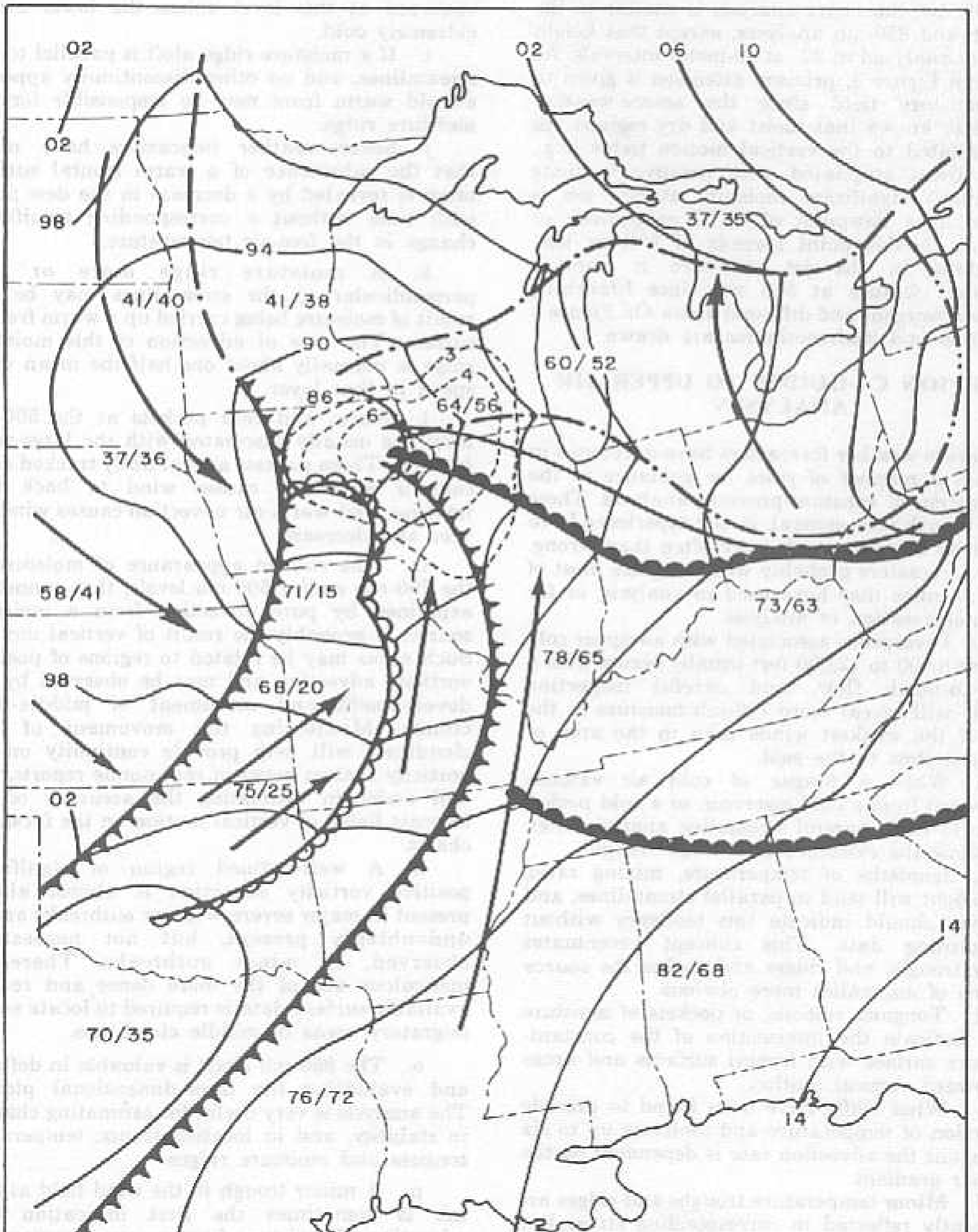

Figure 4. Surface analysis showing air-mass differentiation, the low-level flow and the area of maximum pressure falls

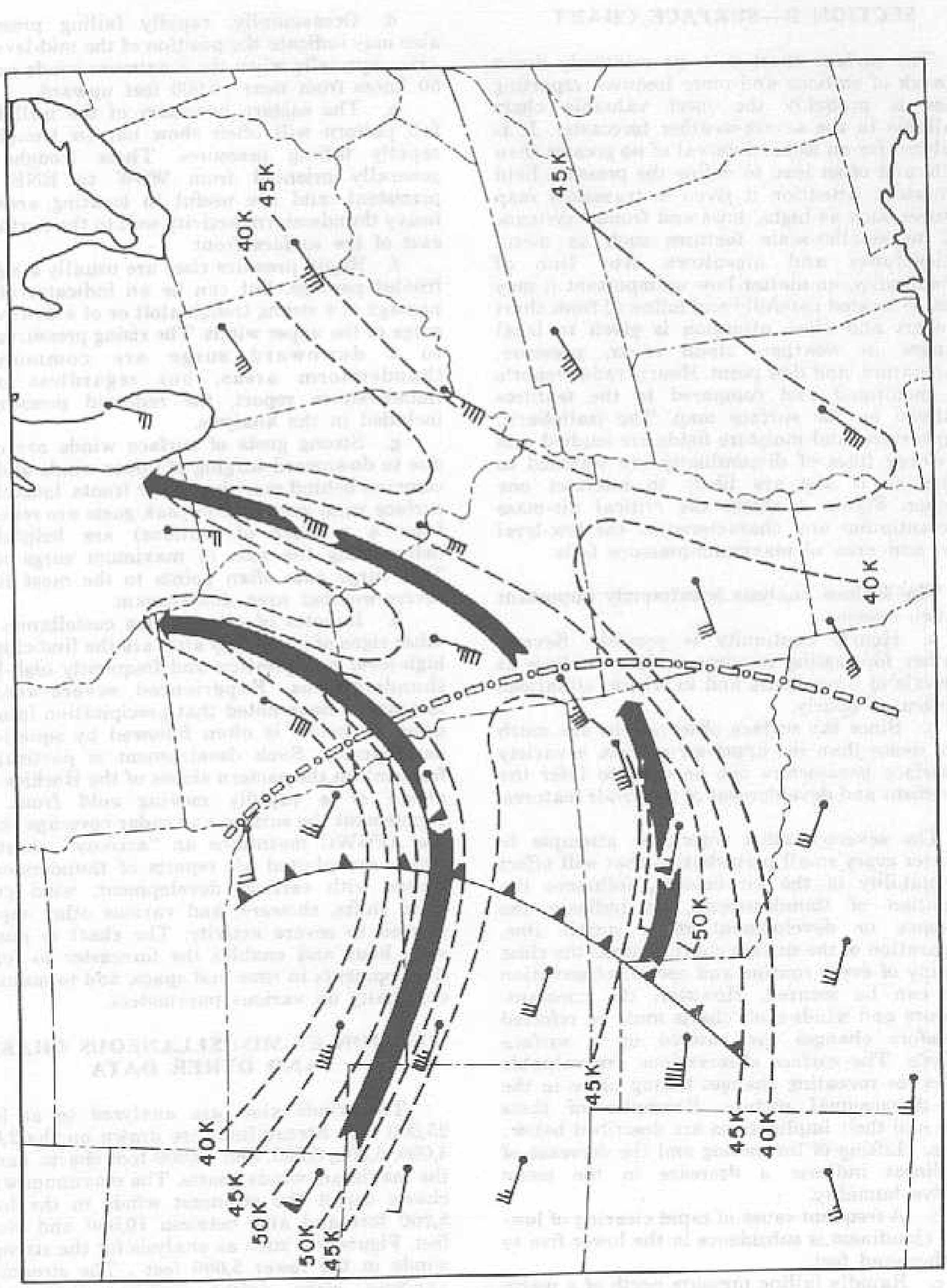

Figure 5. Maximum wind analysis for the lower 5,000 feet

SECTION D—SURFACE CHART

The surface chart with its relatively dense network of stations and more frequent reporting times is probably the most valuable chart available to the severe-weather forecaster. It is analyzed for an isobar interval of no greater than 2-mb, and often less, to define the pressure field accurately. Attention is given to transitory map features such as highs, lows and frontal systems, and to smaller-scale features such as meso-anticyclones and mesolows. Any line of discontinuity, no matter how unimportant it may seem, is located carefully and followed from chart to chart and close attention is given to local changes in weather, cloud cover, pressure, temperature, and dew point. Hourly radar reports are monitored and compared to the features analyzed on the surface map. The isallobaric, temperature, and moisture fields are studied and transitory lines of discontinuity are watched to determine if any are likely to intersect one another. Figure 4 shows the critical air-mass differentiation and characteristics, the low-level flow, and area of maximum-pressure falls.

The surface analysis is extremely important for two reasons:

a. Hourly continuity is possible. Severe-weather forecasting requires surface analysis at intervals of three hours and in critical situations as often as hourly.

b. Since the surface observations are much more dense than the upper-air reports, a variety of surface parameters can be used to infer the movement and development of upper-air features.

The severe-weather forecaster attempts to discover every small perturbation that will affect the stability of the air column, influence the formation of thunderstorms, or indicate the existence or development of a squall line. Preparation of the surface chart requires the close scrutiny of every routine and special observation that can be secured. However, the constant-pressure and winds-aloft charts must be referred to before changes are entered on a surface analysis. The surface observations are valuable guides for revealing changes taking place in the three-dimensional picture. Examples of these clues and their implications are described below:

a. Lifting of the ceiling and the decrease of cloudiness indicate a decrease in the mean relative humidity.

b. A frequent cause of rapid clearing of low-level cloudiness is subsidence in the lower five to six thousand feet.

c. Rapidly falling pressure north of a warm front may indicate a rapid influx of moisture over a relatively flat portion of the frontal surface.

d. Occasionally, rapidly falling pressures also may indicate the position of the mid-level jet axis, especially when the maximum winds exceed 50 knots from near 10,000 feet upward.

e. The eastern boundary of the isallobaric fall pattern will often show narrow troughs of rapidly falling pressures. These troughs are generally oriented from WSW to ENE, are persistent, and are useful in locating areas of heavy thunderstorm activity well to the north and east of the surface front.

f. Rapid pressure rises are usually a sign of frontal passage, but can be an indicator of the passage of a strong trough aloft or of a downward surge of the upper winds. The rising pressures due to a downward surge are common in thunderstorm areas, but regardless of a thunderstorm report, the reported pressure is included in the analysis.

g. Strong gusts of surface winds are often due to downward surging of upper winds and are common behind maritime polar fronts. Isotachs of surface wind gusts (when peak gusts are reported from a number of stations) are helpful in determining the axis of maximum surge aloft. This surge axis often points to the most likely severe-weather area downstream.

h. Reports of altocumulus castellanus and other signs of instability aloft are the first clues to high-level precipitation and frequently high-level thunderstorms. Experienced severe-weather forecasters have noted that precipitation into the drier air below is often followed by squall-line development. Such development is particularly frequent on the eastern slopes of the Rockies and ahead of a rapidly moving cold front. To supplement the surface and radar-coverage charts the AFGWC maintains an "activity" chart on which are plotted all reports of thunderstorms, clouds with vertical development, wind gusts, wind shifts, showers, and various other reports related to severe activity. The chart is plotted each hour and enables the forecaster to follow developments in time and space, and to maintain continuity on various parameters.

SECTION E—MISCELLANEOUS CHARTS AND OTHER DATA

The winds aloft are analyzed to at least 25,000 feet. Streamlines are drawn on the 2,000, 4,000, 6,000, 8,000, and 10,000-foot charts, and on the maximum-winds charts. The maximum-winds charts depict the strongest winds in the lower 5,000 feet and also between 10,000 and 20,000 feet. Figure 5 is such as analysis for the strongest winds in the lower 5,000 feet . The streamline analyses often define features not readily apparent on the standard constant-pressure charts, such as relatively small troughs, ridges,

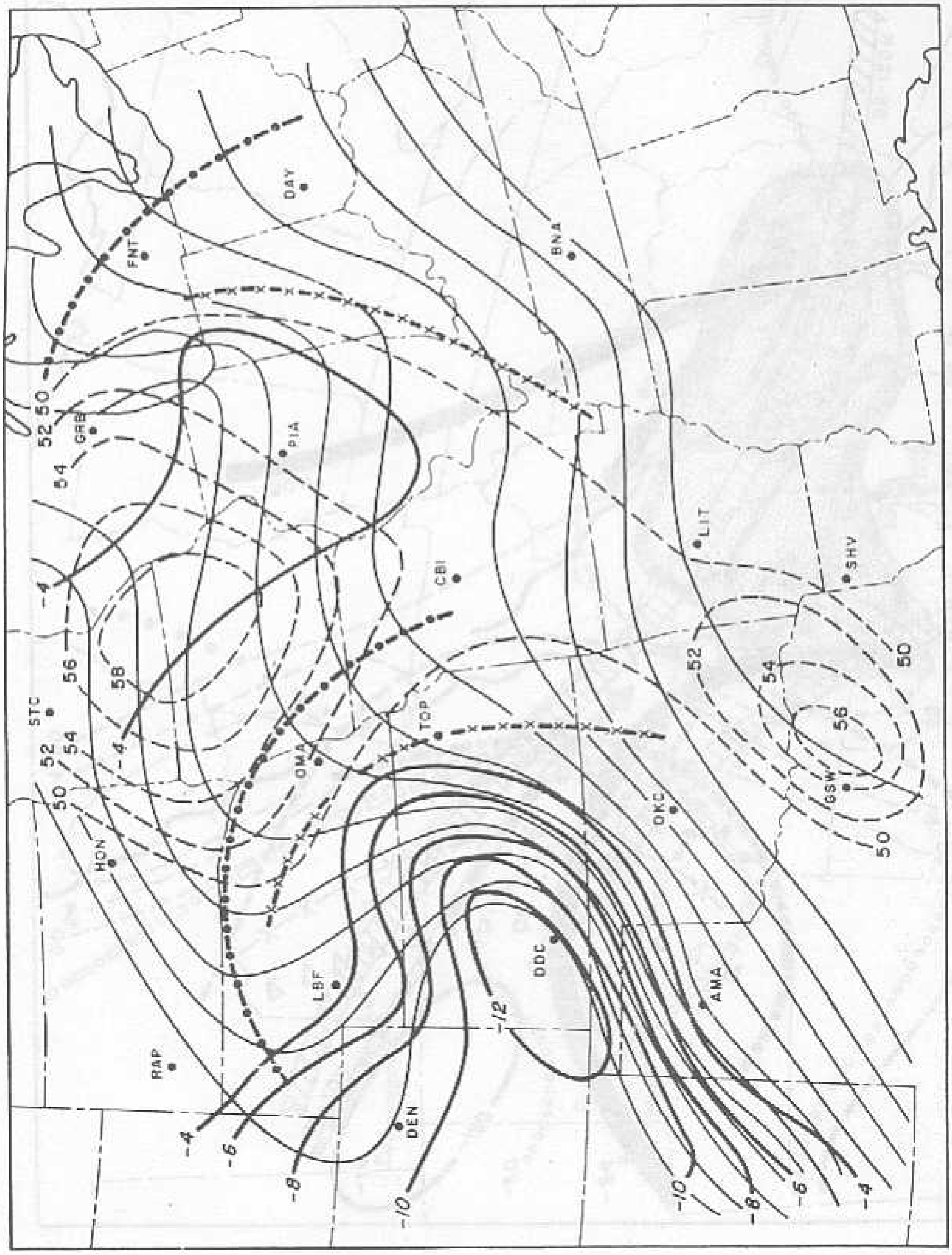

Figure 6. Major features of the thickness analysis showing Total Totals analysis and 12-hr thickness changes

