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AIR WEATHER SERVICE



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



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13 ABSTRACT

This is a revision of AWSTR 200 issued in July 1967.

This collection of notes discusses the various types of severe-weather air masses, how severe weather systems form, which parameters best define the existence and intensity of severe weather, and how to use local information to better forecast the occurrence of phenomena at individual stations. Specifically, wind gust and hailsize forecasting techniques and the usefulness of various stability indexes are presented. Also, a chapter on severe weather in tropical air masses is included. A number of detailed case studies are in the report to help the reader visualize how forecasting concepts are applied, and to emphasize the importance of forecasting experience. The revised material concentrates on the application of computer-derived aids to severe weather forecasting produced by the Air Force Global Weather Central. Foremost among these aids are analyses and prognoses of the Severe Weather Threat (SWEAT) Index.

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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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March 1972

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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.

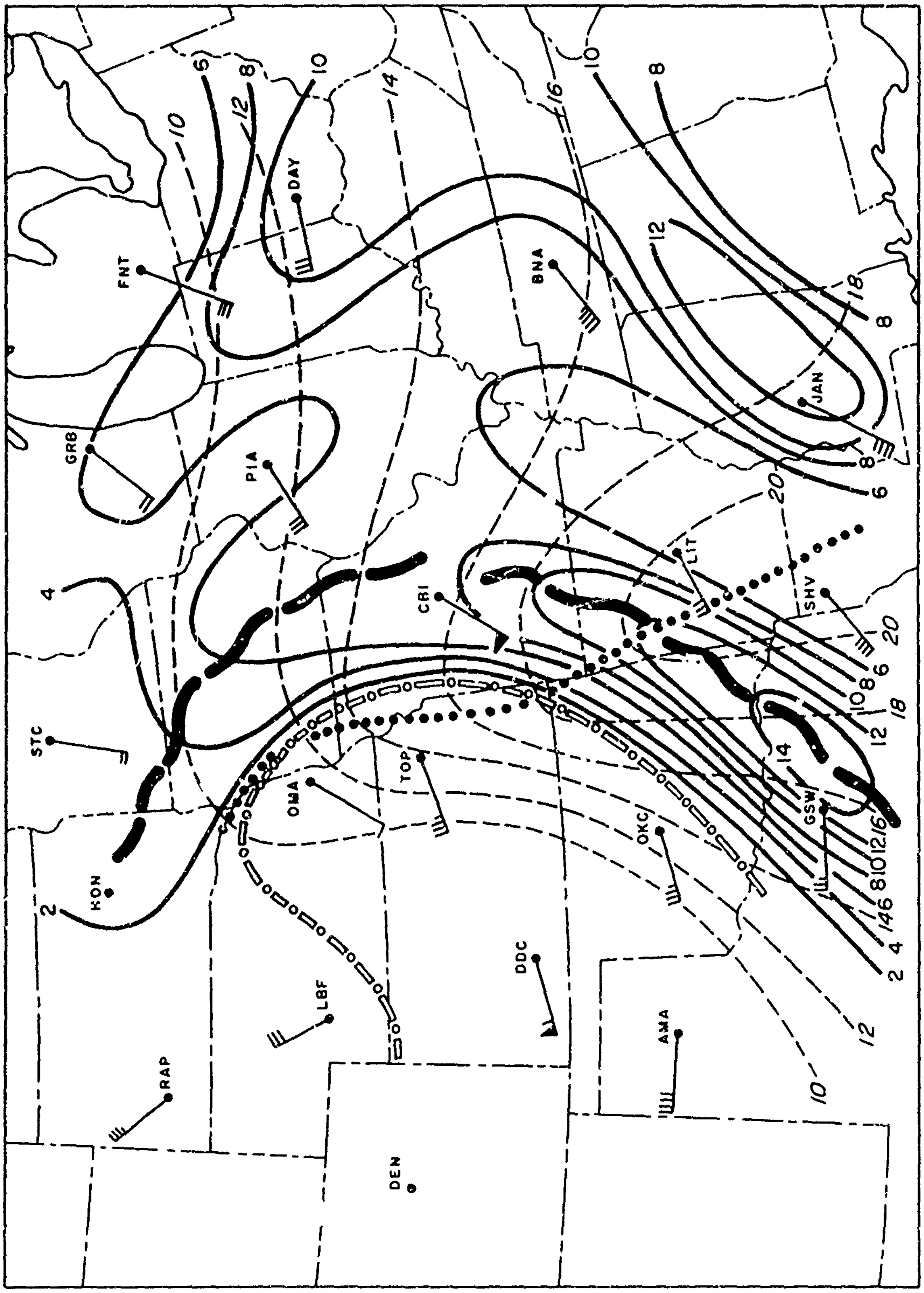



Figure 1 Major features of the 850-mb analysis

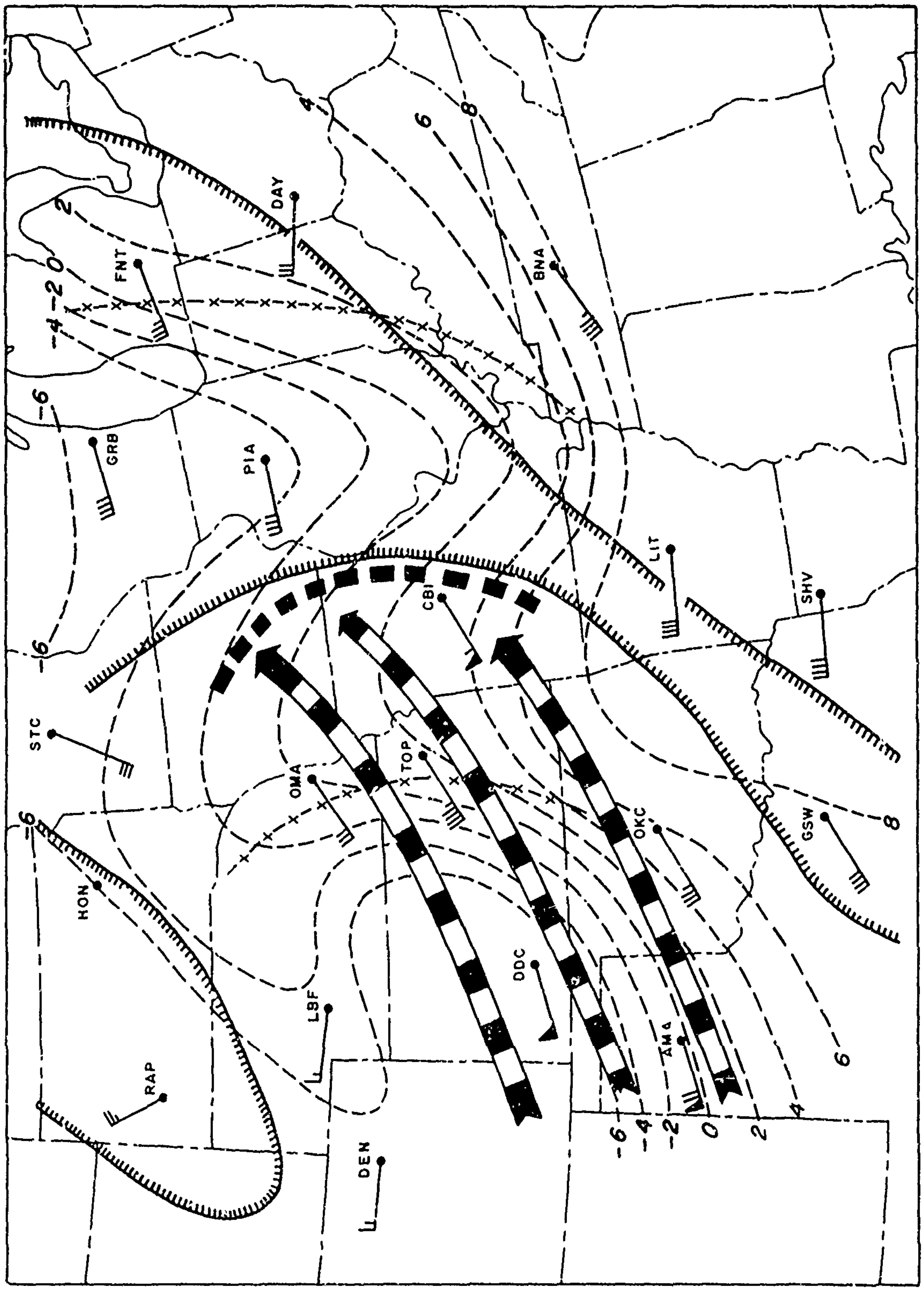



Figure 2. Major features of the 700-mb analysis

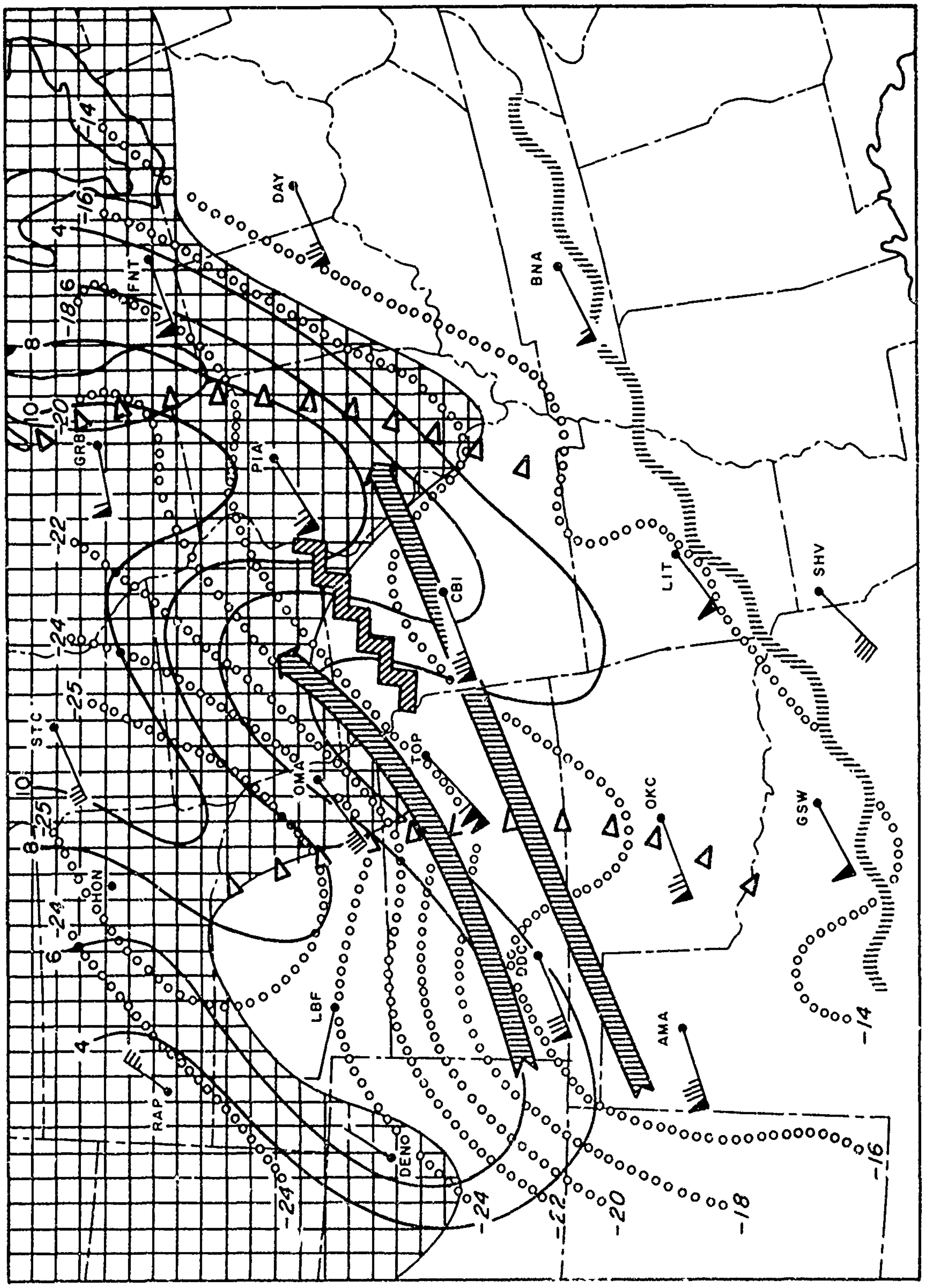



Figure 3. Major features of the 500-mb analysis

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.

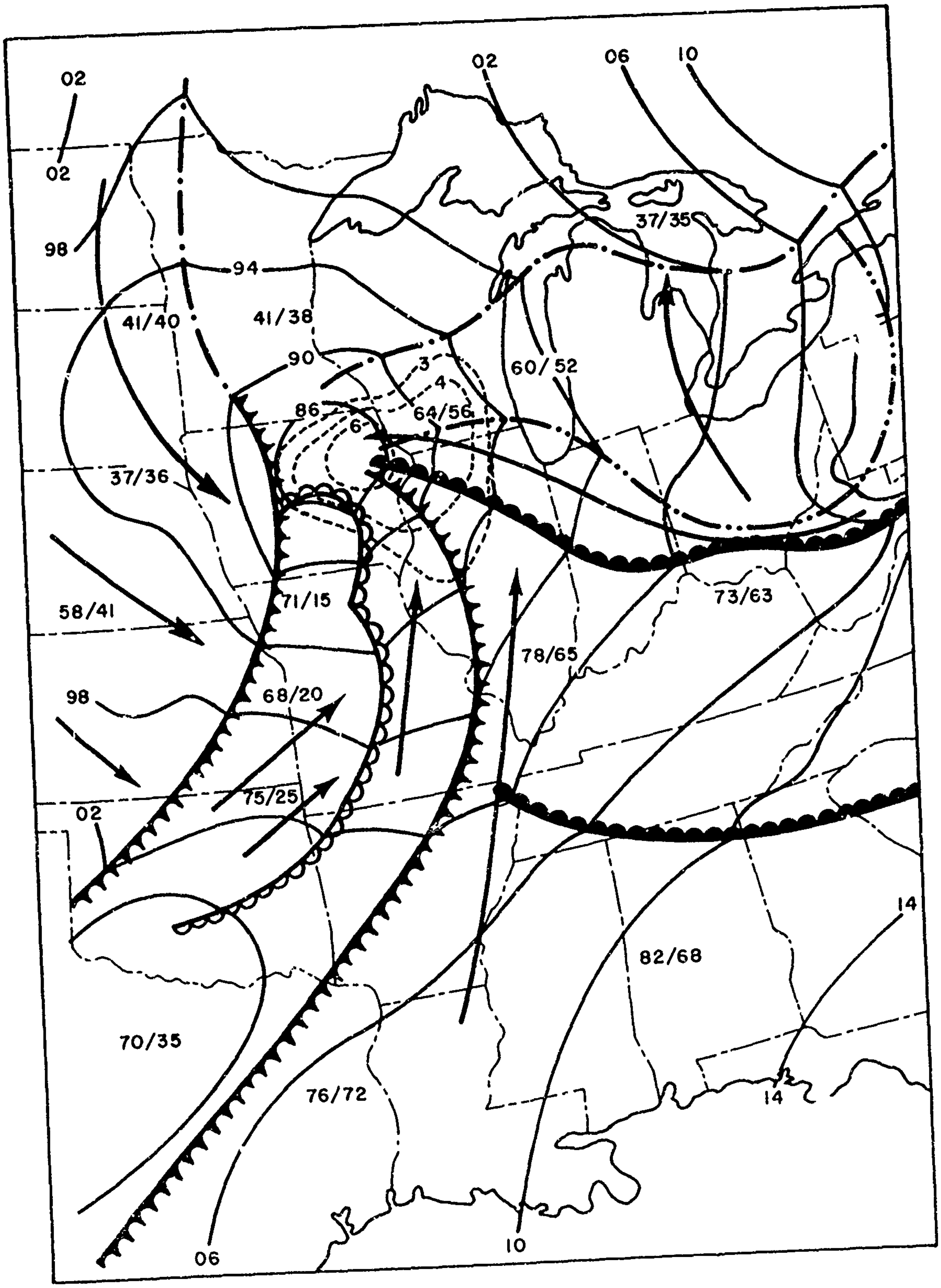



Figure 4. Surface analysis showing air-mass differentiation, the low-level flow and the area of maximum pressure falls

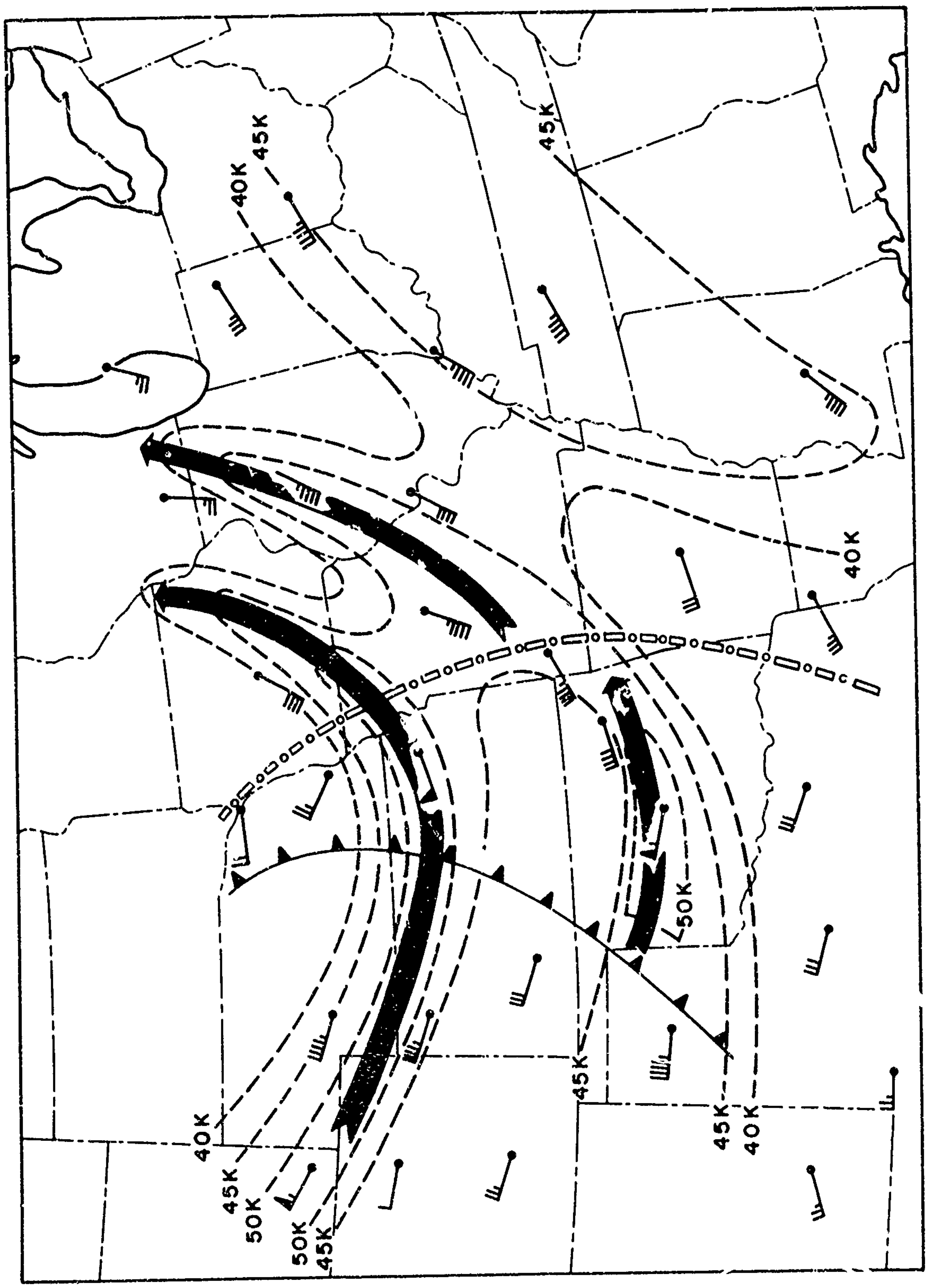



Figure 5. Maximum wind analysis for the lower 5,000 feet

## 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,

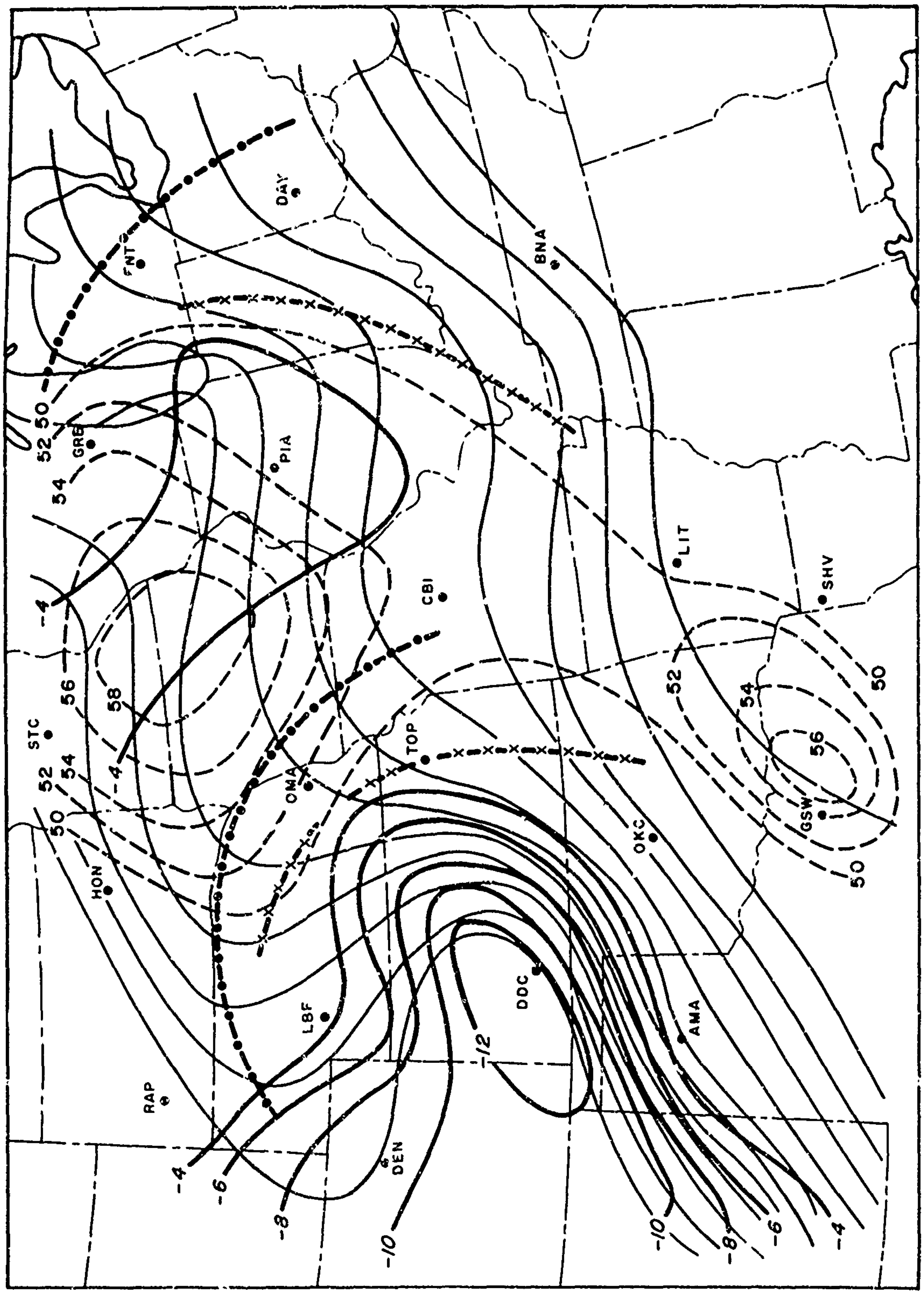



Figure 6. Major features of the thickness analysis showing Total Totals analysis and 12-hr thickness changes

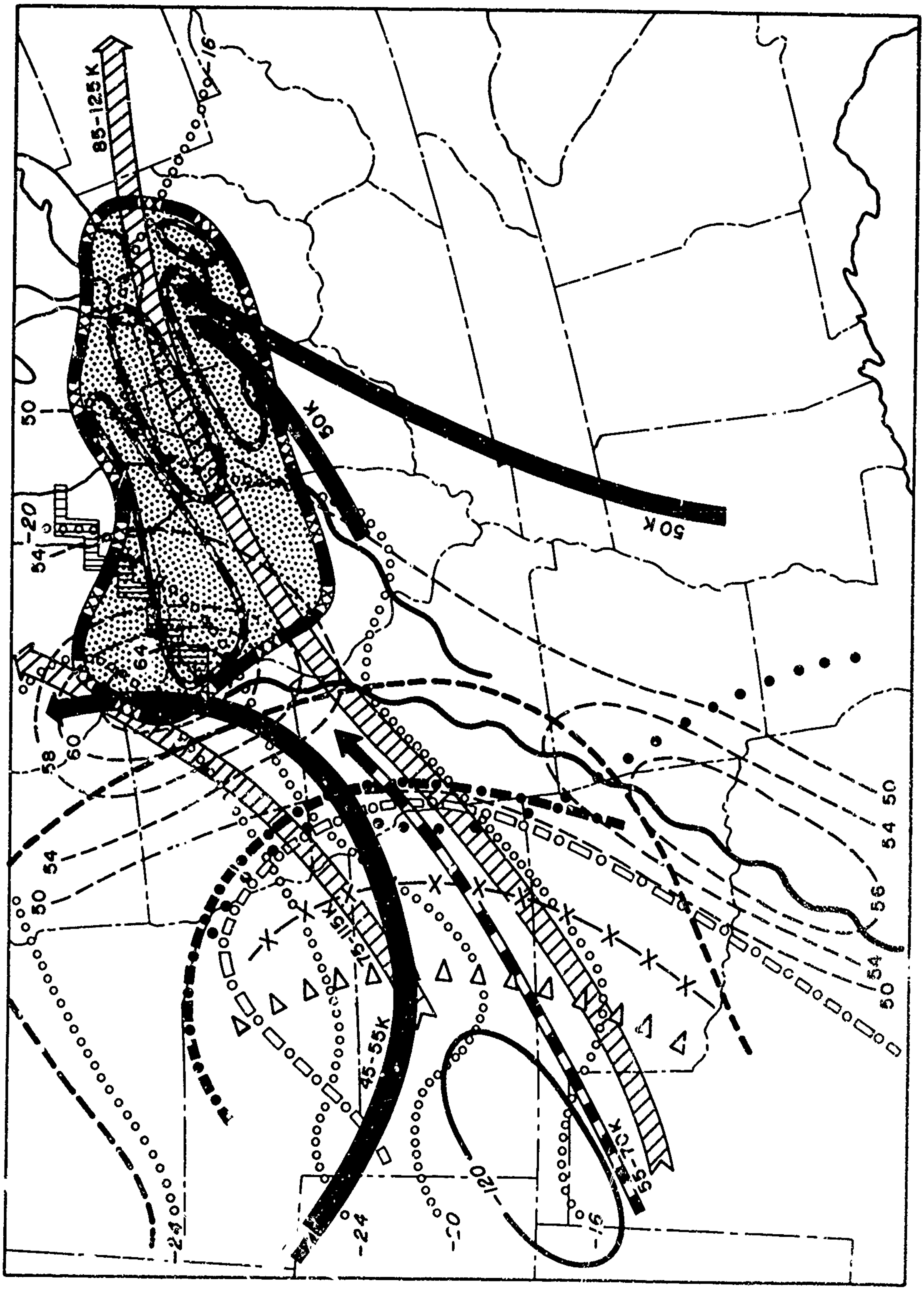



Figure 7. Composite Chart showing most significant features found during analysis

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

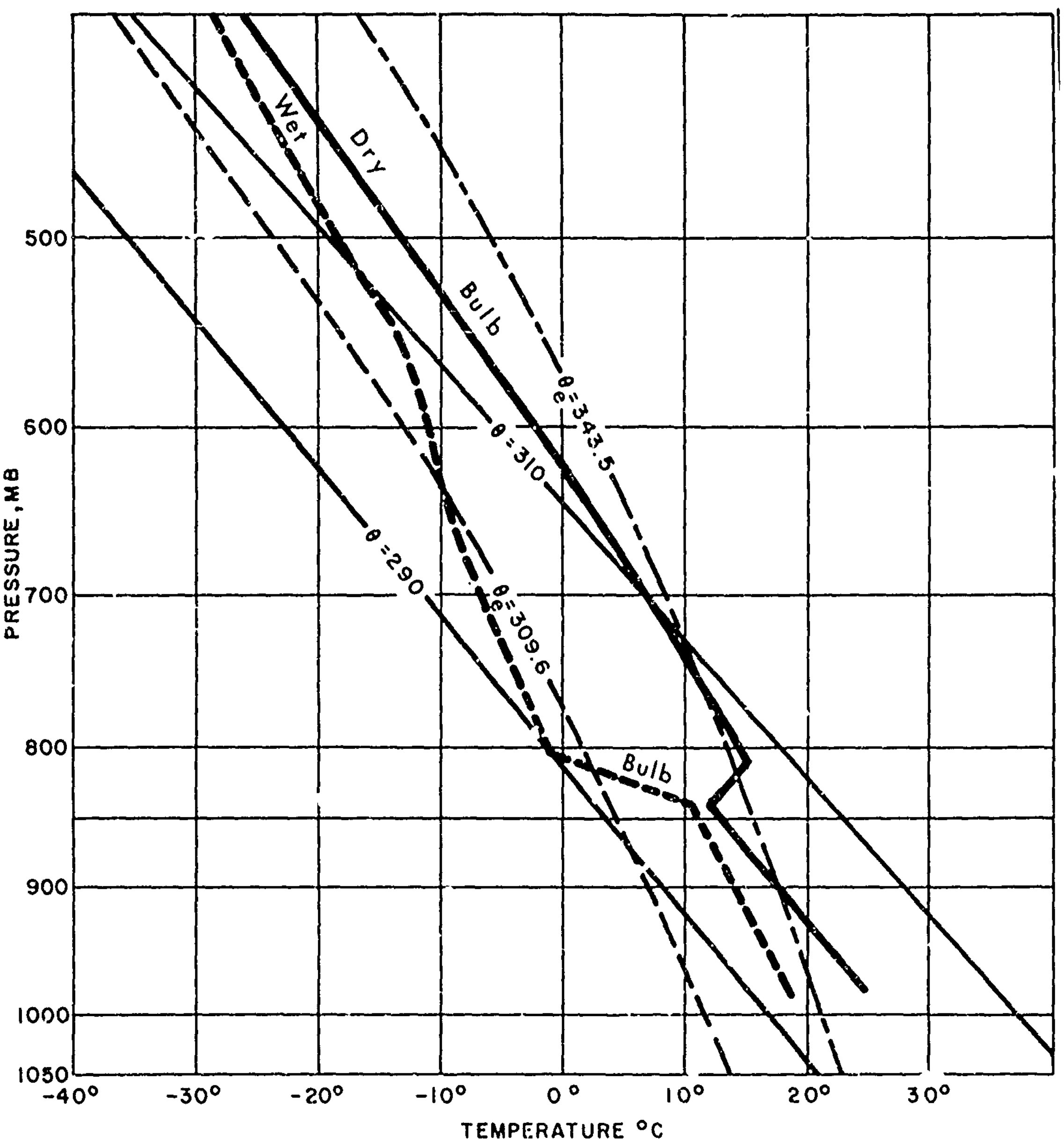



Figure 8 Mean Sounding of Type I Tornado Air Mass

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 40 mb 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.