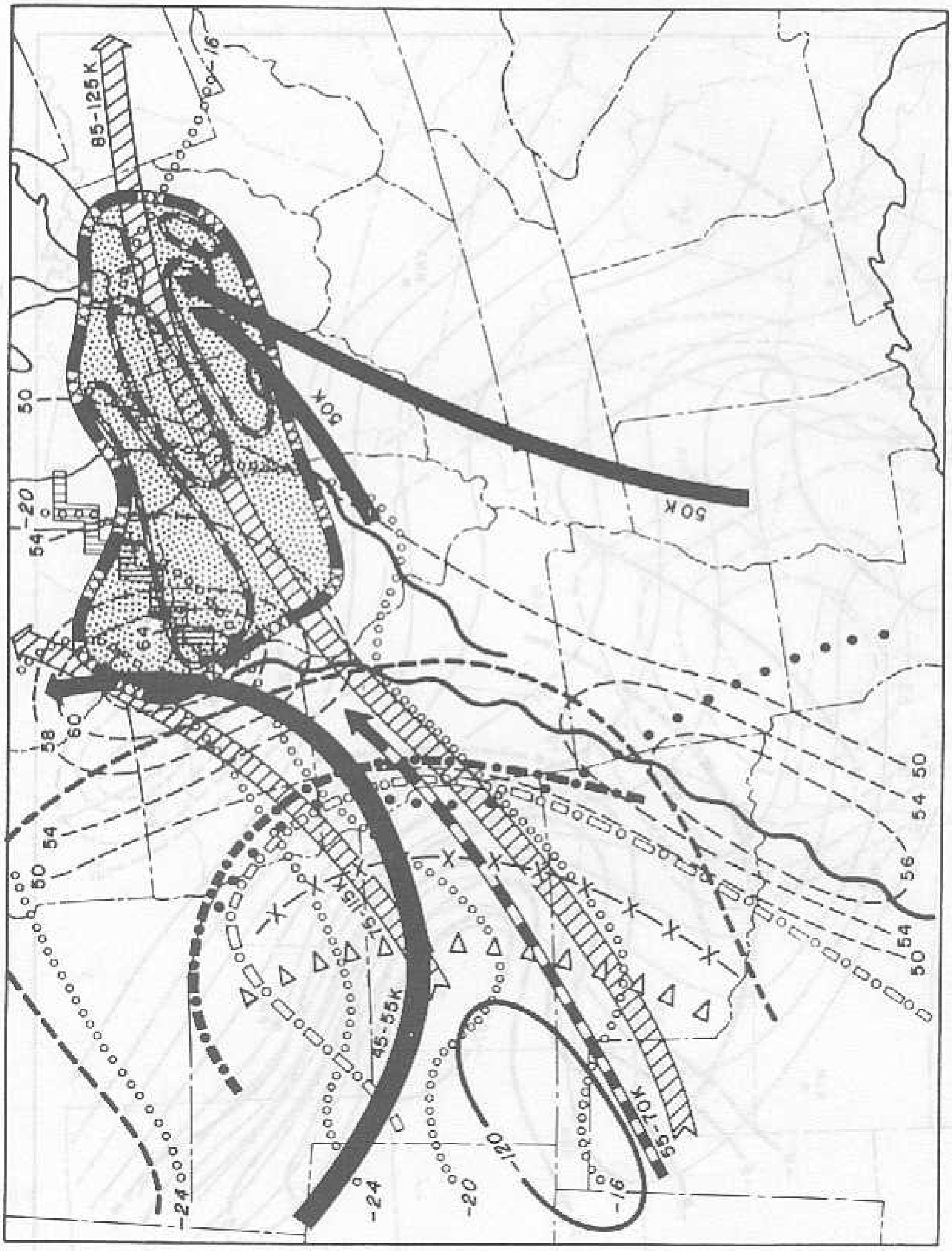

Figure 7. Composite Chart showing most significant features found during analysis

cyclones, anticyclones, and areas of streamline convergence or divergence. All of these features have value for implying changes in moisture and temperature, and for pointing to areas favorable for squall-line formation.

Isotachs are drawn as required for the 12,000, 14,000, 16,000, 18,000, 20,000-foot levels and on the midlevel max-winds chart. Included also are the jet axes, well-defined horizontal speed shears, and zones of convergence and diffluence. Study of these features serves to limit the size of the forecast areas and provide additional clues to squall-line formation and movement. These analyses often alert the severe weather forecaster to physical changes which may soon occur in the air-mass structure. The following examples illustrate such changes:

a. A minor trough in the wind field often is the first indication of advection of moisture from a source region.

b. The appearance of a trough is often followed by an increase in the depth of a moist layer.

c. The appearance of a trough at a level in a westerly flow often indicates strong, warm-air advection at lower levels to the west of the trough's position.

d. Divergent flow aloft sometimes indicates the presence of an upper cold front.

The jet-chart includes the maximum wind reported, the height of this wind, and the height and temperature of the tropopause. This chart and the 200-mb chart are used primarily for locating the upper jet, areas of diffluence, and strong horizontal speed shears. The height and temperature of the tropopause are used primarily for the determination of thunderstorm cloud tops.

The 850/500-mb thickness chart (Figure 6) is analyzed and on it the location of the important thickness ridges and zones of maximum anticyclonic shear in the thermal wind field are noted. Twelve-hour thickness changes are analyzed for 20-meter intervals and the axes of maximum cooling are noted. Twelve-hour no-thickness-change lines are analyzed and the plotted Showalter Stability Index values examined. The Total Totals are analyzed for intervals of 2 or 4 usually starting with a value of 44. The Vertical Totals and Cross Totals analyses are left to the discretion of the forecaster.

Soundings are analyzed primarily for the Lifted Index, the Level of Free Convection, size of hail, height of the Wet-Bulb-Zero and the Downrush Temperature. Figure 6 shows thickness, 12-hr thickness change, Total Totals analysis, thickness ridge lines, and 12-hr no-change thickness lines.

The NMC 500 mb Barotropic, Baroclinic, and Limited Area Fine Mesh (LFM) analyses and prognoses are examined to locate areas of positive and negative vorticity advection.

The Composite Chart consolidates all the analyzed and forecast parameters onto one map. The AFGWC uses the latest available surface chart as a base for the Composite Chart and updates this map throughout the forecast period. There are no rigid rules for entering information from the other charts onto the Composite Chart, but severe-weather forecasters generally follow the same procedures. The type of information on the Composite Charts varies according to the vagaries of the given situation.

Figure 7 is the Composite Chart with the basic surface data and analysis deleted to eliminate as much confusion as possible. In practice, the Composite Chart features are in color. However, in this report the charts could not be reproduced in color, so the parameters are distinguished by different symbolizations not necessarily on the manuscript charts. The procedures and color schemes followed in constructing the manuscript Composite Charts in actual practice are given in Appendix G. The stippled area is the extent of severe-weather occurrences. The smaller areas outlined by dashed double lines located the major tracks and occurrences of tornadoes.

The Composite Chart enables the severe-weather forecaster to consolidate the numerous parameters involved in making a severe thunderstorm forecast. This three-dimensional picture permits an assessment of the strength of the parameters, their relationships to each other, and their relative importance in given situations. Since the picture presented is essentially static, the forecaster will usually find it necessary to predict the probable changes in the various parameters in space and time. The forecaster must determine whether missing parameters will develop or not, whether the parameters present will persist, and whether or not the parameters will be properly distributed in geographical area at the critical time. Extreme care is taken to insure that all factors are considered and that all probable changes in the surface and upper-air patterns are anticipated.

In practice, the AFGWC forecasters rely heavily on the 12-, 24-, and 36-hour fine mesh prognoses produced routinely from the AFGWC data base for the movement of upper air features 850 mb and above and the Boundary Layer Model (BLM) for the positioning of those features at and near the earth's surface. In addition, close attention is given to NMC prognoses including the LFM products and adjusted surface prognostic charts.

The forecasters use their own skill in predicting the short-range movement of the more transitory or sophisticated parameters involved in the specialized severe-weather forecast procedures. No hard and fast rules for prognosis of these parameters can be derived at this time. Instead, the forecaster must rely on meticulous attention to detail, experience, and the ability to anticipate the probable changes in the atmospheric structure. The cardinal principle of severe-weather forecasting is to develop a detailed understanding of the current synoptic situation and trend over the past several hours. There is no other way under the present state of the art to anticipate the short-range changes in the surface and upper-air pattern which result in severe-weather outbreaks.

Chapter 2

SEVERE-WEATHER AIR MASSES

SECTION A—GENERAL

Severe weather is the product of a highly unstable atmosphere. This great instability is the result of the modification of a more stable atmosphere usually by a combination of two or more of the following processes:

a. Temperature advection at various levels.
b. Moisture advection at various levels.
c. Insolation and radiation.
d. Evaporation and condensation.
e. Large-scale vertical motion.

The severe-weather forecaster must determine what air-mass modifications will result from the action of these processes.

In the absence of frontal activity and radical changes in cloud cover, the amount of heating of the lowest stratum of the atmosphere by insolation can usually be determined by examination of the previous day's temperature. Comparison with the latest upper-air soundings then gives a good approximation of the height to which convective currents may be expected to rise, and the size of the positive area is a clue to the intensity of the vertical motion.

Advection of temperature is usually fairly obvious from comparison of the wind and temperature fields, but the effects of subsidence and forced lifting over large areas must be taken into account.

The advection of moisture in the low and middle levels is often not so obvious. In the absence of other information, it is usually best to assume motion in the direction of the wind, at 50% of its speed.

When the air aloft is rather uniformly dry, so that any moisture increase must come from lower levels, convection or lifting must be of an intensity capable of penetrating the dry layer with significant amounts of moisture.

SECTION B—AIR-MASS TYPES

The various air masses common to the United States vary markedly in their capability of producing destructive local storms. The many types of air masses, their combinations and characteristics are discussed in the following paragraphs:

a. *Continental polar air* is incapable of producing strong vertical currents because it is inherently stable.

b. *Continental tropical air* is incapable of producing extensive cloud systems because of its dryness. While vertical currents are often quite severe and produce strong clear air turbulence, the air mass rarely supports the type of storm under discussion, except when overrun by *maritime polar air* at 5,000 to 8,000 feet above the ground. This combination of air masses produces the typical IV "Dry" or "Inverted-V" sounding shown in Figure 11. This type of air mass is a good hail producer; it will be discussed further in this chaper and in Chapter 6.

c. The instability and rich moisture content of *equatorial air masses* are capable of supporting very strong vertical developments. However, the freezing level of the wet-bulb temperature is so high that only occasionally do the severe phenomena (tornadoes, hail, or damaging winds) succeed in reaching the surface. The Type II tornado air structure is representative of an equatorial air mass, and a mean sounding is shown in Figure 9.

d. True *maritime tropical air* in the United States has two characteristics which tend to hinder the production of severe local storms. These are:

(1) The stability of its subsidence inversion which suppresses vertical currents; and

(2) The dissipation of cloud tops which do succeed to penetrating the subsidence inversion.

e. *Maritime polar air masses* are capable of producing intense vertical currents but much of their moisture is removed by frontal and orographic lifting before these air masses reach the Midwest. Those air masses which are warmer than the underlying surface often move inland behind a warm-frontal occlusion. Such air masses undergo less vertical displacement and carry more moisture aloft to inland areas. If maritime polar air overruns an 8,000 to 10,000-foot layer of maritime tropical air, in which Convective Condensation Levels do not exceed 6,000 feet, the optimum air-mass structure for severe thunderstorms, accompanied by tornadoes, hail, and destructive winds, is realized. This is the Type I air-mass structure and a typical sounding is shown in Figure 8.

The ideal severe-weather air-mass structure is reached when this overrunning is accompanied by a large wind shear (veering) between the middle and lower levels.

SECTION C—CHARACTERISTICS OF TYPE I AIR MASS

The accumulation of 155 additional representative soundings has verified the *tornado air mass Type I* descriptions previously published [4, 8, 61]. The greatest refinement is the increase in moisture with height in the dry air above the inversion. Specifically, this air mass has the following characteristics:

a. The temperature lapse rate is conditionally unstable in the strata above and below the inversion or stable layer.

b. The moisture content is stratified with the lowest layer having a relative humidity over 65% and surface dew points over 55°F. Very rapid drying is evident in the inversion (subsidence type), and above the top of the inversion the relative humidity trends to increase slightly, then more rapidly, above 550 mb.

c. Winds increase with altitude with a narrow stream in the dry air above the inversion having a component of at least 30 knots

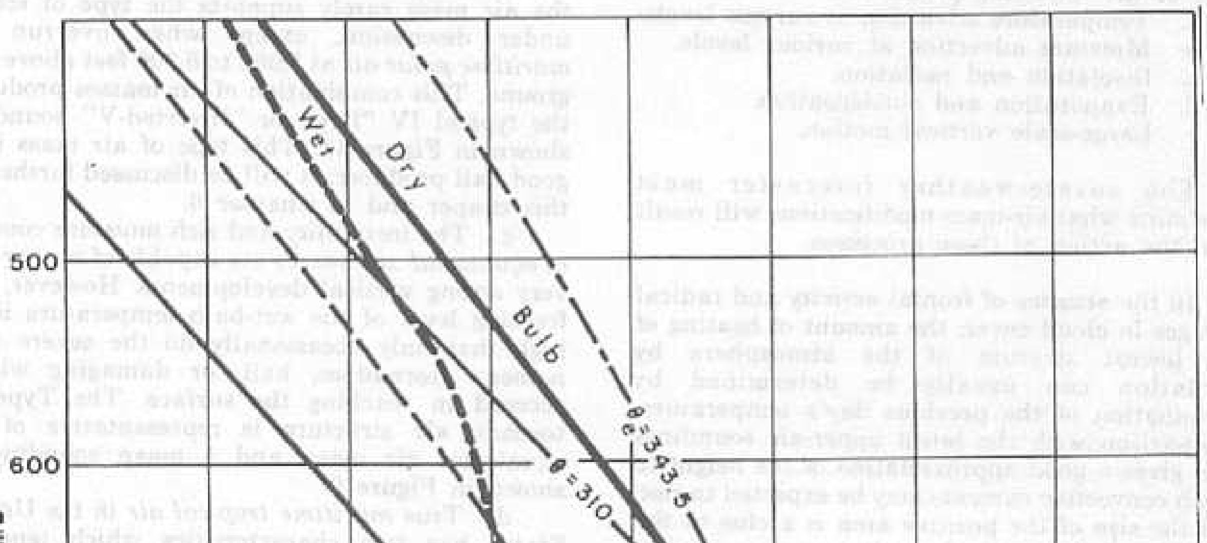

Figure 8. Mean sounding of Type I Tornado Air Mass

perpendicular to the flow in the warm moist air. The median wind shown by the soundings at 850 mb is 219° at 35 knots, and at 500 mb it is 256° at 50 knots.

d. The air from the surface to 400mb is conditionally unstable and has a negative Showalter Stability Index [60]. The Lifted Stability Index is about -6 on the mean sounding. The Vertical Totals Index is 28, the Cross Totals 26, and the Total Totals 54.

e. Tornadoes in this type air mass most frequently occur in families, and their paths are commonly long and wide compared to tornadoes occurring in the other types of air masses. The tornadoes are more numerous in later afternoon, but occur at any time of the day and night, and we are usually accompanied by wide-spread destructive windstorms and large hail. Individual tornadoes have a rather straight path and move rapidly at an average speed of about 35 knots, although exceptions to these characteristics are frequently reported [25, 26, 62, 65].

f. Sky conditions preceding the occurrence of tornadoes in this type of air mass begin initially with reports of morning stratus, followed by temporary clearing and then reports of the development of middle cloudiness. Mammatus commonly occurs with thunderstorms, and is frequently reported near storms of tornadic force. Surface temperature reports are abnormally high for the season and time of day or night, and the dew point often rises very rapidly one to four hours before the storm causing the air to be very oppressive. As the storm passes, the temperature drops very rapidly and returns to normal, unless the activity is followed by a cold front. The surface winds preceding the storm are usually moderate in speed. The surface pressure tendency drops slowly for several hours, rises briefly, then, as the storm reaches the station, falls rapidly. As the storm passes, the surface pressure rises rapidly and in a few minutes returns to normal. In general, the entire weather sequence is marked by rapid changes.

g. Tornadoes occurring in a Type I air mass generally are the result of the intersection of two squall lines, or a squall line intersecting a warm frontal zone in a mesocyclone. Also tornadoes develop along "bubble" produced squall lines. "Bubbles" or "bubble highs" are precipitation-induced mesoanticyclones within an area of general instability, and squall lines often form on their leading edges. Since tornadoes in this type air mass normally occur on squall lines associated with mesolows, their prediction involves timely geographical delineation of squall line formation and movement. The median Type I air mass structure, based on 230 soundings, is shown in Figure 8.