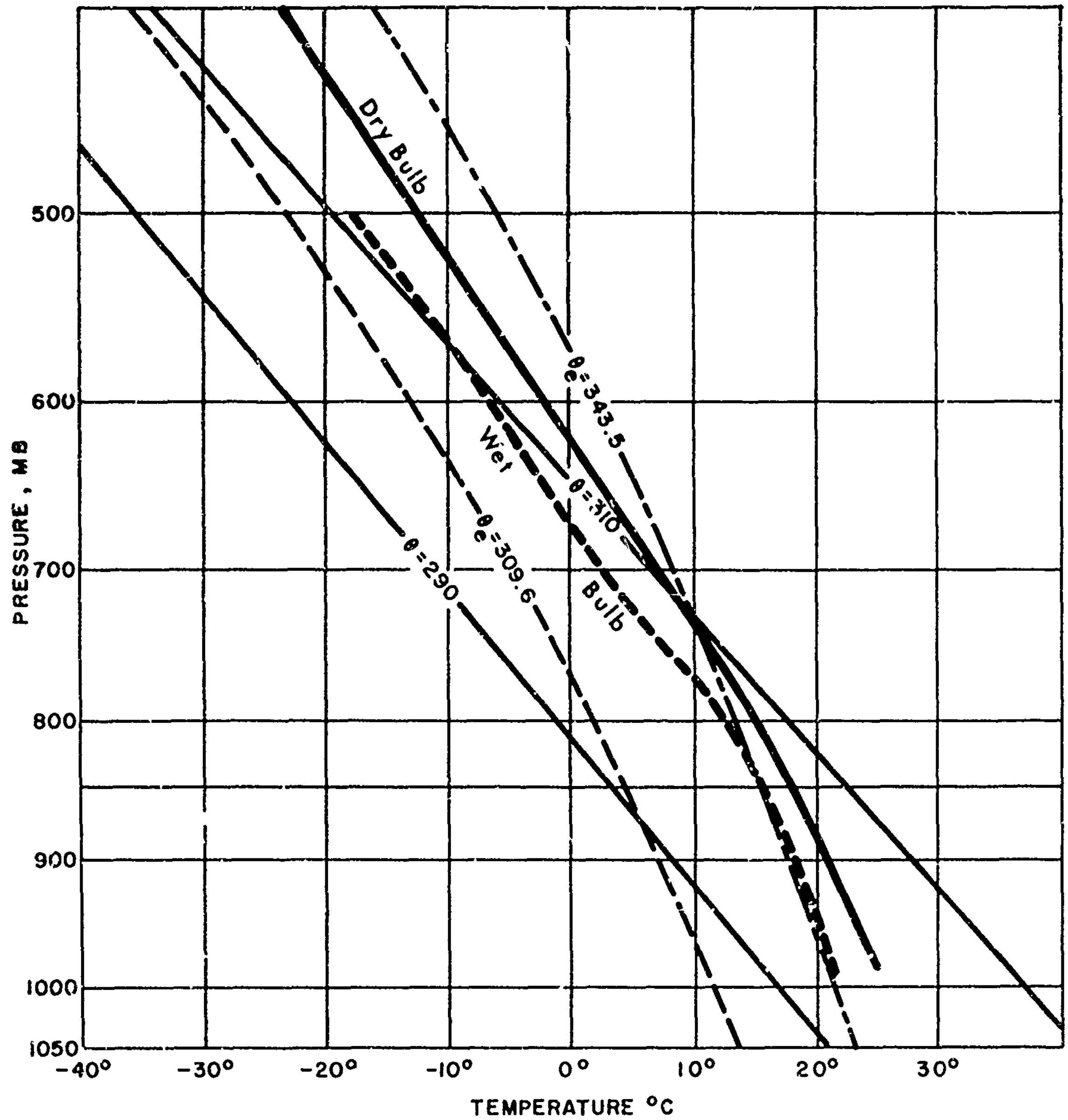



Figure 9. Mean Sounding of Type II Tornado Air Mass

## 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.

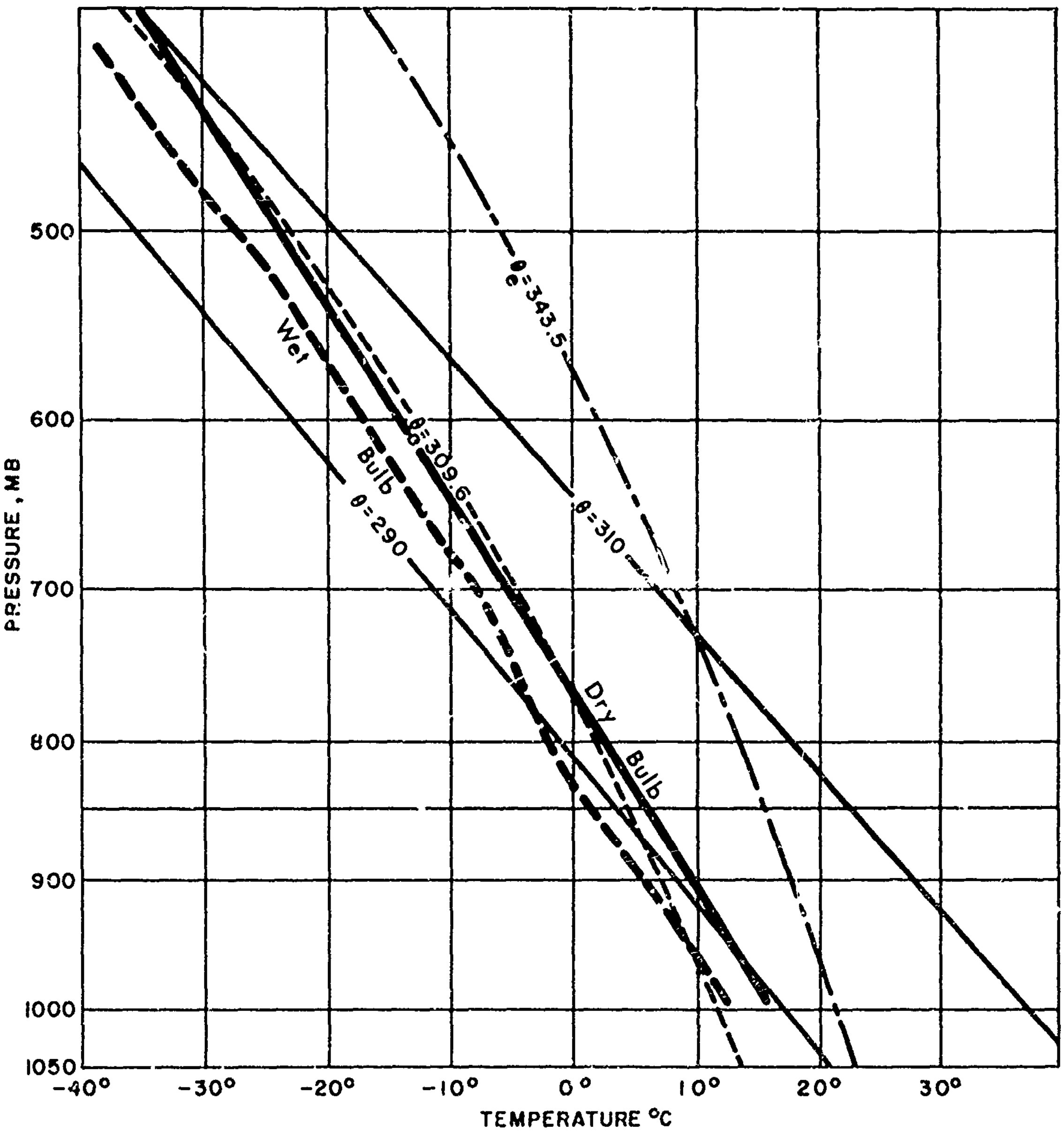



Figure 10. Mean sounding of Type III Tornado Air Mass

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

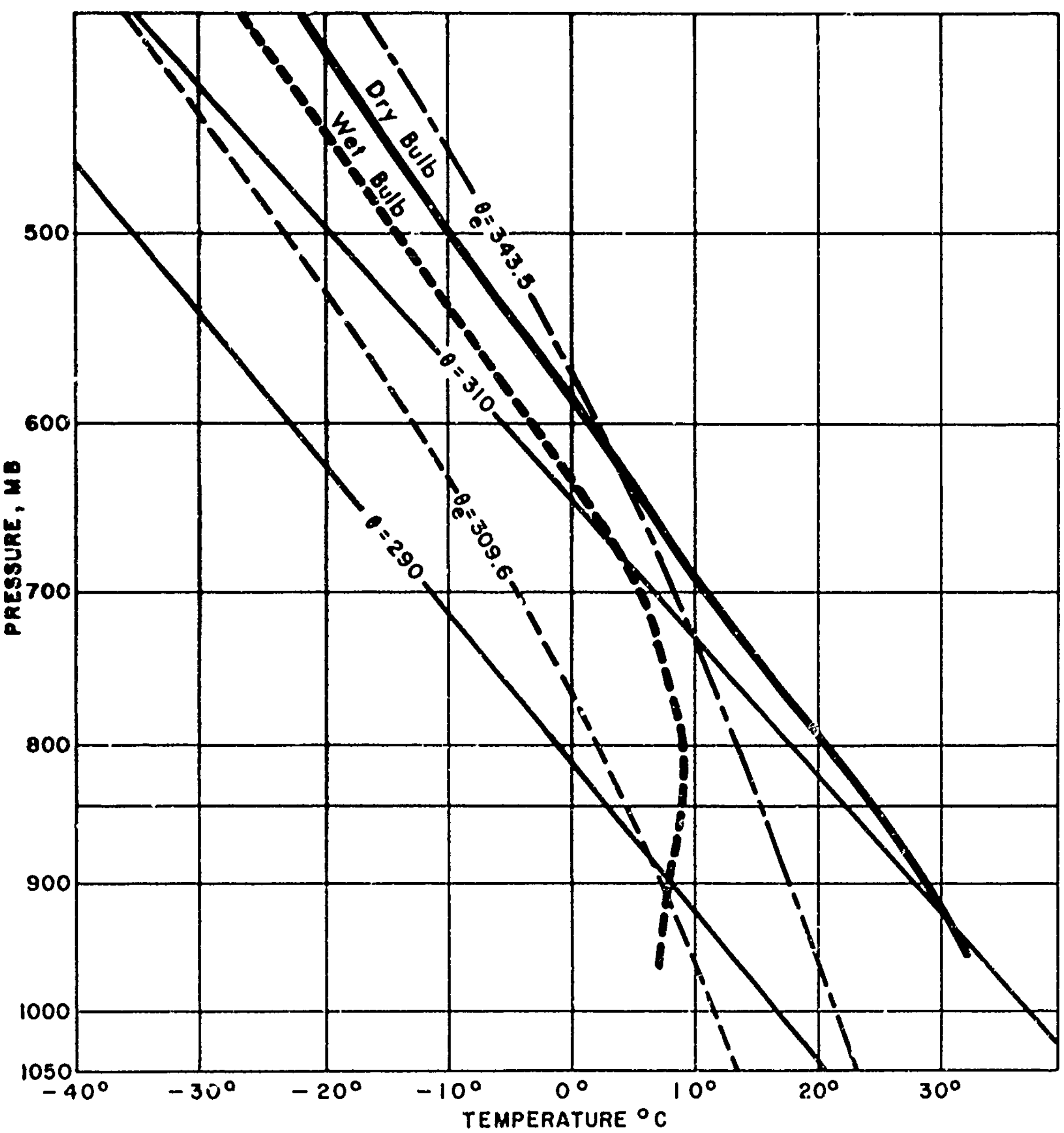



Figure 11. Mean sounding of Type IV Tornado Air Mass

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

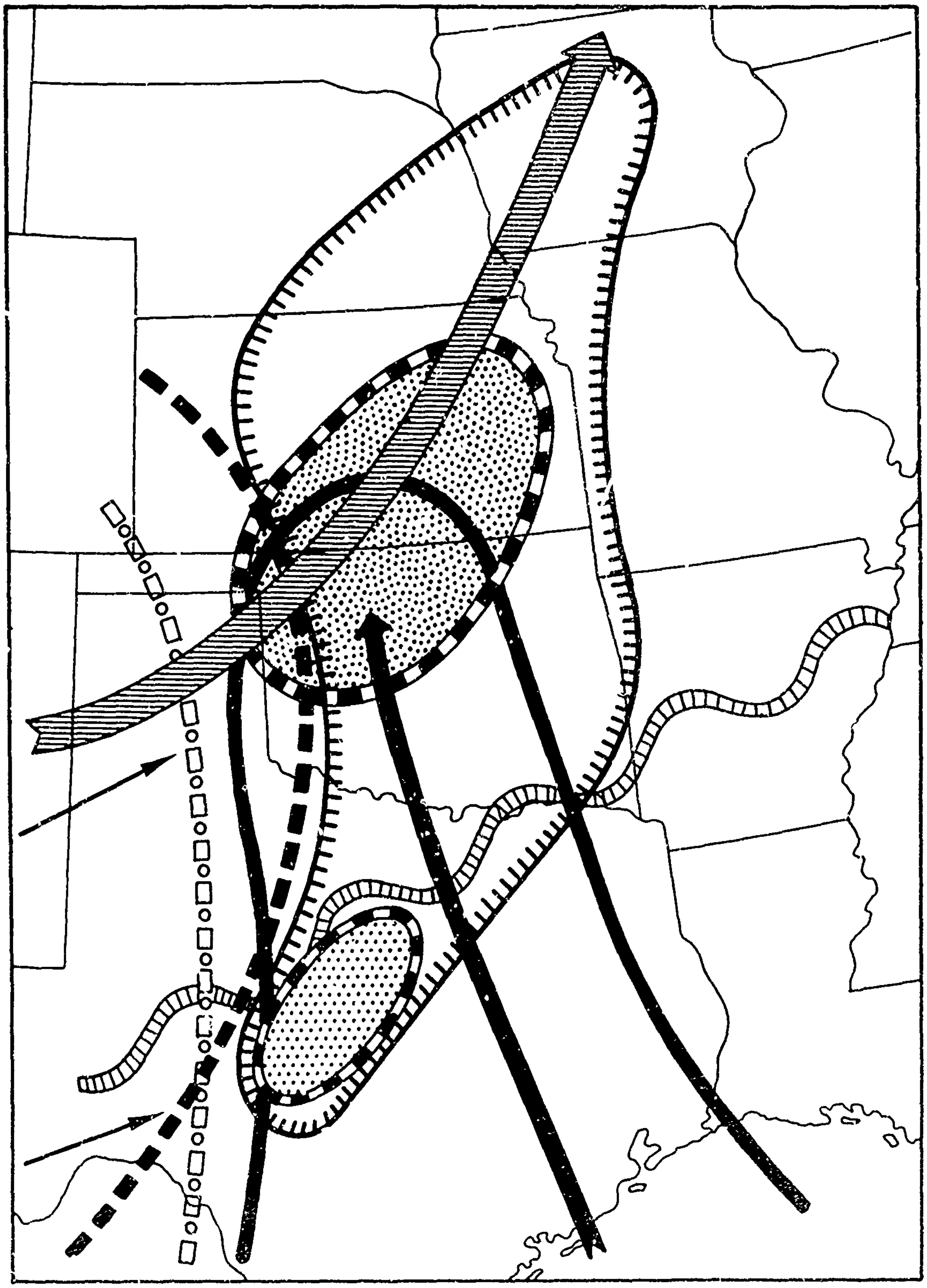


Figure 12. The Type A tornado-producing synoptic pattern
Stippled area outlines location of s ere-weather occurrences.

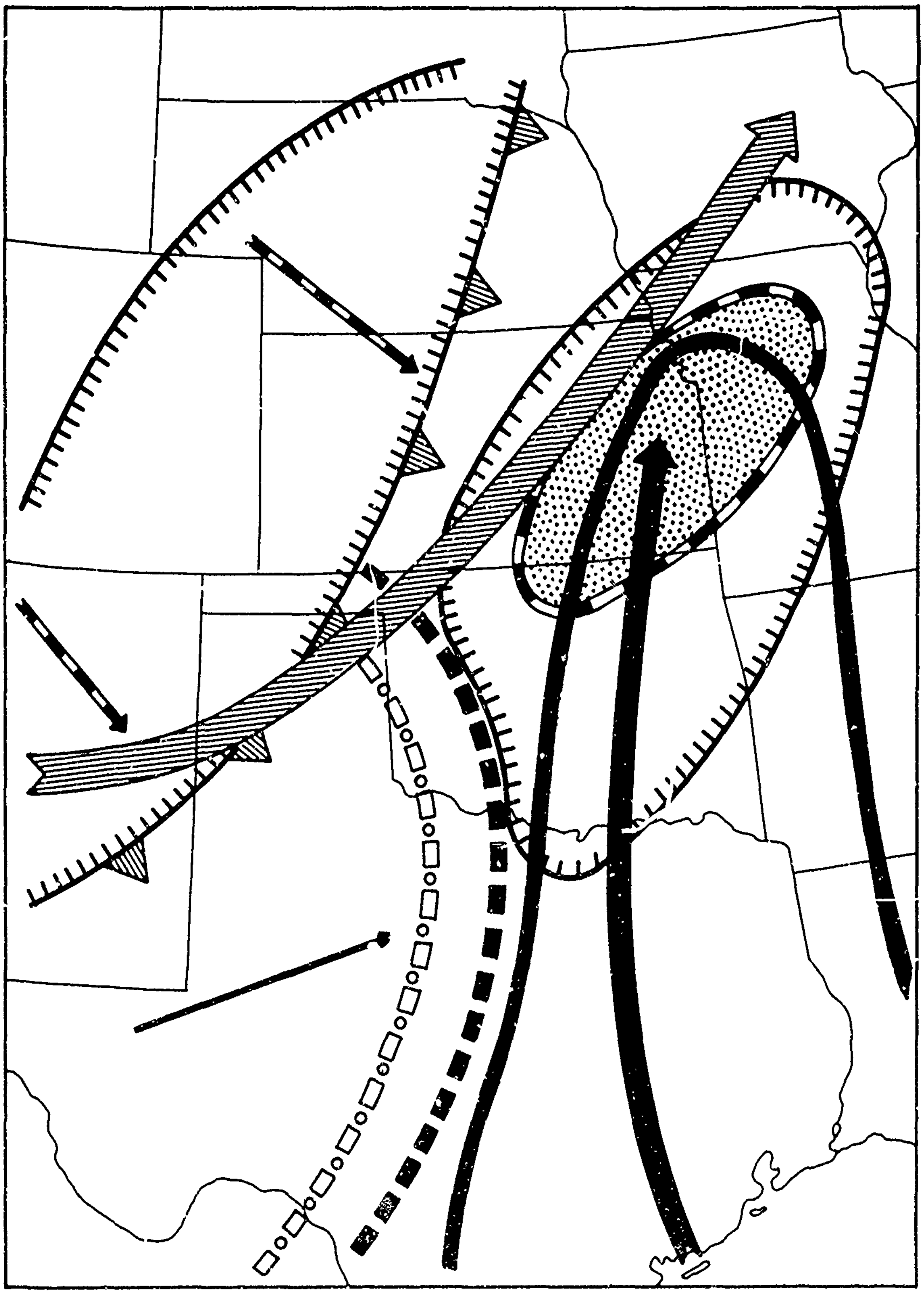


Figure 13. The Type B tornado-producing synoptic pattern. Stippled area outlines locations of severe-weather occurrences.

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 ntinue 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- el shear, the stationary surface front, the axis maximum overrunning (determined by the rongest low-level flow) and the strength and ition of the dry-air intrusion. In practice, the ern boundary of the most severe area will be ab 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.

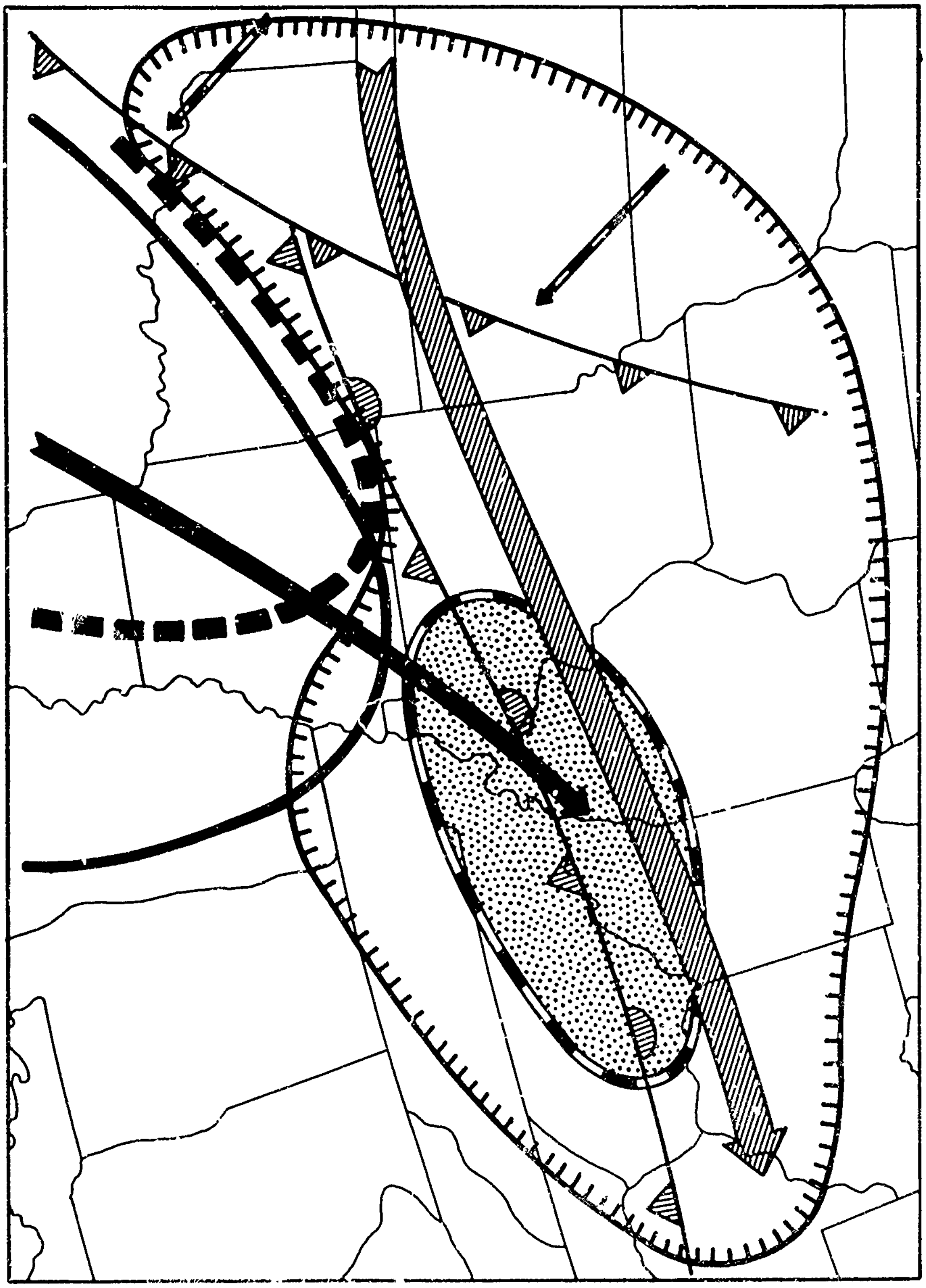


Figure 14. The Type C tornado-producing synoptic pattern. Stippled area outlines locations of severe-weather occurences.

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.

## SECT F—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

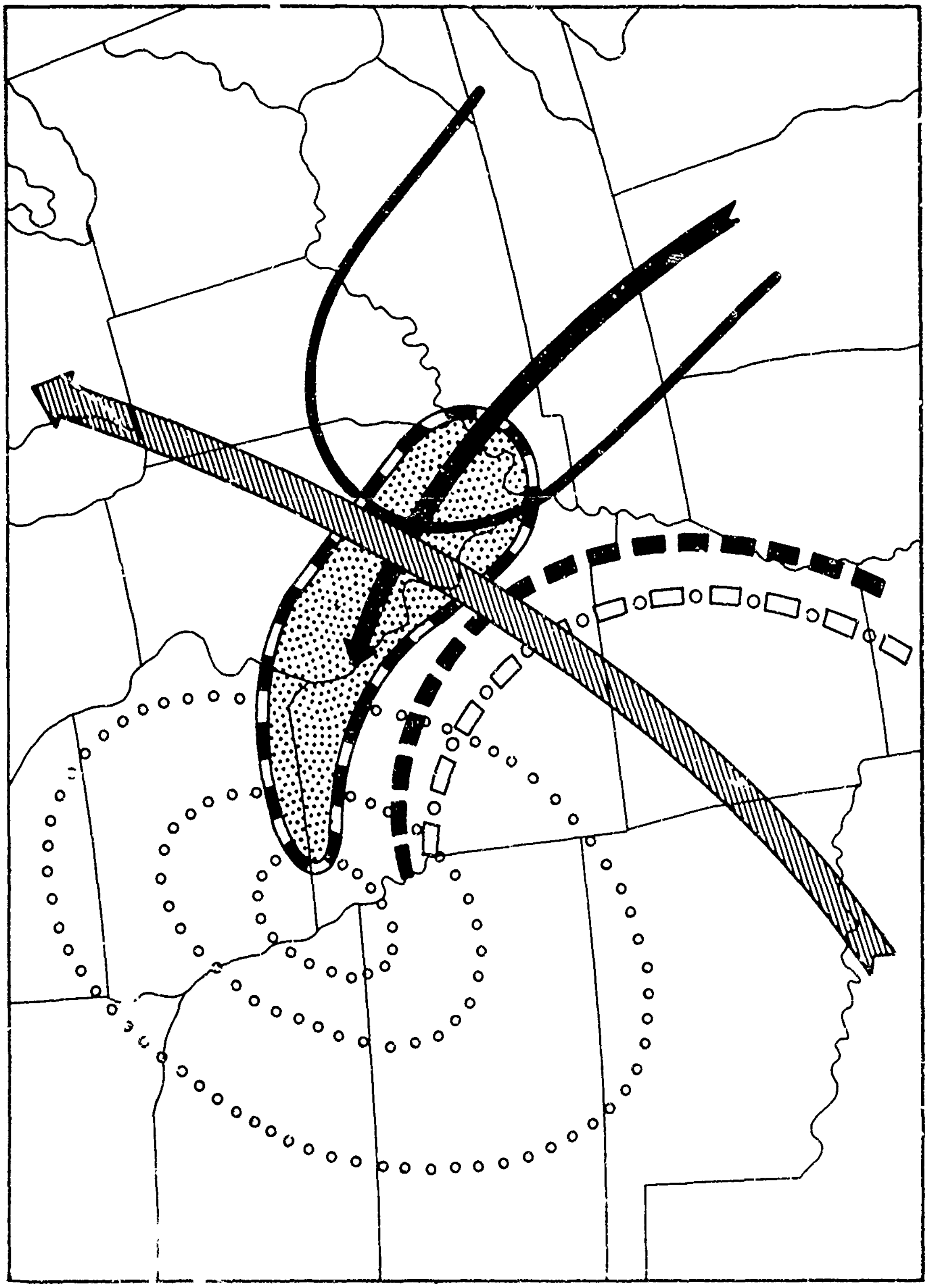


Figure 15 The Type D tornado producing synoptic pattern Stippled area outlines locations of severe weather occurrences

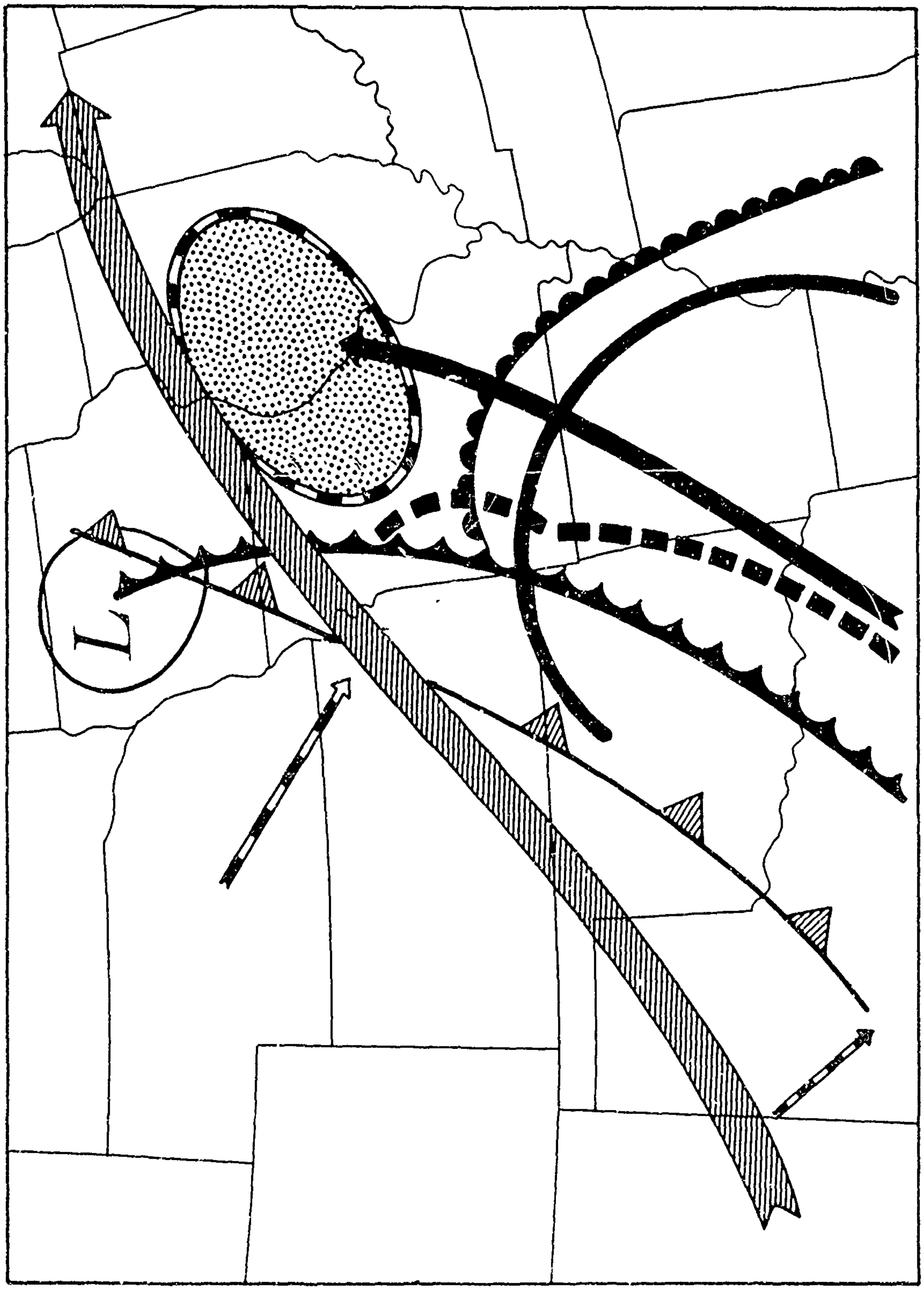



Figure 16 The Type E tornado producing synoptic pattern Stippled area outlines locations of severe weather occurrences

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

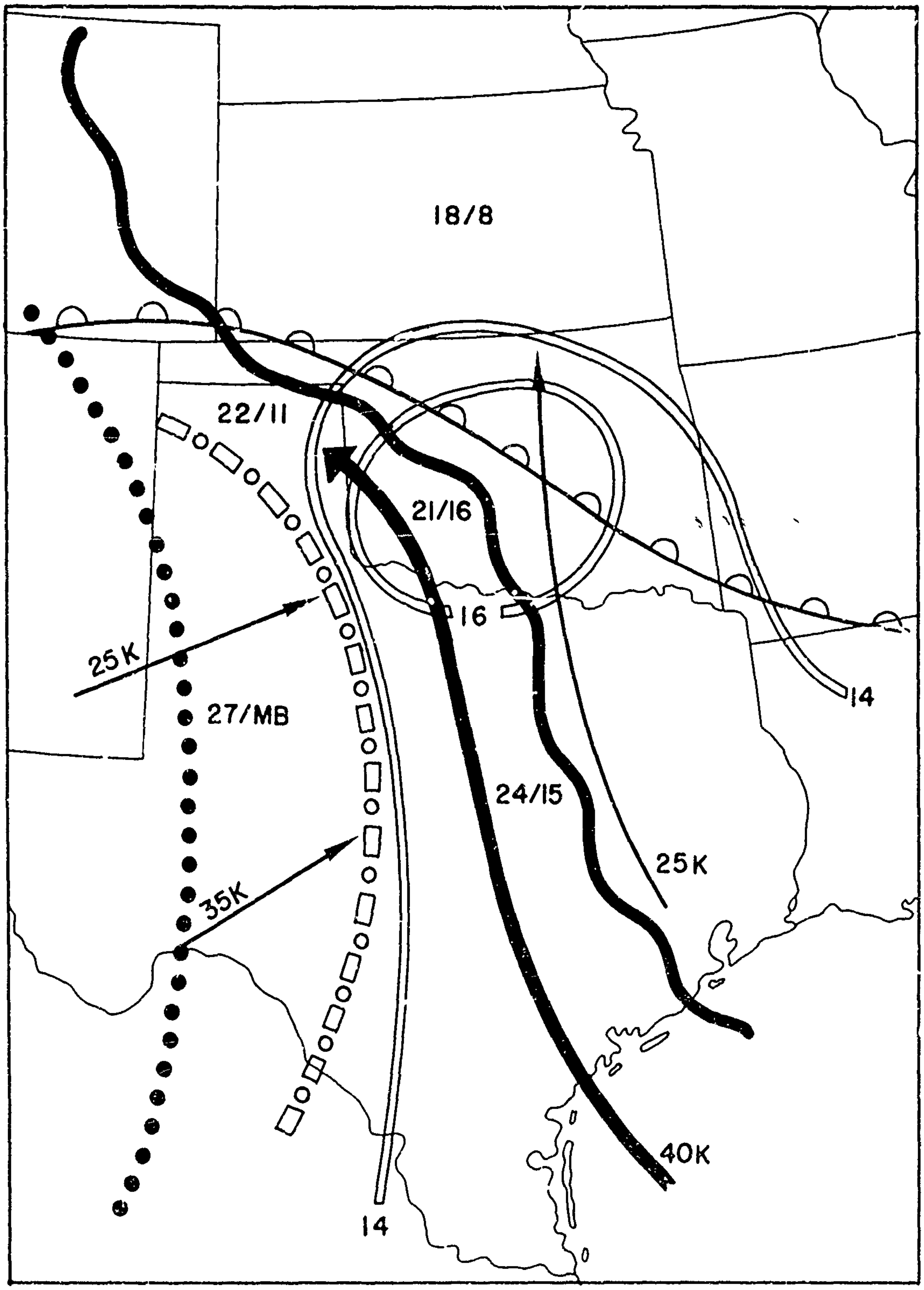



Figure 17 Significant 850-mb data at 2100Z on 25 May 1955

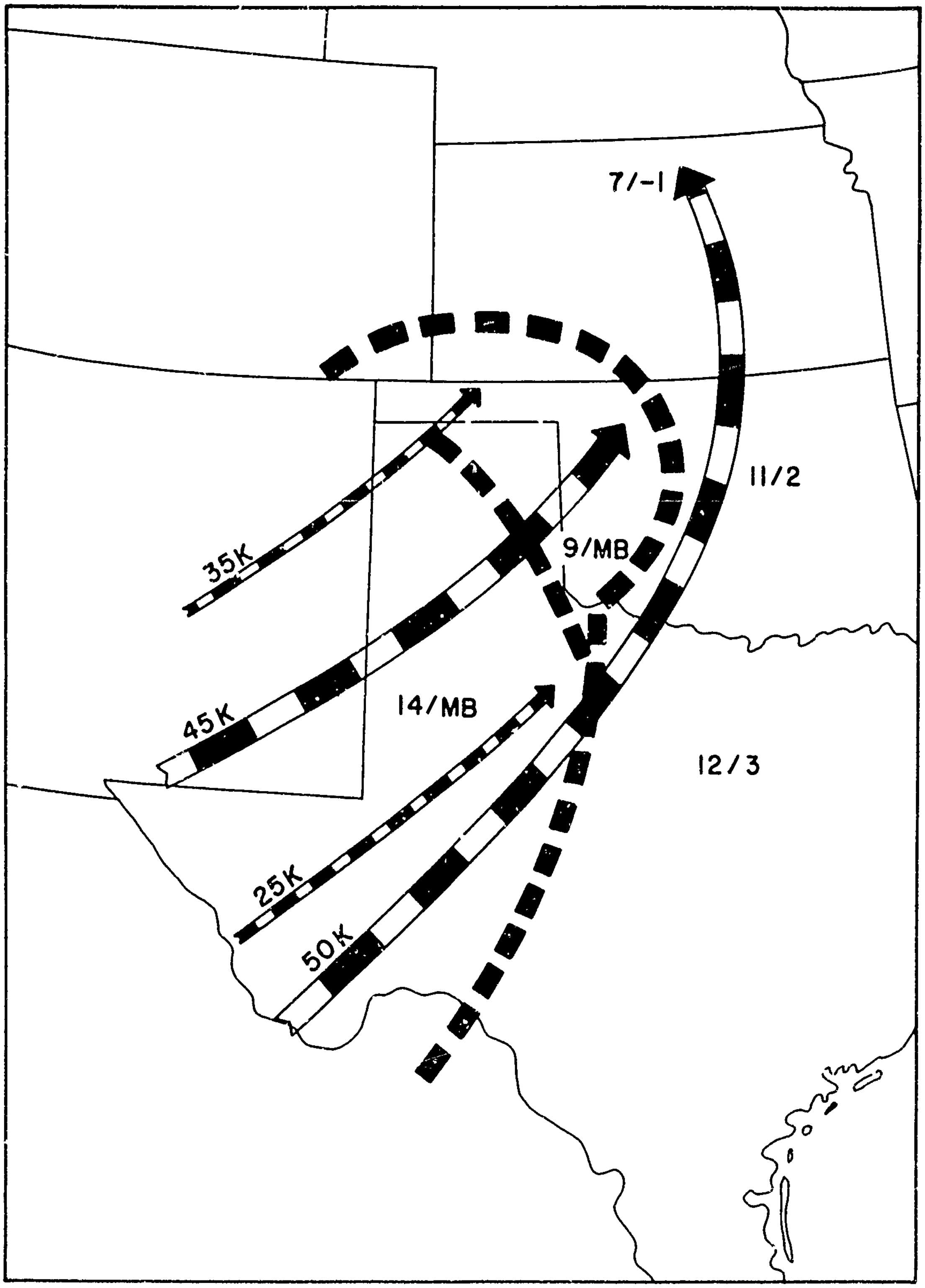



Figure 18 Significant 700-mb features at 2100Z on 25 May 1955.

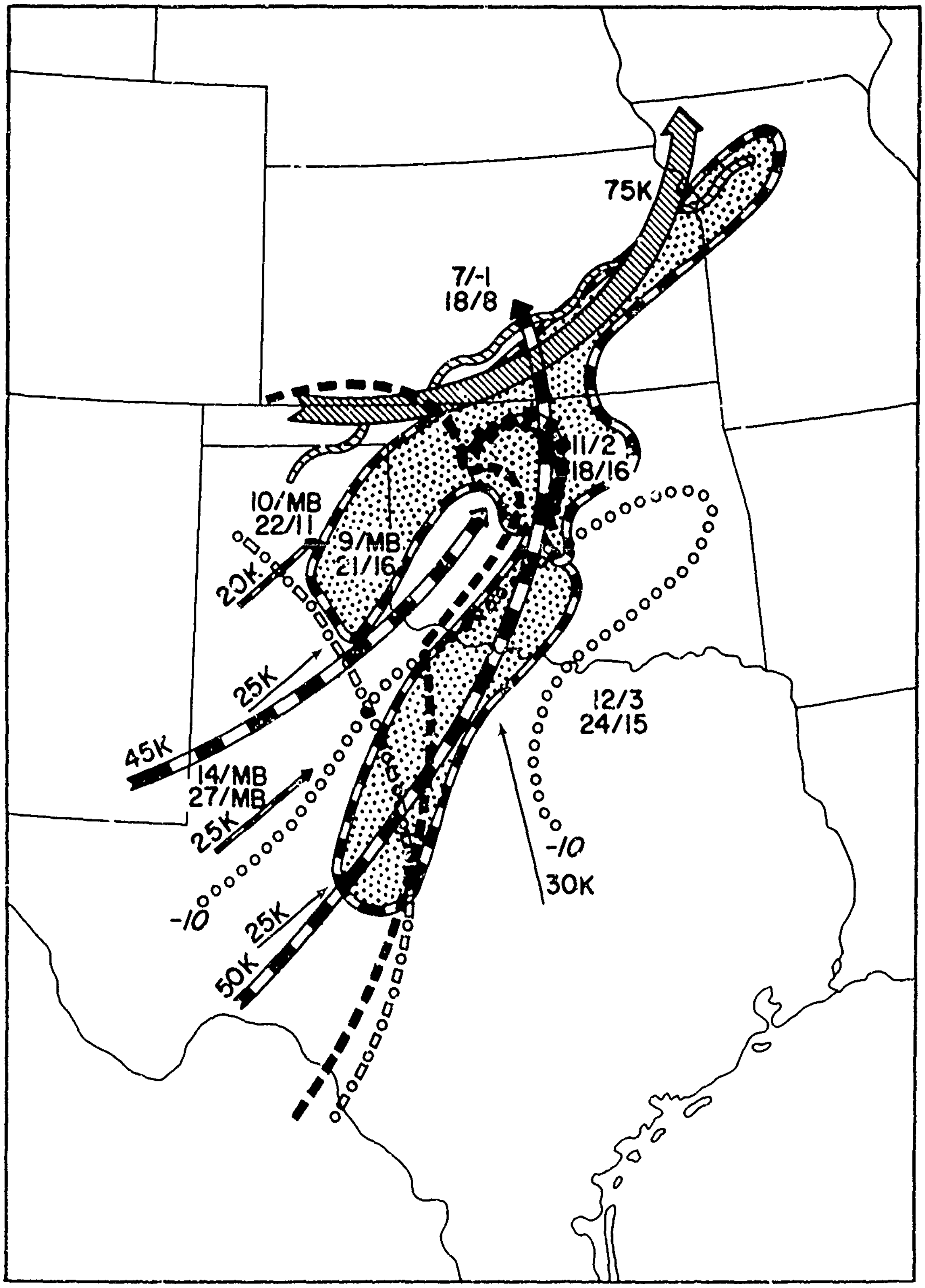



Figure 19 Significant upper air features includinn Oklahoma State University radar echoes Echoes at 0210Z are a line of solid circles and the echoes at 0345Z are a line of solid squares Stippled area outlines locations of severe weater occurrences

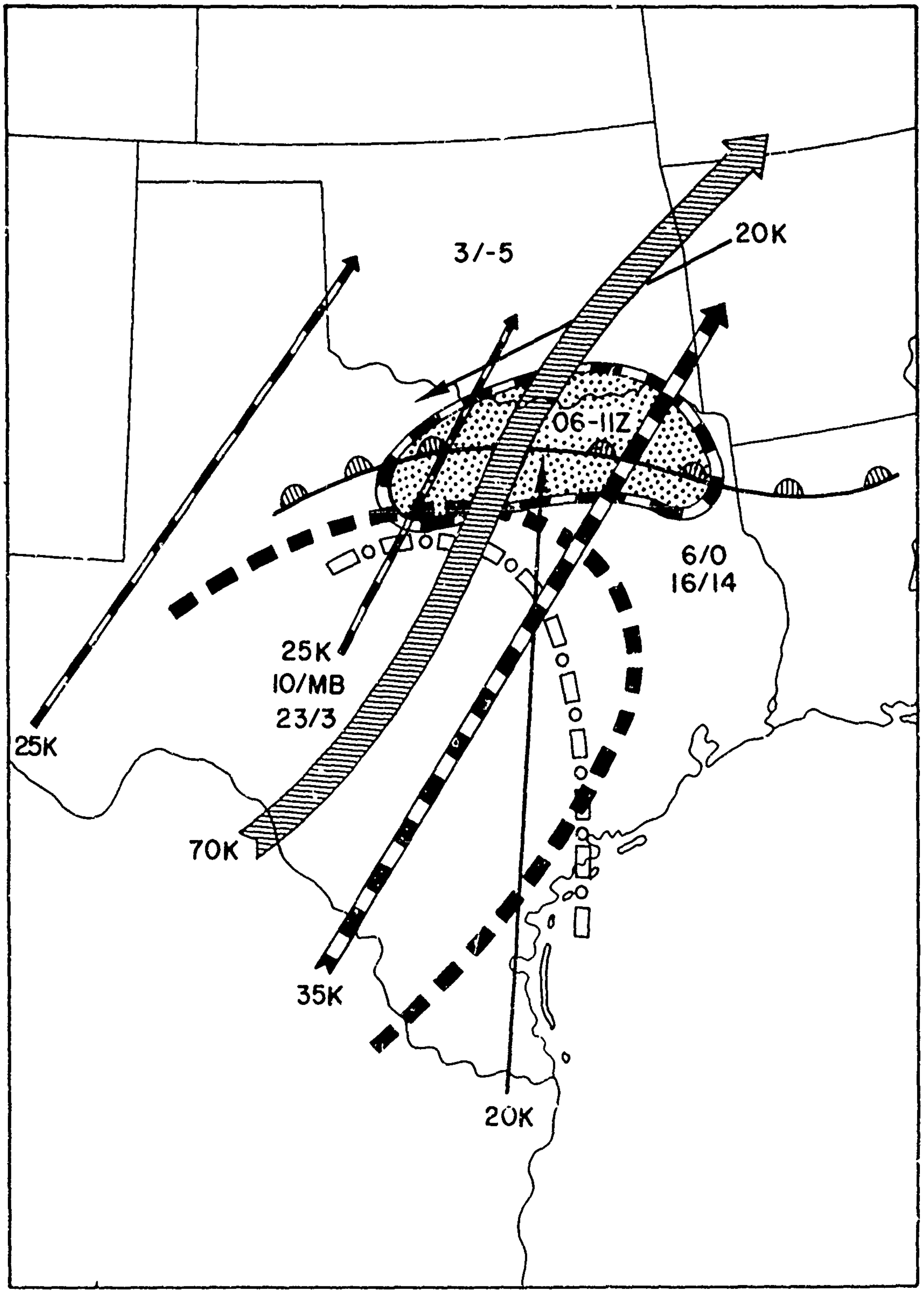



Figure 20 Example of Type A pattern showing major features at 0300Z on 6 April 1955 Stippled area outlines locations of severe weather occurrences

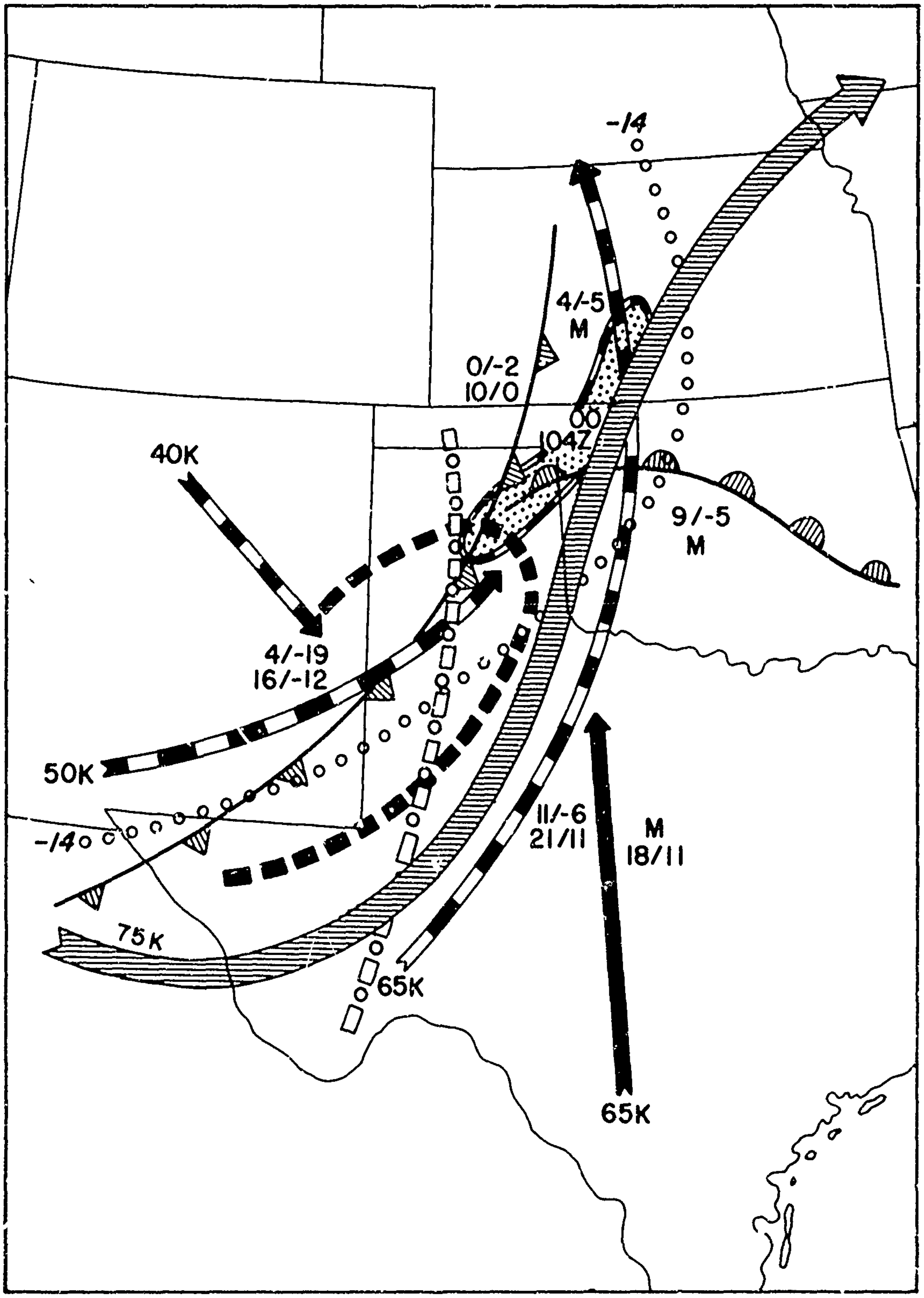



Figure 21 Examples of Type B pattern showing major features at 0300Z on 9 April 1947 Stippled area outlines locations of severe weather occurrences

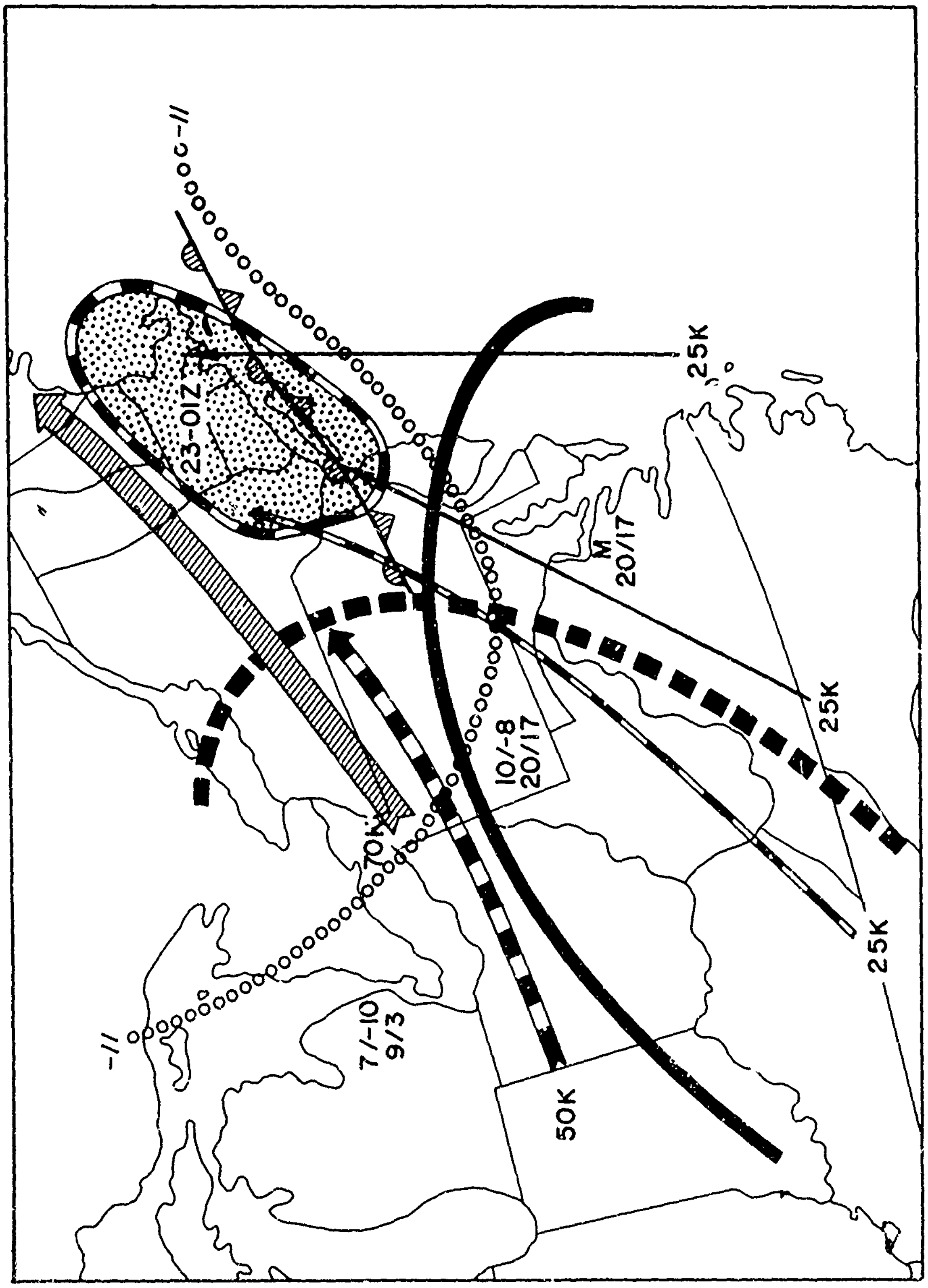



Figure 22 Examples of Type C pattern showing major features at 1500Z on 10 June 1953 ("M" means "Missing") Stippled area outlines locations of severe weather occurrences

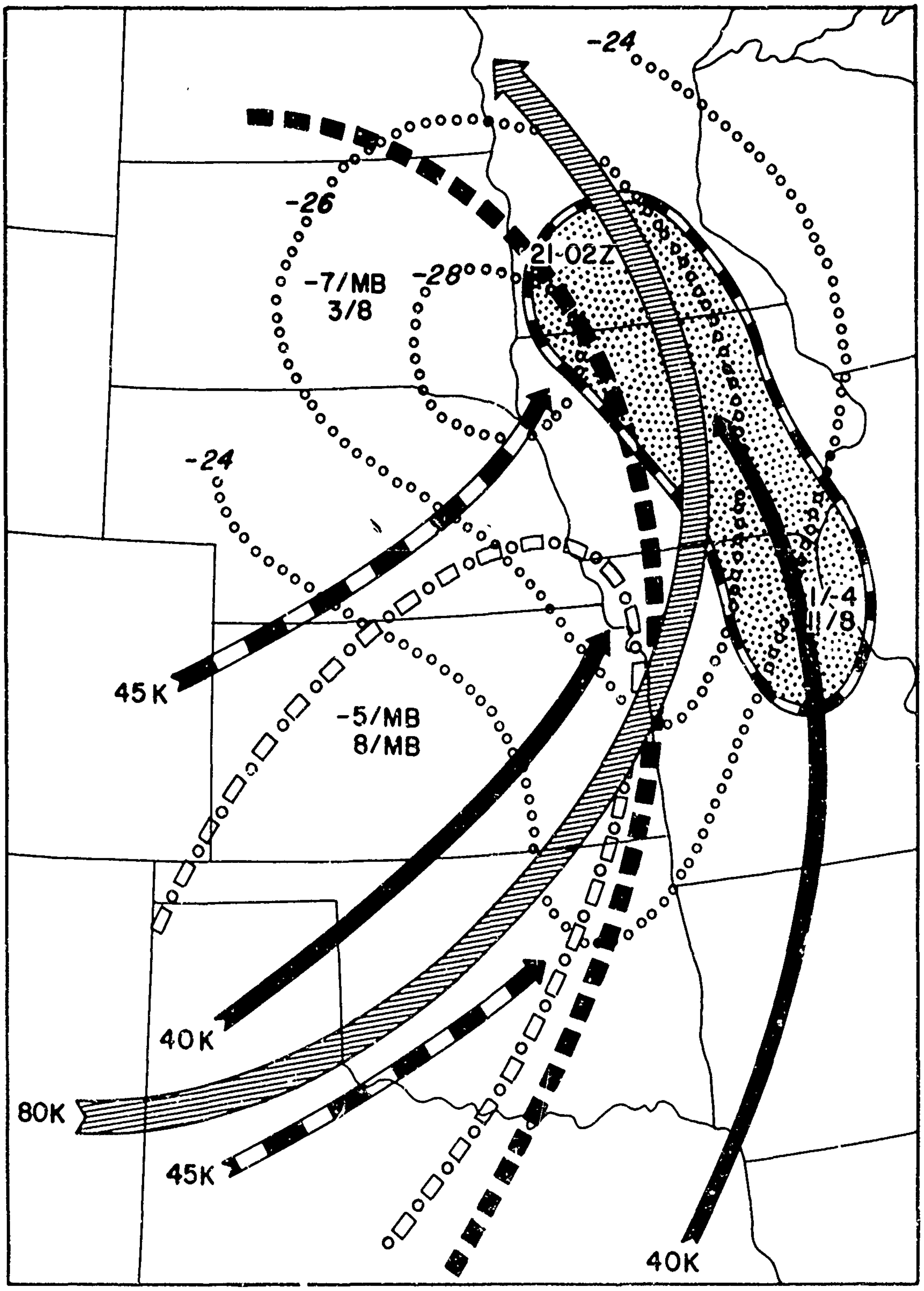



Figure 23 Example or Type D pattern showing major features at 1500Z on 4 April 1955 Stippled area outlines locations of severe weather occurrences

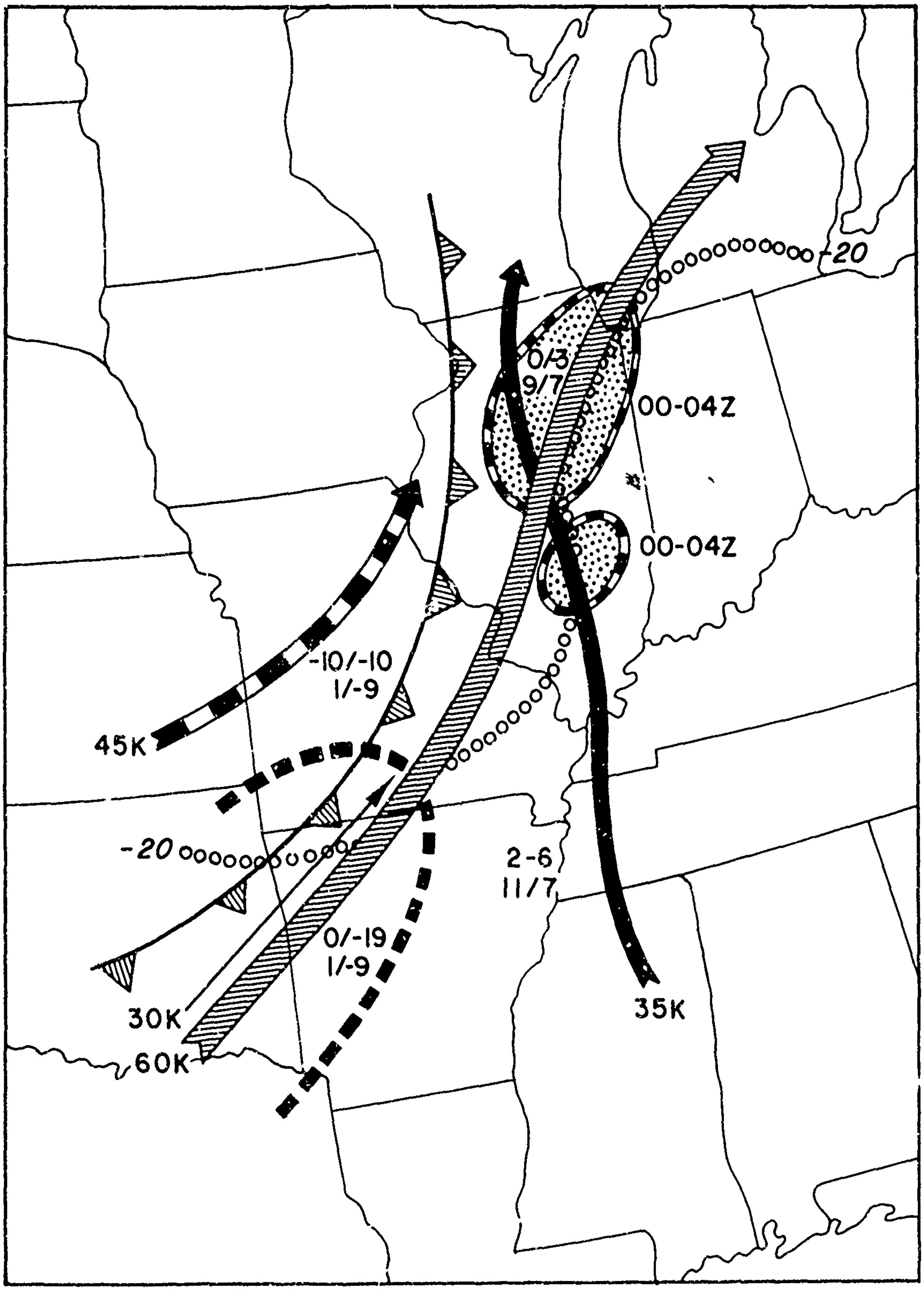



Figure 24. Example of Type E pattern showing significant features at 2100Z on 14 March 1957. Stippled area outlines locations of severe-weather occurrences.