SECTION D—CHARACTERISTICS OF TYPE II AIR MASS

In contrast to the air mass discussed above, tornadoes also form in an equatorial type air mass that is moist to great heights. Such storms are most common along the coast of the Gulf of Mexico to some distance inland and produce the waterspouts so often reported over the Gulf Coastal waters. The following description of the *tornado air mass Type II* is based on 38 representative soundings.

a. The lapse rate of temperature is conditionally unstable with no significant inversion or stable layer. Surface temperature is usually over 80°F. The mean sounding for a Type II air mass is shown in Figure 9.

b. The moisture content is very high, with the relative humidity being over 65% in almost all cases to above 20,000 feet.

c. Winds normally decrease with altitude in this type air mass. It has been observed that the more vicious and persistent tornadoes occur when a significant low- and middle-level wind field is present. The wind at 850 mb has been observed to be as high as 65 knots, and at 500 mb as high as 55 knots. The median direction veers about 30° between these levels.

d. The median values of both the Lifted Stability Index and the Total Totals are the same as in Tornado Air Mass Type I (-6 and 54 respectively), although the absence of an inversion has permitted the extreme cases to reach greater instability values.

e. Tornadoes or waterspouts in this type air mass occur singly rather than in families. When more than one tornado develops, they are usually separated 30 to 50 miles. Their lives are usually short, their paths are relatively narrow, and their speeds are slower than the tornadoes of the Type I Air Mass. While hail aloft is often a hazard to aircraft, surface hail and strong thunderstorm downrush gusts are rarely observed at the earth's surface.

f. The weather preceding and following a tornado occurrence is usually cloudy with showers and scattered thunderstorm activity. There is neither a marked temperature nor a dew-point change after passage of the storm. The pressure falls rapidly prior to the tornado, but otherwise the weather sequence changes very slowly with time.

g. Tornadoes in this type air mass occur primarily in mesocyclones at the intersection of a thunderstorm line with a warm front, and activity associated with "bubble highs" develops along the axis of maximum low-level wind flow. Tornadoes occur less frequently along fronts and squall lines.

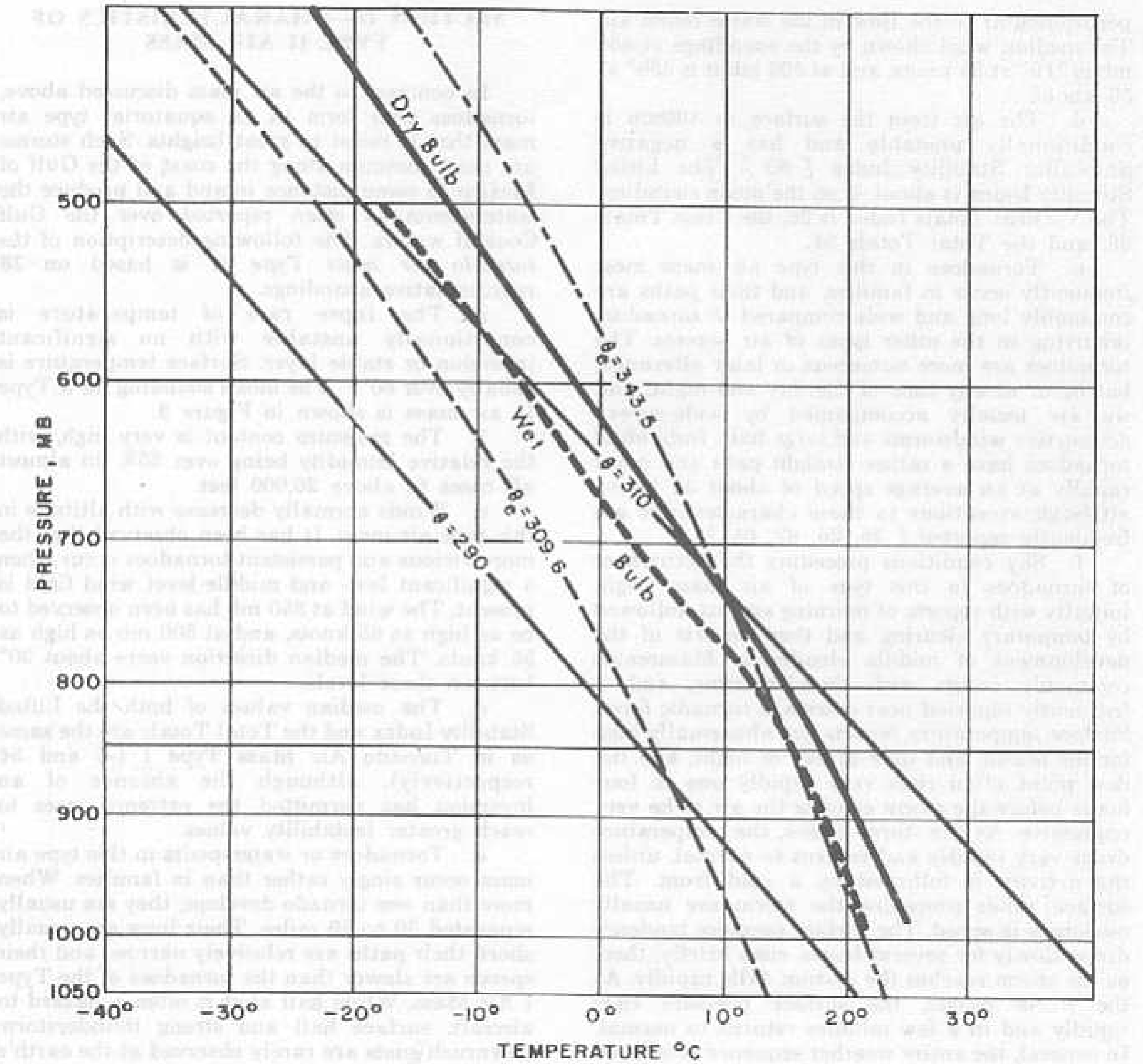

Figure 9. Mean Sounding of Type II Tornado Air Mass

SECTION E—CHARACTERISTICS OF TYPE III AIR MASS

Tornadoes also form in relatively cold moist air, and this *Tornado Air Mass Type III* has yielded eighteen soundings to date. This type of tornado is most often associated with cold-core situations over the extreme western United States, and for that reason is sometimes called the Pacific Coast type. It is responsible for the waterspouts along the West Coast, over the Great Lakes and the northeastern U.S. The characteristics of this type air mass are:

a. The temperature lapse rate is conditionally unstable, and is without significant inversions or stable layers. Compared to Type II, this air mass is quite cold as the surface temperatures range from 20°C down to 10°C.

b. Moisture extends to great heights with the relative humidity commonly exceeding 70% at all levels up to at least 500 mb.

c. Winds increase and generally veer with altitude, the median speeds being 25 knots at 850 mb and 50 knots at 500 mb.

d. The apparent instability from the Lifted Index is not as great as in the first two air-mass types discussed—the median values being -3. However, the Total Totals Index is 57.

e. In general, tornadoes in this type air structure occur singly rather than in families or groups, although mammatus, virga, and funnels aloft often form in the vicinity of an occurrence. The Wet-Bulb-Zero is usually low so that only small hail is indicated, but the hail size may exceed the forecast size due to the unusually strong convergence associated with the synoptic pattern. The thunderstorm gusts are often masked by strong gradient winds. Compared to the tornadoes in Tornado Air Mass Type I, or even Type II, tornadoes in this type situation have a brief life, a short and narrow path, and occur usually in the afternoon. The frequency of funnels aloft and the comparative rarity of surface damage are very likely due to the cushioning effect of the cool surface air.

f. Tornadoes in this type air mass are generally imbedded in an area of extensive cloudiness, scattered rainshowers and isolated thunderstorms. Clouds consist mostly of stratocumulus with embedded buildups and mammatus usually reported. There are no abrupt or unusual changes in the weather elements, except, of course, the pressure and temperature within the tornado itself.

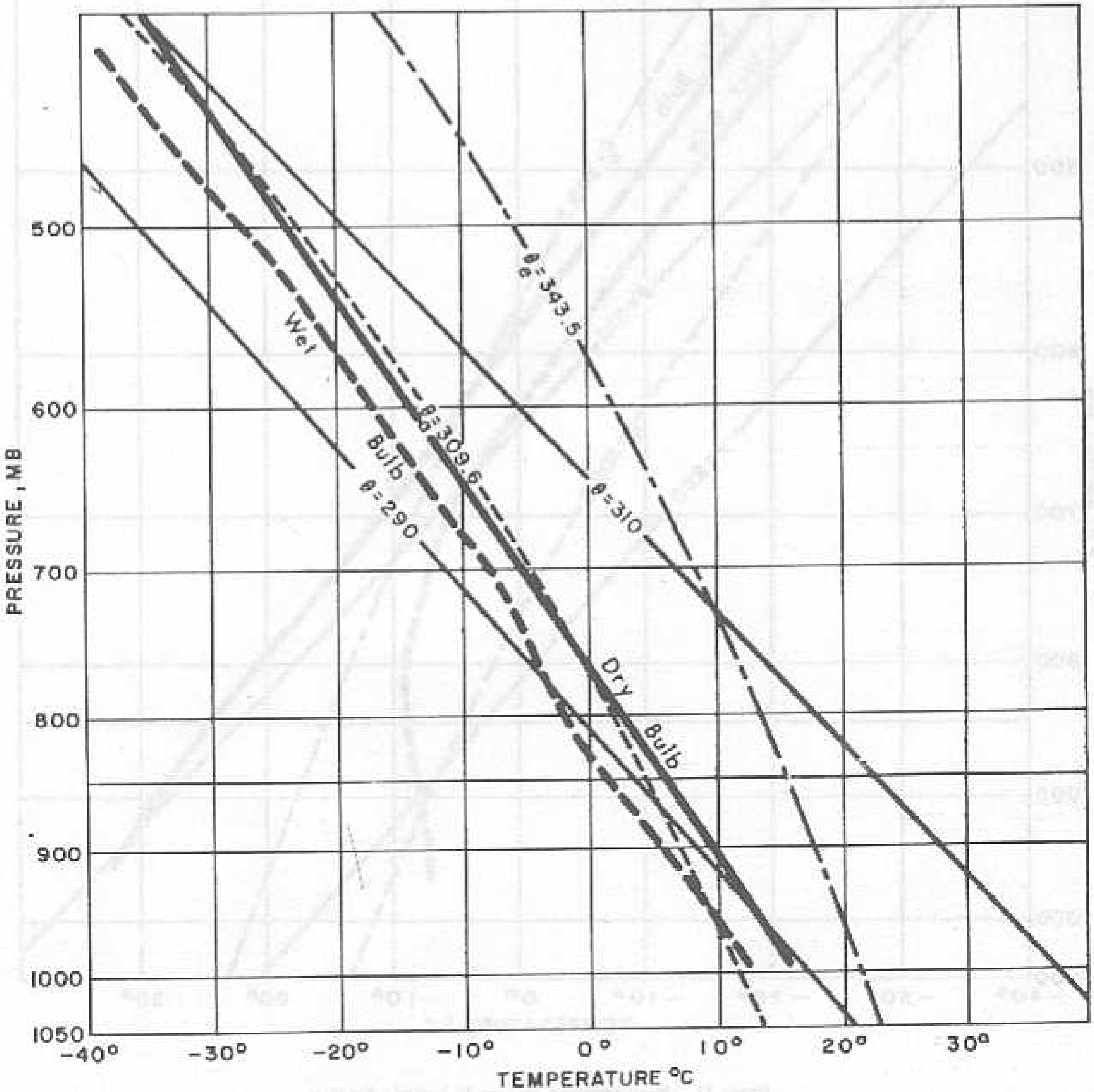

Figure 10. Mean sounding of Type III Tornado Air Mass

g. The most favorable synoptic situations for tornado development include the rear of maritime polar cold fronts, and in well-cooled air behind squall lines and "bubble highs." Unlike the storms associated with the Type I and Type II Air Mass, the tornadoes in this air mass usually do not accompany mesocyclones, but *always* are associated with cold cores aloft. The median of the 18 available soundings representative of the Type III tornado-producing air mass is shown in Figure 10. Note the relative coldness of the air at all levels.