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.

# 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 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

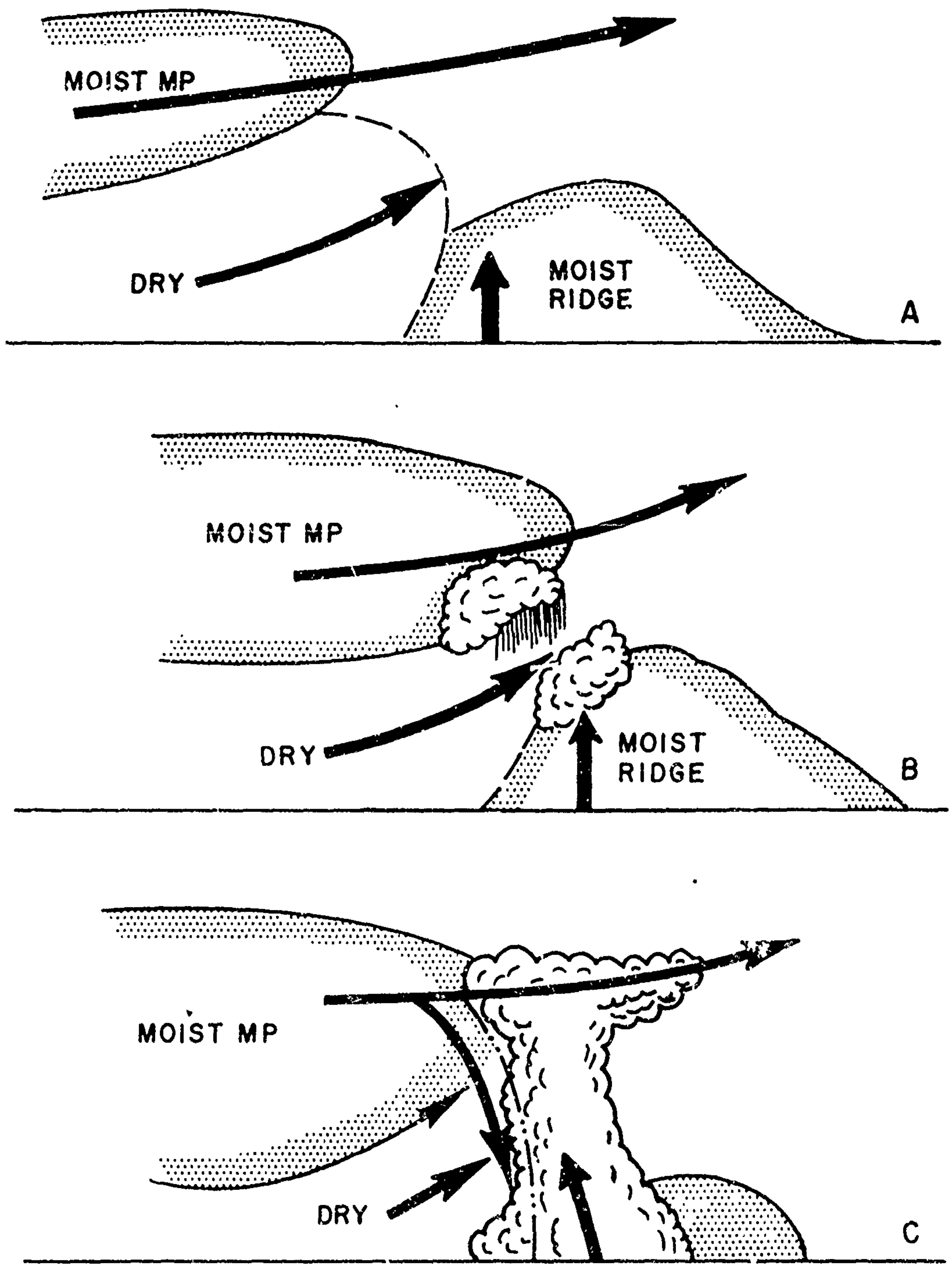



Figure 25. Cross-section of air mass suggesting one way squall lines can develop.

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. A , 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 tne 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

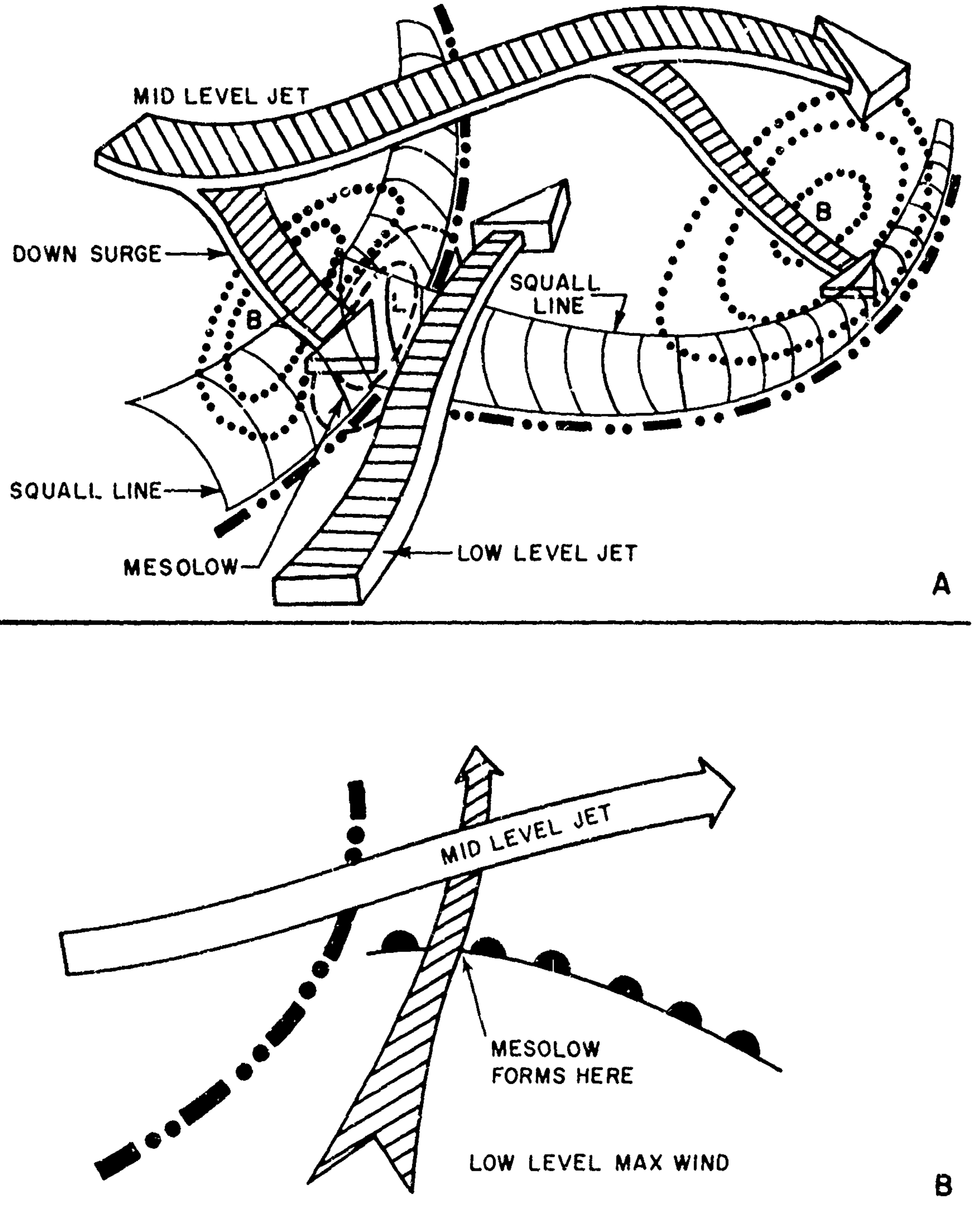



Figure 26 Formation of mesolows and the location of the most intense severe-weather activity The situation of the Waco, Texas storm of 22 May 1953 is shown in Figure 26B

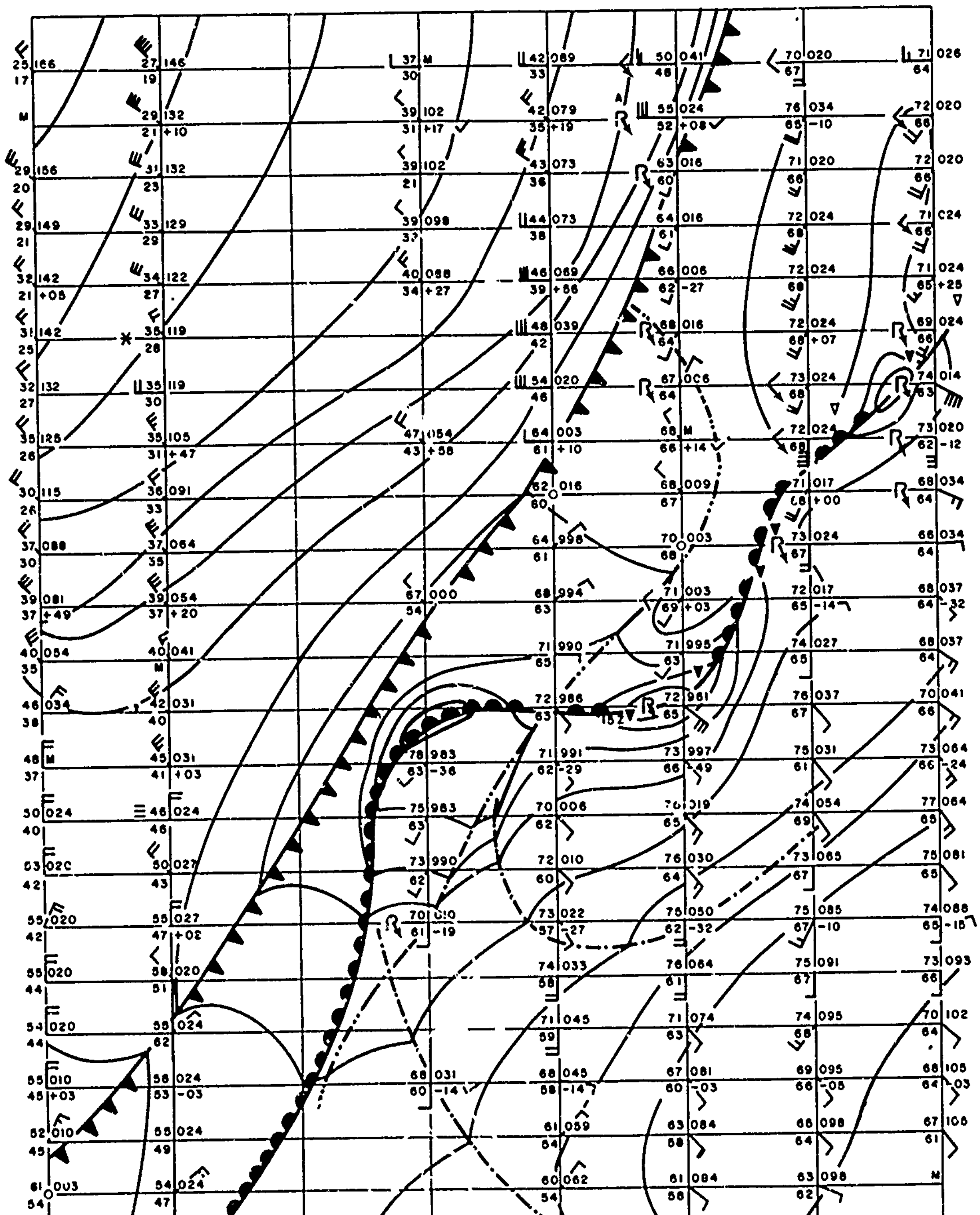



Figure 27. Time cross-section of development and movement of mesolows and accompanying tornadoes of 22 March 1952.

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

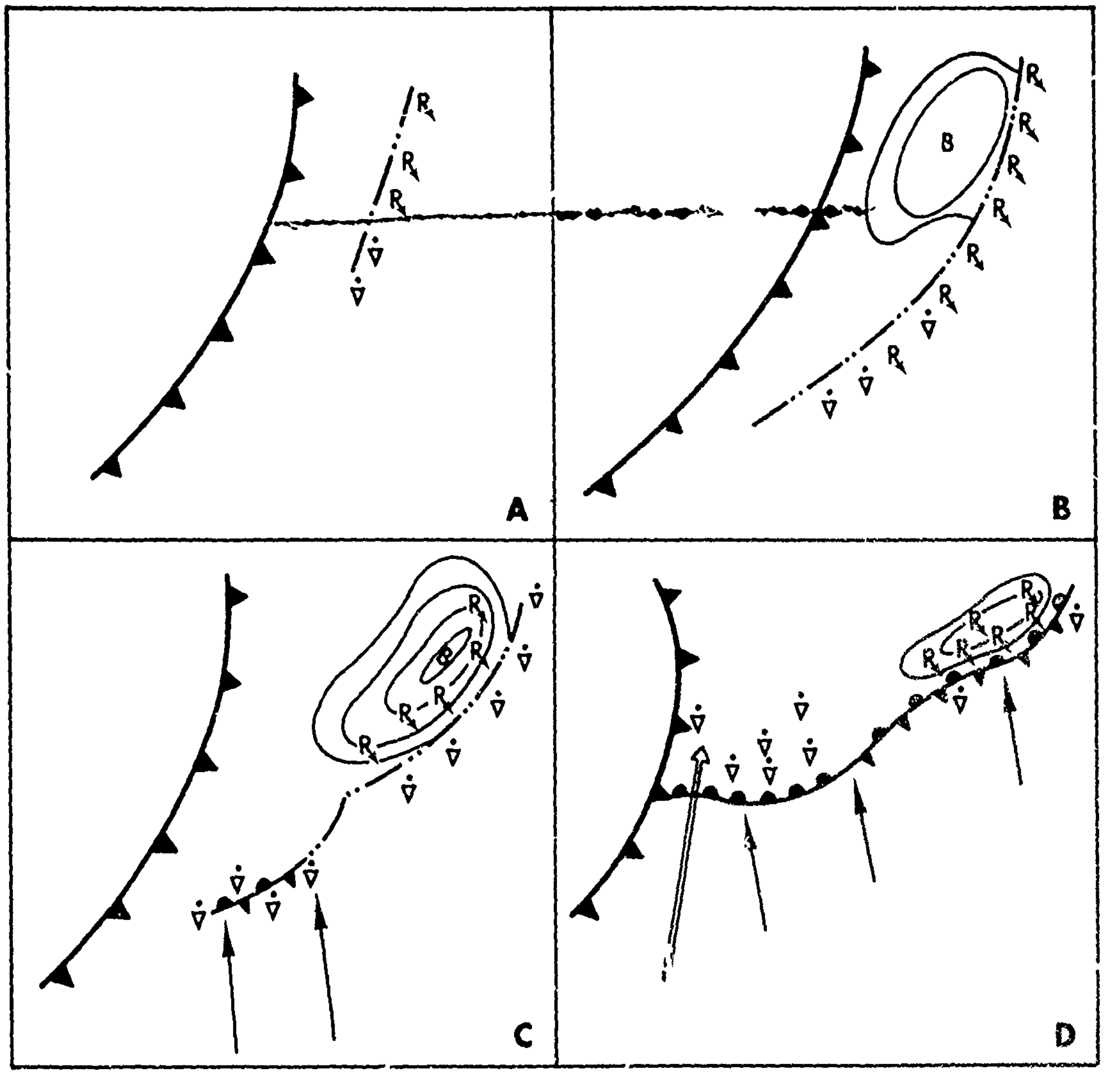


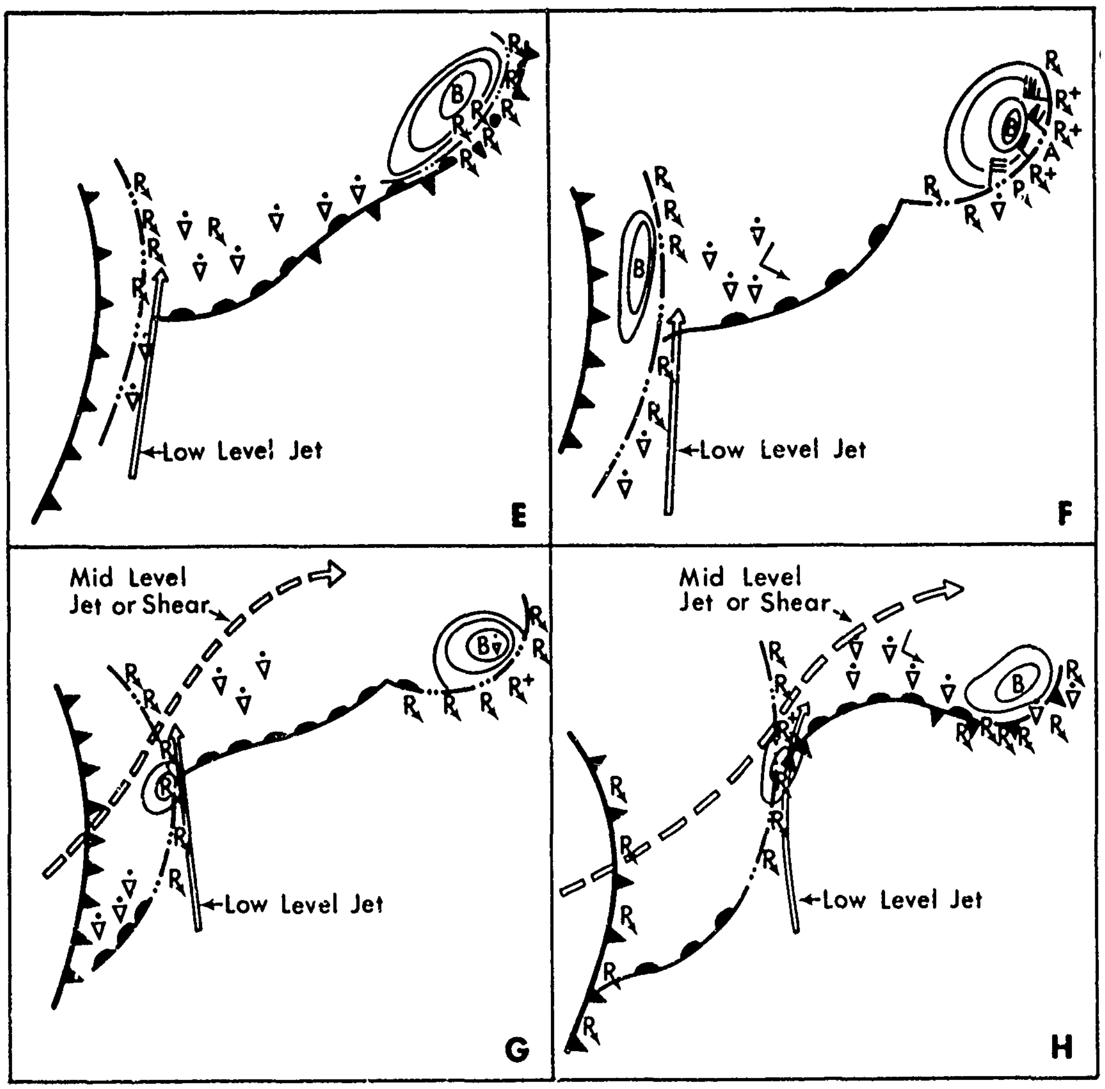

Figure 28. History of the development of squall line and bubble high — Waco, Texas, 11 May 1953.

(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 see representative. However, in the unstable a. 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

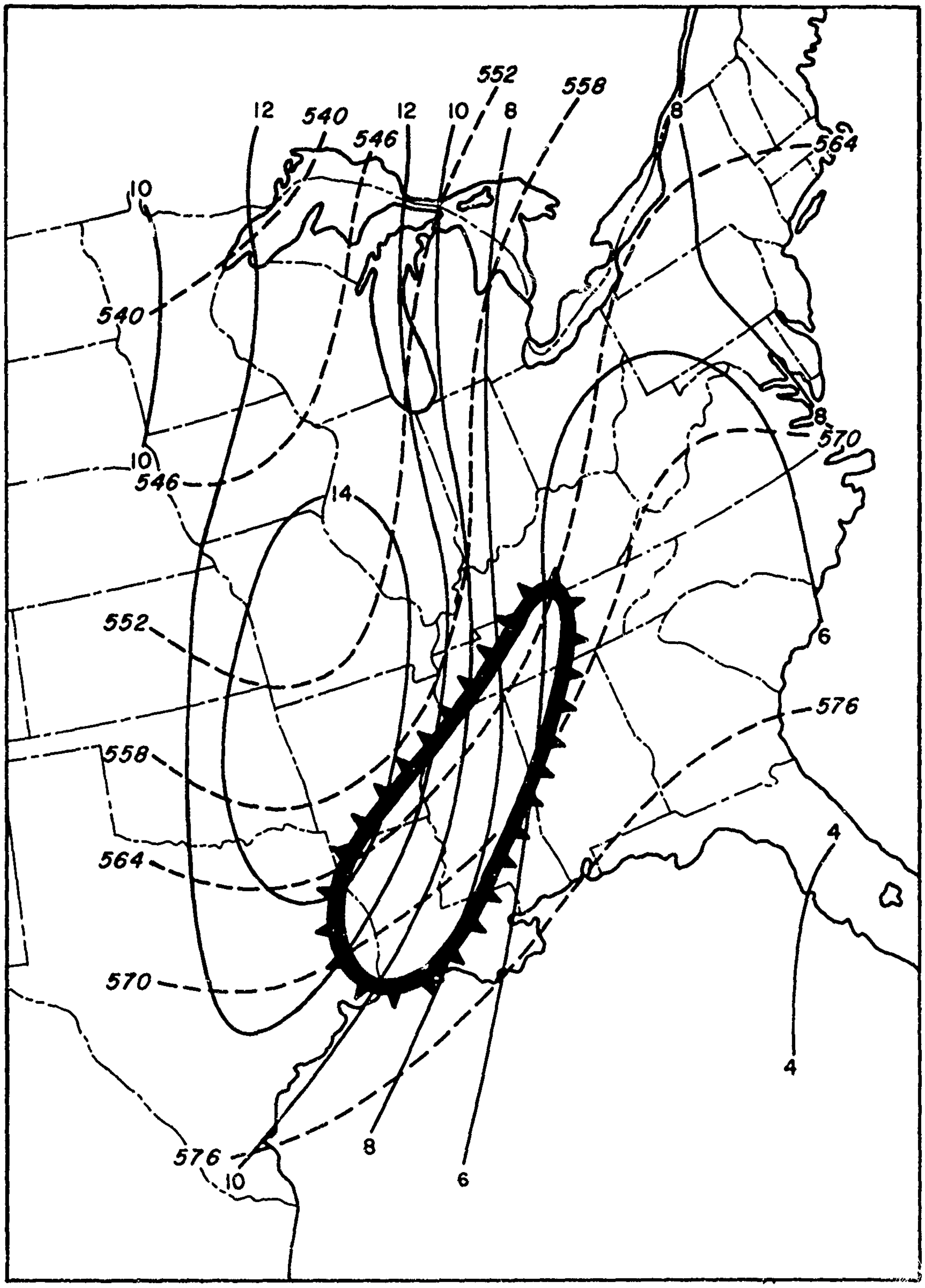



Figure 29. 500-mb contour and vorticity pattern showing strongest PVA.

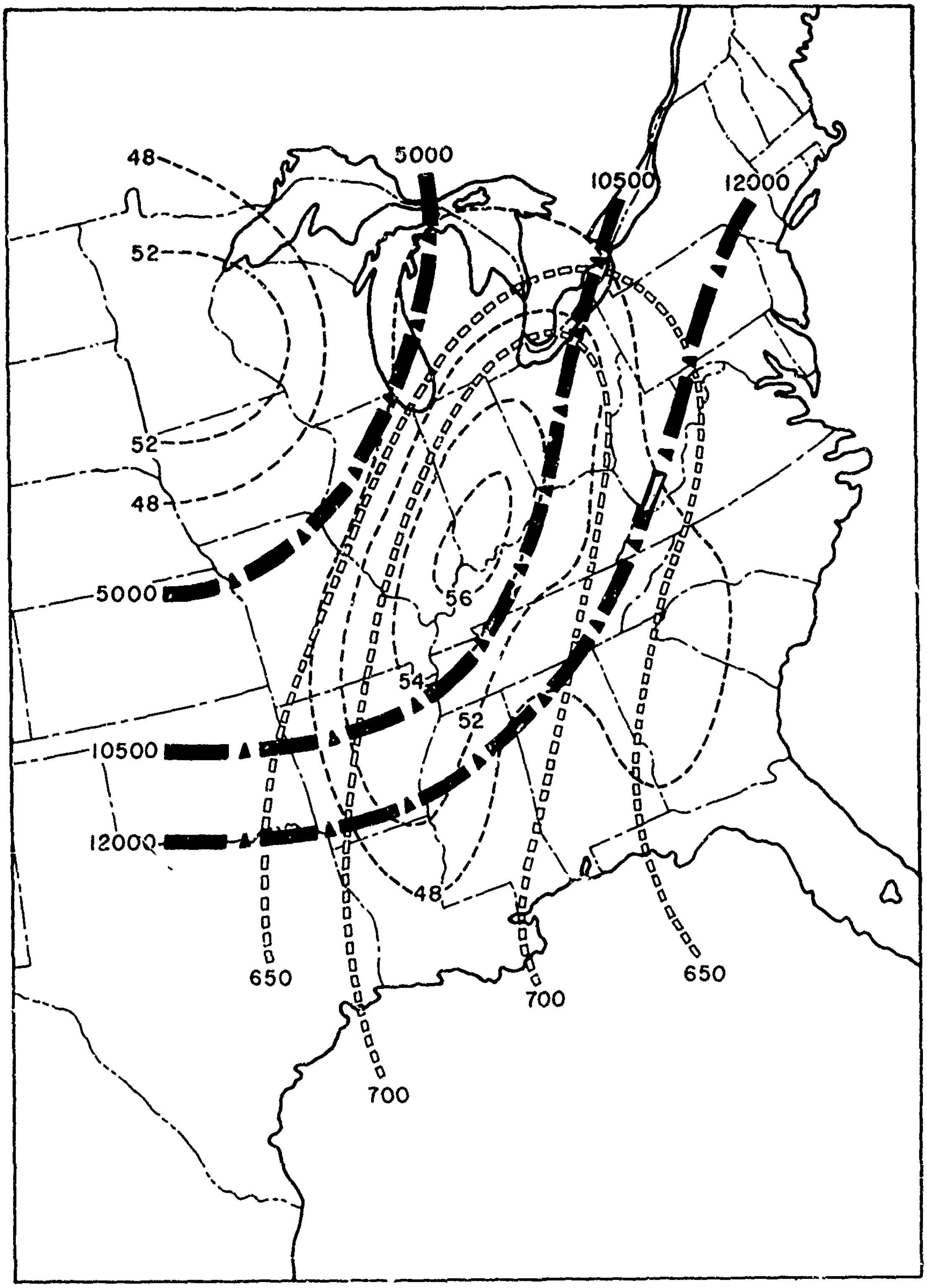



Figure 30. Stability analysis showing Total Totals and Lifted Indexes. Also, isopleths of the height of the Wet-Bulb-Zero and LFC are indicated.