SECTION F—CHARACTERISTICS OF TYPE IV AIR MASS

When *continental tropical air* is overrun by *maritime polar air* at 5,000 to 8,000 feet above the ground the "inverted V" or Type IV tornado sounding may result. This air mass, when triggered, is productive of violent straight line windstorms from the southwestern desert areas, eastward into the high plains in the lee of the Rockies from western Nebraska southward into Texas. Tornadoes seldom reach the ground with

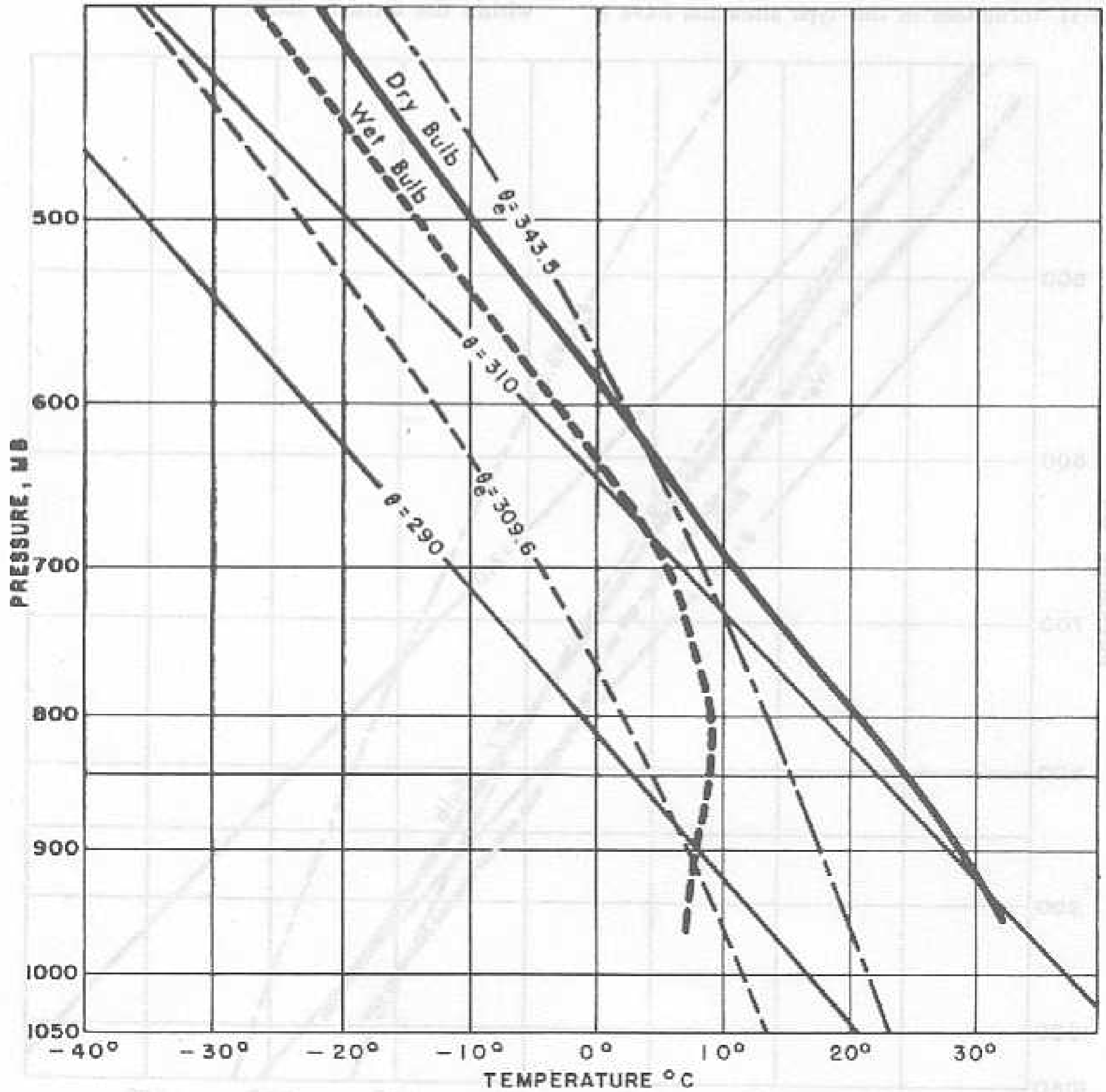

Figure 11. Mean sounding of Type IV Tornado Air Mass

this type of air mass, but when they do the narrow and rope-like funnel causes destruction over a relatively small area. The presence of dry air in this structure coupled with a favorable Wet-Bulb-Zero height defines this air mass as a dangerous hail producer. The Lifted Index for this sounding is not representative since the lower layers are quite dry. However, the Totals Index is 53. The median of 22 Type IV soundings is shown in Figure 11.

Chapter 3
SEVERE-WEATHER SYNOPTIC PATTERNS

SECTION A—GENERAL

The basic forecast rules stated by Fawbush and Miller in 1951 [22] were founded in part on exploratory work by previous investigators, particularly Showalter and Fulks [61]. During the operation of the MWWC it had become evident that three of these basic rules are of prime importance in delineating areas of future severe-weather development, and in defining the basic tornado-producing synoptic patterns. Originally, these rules were as follows:

a. The horizontal distribution of winds aloft must possess a maximum of speed along a relatively narrow band, preferably at some level between 10,000 and 20,000 ft, with a value of 35 knots or greater.

b. In situations preceding significant tornado development, a distinct dry tongue is present in the low or middle levels, and, provided other criteria are satisfied, the primary development will occur where the dry air intrudes into or over the lower moist tongue.

c. The horizontal moisture distribution within the moist lower layer possesses a distinct maximum along a relatively narrow band on the windward side of the inception area. Stated more simply, dry air must be available upwind of the threat area.

"The narrow band of maximum winds aloft in the middle levels" rule has been employed very successfully in determining areas of tornado and severe-weather development. This rule was refined in 1957 [24] to include horizontal wind speed shears in the middle-level wind field. The "narrow band" is also a steering mechanism once the activity has begun. Throughout this paper, the term "jet" refers to this low or middle-level wind band and should not be confused with the higher-level jet pattern, although usually it is a downward reflection of the jet stream.

Since 1954 [17] increased attention has been given to the importance of dry-air intrusions between 850- and 700-mb in forecasting areas of tornado and severe-thunderstorm development. As a result, the validity of the second rule above is now clearly established. Dry-air intrusions not only help in delineating future tornado and severe-weather areas, but apparently provide a major contribution to the trigger mechanism in the majority of tornado situations.

Additional evidence supporting the third rule listed above also has been found. It now appears that nearly all violent thunderstorm activity is associated with intense gradients of moisture along the windward side of the inception area at levels from the surface to 700 mb. In some cases, the contrast between dry and moist air is apparent throughout the layer; and in other situations, it is evident only at the 850-mb or perhaps the 700-mb level. the intensity of severe-weather development is proportional not only to the steepness of the moisture gradient but also the wind component from dry to moist air. In one case in 1956, the Weather Bureau tornado research airplane recorded a moisture gradient of 3.5 g per kg per mile at 800 mb. A well-defined squall line developed along this steep moisture gradient, but severe weather was not reported. This failure of severe weather to develop could be explained by the general weakness of the wind flow from the dry to the moist region and the slight instability of the moist air mass.

During the period from 1954 through 1964 MWWC reanalyzed more than 400 tornado cases or "tornado days." As this project progressed, it became apparent that the similarities between cases involved the three basic tornado forecasting rules. The following criteria were adopted for classifying each tornado situation as to synoptic type:

a. The presence of middle-level jets or shears.

b. The character of the dry-air intrusion and its proximity to the moisture ridge.

c. The value and gradient of the low-level moisture influx. Categorizing the above characteristics for each of the reanalyzed cases required only five types to include practically all the observed situations. Thus, it appeared practicable to use these types as an analog system for forecasting severe weather. The five types may be considered a summary of the most effective rules developed over the past years of operation of the MWWC, and these types should be used with, but not confused with, the tornado-producing air-mass types previously identified by Fawbush and Miller.

SECTION B—SYNOPTIC TYPE A PATTERN

As shown in Figure 12, the Type A tornado-producing synoptic pattern is characterized by a well-defined southwesterly jet aloft and a distinct southwesterly current of warm dry air from the surface to 700 mb positioned to the west of a low-level southerly moisture influx. There is considerable 850- and 700-mb streamline convergence at the boundary between the moist and the dry air.

Thunderstorms occur within the zone of maximum convergence between the moist and dry air—the mixing zone. This zone may be determined by locating the area of greatest effective dry-air advection in the lower and middle levels. Normally, the thunderstorms do not form a sharp, well-defined squall line, but tend to develop rapidly in rather isolated clusters within the maximum convergence zone. These clusters are found in a somewhat irregular pattern along or near the leading edge of the marked dry intrusion. The initial outbreak occurs along the maximum moisture gradient between the dry air and the moist air. In some cases the zone of this maximum gradient slopes toward the moist air in the manner of a warm front, and the outbreaks occur over a wider area. However, the initial severe activity usually will be confined to the area between the leading edges of the dry air at 850 mb and 700 mb.

The area of the most violent thunderstorms may be outlined by the maximum streamline convergence between the moist and dry air and the position of the jet. In practice, the severe-weather area will extend from the jet for about 200 miles to the right (in the zone of diffluence) and downstream from the maximum-convergence line, to the place where low-level moisture decreases to a value insufficient to maintain the high latent instability needed to support severe activity. If there is a marked middle-level horizontal-speed shear crossing the moisture pattern to the south or southeast of the jet, a second area of severe weather may develop. However, the width of the secondary zone is usually about 150 miles instead of 200. Synoptic pattern Type A is characterized by unusually rapid and severe thunderstorm development. It is not uncommon for thunderstorms to develop in the short period of 15 to 30 minutes with the first reports consisting of very large hail, damaging surface winds, or tornadoes. The previously described Type I air mass is always present with the Type A synoptic pattern. The development of convective activity will be retarded by the typical inversion until the air mass is triggered and the latent instability is released. Thunderstorms begin about the time of maximum surface heating or within six hours thereafter.

On the average, violent activity continues about six to eight hours, ceasing only when the intruding dry air loses its identity due to mixing and the wind flow between the moist and dry air becomes weak. This process of pattern-type deterioration is accentuated as the air begins to stabilize during the nighttime hours. There are rare but spectacular exceptions to this rule if the dry-air intrusion is especially well-defined and driven by strong winds. In these cases, the violent activity continues with little abatement as long as there is sufficient latent instability. Tornadoes and very large hail are common with this pattern and tornadoes most often occur in groups or families. Activity has been observed to be more persistent and more intense when associated with the jet than when associated with the middle-level shear zone.

SECTION C—SYNOPTIC TYPE B PATTERN

The Type B pattern, shown in Figure 13, is characterized by the usual southwesterly jet aloft, a rather marked low-level intrusion of dry air, and southerly current of warm moist air from the surface to near 850 mb in the eastern portion of the area of interest. The pattern includes a major low-pressure center, not necessarily associated with the Type A pattern, a cold and warm front distribution with marked cold-air advection to the west or northwest at all levels to 500 mb. There is a distinct upper cold front or cold trough to the immediate west at 700 and 500 mb, with cool moist air along its axis and to the rear, and with dryer moist air just ahead of the trough. The wind flow shows considerable low and middle-level convergence between the warm moist air and the cooler air in the middle levels. It has been observed that either a frontal or pre-frontal squall line develops in all cases and is usually well defined. Thunderstorms initially occur along or just ahead of the surface cold front, due to the combination of warm moist air adjacent to dry air, and cold-air advection in middle and upper levels. This unusual situation develops an extremely unstable air column. The initial outbreak of activity occurs within the zone of maximum lower and middle convergence along the cold front. This zone may be located by comparing the areas of maximum cold-air advection at all levels, and the areas of maximum dry-air advection at 850 and 700 mb. The activity develops gradually along the cold intrusion, eventually forming a squall line positioned from about 150 to 200 miles north of the jet southward to the leading edge of the dry-air intrusion. In many cases, the area of maximum static instability as determined from the Lifted Indexes will lie far ahead of the developing squall line and the thunderstorms do not become really severe until the squall line disturbs this air mass. When the intruding dry air is warmer than the moist southerly current (and the wind field is

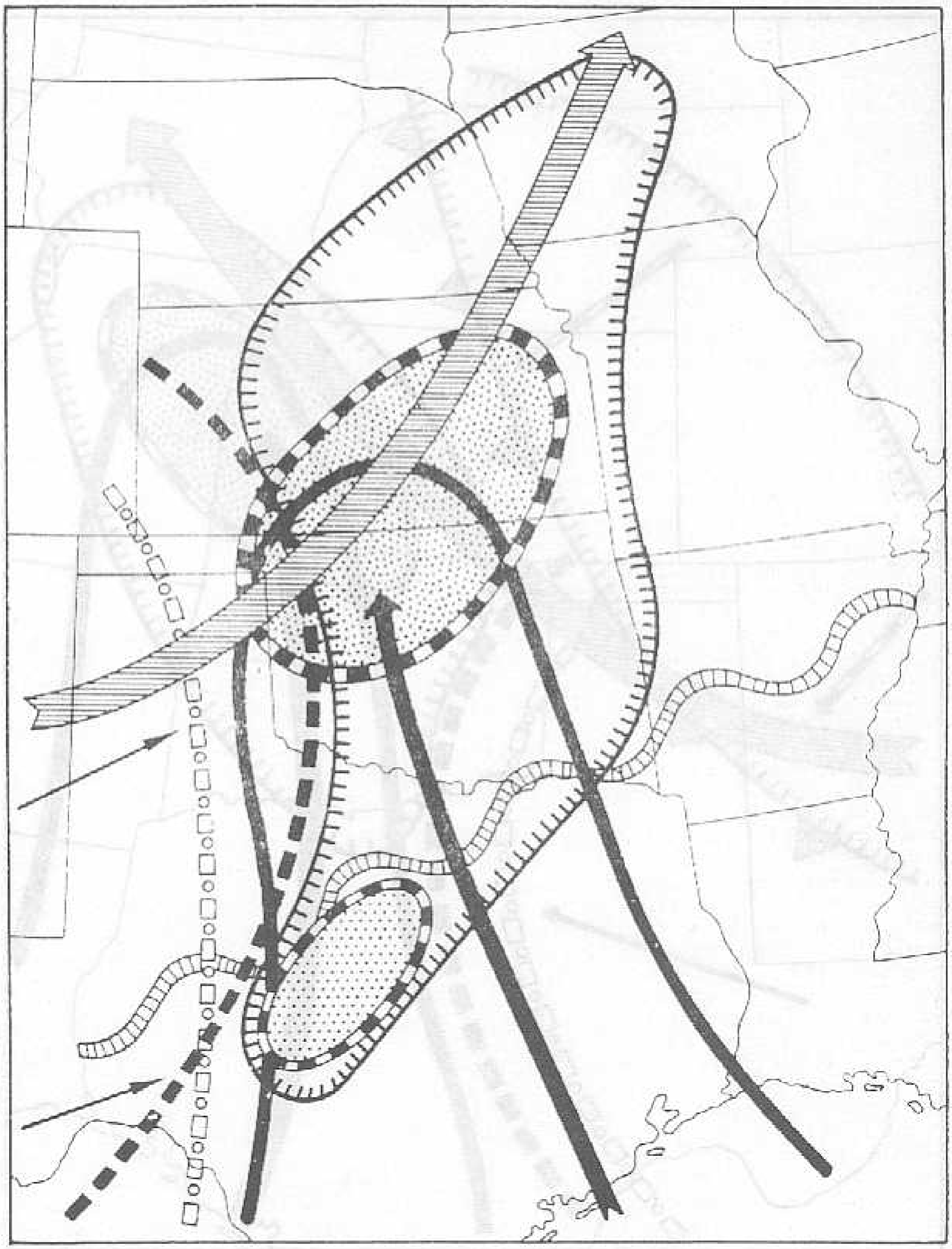

Figure 12. The Type A tornado-producing synoptic pattern. Stippled area outlines location of severe-weather occurrences.