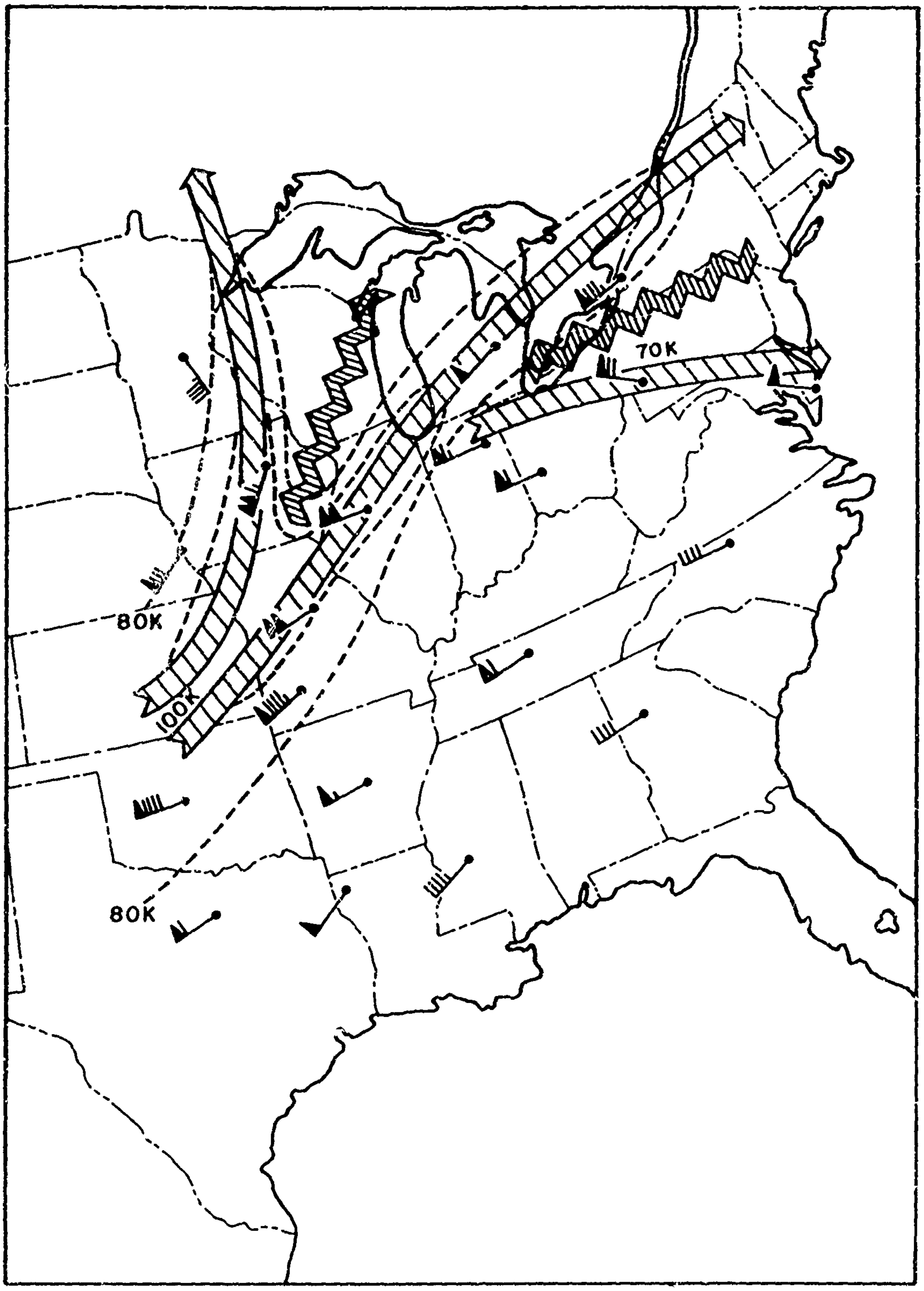



Figure 31. An example of the Maximum-Wind Chart for the Palm Sunday tornadoes of 11 April 1965

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

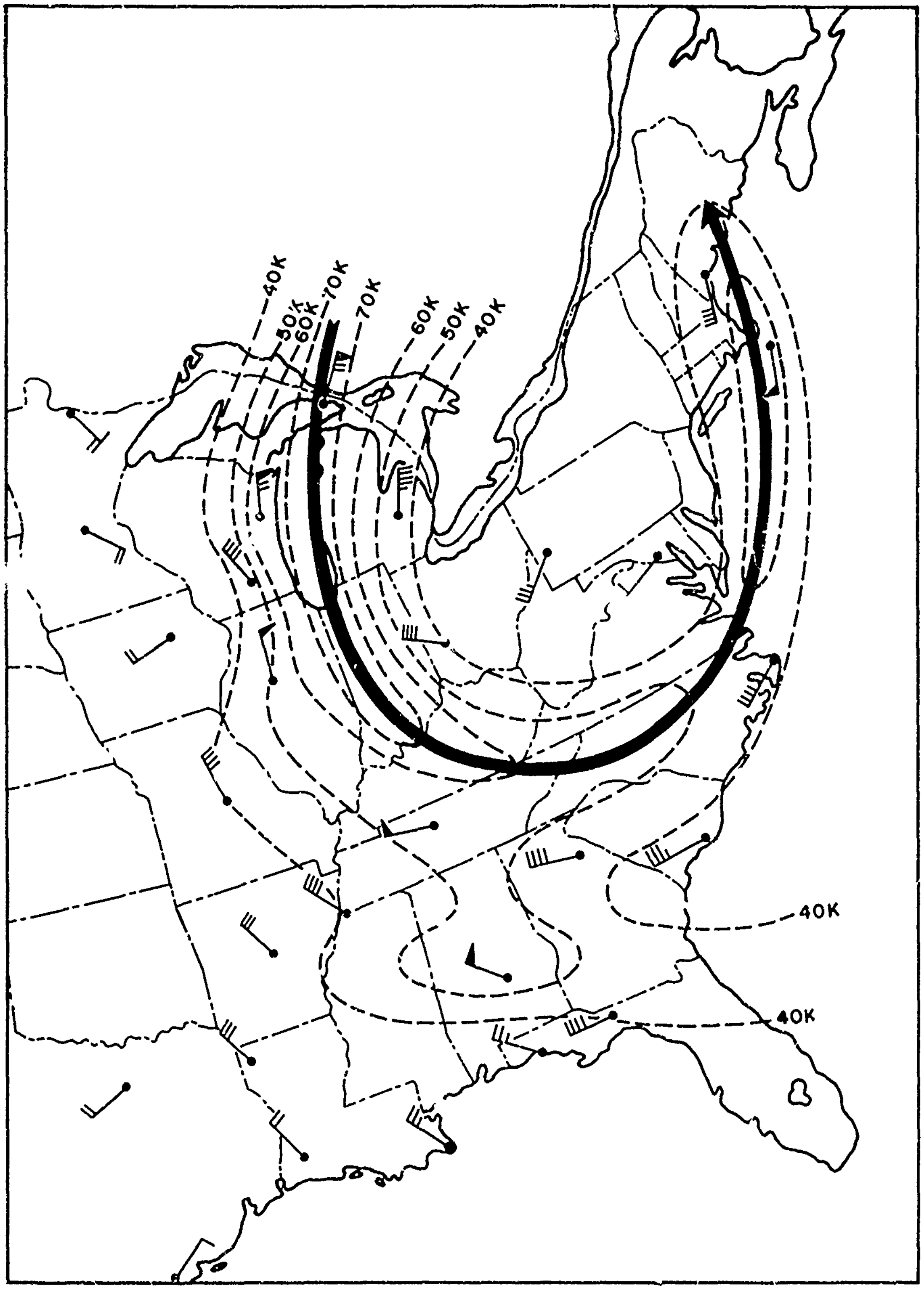



Figure 32. Example of a Low-Level Maximum-Wind Chart.

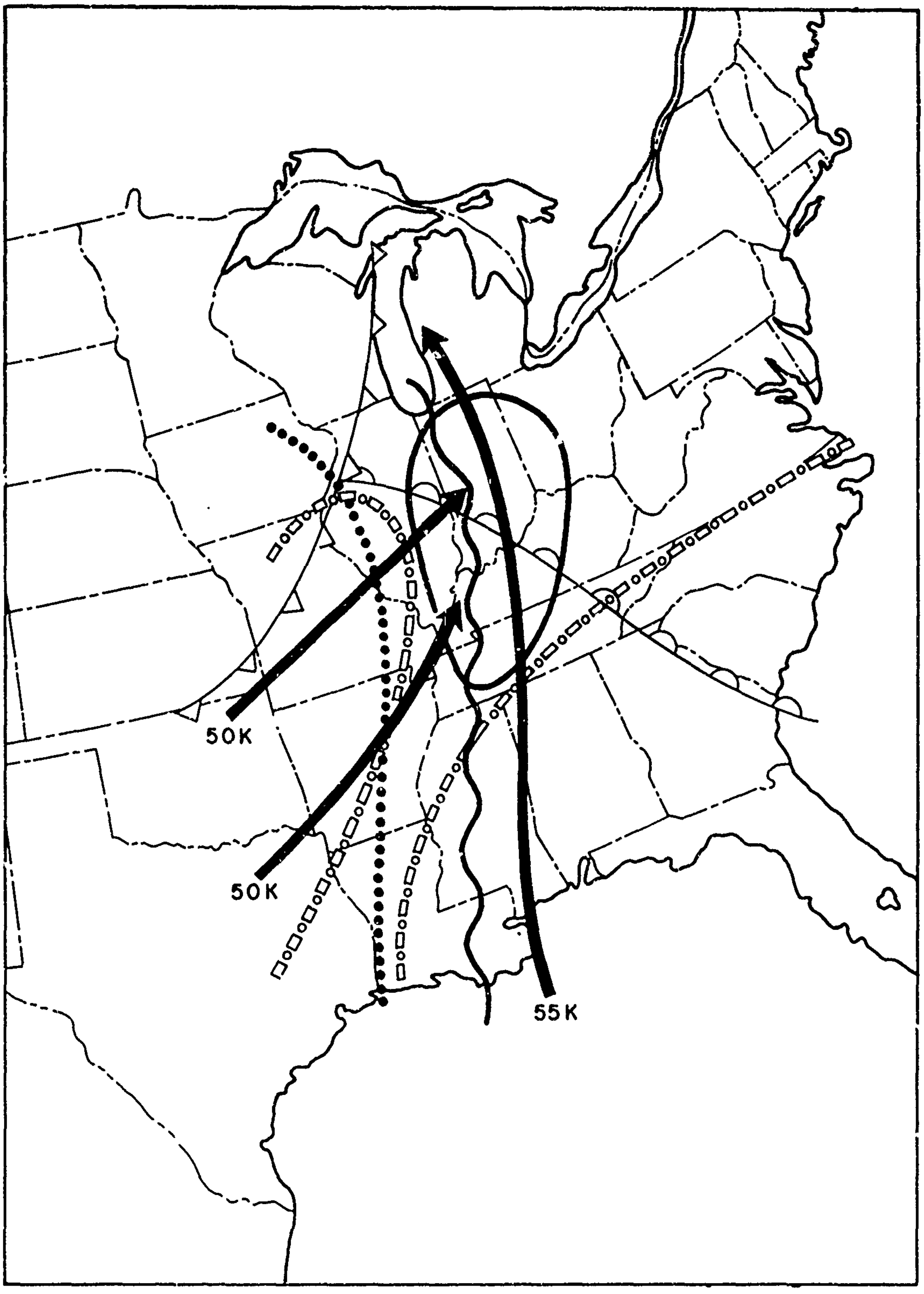



Figure 33. Example of the major features at the 850-mb level showing region of significant moisture and the location of the moisture axis, dry tongues, and low-level jets.

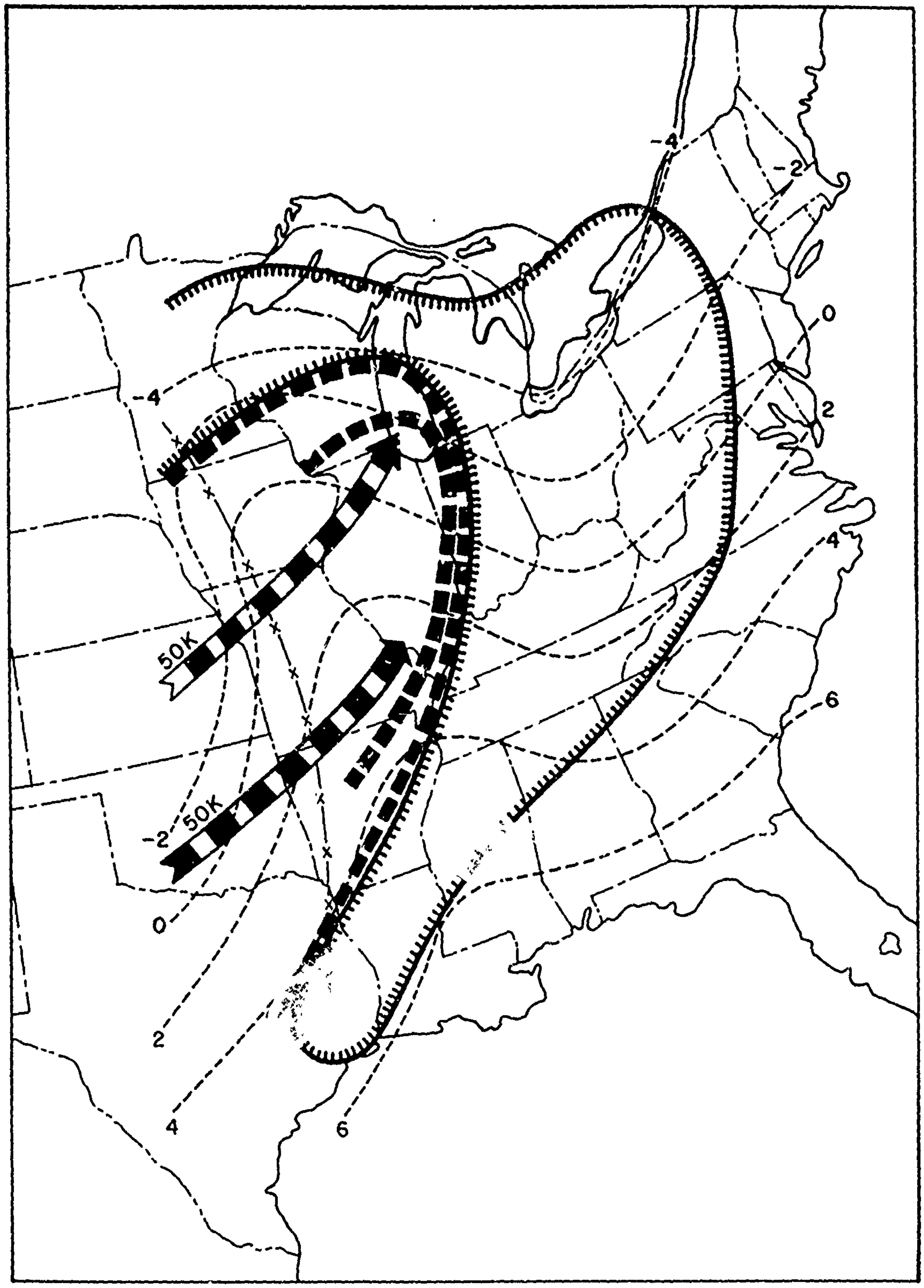



Figure 34. Example of major features at 700-mb level showing jets, dry tongue, and region of significant 700-mb moisture

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°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.

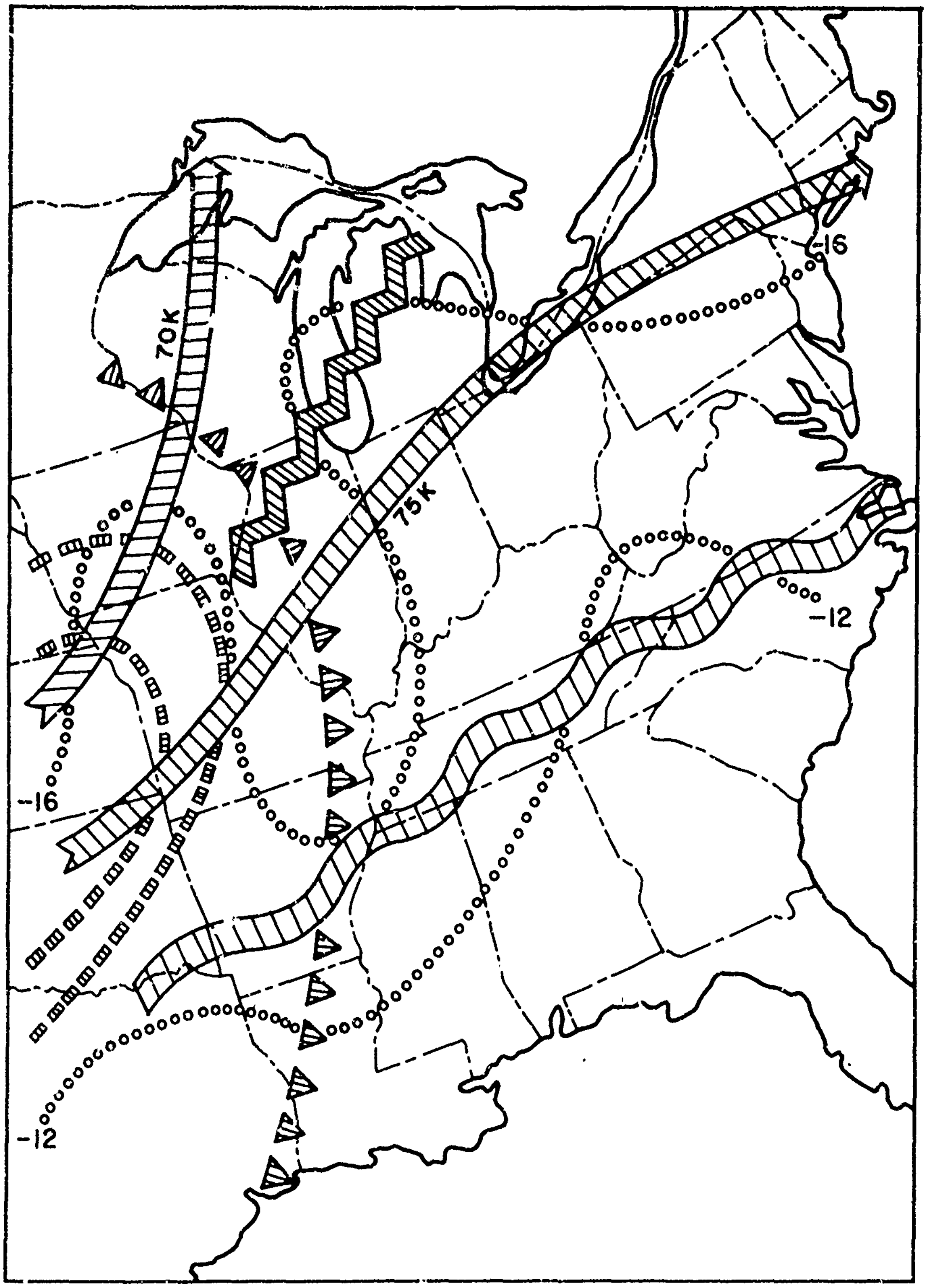



Figure 35. Major features at the 500-mb level

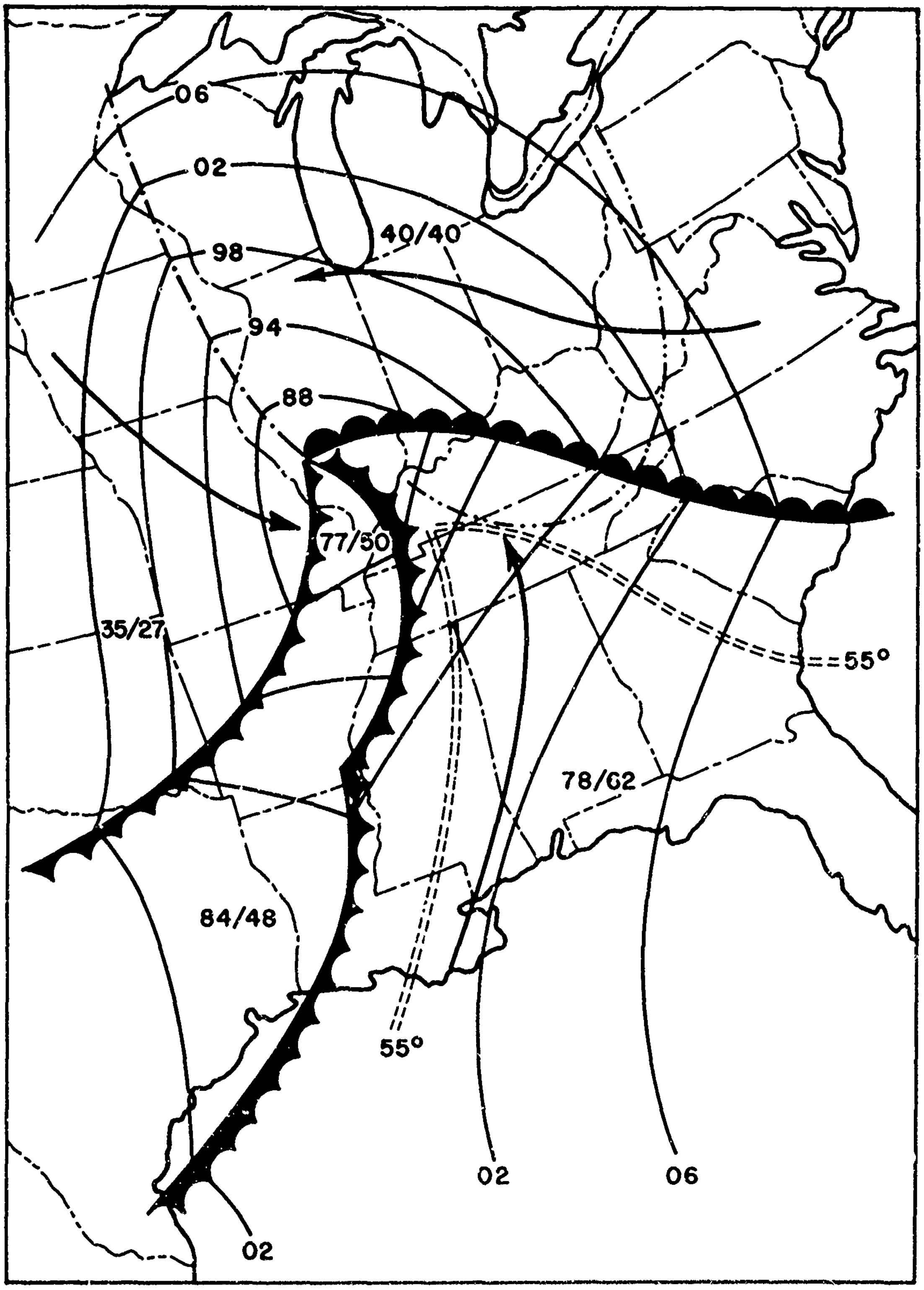



Figure 36. Example of typical surface pattern showing major parameters

(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.

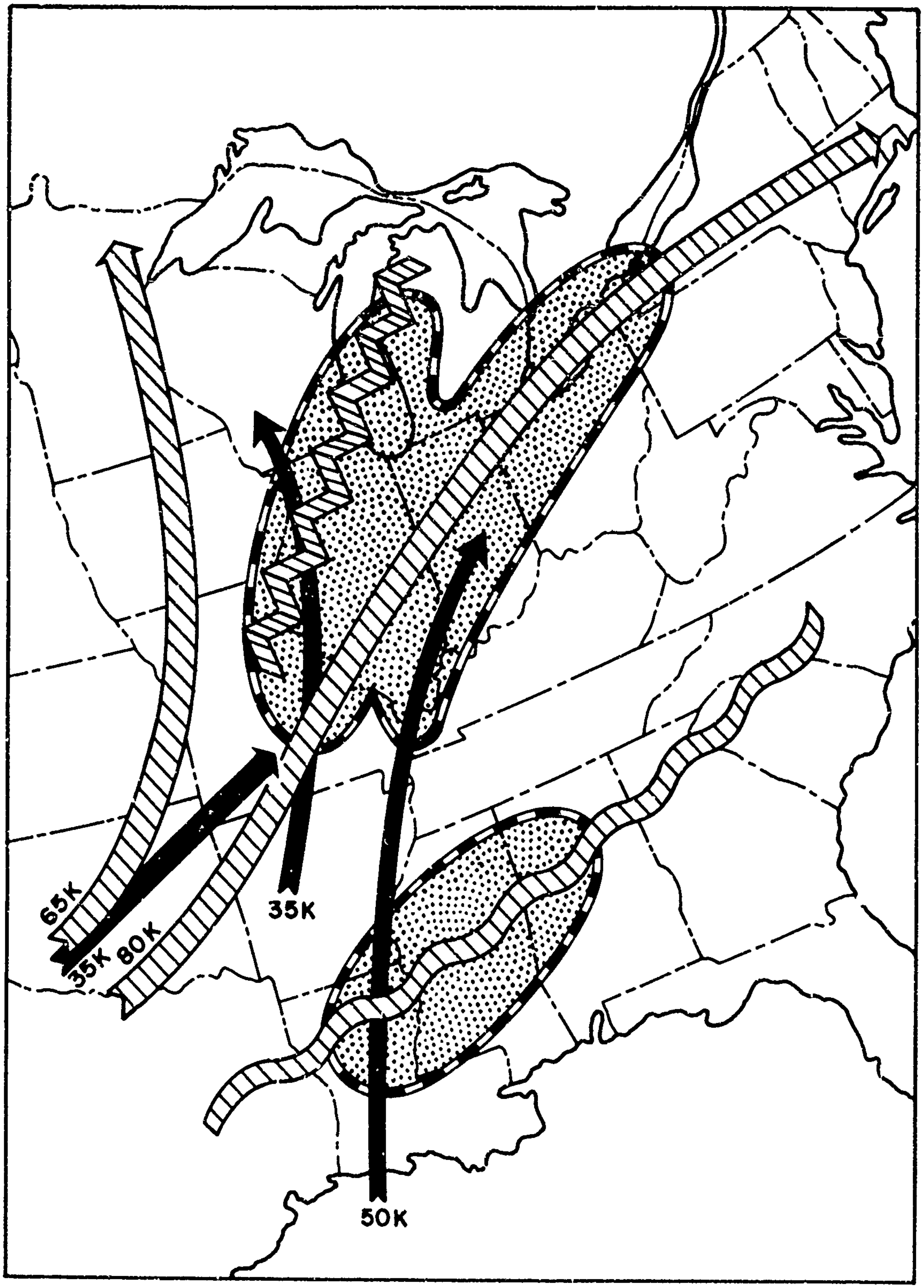



Figure 37. Example of low- and higher-level wind fields. Stippled areas outline regions of severe-weather occurrences.

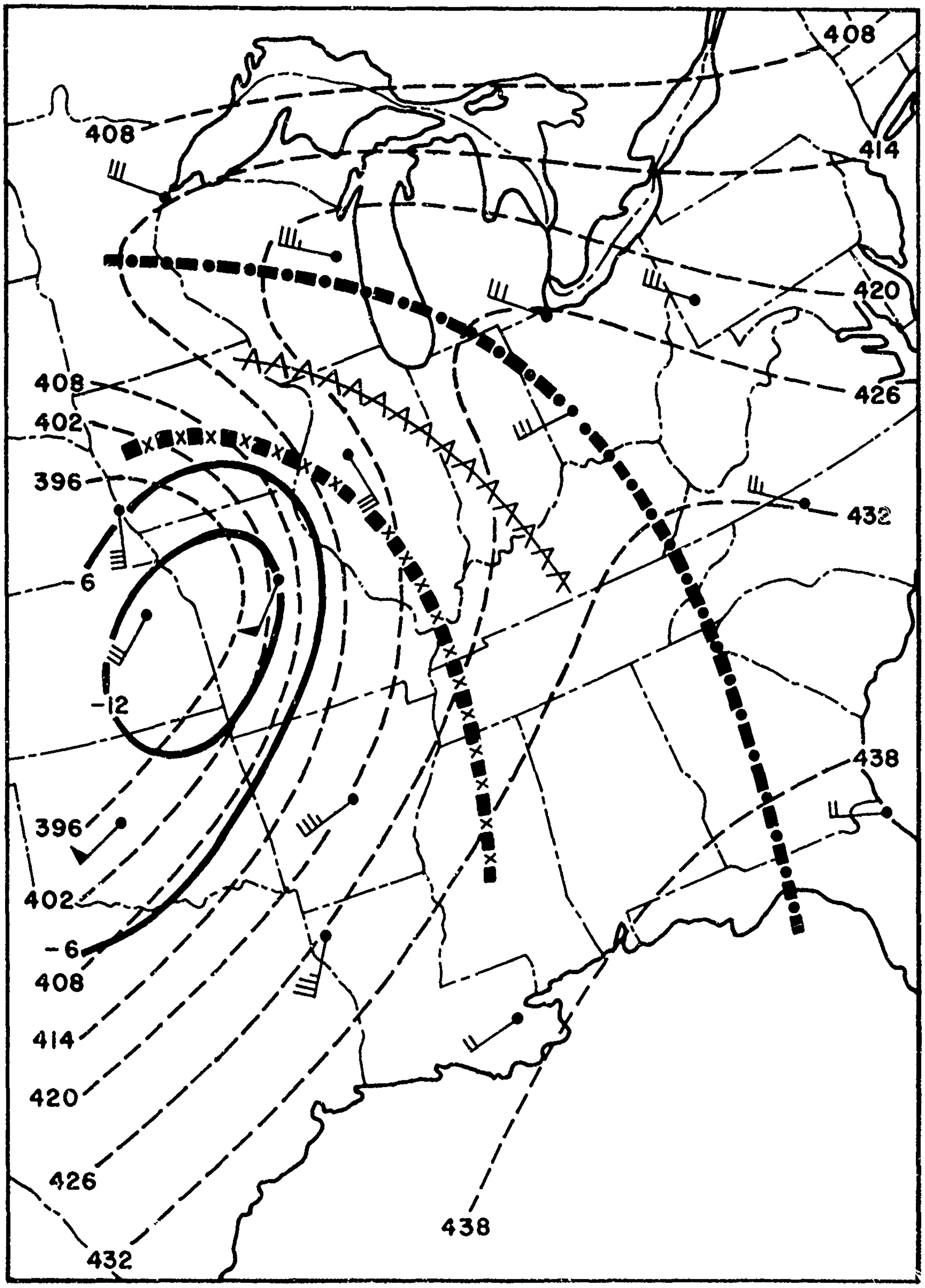



Figure 38. Example of a 850/500-mb Thickness Chart showing max thickness falls, no-change thickness line, thickness ridge and max anticyclonic shear zone.

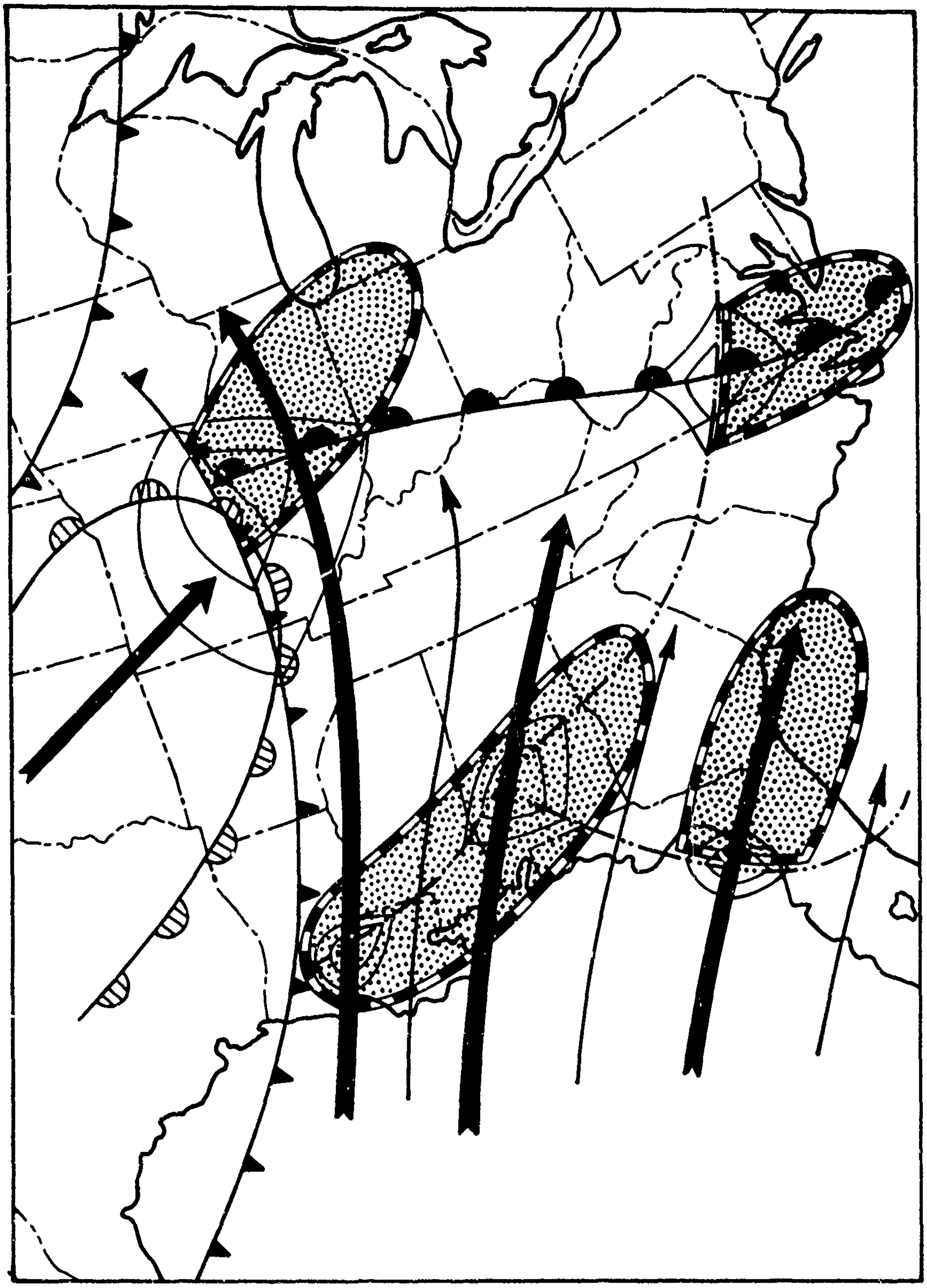


Figure 39. Examples of persistent (warm front) and transitory (squall line) features (and old squall line) in the surface and low-level circulation.

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* fron 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

*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 mesostructure. 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 ines 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

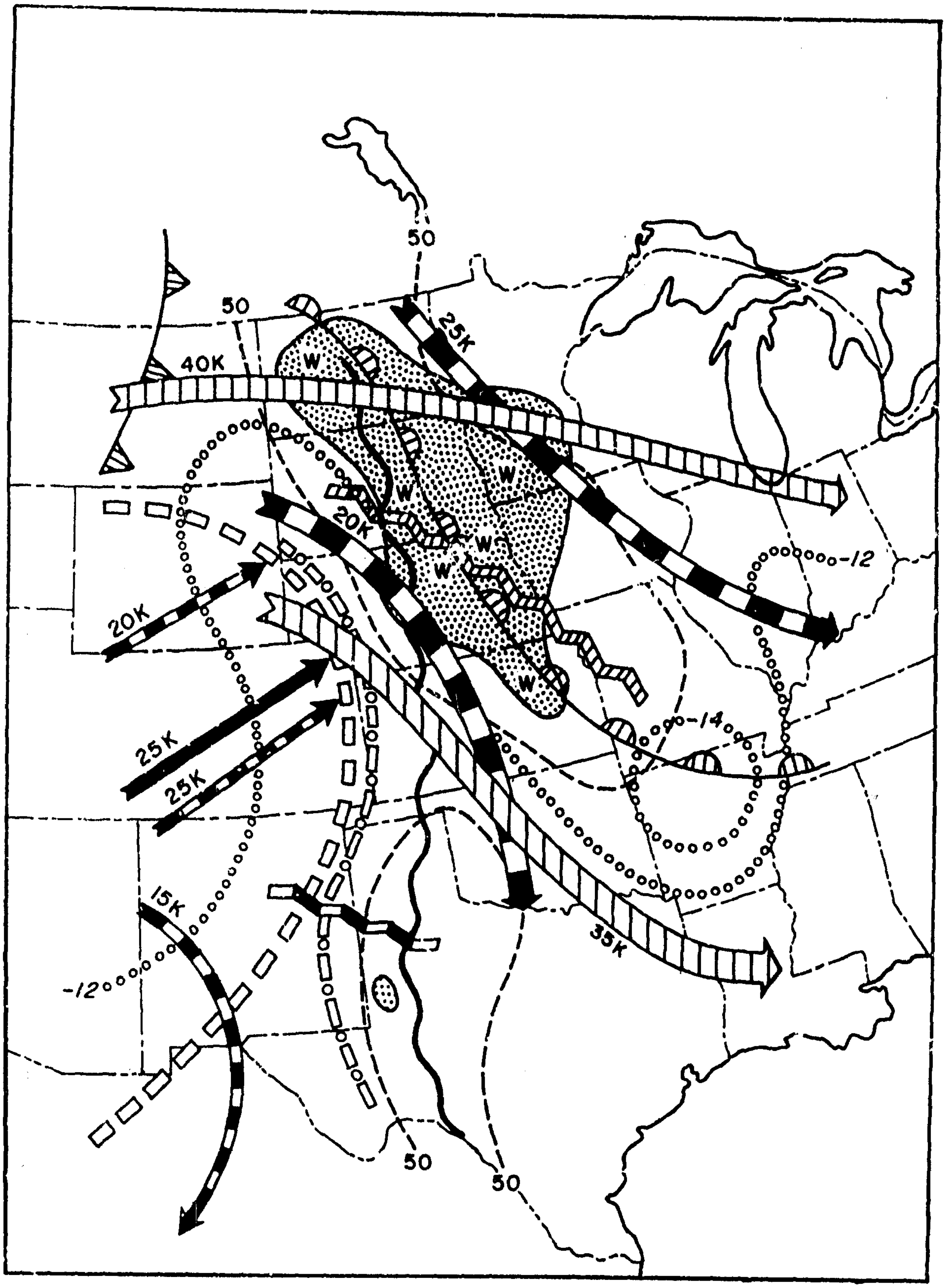



Figure 40. Composite Chart for 1200Z 26 August 1965 is a typical summertime severe-weather pattern

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 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

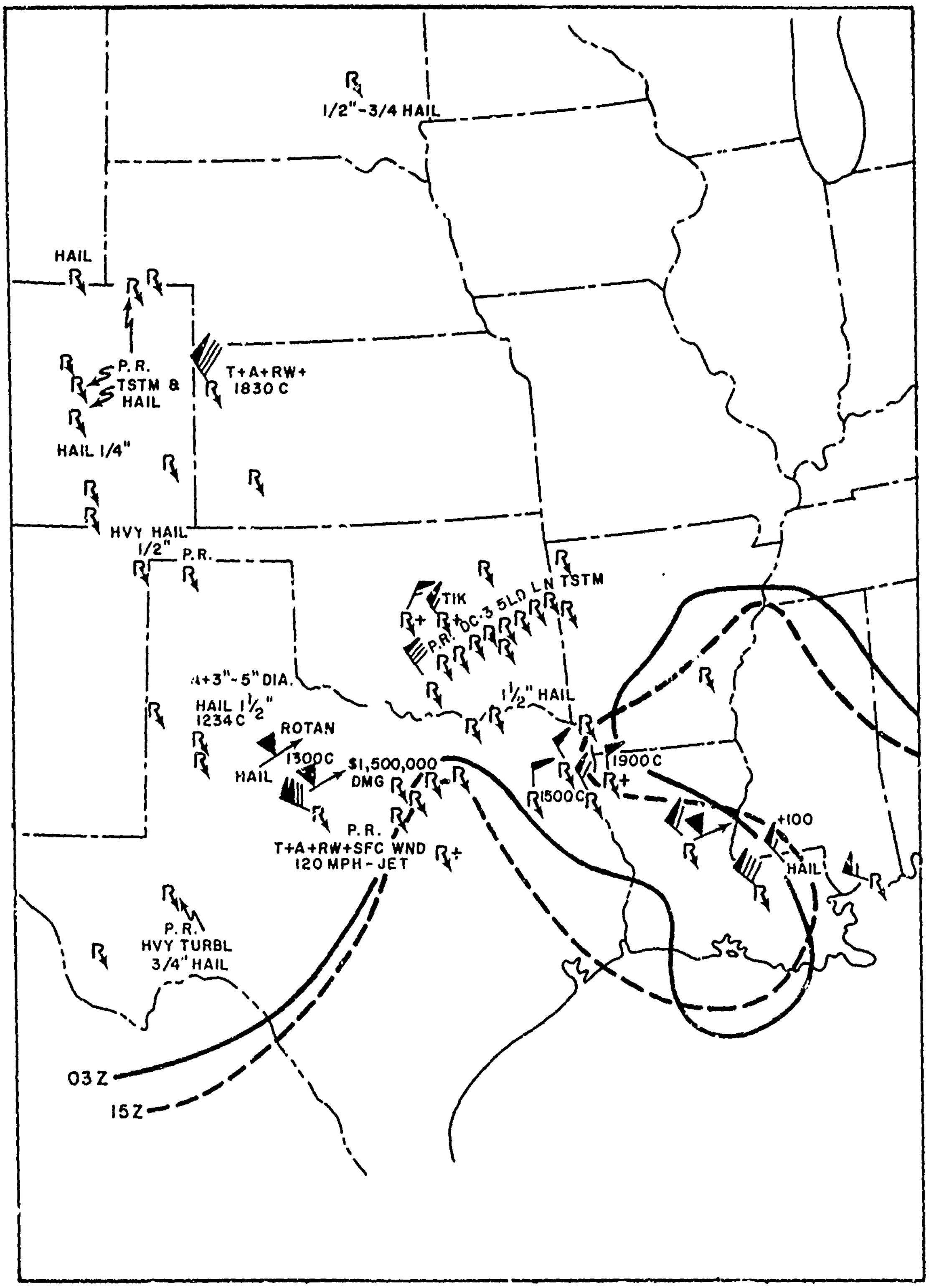



Figure 41. Location of 10,500-foot Wet-Bulb-Zero isopleth and areas of severe-weather activity from 1500Z 10 June to 0300Z 11 June 1951

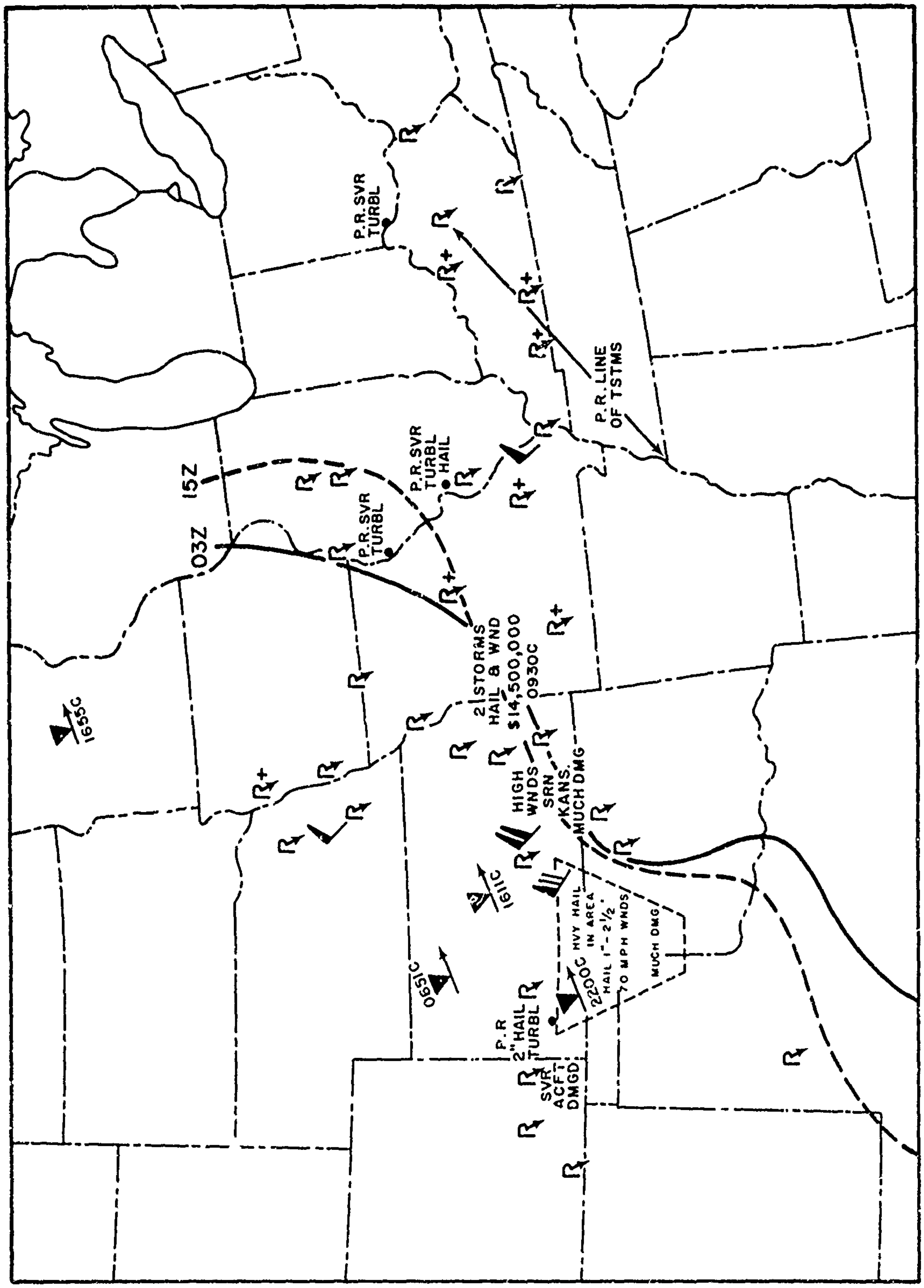



Figure 42 Locati.. of 10,500-foot isopleth and areas of severe-weather activity from 1500Z 23 June to 0300Z 24 June 1951.

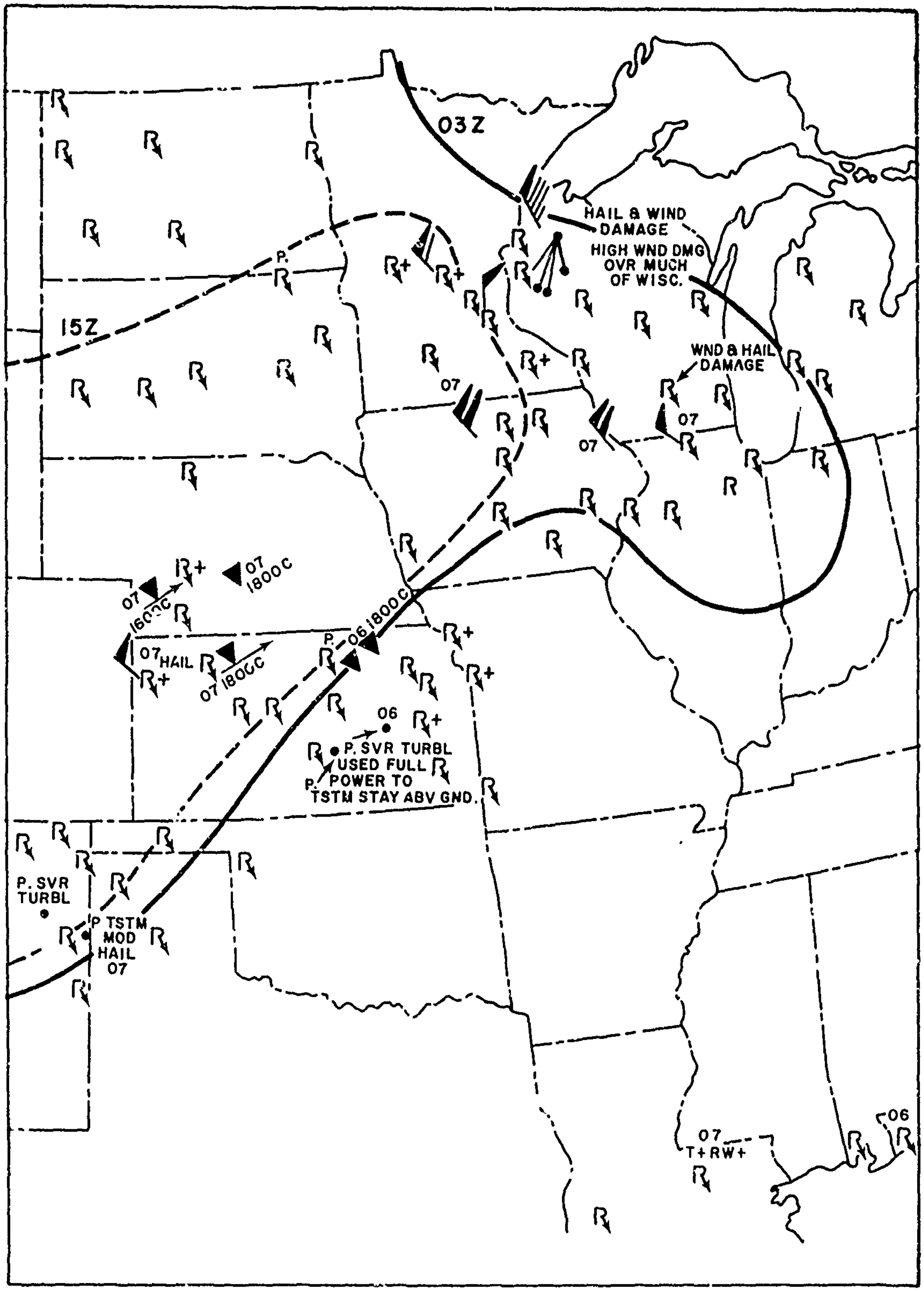



Figure 43 Location of 10,500-foot isopleth and areas of severe activity from 1500Z 7 July to 0300Z 8 July 1951.

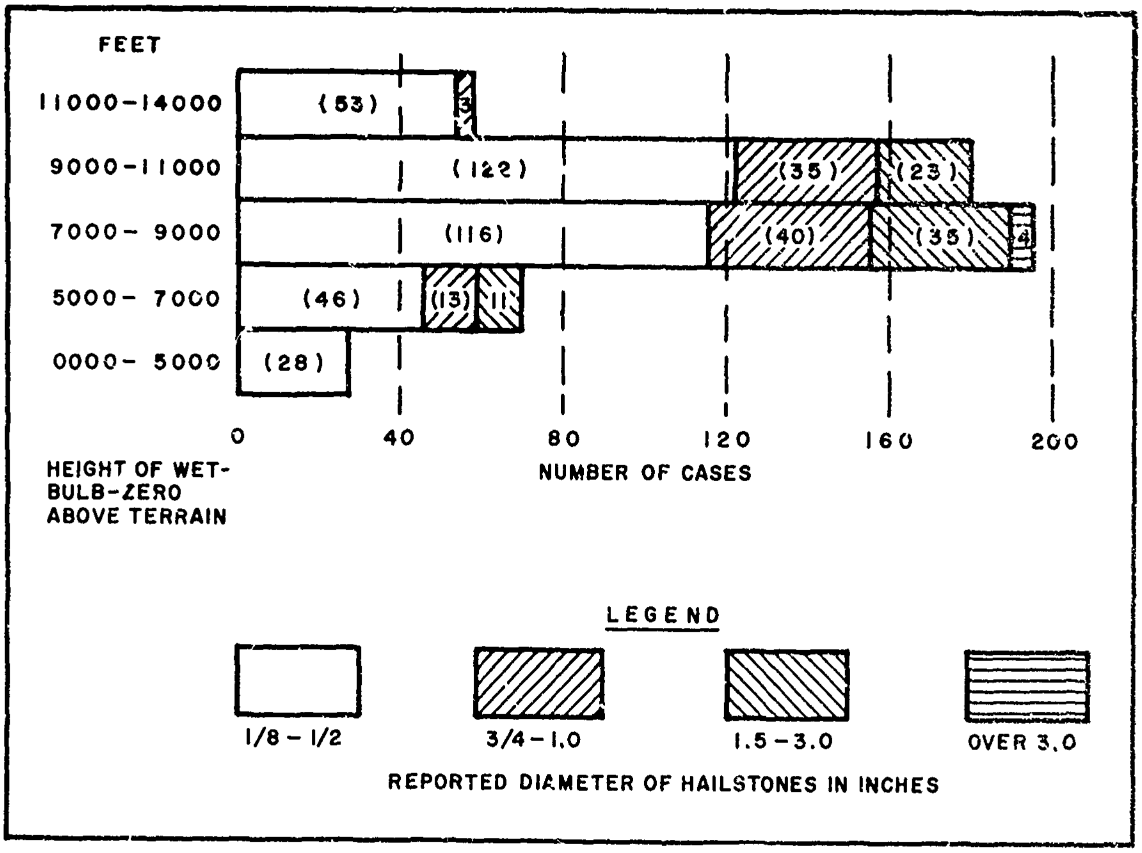



Figure 44. Cases of hail of various sizes by selected ranges of Wet-Bulb-Zero height above the terrain (529 Reports).

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

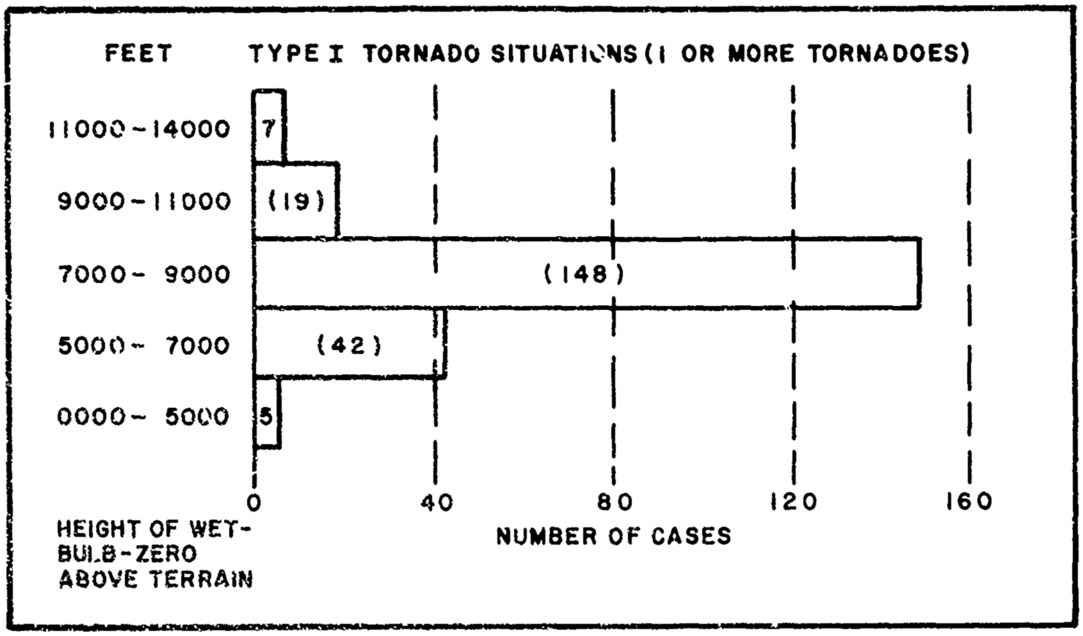



Figure 45. Cases of Type I tornado situations (1 or more tornadoes) occurring with selected ranges of Wet-Bulb-Zero height above the terrain.

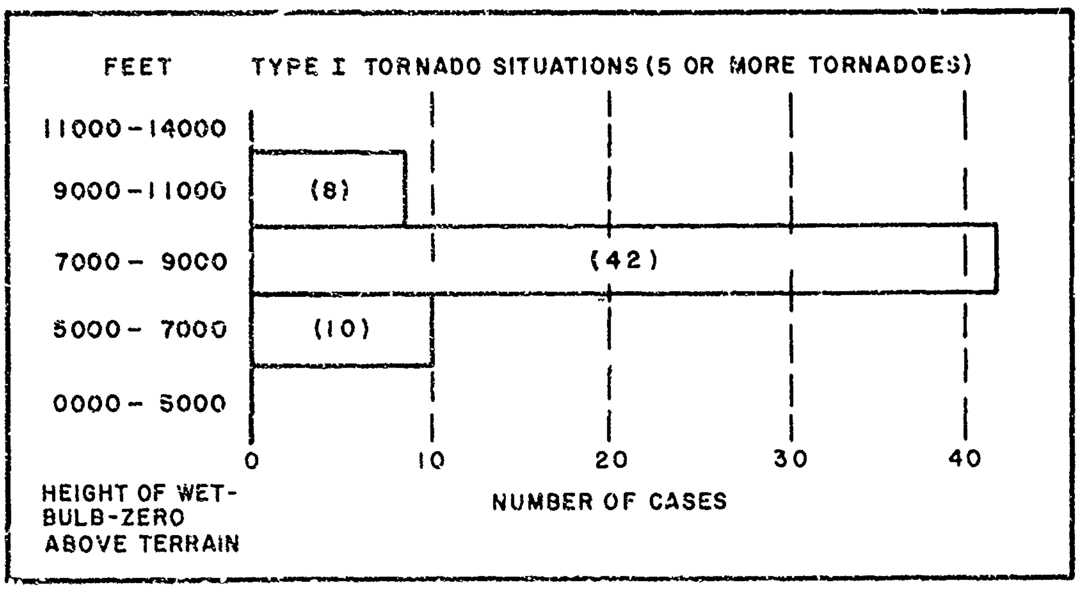



Figure 46. Cases of Type I tornado situations (5 or more tornadoes) occurring with selected ranges of Wet-Bulb-Zero height above the terrain.

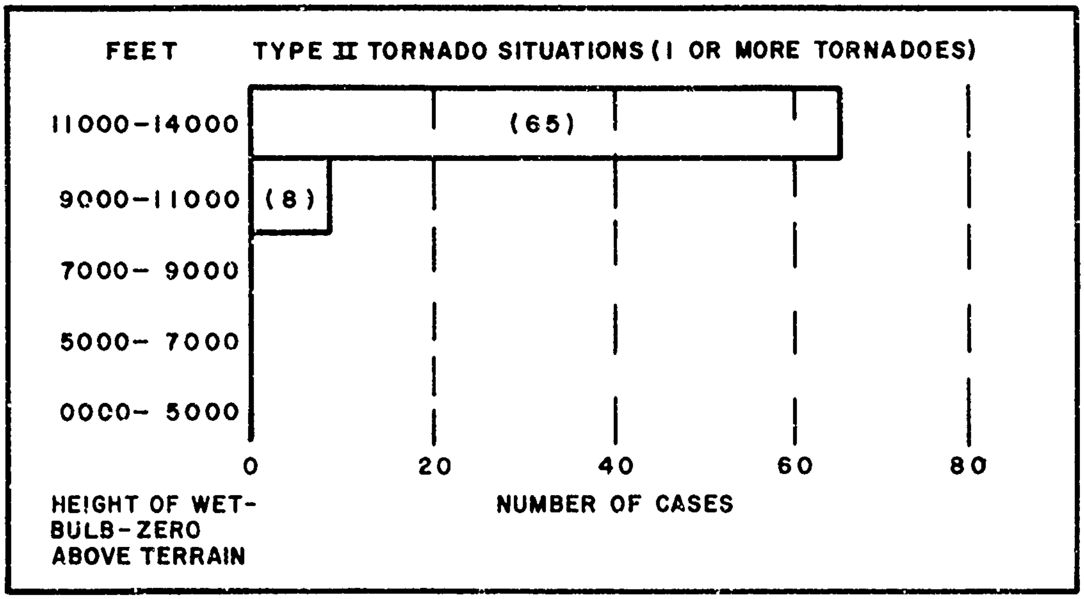



Figure 47. Type II tornado cases (one or more tornadoes) occurring with selected ranges of Wet-Bulb-Zero height above the terrain.

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.

# Chapter 8
# THE TOTALS INDEX

## SECTION A—GENERAL

Since the severe-weather forecaster has little time to digest a large amount of information, the MWWC developed several semi-objective forecast short-cuts. One of these time-savers is to use a computer to analyze and plot sounding data. During the past two years, considerable success has been achieved by using the early radiosonde (SLAM) data to prepare a stability analysis based on the 500-mb temperatures and the 850-mb temperature and dew point. This machine-plotted chart is now prepared twice daily by the AFGWC and is available to the forecaster one hour and 30 minutes after data time. The plotted data consists of the 850/500-mb thickness, the 12-hour thickness change, the Showalter Index, the thermal wind, and the Vertical and Cross Totals. Vertical Totals is the 500-mb dry-bulb temperature subtracted from the 850-mb dry-bulb temperature. Cross Totals is the 500-mb dry-bulb temperature subtracted from the 850-mb dew-point temperature.