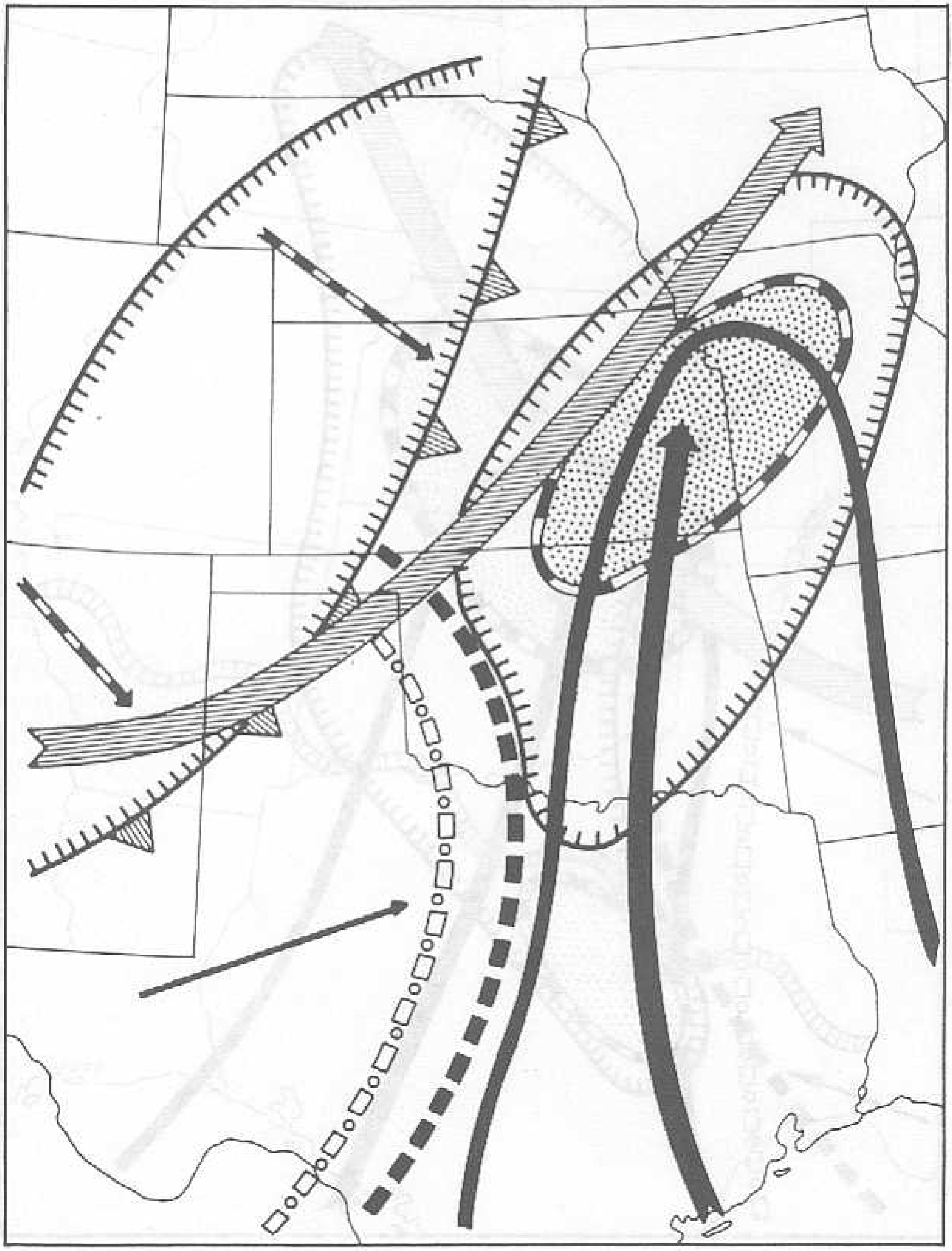

Figure 13. The Type B tornado-producing synoptic pattern. Stippled area outlines locations of severe-weather occurrences.

favorable), isolated severe thunderstorms initially may form along its leading edge in the same fashion as in a Type A outbreak.

The area of maximum severe thunderstorm activity is delineated by the position of the jet and zone of diffluence or a well-defined middle-level horizontal shear zone, and the convergence between moist and dry air in lower and middle levels. In this pattern, the leading edge of the dry-air intrusion is usually more obvious on the 850-mb chart. In practice, these criteria describe an area along and extending some 150 to 200 miles to the right of the jet. The upwind boundary is defined by the moisture discontinuity of the dry-air intrusion and the forecast location of the developing squall line. The downwind boundary is subjectively determined to be where the low-level moisture decreases to a value incapable of providing the necessary extreme latent instability. In this type of situation, violent thunderstorms occur at all hours of the day and night, for the triggering mechanisms are not as dependent on diurnal heating as Type A outbreaks. However, the activity is more widespread and vigorous when it does develop near or extend into the time of maximum surface heating. The actual starting time of thunderstorm formation depends on the rate of movement of the cold front and dry-air intrusion into sufficiently unstable air. Severe storms will continue as long as the air mass ahead of the squall line remains critically unstable. Type B patterns usually produce one or more transitory mesocyclones, 25 to 100 miles in diameter, as the squall line moves along the warm front. These short-lived, but dangerous low-pressure systems most frequently form at the intersection of the low-level jet with the middle-level jet or with the warm front. They are also common at intersections of precipitation-induced discontinuities with the squall line or with other lines of discontinuity. The family outbreaks of tornadoes and severe wind storms common with this synoptic situation are usually closely associated with the mesocyclones.

The Type A and B patterns are quite similar in configuration and general development. The major difference between the two is the noticeable presence of a major upper trough and frontal system to the west of the threat area in the Type B pattern. This association with the trough and frontal systems designates the Type B pattern as the last of a series of severe-weather producing systems. On the other hand, the Type A often repeats from day-to-day until the major trough moves away. Another difference is that the Type A dry air is upwind of the threat area while moist air covers the threat area. The Type B mid-levels are usually dry but moisture associated with the middle-level trough is upwind from the threat area.

SECTION D—SYNOPTIC TYPE C PATTERN

The Type C tornado-producing synoptic pattern shown in Figure 14, is characterized by a jet from a more westerly direction than in Types A and B; or, in some instances, by a strong westerly shear zone in the middle levels. The dry-air intrusion is most often evident at the 700-mb level and is carried into the threat area on a southwesterly current. The area north of the nearly east-west quasi-stationary surface front usually will show neutral advection or slight cooling at the 700- and 500-mb level. The low-level warm moist flow overruns the quasi-stationary front causing thunderstorms to develop because of this lifting action and the increase in potential instability in the low-level air moving northward under colder air aloft. Thunderstorms in a developing Type C synoptic pattern remain scattered over the area between the quasi-stationary front at the surface and the location of the high-level jet to the north.

This scattered thunderstorm pattern persists until the dry-air intrusion penetrates and agitates this active zone. Thunderstorms then increase rapidly in number and intensity, with an active squall line usually forming along the leading edge of the dry air. The area of the most severe activity is determined by the position of the jet or high-level shear, the stationary surface front, the axis of maximum overrunning (determined by the strongest low-level flow) and the strength and position of the dry-air intrusion. In practice, the western boundary of the most severe area will be about 50 miles west of the axis of maximum low-level moist flow over the frontal surface. The jet and front provide reasonable north and south limits, but the eastern boundary is more difficult to define. The position of the eastern boundary may depend on a decrease in temperature lapse rate, a decrease in available moisture, a decrease in active overrunning, or a combination of these stabilizing effects. Furthermore, it has been observed that if the dry-air intrusion is lost for any reason, the storms will subside to below severe category. The Type C pattern is similar to Type B in that thunderstorms may develop at any time of the day or night. The maximum activity may be expected for about six hours beginning with the time of maximum surface temperatures in the warm moist intruding air, but the onset of violent weather appears to be closely related to the time of dry-air intrusion into an already active zone of heavy thunderstorms. The severe storms then continue with only minor diurnal variations until terminated as described in the preceding paragraph.

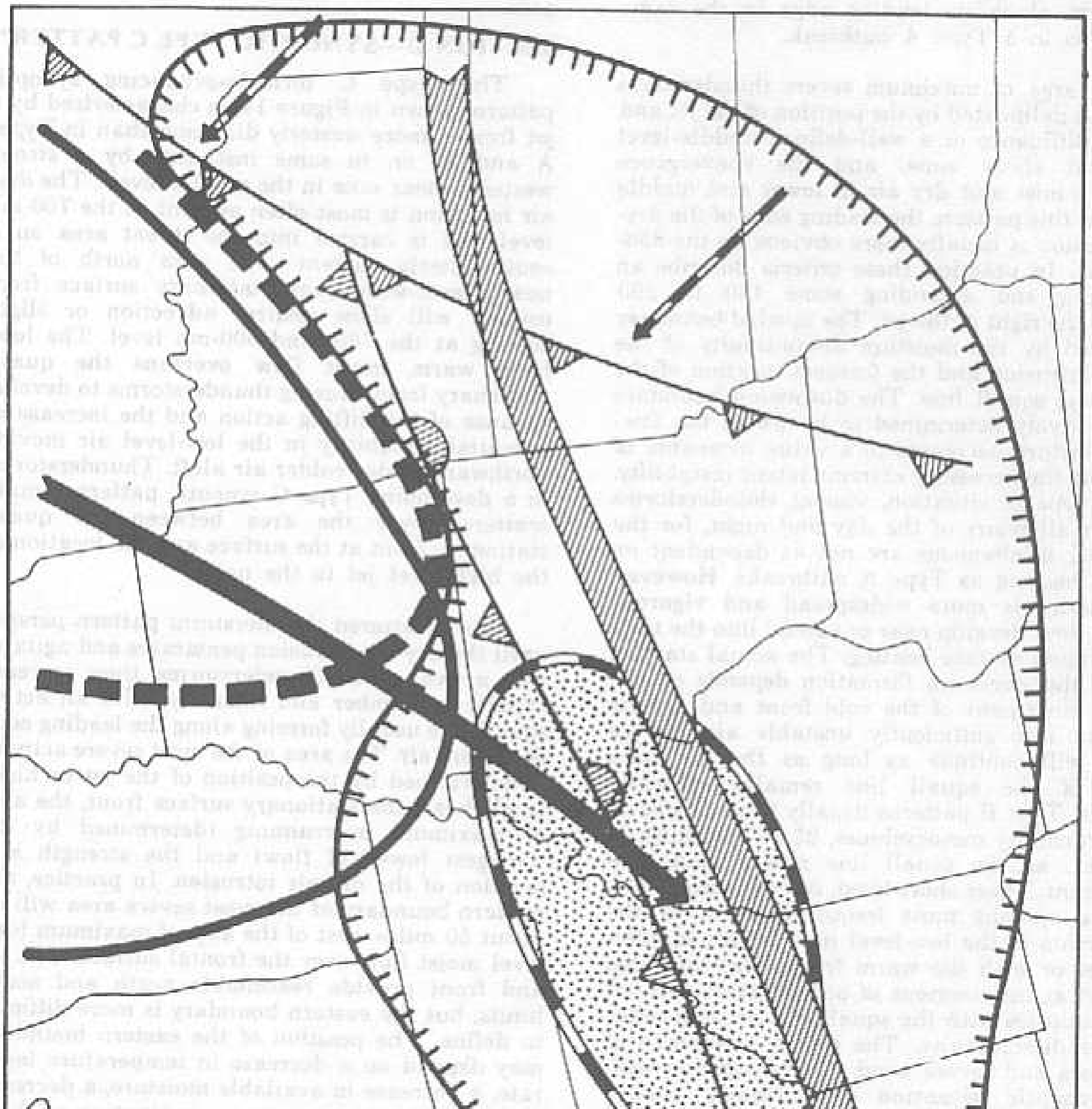

Figure 14. The Type C tornado-producing synoptic pattern. Stippled area outlines locations of severe-weather occurences.

Type C situations are very favorable for the development of bubble-type precipitation-induced highs and their associated mesolows within the thunderstorm area. These short-lived, small-scale features move about 30 degrees to the right of the middle-level wind flow, toward lower pressures, and toward maximum surface temperatures. These mesocale features usually have a life history of less than 6 hours, but extremely severe thunderstorms, considerable hail, strong surface gusts and an occasional tornado occur with the intense pressure gradients in this synoptic pattern. Since most of the activity associated with the Type C occurs in the overrunning zone, tornadoes have difficulty in reaching the ground except when extreme instability conditions are present, or if there is an unusually strong dry-air intrusion. When the low levels are very cold (below 50°F) tornadoes should never be forecast. When tornadoes do develop in a Type C pattern they usually occur singly or by twos and threes and are separated by intervals of 25 to 50 miles. Practically all the strong surface gusts and damaging winds are directly associated with the leading edges of bubble highs, or squall lines, and are in association with mesolows. Surface hail is frequently widespread, for the wet-bulb freezing level is favorably low.

When a well-defined cold front accompanied by strong cold-air advection overtakes the active storm area, it often transforms the Type C pattern into a Type E pattern. Thus, the severe cells lose part of their dependence on the strong lifting by overrunning. The severe activity spreads and becomes associated with the cold front and may extend southward along the front in the warm air.

SECTION E—SYNOPTIC TYPE D PATTERN

The Type D tornado-producing synoptic pattern is shown in Figure 15. The jet aloft is usually from a more southerly direction than in other types. The dry-air advection around the bottom of the rapidly deepening low-pressure center is cool at all levels. Also, the southerly or southeasterly current of warm moist air in the low levels underruns the colder air aloft. The surface low-pressure center usually moves in a northerly direction accompanied by a 500-mb cold low centered just to the west.

The thunderstorms are triggered by intense low-level convergence and the increasing potential instability due to the advection of cold-air aloft over the underrunning warm moist air in the lower levels. The initial outbreak usually is found in the underrunning warm air between the position of the jet and the closed cold isotherm center at 500 mb. This area of maximum static instability as determined from the Lifted Indexes lies in the zone of maximum convergence ahead of a cool dry-air intrusion from the southwest. After the initial outbreak, thunderstorm activity spreads eastward. As with the other types, the area of violent activity is located from the position of the convergence zone in the low and middle levels, the position of the jet, and the leading edge of the cold dry air in the southwest. In addition, the location of the 500-mb cold center helps establish a boundary. In actual practice, these criteria outline an area of perhaps 150 miles from the jet to the 500-mb cold center, and a more variable distance from the leading edge of the southwesterly cold-air advection to the limit of the unstable underrunning warm moist air. In Figure 15 the severe-weather area has been extended a short distance to the right of the jet. This boundary is determined from the eastern limit of the areas of strong convergence and latent instability and from the forecast eastward or northeastward drift of the jet.

Thunderstorms associated with the Type D pattern occur at all hours, but the very violent storms are usually limited to the period between noon and dark when the warm moist air is most unstable because of diurnal heating. The decrease in intensity after dark is rather rapid, although storms of moderate intensity often continue for some hours.

Numerous reports of funnel clouds aloft are received during Type D situations, but only occasionally do tornadoes reach the ground. Tornadoes that do develop occur singly and not in families as in Type A and B. In order to produce a tornado in the Type D pattern, the low-level air mass must be heated and moved under a very cold air mass at 500 mb. However, hail is often widespread and severe, and increases in size and amount westward from the jet toward the 500-mb cold core. Frequently, the size of the hail will exceed the value predicted by the Fawbush-Miller hail graph [16]. This underforecast is due to the intense low- and middle-level convergence in this particular synoptic situation.

SECTION F—SYNOPTIC TYPE E PATTERN

The final synoptic Type E, is characterized by a well-defined jet from a westerly direction, a dry source defined by the 700-mb warm sector, and a low-level warm moist tongue carried by a southerly to southwesterly current. The warm moist air overruns cooler air, usually because of the presence of a warm front. The Type E differs from the Type C pattern in that it always includes a major surface low with associated warm and cold fronts. Figure 16 shows the typical pattern

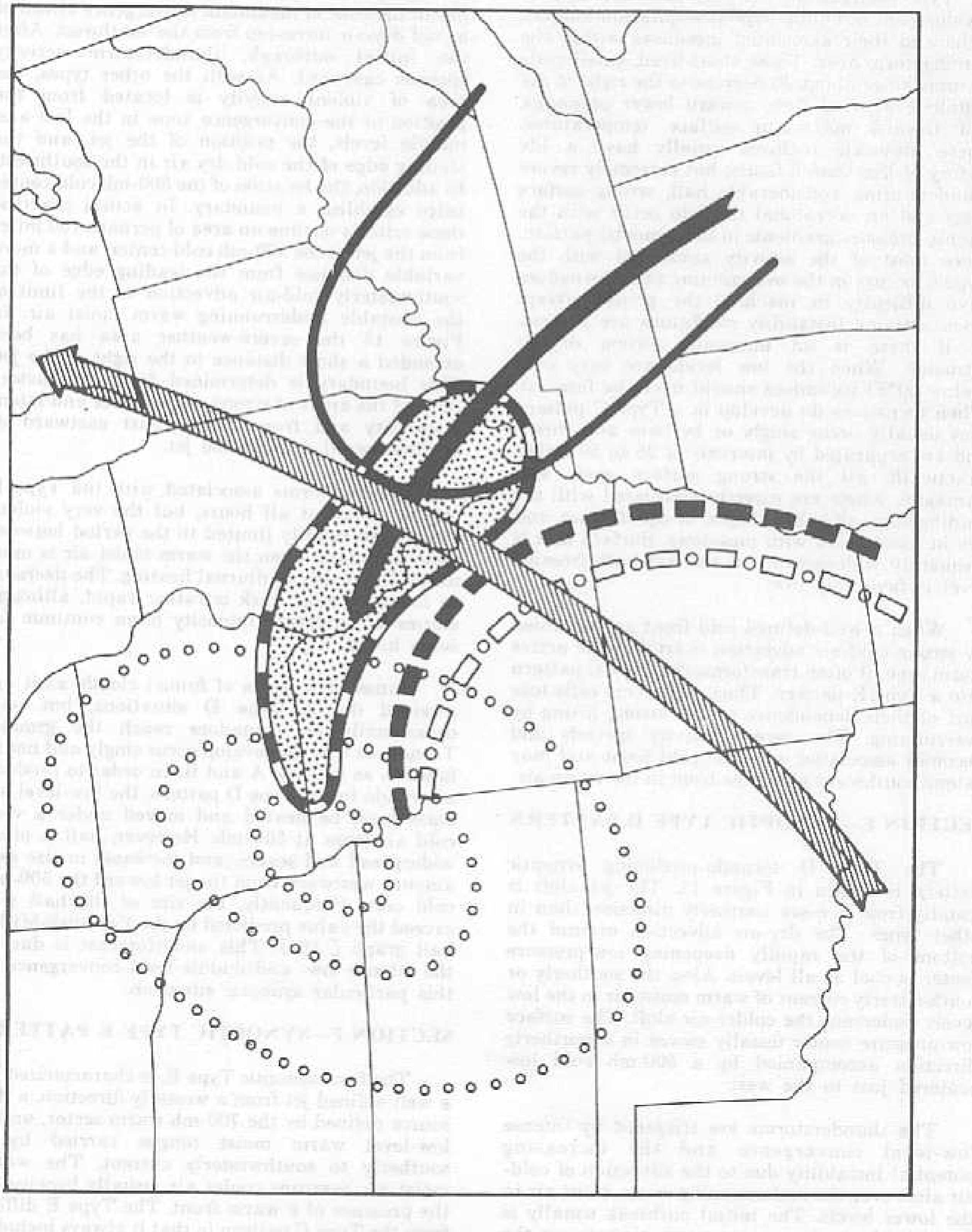

Figure 15. The Type D tornado-producing synoptic pattern. Stippled area outlines locations of severe-weather occurrences.

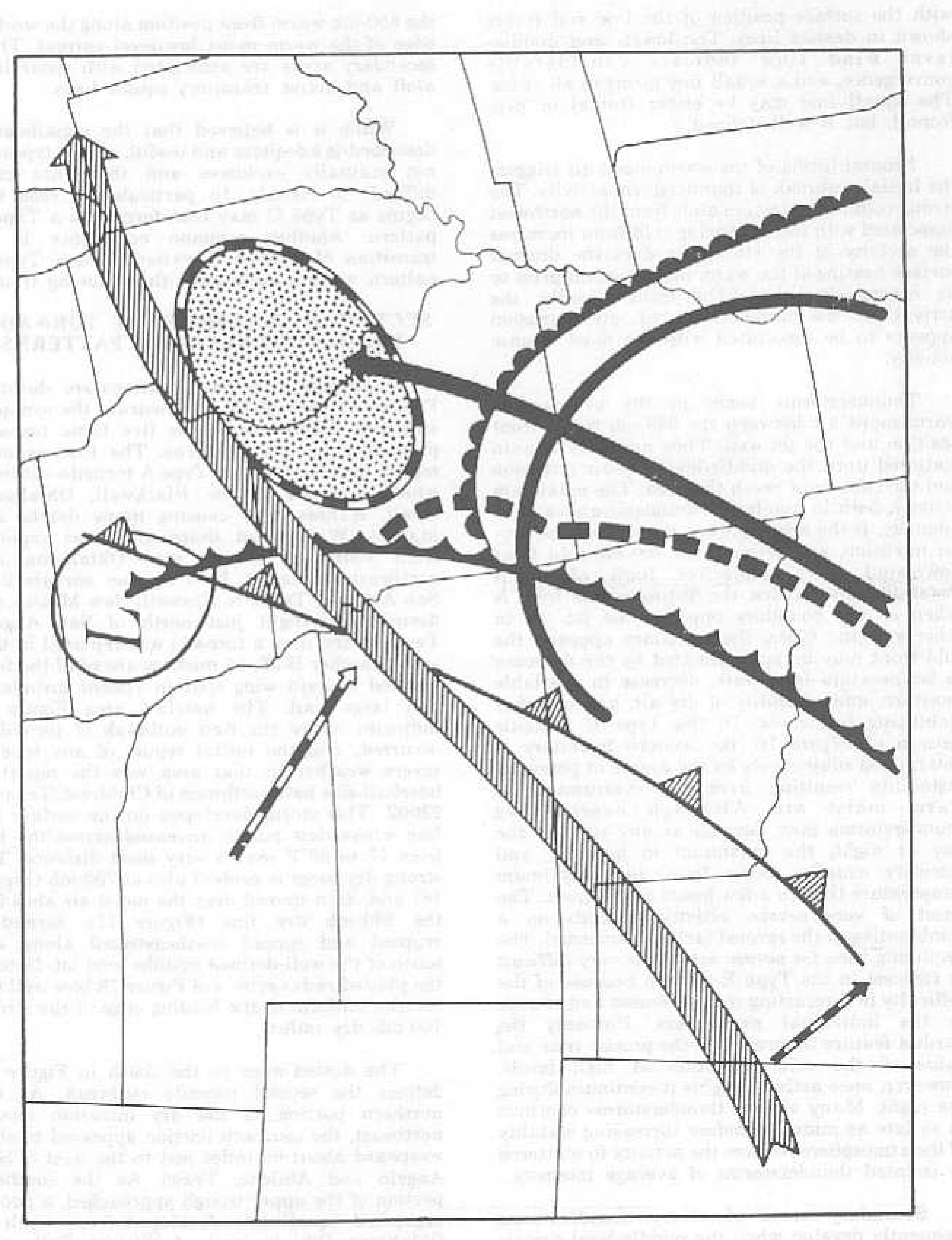

Figure 14. The Type E tornado-producing synoptic pattern. Stippled area outlines locations of severe-weather occurrences.

with the surface position of the low and fronts shown in dashed lines. The lower- and middle-level wind flow indicate considerable convergence, and a squall line forms in all cases. The squall line may be either frontal or pre-frontal, but is well defined.

Frontal lifting of the warm moist air triggers the initial outbreak of thunderstorm activity. The strong cold-air advection aloft from the northwest associated with the advancing cold front increases the severity of the storms as does the diurnal surface heating of the warm moist current prior to its overrunning the warm front. Finally, the arrival of the middle-level dry-air intrusion appears to be associated with the most intense activity.

Thunderstorms begin in the overrunning warm moist air between the 850-mb warm front position and the jet axis. They normally remain scattered until the middle-level dry-air intrusion and the cold front reach the area. The maximum activity, both in number of thunderstorms and in intensity, is the area between the jet and the dry-air intrusion, and between the 700-mb cold front downwind to a subjective limit of latent instability. In practice, the 850-mb warm front is taken as the boundary opposite the jet. As in other synoptic types, the boundary opposite the cold front may be approximated by the decrease in temperature lapse rate, decrease in available moisture, unavailability of dry air, and by other stabilizing influences. In the Type E synoptic pattern of Figure 16, the eastern boundary is determined subjectively by the degree of potential instability resulting from the overrunning of warm moist air. Although overrunning thunderstorms may develop at any time of the day or night, the maximum in quantity and intensity usually occurs from near maximum temperature time to a few hours after sunset. The onset of very severe activity depends on a combination of the several factors mentioned. The beginning time for severe activity is very difficult to forecast in the Type E pattern because of the difficulty in forecasting the movement and change in the individual parameters. Probably the hardest feature to forecast is the precise time and value of the cold advection at high levels. However, once activity begins it continues during the night. Many violent thunderstorms continue to as late as midnight before increasing stability of the atmosphere reduces the activity to scattered or isolated thunderstorms of average intensity.

Secondary areas of severe thunderstorms frequently develop when the middle-level dry-air intrusion is sufficiently strong to cause the squall line to develop or extend itself well to the south of the 850-mb warm front position along the western edge of the warm moist low-level current. These secondary areas are associated with shear lines aloft and active transitory squall lines.

While it is believed that the classification described is adequate and useful, all the types are not mutually exclusive and there are cases difficult to classify. In particular, a case that begins as Type C may transform into a Type E pattern. Another common occurrence is the transition of a Type A pattern into a Type B pattern when associated with a moving trough.

SECTION G—EXAMPLES OF TORNADO-PRODUCING SYNOPTIC PATTERNS

A number of actual situations are shown in Figures 17 through 24 to illustrate the synoptic-structure differences of the five basic tornado-producing synoptic patterns. The first example represents a very severe Type A tornado outbreak which occurred in the Blackwell, Oklahoma-Udall, Kansas area causing many deaths and injuries. Widespread destruction was reported from southwest Texas into Oklahoma and northeast Kansas. A B-36 bomber enroute from San Antonio, Texas to Roswell, New Mexico was destroyed in-flight just north of San Angelo, Texas at the time a tornado was reported in that area. Another B-36, 15 minutes ahead of the first, cracked a main wing spar in violent turbulence and large hail. The hatched area Figure 19 indicates where the first outbreak of tornadoes occurred, and the initial report of any type of severe weather in that area was the report of baseball-size hail northwest of Childress, Texas at 2200Z. This storm developed on the surface dry line where dew points increased across the line from 17 to 68°F over a very short distance. The strong dry surge is evident also at 700 mb (Figure 18) and, as it moved over the moist air ahead of the 850-mb dry line (Figure 17), tornadoes erupted and spread northeastward along and south of the well-defined middle-level jet. Note in the plotted radar echoes of Figure 19 how well the returns conform to the leading edge of the strong 700-mb dry influx.

The dotted area to the south in Figure 19 defines the second tornado outbreak. As the northern portion of the dry intrusion moved northeast, the southern portion appeared to shift westward about 60 miles just to the west of San Angelo and Abilene, Texas. As the southern portion of the upper trough approached, a poorly organized squall line developed from south of Oklahoma City to west of Wichita Falls and southward to Del Rio, Texas. The tornadoes occurred with a mesolow which developed near

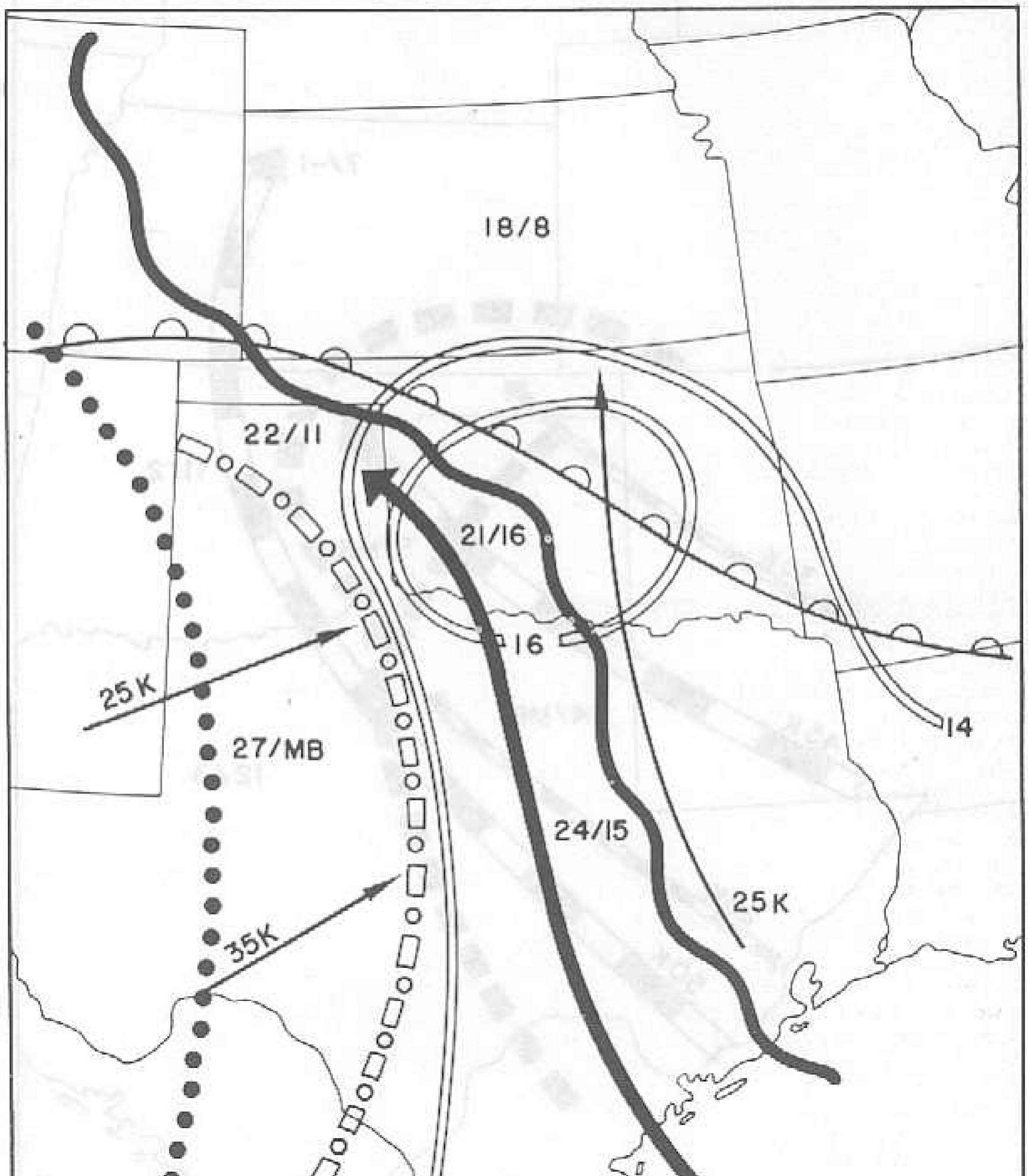

Figure 17. Significant 850-mb data at 2100Z on 25 May 1955.