The significant isotherms at 500-mb for the season of the year are often plotted on the chart. Significant isotherms at 500 mb are a critical or threshold value of temperature at that level for moderate to severe thunderstorm activity during certain seasons of the year. Critical values currently in use by the AFGWC are as follows:

a. December, January, February (-16°C)
b. March, April, October, November (-14°C)
c. May, June (-12°C)
d. July, August, September (-10°C)

These values enable the forecaster to maintain continuity on the advection pattern and serve to alert him to potential threat areas. The temperatures over the threat area are studied, but of more importance are the temperatures upwind of the threat area, especially if cold-air advection toward the area is probable.

## SECTION B—STABILITY VERSUS THUNDERSTORM OCCURRENCE

In nearly all cases of major severe thunderstorm outbreaks, little cooling occurs at 500-mb over the threat area. In actuality, slight warming due to advection or the release of latent heat is likely to occur. As long as heat and moisture are added to the lower levels of the air mass, slight warming in the middle and upper levels will not increase the actual stability. The severe-weather forecaster looks for three possible non-adiabatic modifications in the structure of the atmosphere which will cause the air mass to become more unstable (actually and/or potentially):

a. Holding the top of the air column constant or warming it slightly, and adding heat and moisture to the bottom;
b. Cooling the top of the column and holding the lower-level temperature and dew-point values nearly the same; and
c. The simultaneous occurrence of cooling at the top and heating at the bottom of the air column (which seldom happens).

The Totals Chart is very useful in locating potential areas of thunderstorm development. Further refinement of these areas is dependent upon accurate analysis and prognosis of the wind and moisture fields, frontal systems, and areas of positive vorticity advection (PVA).

Vertical Totals (VT's) are analyzed for values of 24 or greater by 2-degree intervals. In the United States the value of 26 appears to be reasonable for a thunderstorm occurrence without regarding moisture, except along the coastal areas of the Gulf States where values less than 26 are often associated with thunderstorm activity. In the British Isles this value is near 22 and in western Europe is about 28. Since the Vertical Totals are derived without regard to moisture, it is not practicable to call for thunderstorm activity based on the VT's alone, except in an island climate or along the windward side of coastal mountains, or over large bodies of water such as the Great Lakes. To further delineate the potential thunderstorm areas and probable intensities, the Cross Totals (CTs) data are analyzed for 2-degree intervals.

## SECTION C—USE OF THE STABILITY CHART

The severe weather forecaster first outlines those areas having Vertical Totals of 26 or greater, Cross Totals of 18 or more, or a Total Total (TT) of 44. These areas are then refined by the 500-mb moisture field. For the area west of the Rockies, significant 500-mb or 700-mb moisture will initiate thunderstorms regardless of the value of the Cross Totals. ("Significant moisture" is a 6-degree temperature-dew-point spread at either level, or a dew point of -17°C or warmer at 500-mb, and 0°C or warmer at 700-mb.) Lack of 700-mb moisture will not preclude development as long as sufficient 500-mb moisture is present. However, development is more certain and cells are more numerous when both levels indicate available moisture. These thunderstorms are largely orographic in nature and their development is highly correlated with Vertical Totals and the presence of available moisture. Assuming an adequate moisture field the following values are usually effective in producing thunderstorms *west* of the Rockies.

a. If the Vertical Totals are less than 28, forecast no thunderstorms.

b. If the Vertical Totals are between 29 and 32, forecast a few thunderstorms.

c. If the Vertical Totals are over 32, forecast scattered thunderstorms.

Usually these forecast thunderstorms will produce gusts of less than 35 knots and/or small hail only. Heavy and severe thunderstorms require a large supply of low-level moisture at the 850- and/or 700-mb level, depending on terrain height. Moisture need not, of course, be directly over the area of concern, but in a position to affect the area.

*East* of the Rockies the same relationships hold true with the proviso that low-level moisture is present. Here the Cross-Total threshold value of 18 is used as the lower limit for thunderstorms, and a Total Total of 44 is a minimum. These values are only guides since terrain and local effects will occasionally combine to produce thunderstorms outside the forecast area. However, such occurrences will be in the minority and will usually be confined to the following areas:

a. Along the immediate Gulf Coast and over the Gulf Stream the Cross Totals appear to be the deciding factor. A CT of 16 or more coupled with a VT of 23 or 24 often will produce a thunderstorm.

b. Along the windward slopes of the Pacific coastal mountains the Vertical Totals are most important, especially when associated with positive vorticity advection and cyclonic flow aloft. Vertical Totals over western Oregon and Washington and northern California of 30 or more will usually produce scattered cumulonimbus, a few thunderstorms and hail pellets.

c. Over the Great Lakes, the Vertical Totals are again the most important. A VT of 30 or greater should be suspect, except when the Lakes are mostly frozen over.

After outlining those areas where the air mass is capable of supporting thunderstorm activity, the severe-weather forecaster must further refine his forecast by an appraisal of the changes to be expected in the overall synoptic pattern during the forecast period. The NMC facsimile analyses and prognoses are available and special emphasis is placed on the 12-hour vorticity prognosis. The movement of vorticity centers and any changes in the advection pattern are carefully noted and forecast areas adjusted accordingly. The Vertical, Cross, and Total Totals are used to assign degrees of intensity to the various areas under study according to categories listed in Table 2. The colors refer to intensities of severe weather activity and are discussed in Chapter 11.

These Cross Totals along with Vertical Totals of 26 or greater are adequate for a first approximation of intensity. The higher the Vertical Totals overlying the area of significant Cross Totals, or the higher the Vertical Totals upwind, the greater will be the severity and certainty of thunderstorm development. The final refinement of the forecast areas is dependent on the accurate timing of the development and movement of anticipated trigger action.

The AFGWC has placed increasing emphasis on the use of the Total Totals (TT) in day-to-day forecasting. While it is still advisable to consider the Vertical and Cross Totals, it does appear that the TT is more reliable single predictor of severe activity in both warm- and cold-air situations. During 1964 and 1965, 92% of all reported tornadoes occurred in air masses having a TT of 50 or greater. Most of the family-type outbreaks accurred with a TT of 55 or greater. However, Total Totals must be used with careful attention to either the Cross Totals or the low-level moisture, since it is possible to have large Total Totals due to the temperature lapse rate with little supporting low-level moisture. Appendix B provides an excellent discussion on the use of Totals charts.

**Table 2 - Relationship of Severe Weather Intensities to Magnitude of Cross, Vertical and Total Indexes**

| FORECAST | CT | VT | TT |
|---|---|---|---|
| Isolated to few Thunderstorms Orange | 18-19 | 26 or more (with excep. prev.noted) | 44 |
| Sctd tstms orange, with few green | 20-21 | 26 | 46 |
| Sctd tstms orange few green tstms isolated blue | 22-23 | 26 | 48 |
| Sctd green - few blue - isolated red | 24-25 | 26 | 50 |
| Sctd to numerous green - few to sctd blue - few red | 26-29 | 26 | 52 |
| Numerous green - sctd blue and red | 30 | 26 | 56 |

# Chapter 9

# FORECASTING HAIL SIZE

## SECTION A—GENERAL

Hail size forecasts are made from a diagram prepared at the MWWC. This diagram (Figure 48) is based on data obtained in reports of wind-tunnel hail tests and estimates of the updraft velocities in thunderstorms [16].

## SECTION B—DESCRIPTION OF TECHNIQUE

The first step in forecasting hail is to determine the Convective Condensation Level (CCL). This parameter is evaluated on the adiabatic chart by finding the mean mixing ratio in the moist layer of the lowest 150 mb, and following this saturation mixing ratio line to its intersection with the sounding dry-bulb temperature curve. Next, the moist adiabat through the CCL is traced up to the pressure level where the dry-bulb air temperature is -5°C. This pressure level, the dry-bulb temperature curve and the moist adiabat through the CCL form a triangle outlining a "positive" area. The horizontal coordinate in Figure 48 is the length of the horizontal side of the triangle in degrees Celsius.

The vertical coordinate in Figure 48 is the length (in degrees) of a dry adiabat through the triangle. This length is measured from the pressure at the base of the triangle to the pressure of the CCL.

## SECTION C—EXAMPLE OF TECHNIQUE

In the sounding shown in Figure 49, the CCL is Point A. The moist adiabat from the CCL to the pressure level where the free-air temperature is -5°C is the line AB′. The isobar from the point where the air temperature is -5°C to its intersection with the moist adiabat is the line BB′. The dry adiabat from the isobar BB′ through the triangle to the pressure of the CCL is the line HH′. The base of the triangle (BB′), in degrees Celsius is 6° (from plus 1° to minus 5°). The length of the dry adiabat through the triangle is 21°C (from minus 4° to plus 17°). The value on the hail graph with a horizontal coordinate of 6 and a vertical coordinate of 21 is a forecast of one-inch hail.

## SECTION D—TROPICAL AIR MASSES

Along the Gulf Coast or in any air mass where the Wet-Bulb-Zero height is above 10,500 feet, the hail size derived from Figure 48 is too large. Corrections for this effect are obtained by the graph in Figure 50. The hail size derived from Figure 48 is entered on the horizontal coordinate of Figure 50 and the corrected hail size read off is compatible with the height of the Wet-Bulb-Zero temperature. For example, a hail size of one inch from Figure 48 is reduced to a 1/4-inch hail forecast if the Wet-Bulb-Zero height is 11,800 feet.

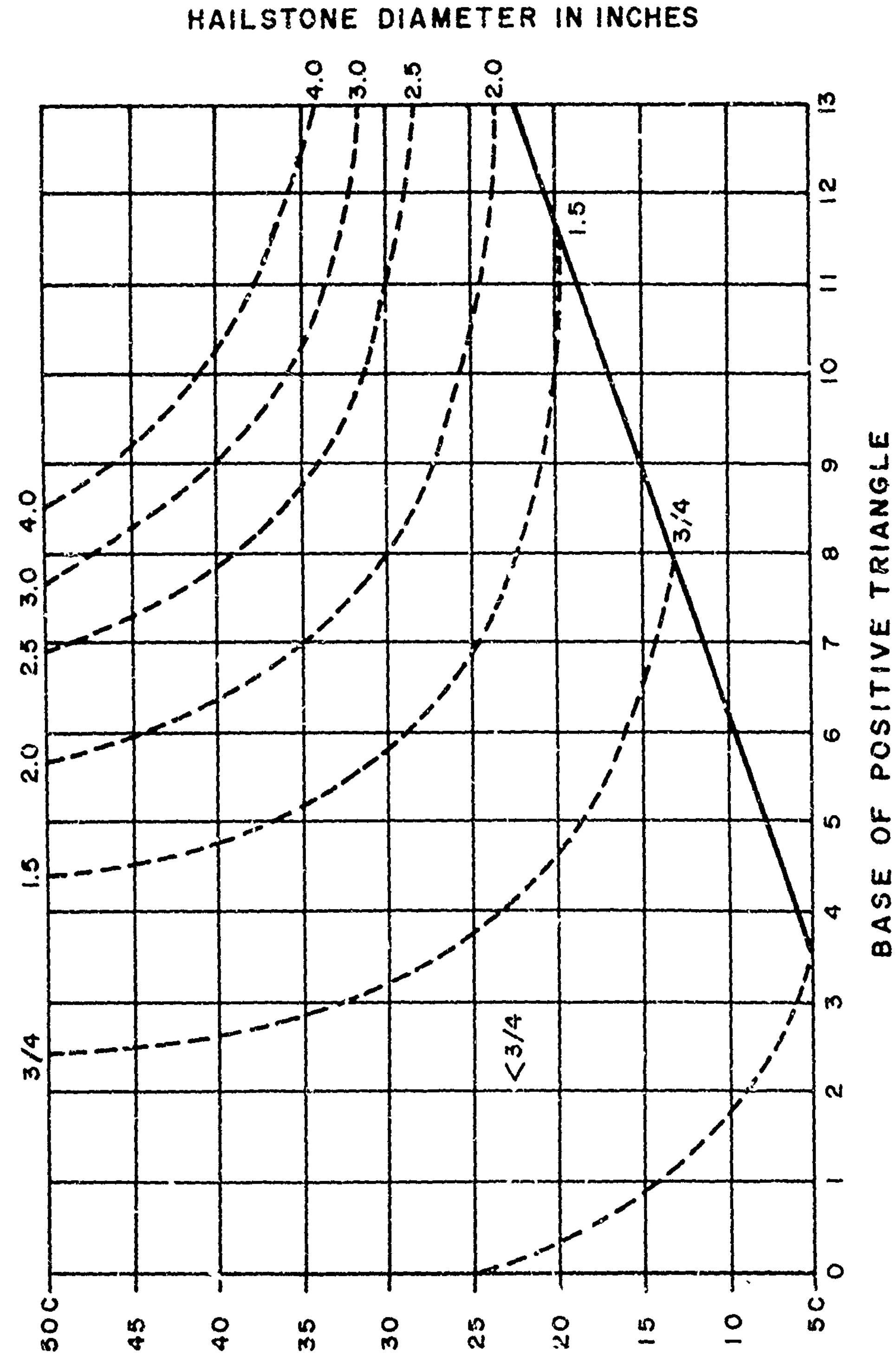



Figure 48 The Fawbush-Miller Hail Graph showing the forecast hailstone diameter in inches. Graph revised November 1965 on the basis of 622 hail reports.

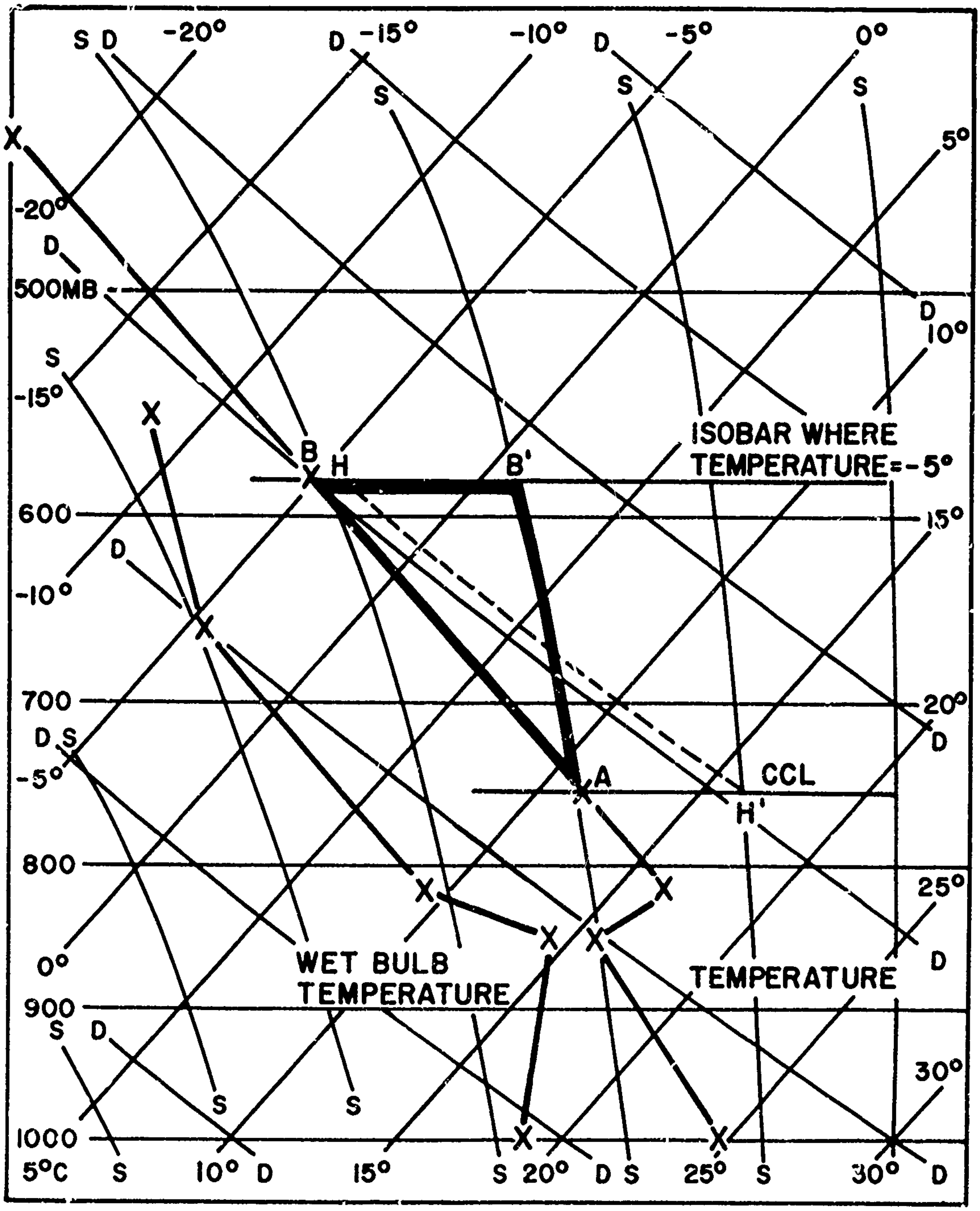



Figure 49. Example of hail size forecast from sounding. BB' is the base of the positive triangle and HH' measures the altitude. In this case 6 and 21 respectively. These values are equivalent to one-inch hailstones in Figure 45.

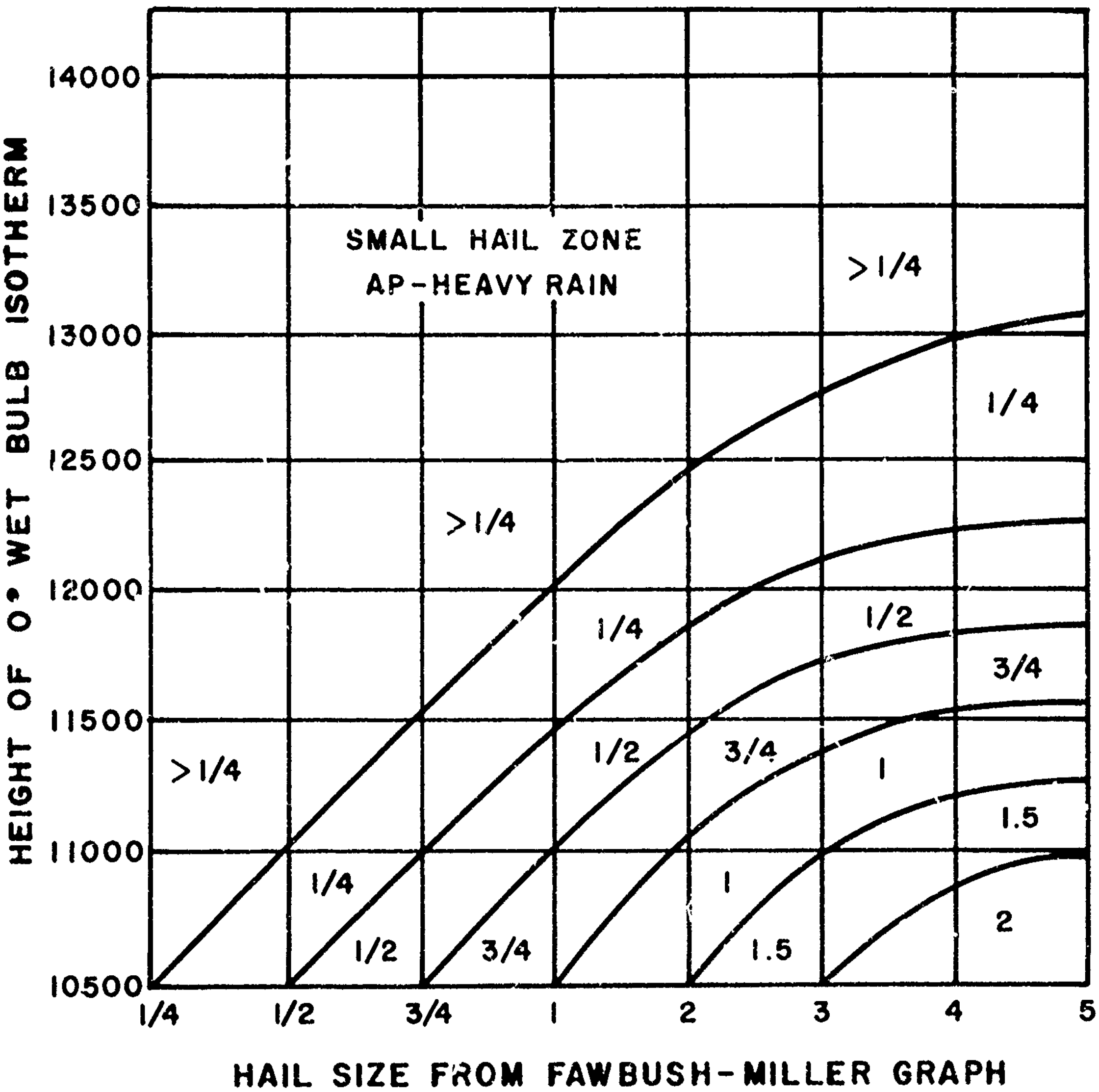



Figure 50. Hail size at surface expected in Type II air mass.

# Chapter 10

# FORECASTING MAXIMUM WIND GUSTS OF CONVECTIVE ORIGIN

## SECTION A—GENERAL

The AFGWC uses Table 3 to forecast the speed of maximum wind gusts. Table 3 is based on the empirical formula

$$(1) \quad V' = 13 \sqrt{T_1}$$

Since a large number of soundings are evaluated at the MWWC, this formula was devised as a simplification of a more basic formula [41]:

$$(2) \quad V' = 13 \sqrt{\frac{T_1 + T_2}{2}} + V$$

where:

a. V' is the speed of maximum wind gusts;

b. $T_1$ is the Dry Instability Index; and is defined in Section B;

c. $T_2$ is the Downrush Temperature subtracted from the dry-bulb temperature just prior to thunderstorm passage; and

d. V is one-third of the mean wind speed expected in the lower 5,000 feet above the ground. Local forecasters are urged to use the formula of equation (2) for the local refinement of wind warnings. For computing $T_1$ use Figure 51, and for $T_2$ use Figure 52.

The $T_1$ method is quite reliable in indicating maximum average wind gusts. To calculate the probable maximum peak gust, one-third of the mean wind speed expected in the lower 5,000 feet above the ground (V) should be added to the average value obtained.

## SECTION B—DETERMINATION OF $T_1$ AND $T_2$

$T_1$ is found in one of two ways:

a. If the sounding has an inversion, the moist adiabat is followed from the warmest point in the inversion to 600 millibars. The temperature difference between the intersection of the moist adiabat at the 600-mb isobar and the temperature of the dry bulb at 600-mb is $T_1$. The inversion (top) point should be within 150 or 200 mb of the surface and must not be susceptible to becoming wiped out by surface convection

b. If no inversion appears on the sounding, or if the inversion is relatively high (more than 200 mb above the surface), a different method is used to find $T_1$. The maximum temperature at the surface is forecast in the usual manner. A moist adiabat is projected from the maximum temperature to the 600-mb level. The temperature difference between the intersection of the moist adiabat and the 600-mb surface and the dry-bulb temperature at 600-mb is $T_1$.

$T_2$ is found by first locating the 0°C isotherm on the wet-bulb curve. A moist adiabat through that point is followed down to the surface and the temperature at that point recorded. This temperature is subtracted from the dry-bulb temperature (or the forecast free-air temperature) giving the value of $T_2$.

## SECTION C—DETERMINING THE GUST DIRECTION

For the direction of the maximum wind gust, the mean wind direction in the layer between 10,000 and 14,000 feet above the terrain is used.

The effect of the shift in speed and direction between the existing (or forecast) surface wind and the thunderstorm gust wind must be evaluated, in each instance, by the station weather officer. For example, a strong southwest surface wind which will be followed by a maximum gust from the northwest may require modification of local plans to protect parked aircraft. Hence, local wind warnings should be quite explicit when this type of situation appears likely.

## SECTION D—ALTERNATIVE FORECASTING METHOD

The AFGWC has a second method for forecasting maximum gusts, which is particularly useful when applied to isolated air-mass thunderstorms and/or squall lines. This empirical system uses the graph in Figure 53. The graph then indicates the probable minimum, mean, and maximum gust speeds. This method also predicts the direction of the maximum gust to be in the same direction as the mean wind between 10,000 and 14,000 feet above the terrain.

## SECTION E—SAMPLE FORECAST

Assuming the sounding as shown in Figure 51, a gust forecast is found by the following steps:

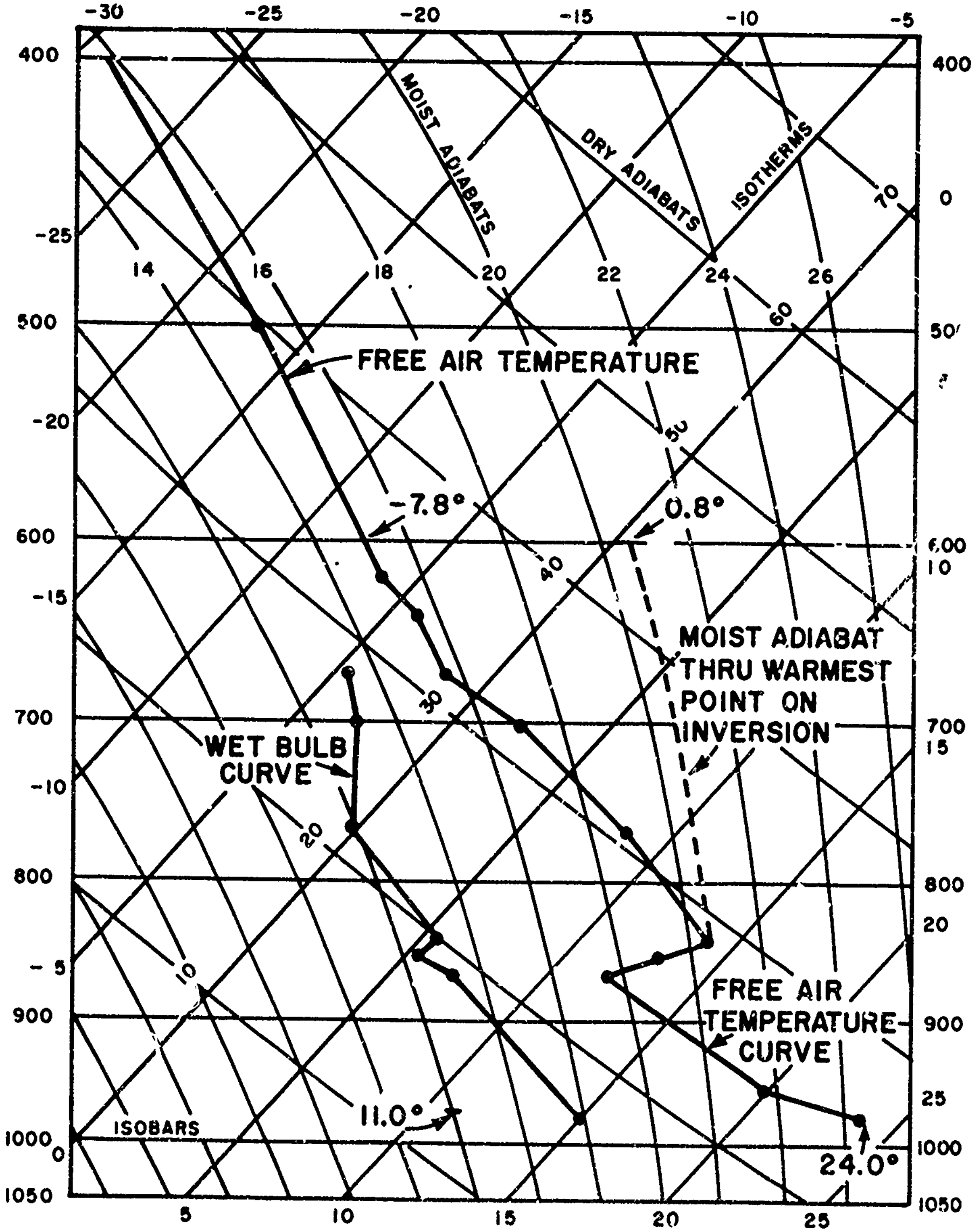



Figure 51. Example of sounding for wind gust forecast.

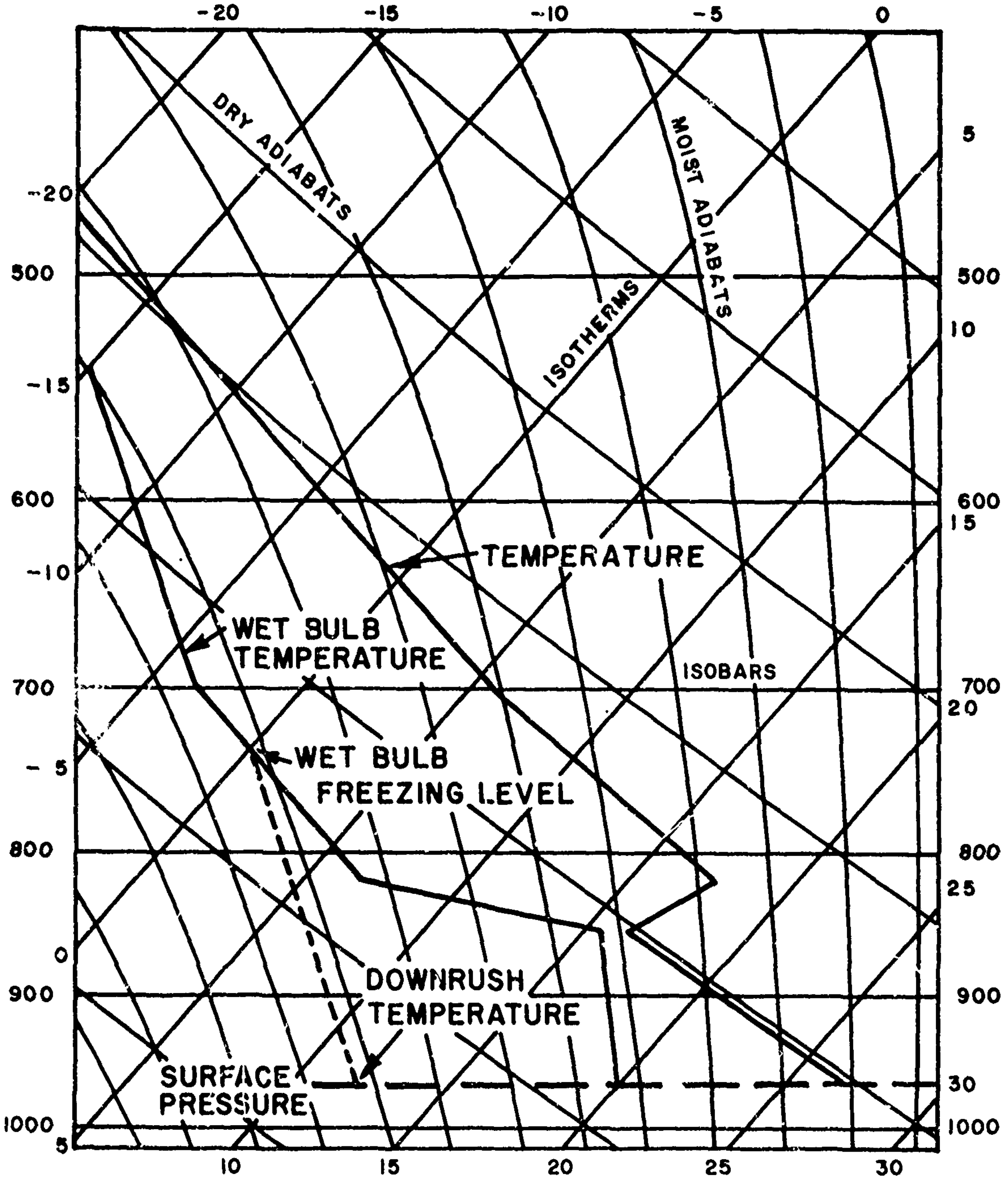



Figure 52. Determination of downrush temperature by tracing a saturation adiabat from intersection of wet bulb curve and 0°C isotherm to the surface pressure.