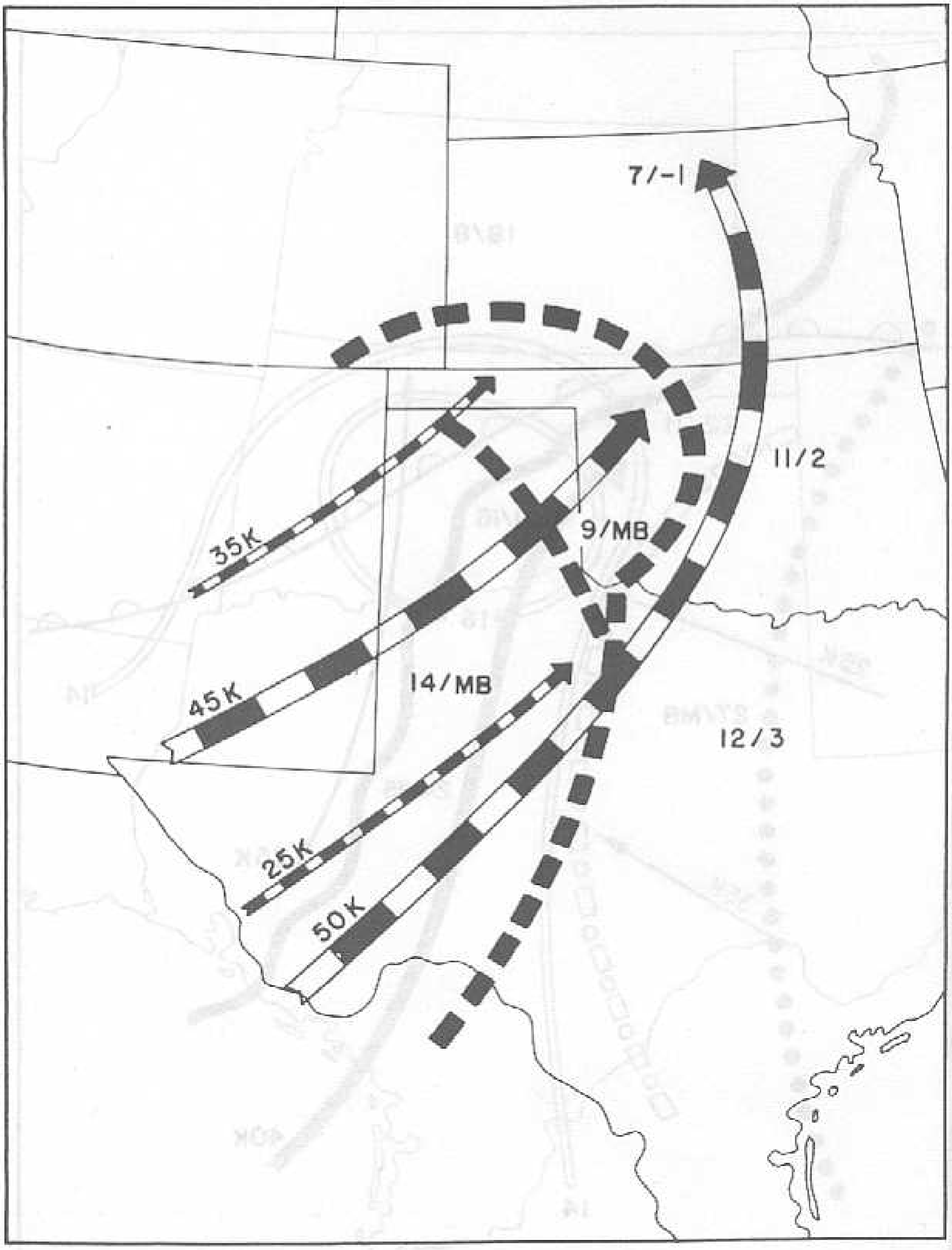

Figure 18. Significant 700-mb features at 2100Z on 25 May 1955.

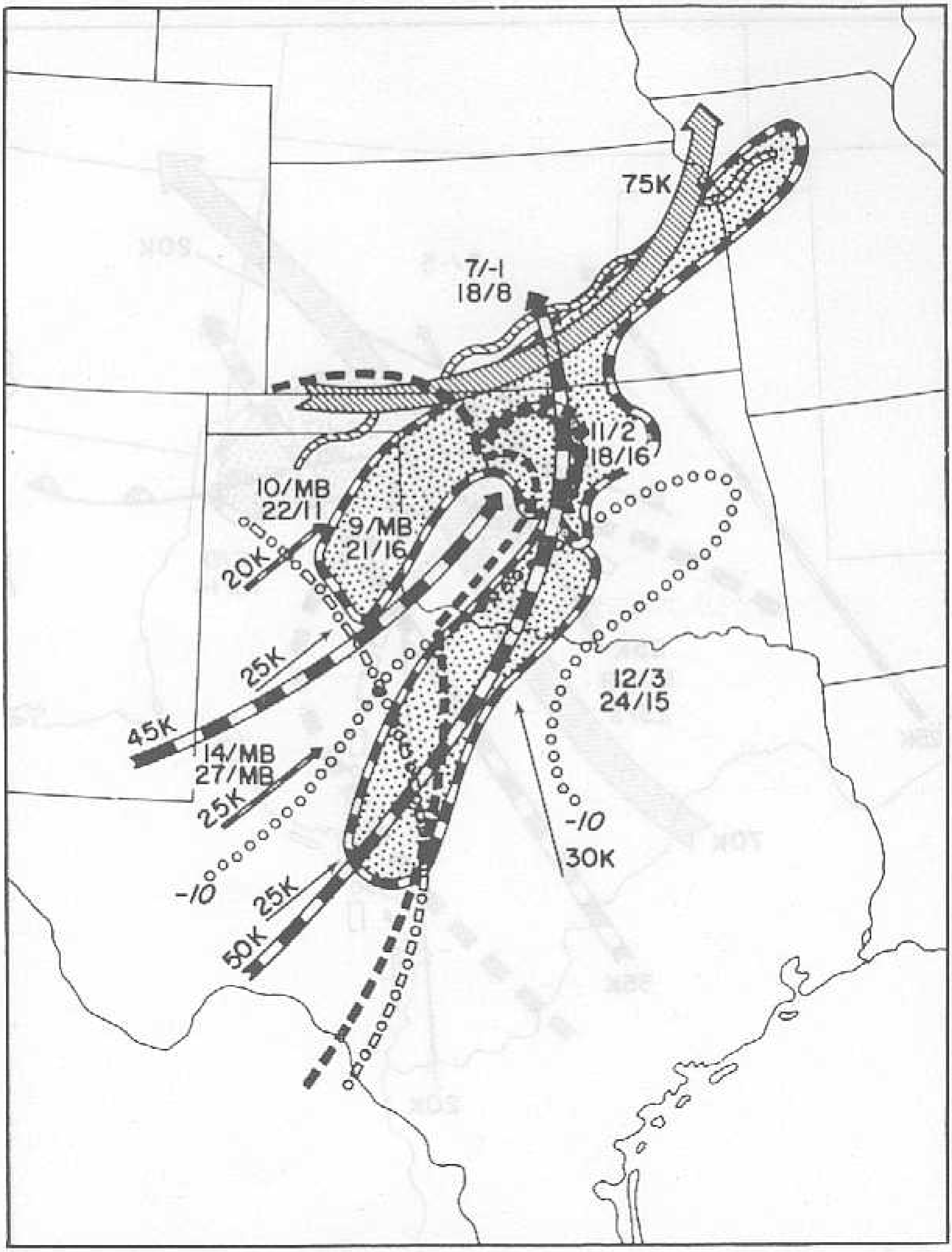

Figure 19. Significant upper-air features including Oklahoma State University radar echoes. Echoes at 0210Z are a line of solid circles and the echoes at 0345Z are a line of solid squares. Stippled area outlines locations of severe-weater occurrences.

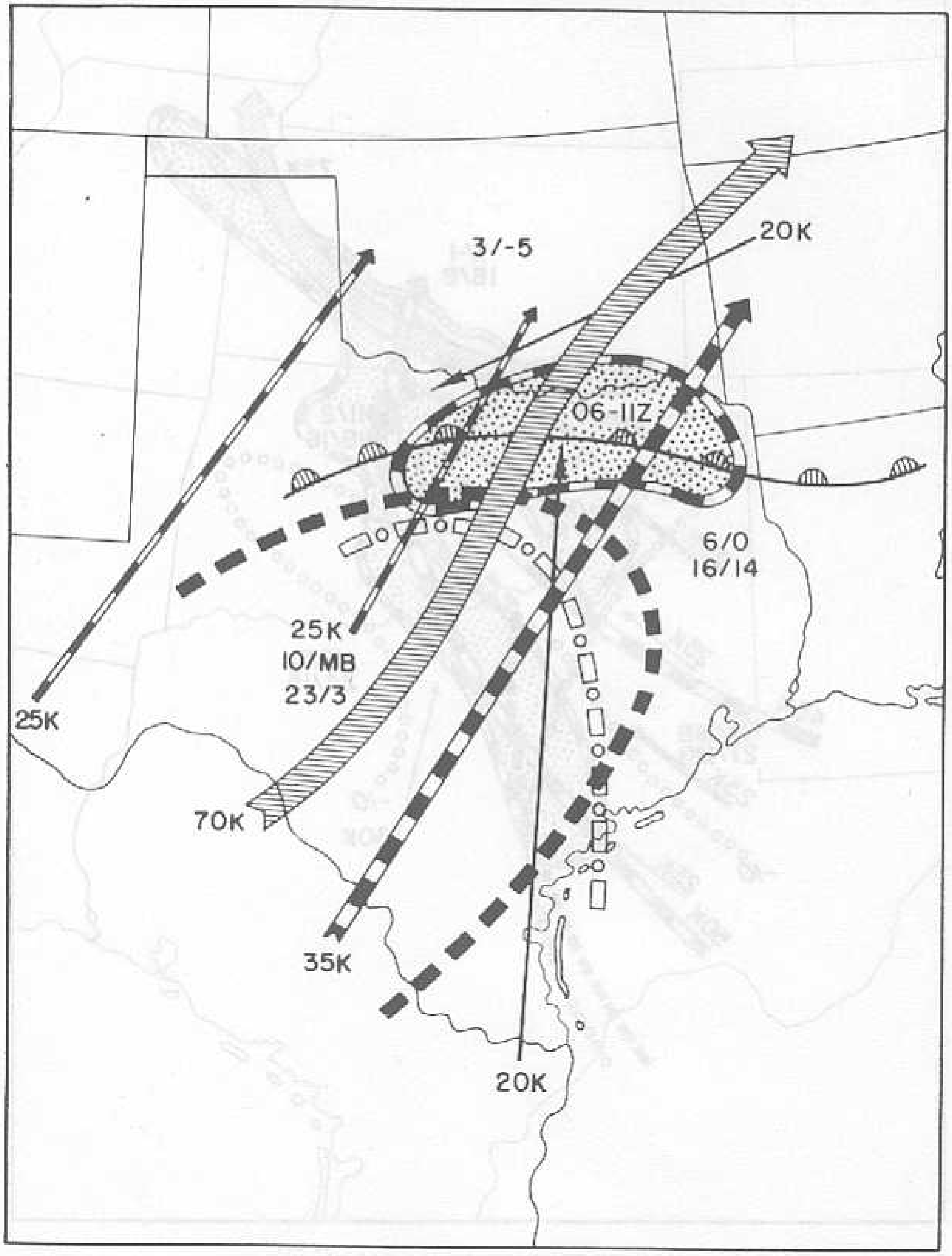

Figure 20. Example of Type A pattern showing major features at 0300Z on 6 April 1955. Stippled area outlines locations of severe-weather occurrences.

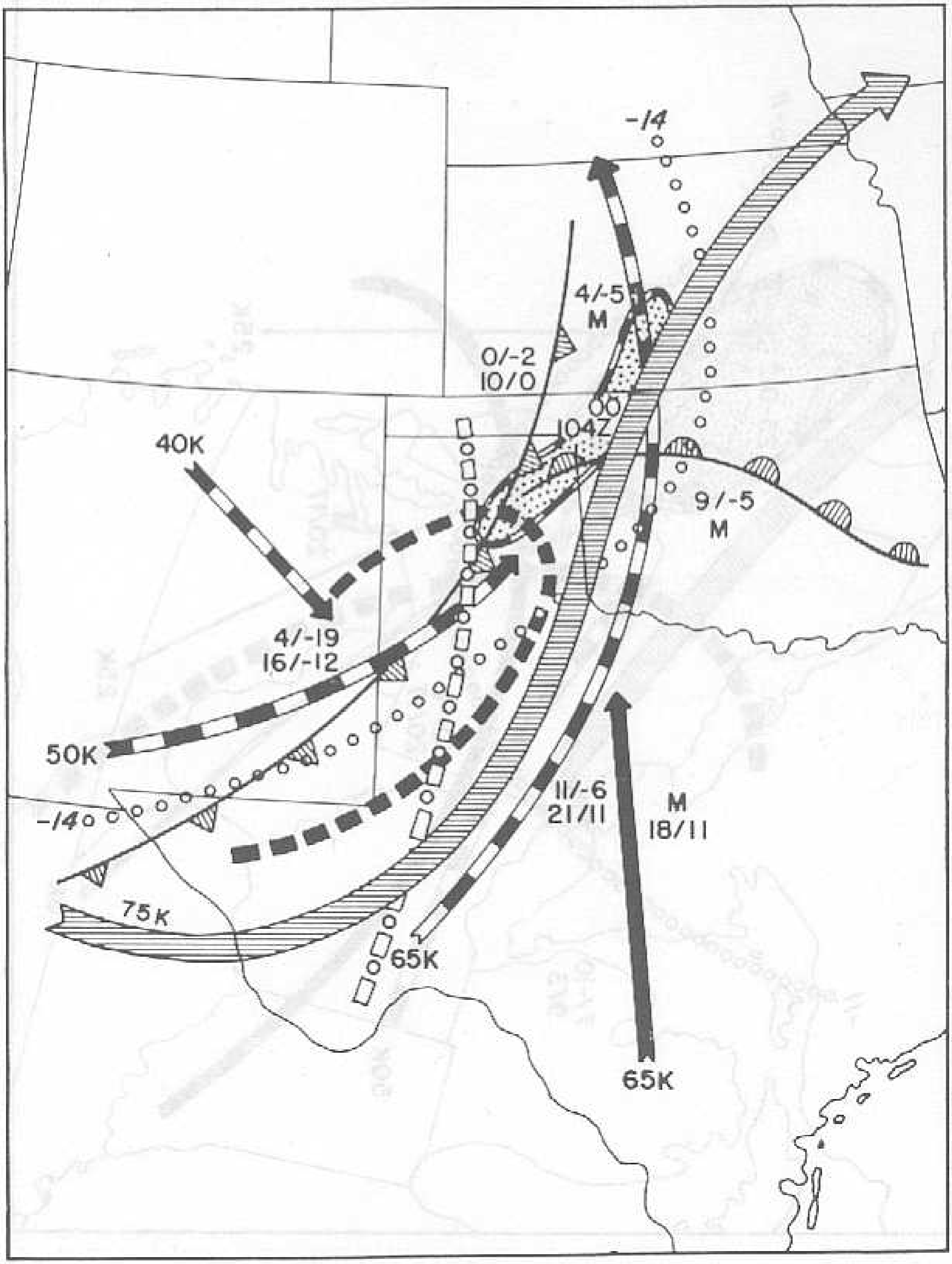

Figure 21. Examples of Type B pattern showing major features at 0300Z on 9 April 1947. Stippled area outlines locations of severe-weather occurrences.

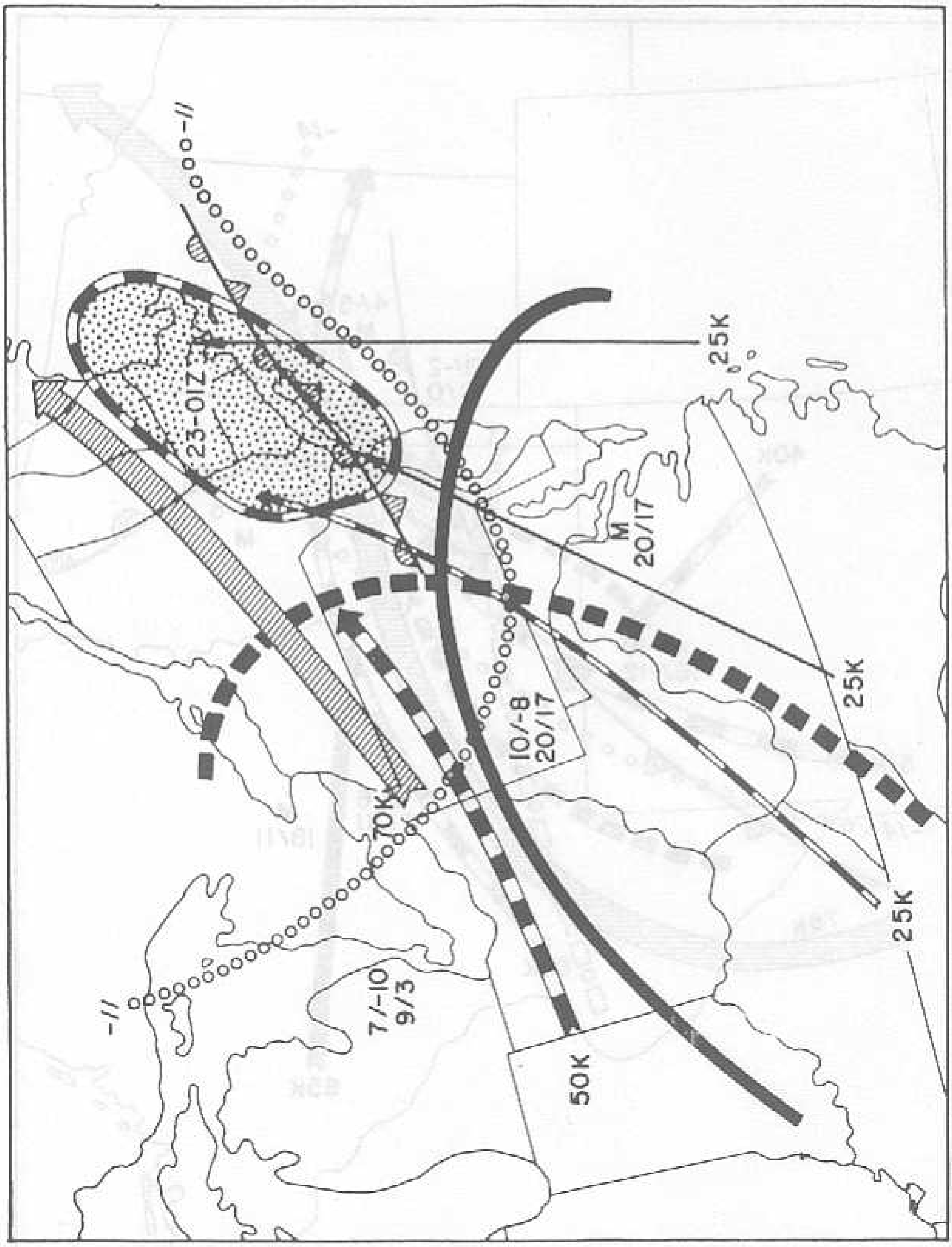

Figure 22. Examples of Type C pattern showing major features at 1500Z on 10 June 1953 ("M" means "Missing"). Stippled area outlines locations of severe weather occurrences.

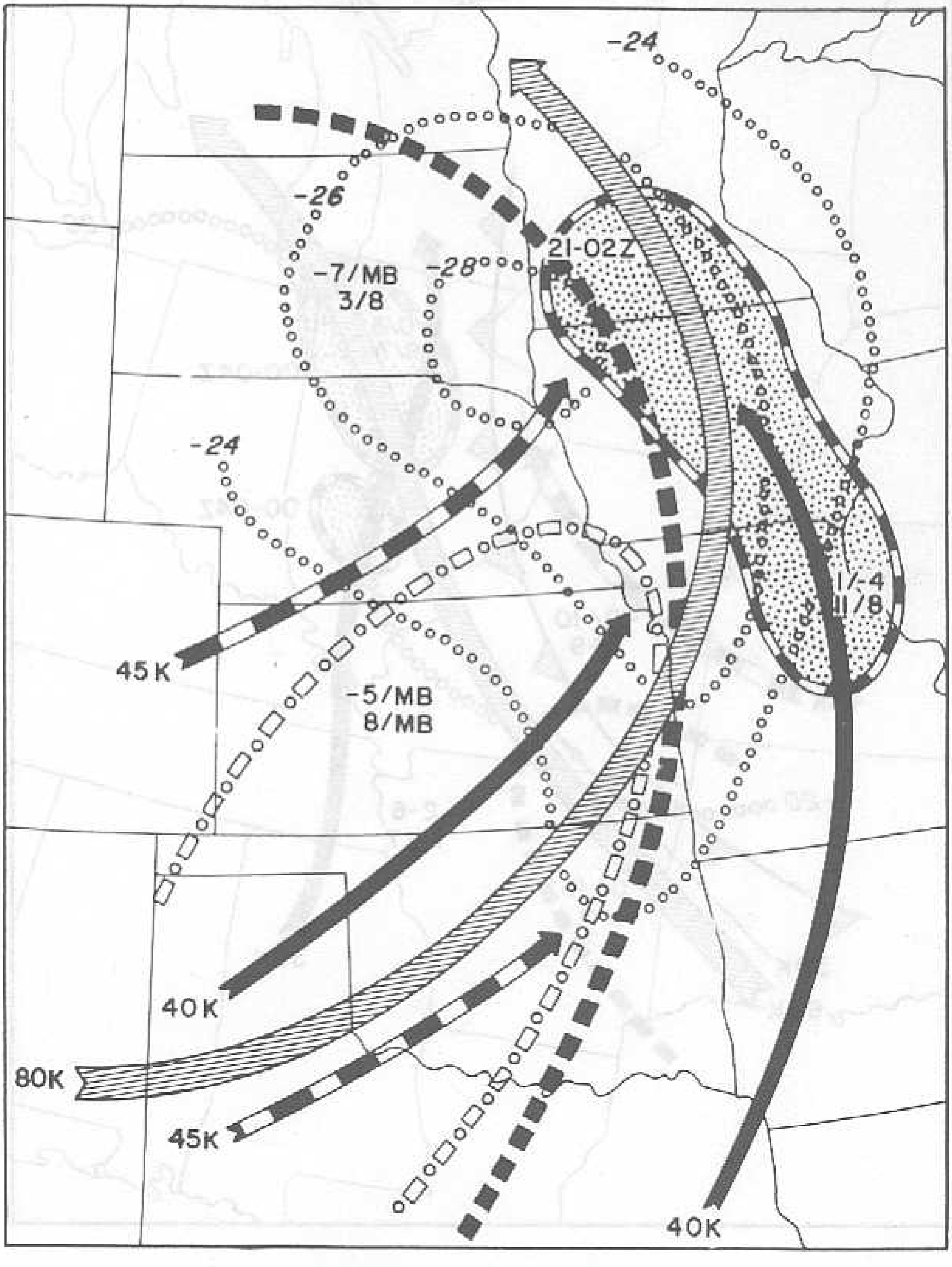

Figure 22. Example or Type D pattern showing major features at 1500Z on 4 April 1955. Stippled area outlines locations of severe-weather occurrences.

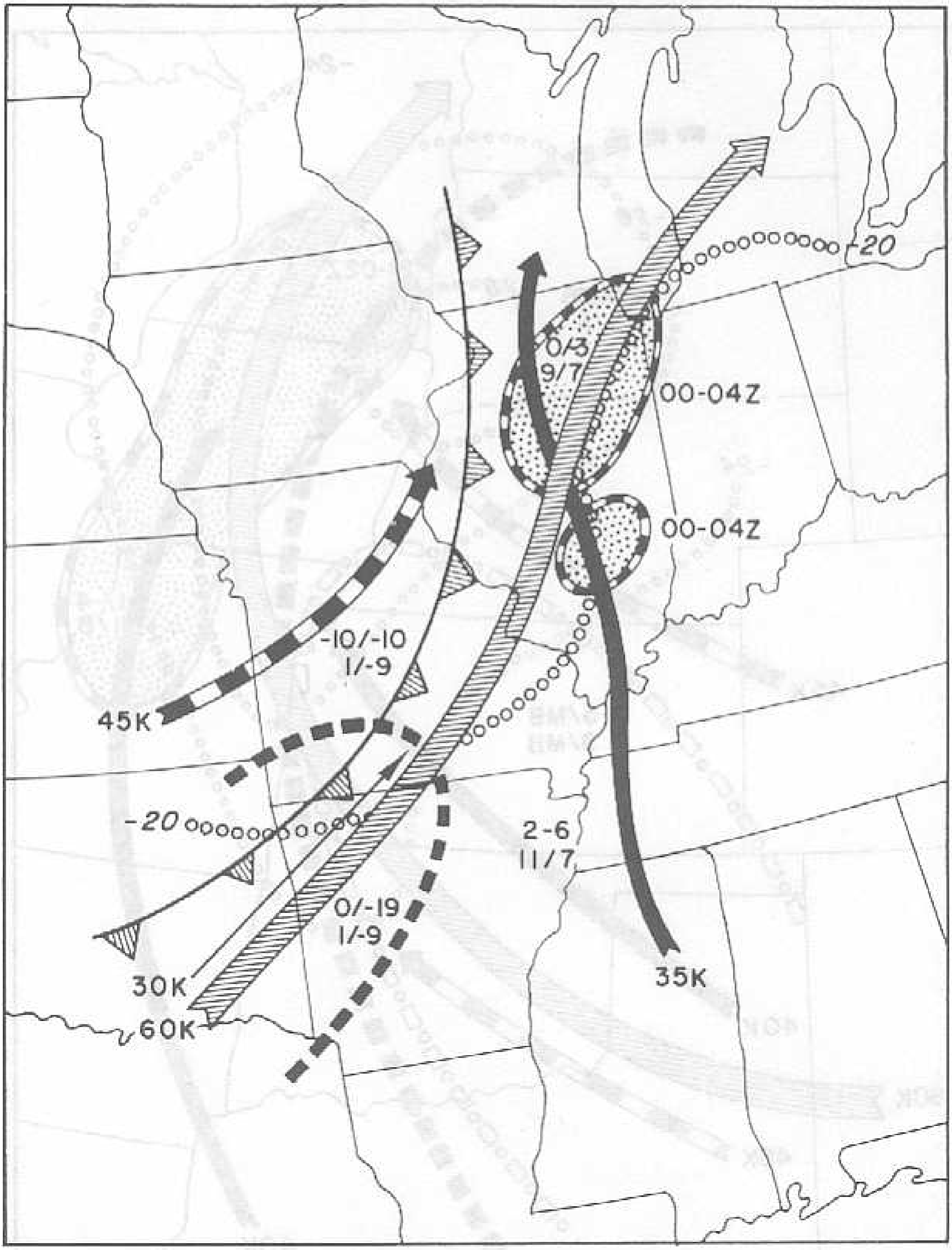

Figure 24. Example of Type E pattern showing significant features at 2100Z on 14 March 1957. Stippled area outlines locations of severe-weather occurrences.

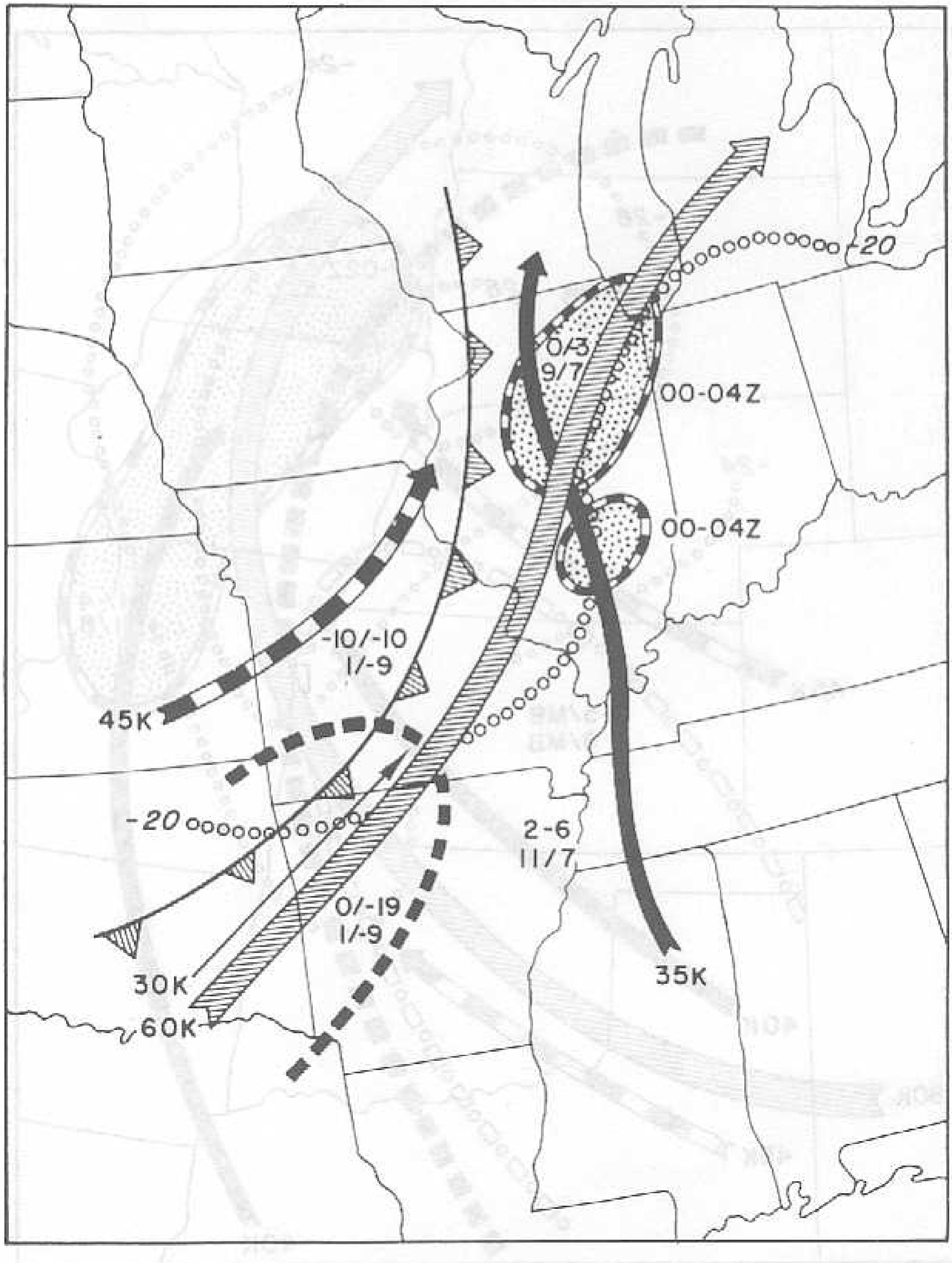

Figure 24. Example of Type E pattern showing significant features at 2100Z on 14 March 1957. Stippled area outlines locations of severe-weather occurrences.

San Angelo and moved NNE under the 50 knot, 700-mb flow. The eastward progress in Texas was limited by a northward movement of the main low into Minnesota. Severe Type B storms occurred again the next day in Texas, southwest Oklahoma, and Missouri, in connection with the eastward movement of the primary upper trough. The remaining figures (Figure 20 through 24) are other examples of the Type B, C, D, and E synoptic situations.