Table 3 - Use of $T_1$ for Maximum Wind Gusts

| $T_1$ Values in °C | Maximum Gust Speed (V') | $T_1$ Values in °C | Maximum Gust Speed (V') |
|---|---|---|---|
| 3 | 17 | 14 | 47 |
| 4 | 20 | 15 | 49 |
| 5 | 23 | 16 | 51 |
| 6 | 26 | 17 | 53 |
| 7 | 29 | 18 | 55 |
| 8 | 32 | 19 | 57 |
| 9 | 35 | 20 | 58 |
| 10 | 37 | 21 | 60 |
| 11 | 39 | 22 | 61 |
| 12 | 41 | 23 | 63 |
| 13 | 45 | 24 | 64 |
| | | 25 | 65 |

a. A moist adiabat is projected from the warmest point of the inversion to the 600-mb surface, and the temperature at that intersection point is found to be 0.8°C.

b. The dry-bulb temperature at 600-mb is -7.8°C, so that $T_1$ is about 9°.

c. Entering Table 3, the value of V' is found to be 35 knots. To this value add one-third the mean wind speed in the layer from the surface to 5,000 feet to obtain the maximum peak gust.

d. The forecast wind direction of the maximum gust is the same as the mean wind direction from 10,000 to 14,000 feet above the terrain.

Another forecast example uses the sounding of Figure 52.

a. A moist adiabat from Wet Bulb Freezing Level is projected downward to the surface and the temperature at the intersection point is found to 12°C.

b. Since the surface dry-bulb temperature is 27°C, the value of $T_2$ is 15°C.

c. Entering the Figure 53 at $T_2 = 15$, the probable minimum wind speed is 38 knots, the mean speed is 45 knots and the probable maximum is 52 knots.

d. Again the gust direction is the same as the mean wind in the 10,000 to 14,000 foot layer.

It is important to remember that the Table 3 method will indicate the maximum gust to be expected in a thunderstorm. In both examples the thunderstorm must pass over the forecast point and moderate to heavy rain must occur to attain the gust speeds forecast. If these unique conditions are not fully met, the method will appear to overforecast gust speeds.

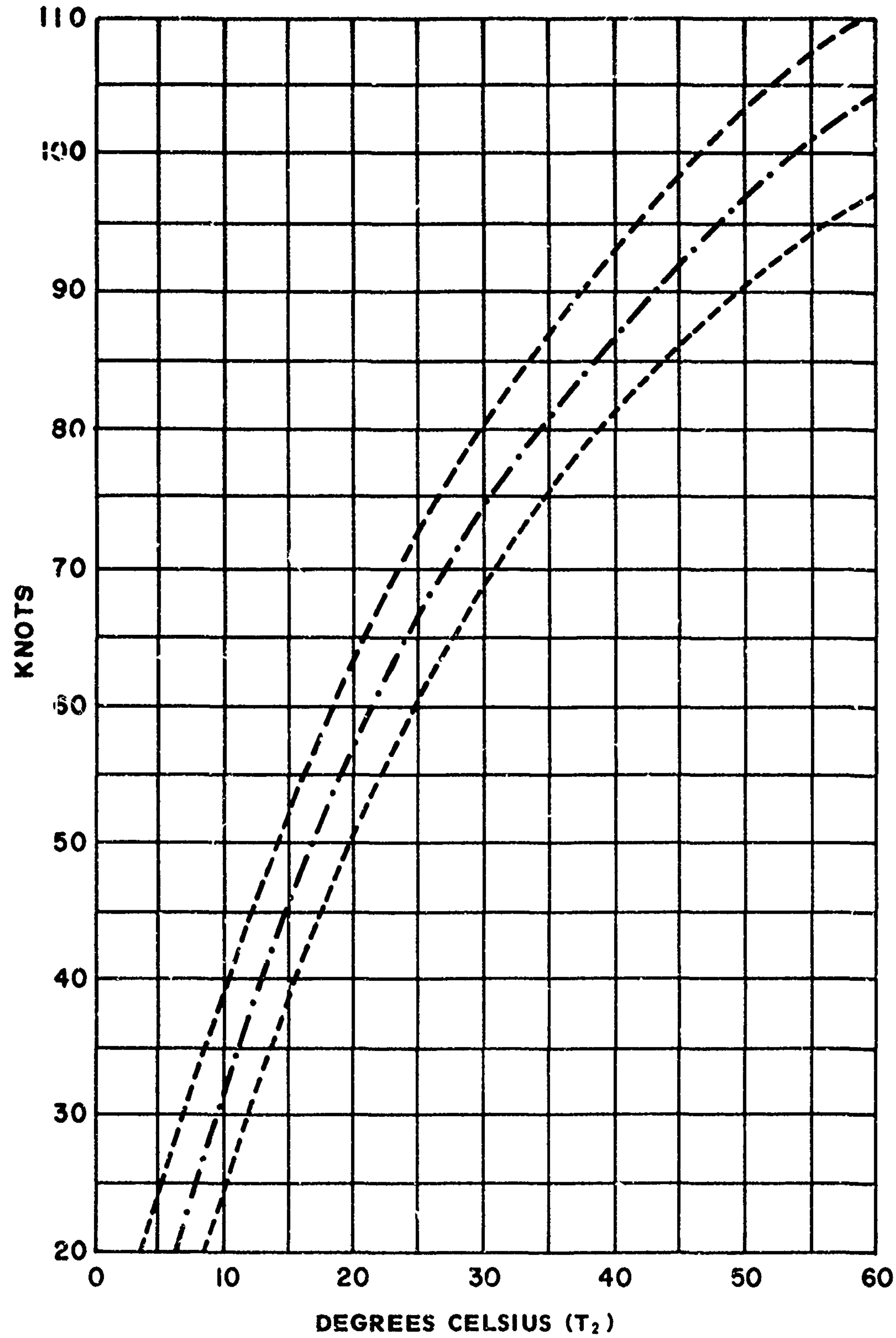



Figure 59. Alternative gust forecasting technique. Useful in the Type II air mass.

# Chapter 11

# CENTRALIZED AND LOCAL ADVISORIES AND WARNINGS

## SECTION A—GENERAL

The AFGWC has the unique mission and capability as the primary centralized severe weather warning facility within the Department of Defense (DOD). As such, the AFGWC provides centralized severe weather advisories and point warning service to designated military organizations and installations of the DOD and provides other meteorological services related to severe weather as directed by the Commander, AFGWC.

The AFGWC prepares and issues general area advisories and specific point warnings of potential or expected severe weather covering the 8 different phenomena shown in Table 4; and conducts studies and research to develop and apply improved severe weather forecast methods, with primary emphasis on computerized products.

Technical liaison is also maintained with the National Severe Storms Forecast Center (NSSFC) of the National Weather Service, Department of Commerce, Kansas City, Missouri. This is accomplished by direct hot-line contact with the NSSFC.

A color code has been adopted to identify the intensities of severe weather. This code reduces communication time and alerts the field forecasters to the most intense severe-weather areas. The colors and the corresponding intensities are often used for shading maps to display the warnings.

Advisories and point warnings of AFGWC are for the use of authorized military activities and personnel, and are not issued to other governmental agencies or civilian organizations.

## SECTION B—AFGWC ADVISORIES AND WARNINGS

The ultimate objective of the AFGWC is to indicate, within the smallest possible area of space and time, the probable intensity of unique severe weather occurrences which threaten the life, property, and operational capability of military installations. To accomplish this, two basic forecast products are provided: general area advisories and specific point warnings.

The area advisories provide basic guidance of expected broad scale severe weather developments to the forecaster in the field. The point warning specifically alerts the forecaster or installation authority at a location which is expected to be affected by severe weather.

The area advisories are disseminated over COMET II weather teletype circuits and the facsimile net operated by the Air Force Communications Service. Point warnings are disseminated over the COMET II weather teletype circuits and also by phone when conditions dictate. In addition, AFGWC provides severe weather input to other functions such as the low-level support function, terminal forecast function, and special mission support.

The Military Weather Warning Advisory (MWWA) is prepared every six hours and amended as necessary. It describes, in combination map and text format, the areas throughout the conterminous United States where phenomena which meet warning criteria are expected to occur during the subsequent 12-hour period. It is an estimate of the weather producing potential of the existing synoptic pattern and air masses, based on the assumption that subsequent changes in these features occur as forecast.

Although the forecaster must analyze and integrate large amounts of complex data to prepare the advisory, limited time is allowed for its completion and transmission. Thus, the data which it incorporates and the information which it conveys is made available to the user at the earliest feasible time. As a result, the forecast areas may be considerably larger and the valid period constantly longer than desirable for operational use. Nevertheless, this method of preparation and presentation effectively applies the concept of centralized forecasting. Since the relocation of the MWWC from Kansas City to the AFGWC, the preparation, dissemination, and overall accuracy of the MWWA has been vastly improved by heavy utilization of the analytic and prognostic information provided by the AFGWC data base.

The advisory makes available to the field forecaster, in directly useful form, the specialized attention, experience, and techniques which are available in the AFGWC. It alerts him to the probability of severe weather in his own area of concern. It serves him as an aid in briefing flight and control personnel on the broad-scale patterns of severe weather activity. It gives the field forecaster more time to solve his specific forecast problems and to apply the answers to the operation he supports. Since the advisory is an integral part of the AFGWC data base, it also provides input to other functions within the AFGWC in the preparation of forecast products.

Specific point warnings are the second and equally important product of the AFGWC. While area advisories provide general guidance to all military forecasters in terms of synoptic and mesoscale developments, point warnings are issued for and to specific locations in the smallest scale of space and time consistent with the availability of data and state of the art.

The approximate 500 locations for which the AFGWC has warning responsibility are listed in Volume II, AWSM 105-2. Since some of these locations include two, three, or four installations in one locality, the total number of installations served is well over 500. Approximately 50% of these are Air Force, 45% Army, and 5% Navy. Included are National Guard units, arsenals, ammunition plants, radar sites, and those civilian activities under contract to the Department of Defense.

Although the area advisory is issued at scheduled intervals for fixed valid periods, point warnings are issued as the situation warrants and amended, extended, or cancelled as necessary. Obviously, it is desirable to issue a warning sufficiently far in advance for the user to plan and take adequate protective measures with minimum interference to his operation. For the sake of forecast accuracy, however, the optimum lead time is that just long enough to permit necessary protective action. Developing an optimum lead time for each phenomena is a constant objective of the AFGWC; current efforts are concentrated on developing a lead time of 3 hours.

## SECTION C—DATA AVAILABLE TO AFGWC

Although the area advisory and point warning differ in content, format, dissemination, and use, they are closely related products of a joint team effort supported by the flow of observed data and forecast information from the AFGWC data base. In addition, the AFGWC has access to analyses and prognoses received by facsimile from the National Meteorological Center of the National Weather Service (NWS).

Also received are pilot reports from all military and civilian sources Hourly synoptic charts of all weather radar data are plotted by the AFGWC observers from data received over the NWS RAWARC Circuits. This is an inter-office teletype network which ties together all principal NWS offices.

Hourly surface observations are received from all civilian and military reporting stations. Observations are computer scanned and those pertaining to specific parameters of interest to the severe weather forecaster are routed to special teletype circuits. Flash reports of severe activity are also available as transmitted over the NWS RAWARC Circuits.

## SECTION D—SYNOPTIC PATTERNS AND LOCAL EFFECTS

Forecasters must consider all aspects of the broadscale synoptic pattern in order to evaluate the influence of a severe-weather advisory or point warning on their local area of responsibility. In particular, they should consider the following general meteorological conditions:

a. Position and movement of fronts, troughs, and other discontinuities.

b. Source, trajectory, and modification of air masses.

c. Wind flow at all levels.

Also, local influences play an important role in accelerating or modifying the development of severe weather. These influences include:

a. Terrain and other geographical peculiarities of the area.

b. Intensity of wind and weather critical for the installation and lead time required for adequate precautions.

c. Antecedent weather conditions and tendencies.

## SECTION E—RADAR OBSERVATIONS

Local radar observations have many uses, including:

a. Comparison with observations from surrounding stations.

b. Discovery of approaching squall lines.

c. Detection of the area of maximum echo intensity. If the area is upwind of the mid-level wind flow, the station probably lies in the path of the most severe storms.

d. Recognition of severe-weather echoes. Photographs in recent years have identified certain echo configurations as being productive of tornadoes and damaging winds, the most prominent of these being the "hook" echo. Such echoes should be viewed with suspicion. However, in most cases the hook is not in evidence, perhaps because it may be masked by precipitation.

e. Detection of perturbations on squall lines. Lines of echoes or squall lines are rarely smooth. Mesoanalysis of the direction of motion and the speed of movement of segments may indicate points where wave development is taking place. Such perturbations are favored locations for severe storms.

f. Monitoring the movement and characteristics of individual cells.

(1) Cells that move more rapidly than others are likely to produce the maximum downrush velocities. When two cells merge, intensification results and severe weather phenomena often result. Eyewitness accounts of numerous tornadoes indicate formation when two cells or thunderstorms merge. Usually one comes from the west and one from the southwest.

(2) Many observations of severe storms on radar have shown dark spots within echoes. Altering the antenna angle shows the dark spot to extend to great heights and tilt somewhat forward in agreement with the speed of upper-level winds. These dark spots sometimes termed "vaults" [6] [7] appear to occur often with the most severe storms and tornadoes. Some recent radar photographs indicate these dark spots, or holes, are connected with the lower "hook" portions of the echo.

(3) Careful interpretation of radar echoes, coupled with mesoanalysis of surface observations, permits identification of intersecting lines of activity. These intersections locate and follow mesolows which serve as triggering mechanisms for tornadic activity.

## SECTION F—TERMINAL OBSERVATIONS

Local terminal observations provide useful information, including:

a. Ceiling and cloud cover.

(1) In some instances, lower clouds will decrease with the approach of a severe storm, even an hour or more in advance.

(2) Any advance of middle clouds should be studied for evidences of mammatus. The paths of severe storms are generally south of the lowest axis of mammatus formation. If the mammatus is below 14,000 feet, the barometer trace may be erratic indicating turbulent conditions aloft. This sign may be indicative of rapidly developing severe weather.

b. Pressure:

(1) Increasing instability of the air structure is generally reflected in erratic behavior of the barometer.

(2) Without contradicting the concept of falling pressure with the approach of the storm, it is sometimes noted that, with the approach of a fast-moving squall line or bubble, the fall will decelerate or even a slight rise set in prior to a more rapid fall.

(3) If the barometer is falling very rapidly, there usually is intense vertical motion in the local area.

c. Temperature and dew point.

(1) An increase in temperature and dew point greater than the normal diurnal change shows that heat and moisture are being added to the lower levels of the local air column. If comparison with surrounding stations indicates that the maximum positive change is in the local vicinity, the station is, or will be, in the area of maximum severe activity.

(2) If a falling barometer accelerates its fall simultaneously with an increase in temperature and dew point, the probability of a storm occurrence is substantially increased.

d. Wind.

(1) The surface winds usually decrease in speed and back with the approach of a severe storm; however, this tendency is generally too late to be of much help.

(2) If the surface wind increases in speed and shifts from southerly to westerly, the disturbance is probably developing north of the station.

(3) If the surface wind increases in speed and shifts from easterly to southerly, the storm is probably approaching.

(4) If the wind above 8,000 feet MSL increases rapidly in comparison to previous observations and the speeds exceed the geostrophic, the installation is probably near the area of destructive winds.

(5) If the wind above 8,000 feet MSL shows a sharp decrease in speed, the probability of tornadoes is increased, for the station is in the vicinity of a sharp horizontal wind shear and/or strong vertical currents are developing.

e. Remarks of neighboring stations should be monitored constantly for indications of the formation and movement of instability phenomena. Each station should include pertinent remarks in its own transmission for the benefit of its neighbors.

## SECTION G—SUMMARY

If the general air structure is favorable for tornado and other severe-storm development, the correlation of the synoptic situation and radar observations with a mesoanalysis of the local area and fluctuations of station instruments will provide guidance on the activity to be expected at least an hour in advance. While it is often difficult, the problems involved in forecasting local storms are not insurmountable for the persistent and conscientious forecaster.

Table 4 - Definition of Severe Weather Intensities by Color

| Color | Severe Weather |
|---|---|
| Red | Tornadoes or tornado waterspouts. |
| Blue | Severe Thunderstorms (those with maximum wind gusts of 50 knots or greater or hail greater than one inch in diameter or locally damaging windstorms). |
| Green | Moderate Thunderstorms (those with maximum wind gusts greater than 34 knots but less than 50 knots and hail, if any, one-half inch or greater but equal to or less than one inch in diameter). |
| Orange | Thunderstorms (those with maximum wind gusts less than 35 knots and hail, if any, less than one-half inch in diameter). |
| Black | Strong surface winds (35 knots or more and not associated with thunderstorms). |
| Purple | Heavy Rain (two inches or more in a 12-hour period). |
| Hatched Purple | Heavy Snow (two inches or more in a 12-hour period). |
| Brown | Freezing Precipitation (other than very light). |

## REFERENCES

(1) Asp, M.O.: "History of Tornado Observations and Data Sources," Met Records Documentation No. 3.131, Washington, D.C., 1963, 25 pp.

(2) Bates, F.C.: "The Great Plains Squalling Thunderstorm-a Model," PhD Dissertation, St. Louis University, 1961, 164 pp.

(3) Beebe, R.G.: "An Instability Line Development as Observed by the Tornado Research Airplane," *Jn. of Met.,* Vol. 15, No. 3, June, 1958, pp 278-282.

(4) Beebe, R.G.: "Tornado Proximity Soundings," *Bull. Amer. Met Soc.,* Vol. 39, No. 4, April, 1958, pp. 195-201.

(5) Beebe, R.G., and Bates, F.C.: "A Mechanism for Assisting in the Release of Convective Instability," *Mon. Wea. Rev.,* Vol. 83, No. 1, January, 1955, pp 1-10.

(6) Bidner, A.: "The AFGWC Severe Weather Threat Index," (A Preliminary Report). AWS TR242, 1970, pp 229-231 (AD 724093)

(7) Brooks, E.M.: "Origin of a Tornado's Rotation," Third Conference on Severe Local Storms, AMS, Urbana, Illinois, 1963.

(8) Browning, K.A., and Donaldson, R.J., Jr.: "Airflow and Structure of a Tornadic Storm," *Jn of Atmo. Sci.,* Vol. 20, No. 5, November, 1963, pp. 533-545.

(9) Browning, K.A., and Fujita, T.: "A Family Outbreak of Severe Local Storms," AFCRL Spec. Rep., No. 32, September, 1965, 346 pp.

(10) Byers, H.R., and Braham, R.R.. *The Thunderstorm,* U.S. Government Printing Office, Washington, D.C., 1949.

(11) Changnon, S.A., Jr. and Stout, G.E.: "Tornadoes in Illinois," Circular 63, State Weather Survey Division, Urbana, Illinois, 1957.

(12) Chappell, C.F.: "The Importance and Analysis of the Surface Chart in Severe-Weather Forecasting," U.S. Weather Bureau Library, Kansas City, Mo. (Multilith)

(13) Chappell, C.E.: "Some Surface Synoptic Characteristics of Severe-Weather Occurrences." U.S. Weather Bureau Library, Kansas City, Mo. (Multilith)

(14) Crumrine, H.A.: "The Use of the 850/500-MB Thickness, the 850/500-MB Thickness Change, and the 850-MB Wind Shear in Severe-Weather Forecasting," U.S. Weather Bureau Library, Kansas City, Mo. (Multilith)

(15) Darkow, G.L.: "The Total Energy Environment of Severe Storms," *Jour. Appl. Meteor.,* Vol. 7, No. 2, 1968, pp. 199-205.

(16) Fawbush, E.J., and Miller, R.C.: "A Method of Forecasting Hailstone Size at the Earth's Surface," *Bull. Amer. Met. Soc.,* Vol. 34, No. 6, June, 1953, pp. 235-244.

(17) Fawbush, E.J., and Miller, R.C.: "The Types of Air Masses in Which American Tornadoes Form," *Bull. Amer. Met. Soc.,* Vol. 35, No. 4, April, 1954, pp. 154-165.

(18) Fawbush, E.J. and Miller, R.C.: "A Method for Forecasting Peak Gusts in Non-Frontal Thunderstorms," *Bull. Amer. Met. Soc.,* Vol. 35, No. 1, January, 1954, pp. 14-19.

(19) Fawbush, E.J. and Miller, R.C.: "A Mean Sounding Representative of the Tornado Air Mass," *Bull. Amer. Met. Soc.,* Vol. 33, No. 7, September, 1952, pp. 303-307.

(20) Fawbush, E.J. and Miller, R.C.: "The Tornado Situation of March 17, 1951," *Bull. Amer. Met. Soc.*, Vol. 34, No. 4, April, 1953, pp. 139-145.

(21) Fawbush, E.J. and Miller, R.C.: "Forecasting Tornadoes," *Air University Quarterly Review*, Maxwell AFB, Alabama, Spring, 1953, pp. 108-177.

(22) Fawbush, E.J., Miller, R.C., and Starrett, L.G.: "An Empirical Method for Forecasting Tornado Development," *Bull. Amer. Met. Soc.*, Vol. 32, No. 1, January, 1951, pp. 1-9.

(23) Fawbush, E.J., Miller, R.C., and Starrett, L.G.: "Severe-Weather Forecasting," *Miscelanea Geofiscia*, Luanda, Angola, 1956, pp. 229-250.

(24) Fawbush E.J., Miller, R.C., and Starrett, L.G.: "Severe Weather Occurrences and Mid-Tropospheric Flow Patterns," *Bull, Amer. Met. Soc.*, Vol. 38, No. 3, March, 1957, pp. 113-123.

(25) Finley, J.P.: "Report on the Character of Six-Hundred Tornadoes," Professional Papers, U.S. Signal Service, No. VII, Washington, D.C., 1884.

(26) Flora, Snowden: *Tornadoes of the United States*, University of Oklahoma Press, Norman, Oklahoma, 1953.

(27) Foster, D.S.: "A Revised Hail Forecasting Technique," U.S., Weather Bureau Library, Kansas City, Mo., April, 1961, (Multilith)

(28) Foster, D.S.: "Relationship Between Tornadoes, Vorticity Acceleration, and Air-mass Stability," Third Conference on Severe Local Storms, AMS, Urbana, Illinois, 1963.

(29) Fujita, T.: "Formation and Steering Mechanisms of Tornado Cyclones and Associated Hook Echoes," *Mon. Wea, Rev.*, Vol. 93, No. 2, February. 1965, pp. 67-78.

(30) Fujita, T.: "A Detailed Analysis of the Fargo Tornadoes of June 20, 1957," *Research Paper No. 42*, U.S. Weather Bureau, Washington, D.C., 1960, 67 pp.

(31) Fujita, T.: "Results of Detailed Studies of Squall Lines," *Tellus*, Vol. 7, No. 4, November, 1955, pp. 405-436.

(32) Fujita, T.. "Structure and Movement of a Dry Front," *Bull. Amer. Met. Soc.*, Vol. 39, No. 11, November, 1958, pp. 574-582.

(33) Galway, J.G.: "The Lifted Index as a Predictor of Latent Instability," *Bull. Amer. Met. Soc.*, Vol. 37, No. 10, December, 1956, pp. 528-529.

(34) Galway, J.G.: "Some Aids in Localizing Activity Within Severe Local Storms Forecast Areas," U.S. Weather Bureau Library, Kansas City, Mo, October, 1957. (Multilith)

(35) Galway, J.G. and Lee, J.T.: "The Jet Chart," *Bull. Amer Met. Soc.*, Vol. 39, No. 4, April, 1958, pp. 217-223.

(36) George, J.J.: *Weather Forecasting for Aeronautics*, Academic Press, N.Y., 1960, 673 pp.

(37) Hadeen, K.D.: "AFGWC Boundary Layer Model," AFGWC Technical Memorandum 70-5, 1970. 59 pp. (AD 713058)

(38) House, D.C.: "The Mechanics of Instability Line Formation," *Jn. of Met.*, Vol. 16, No. 2, April, 1959, pp. 108-120.

(39) House, D.C., and Pautz, M.E.: "Forecasting Tornadoes and Severe Thunderstorms." Third Conference on Severe Local Storms, AMS, Urbana, Illinois, 1963.

(40) Humphreys, W.J.: *Physics of the Air*, 3rd Edition, McGraw-Hill Book Co., New York, New York, 1940.

(41) Jordan, H.: "Gust Forecast," *AAF Weather Service Bulletin,* Vol. 3, No. 7, Jul/Aug 1945, pp. 22-23.

(42) Koceilski, A.: "A Preliminary Computer Analysis of Parameters Associated with Tornadic Activity," U.S. Weather Bureau Library, Kansas City, Mo.

(43) Lee, J.T., and David, C.L.: "Squall-Line Structure and Development as Depicted by Horizontal Traverses by the Tornado Research Aircraft," *Bull. Amer. Met. Soc.,* Vol. 42, No. 9, September, 1961, pp. 595-602.

(44) Lee J.T. and Galway, J.G.: "Preliminary Report on the Relationship Between the Jet and the 200-MB Level and Tornado Occurrence," *Bull. Amer. Met. Soc.,* Vol. 37, No. 7, September, 1956, pp. 327-332.

(45) Lloyd, J.R.: "The Development and Trajectory of Tornadoes," *Mon. Wea. Rev.,* Vol. 70, No. 4, April, 1942, pp. 65-75.

(46) Ludlam, F.H.: "Severe Local Storms: A Review," Monograph on Severe Local Storms, AMS, Boston, Mass. 1963.

(47) Magor, B.W.: "Mesoanalysis: Some Operational Analysis Techniques Utilized in Tornado Forecasting," *Bull. Amer. Met. Soc.,* Vol. 40, No. 10, October, 1959, pp. 499-511.

(48) Magor, B.W.: "A Mesolow Associated With a Severe Storm," *Mon. Wea. Rev.,* Vol. 86, No. 3, March, 1958, pp. 81-90.

(49) Magor, B.W.: "Further Tests of Operational Mesoanalysis," *Mon. Wea. Rev.,* Vol. 86, No. 3, March, 1958, pp. 116.

(50) Miller, R C., Bidner A., and Maddox, R.A: " The Use of Computer Products in Severe Weather Forecasting," Preprints, Seventh Conference on Severe Local Storms, AMS, Kansas City, Mo., 1971, pp. 1-6.

(51) Miller, R.C.: "Tornado Producing Synoptic Patterns," *Bull. Amer. Met. Soc.,* Vol. 40, No. 9, September, 1959, pp. 465-472.

(52) Miller, R.C., and Starrett, L.G.: "Forecasting Thunderstorms in Great Britain," *The Meteorological Magazine,* Vol. 91, No. 1082, September, 1962, pp. 247-254.

(53) Miller, R.C., and Starrett, L.G.: "Severe Thunderstorm Forecasting in Europe," *Operations Digest,* 2nd Weather Wing, AWS, Weisbaden, Germany, Spring, 1961.

(54) Miller, R.C., W[illegible] A., and Bartlett, L.: "The Use of the 500/850-MB Totals in Severe-Weather Forecasting," U.S. We[illegible]eau Library, Kansas City, Mo., 1965, 42 pp.

(55) Miller, S.R. and David, C.l.: "A Statistically Generated Aid for Forecasting Severe Thunderstorms and Tornadoes," Preprints, Seventh Conference on Severe Local Storms, AMS, Kansas City, Mo., 1971, pp 42-44.

(56) Newton, C.W.: "Dynamics of Severe Convective Storms," NSSP Project Report, No. 9, July, 196[illegible], 44 pp.

(57) Pautz, M.: "Severe Local Storm Occurrences 1955-1967," ESSA Tech Memorandum, WBTM FCST 12, 1968, 77 pp.

(58) Rhea, J.O.: "A Theory of Thunderstorm Formation Along Dry Lines," Third Conference on Severe Local Storms, AMS, Urbana, Illinois, 1963.

(59) SELS Staff: "Forecasting Tornadoes and Severe Thunderstorms," Forecasting Guide No. 1, U.S. Weather Bureau, Washington, D.C., 1956, 34 pp.

(60) Showalter, A.K.: "Stability Index for Forecasting Thunderstorms," *Bull. Amer. Met. Soc.,* Vol. 34, No. 6, June, 1953, pp. 250-252.

(61) Showalter, A.K., and Fulks, J.R.: "A Preliminary Report on Tornadoes," U.S. Weather Bureau, Washington, D.C., 1943.

(62) U.S. Weather Bureau: "Tornadoes 1916-1961," Letter Supplement 59B, U.S. Weather Bureau, Washington, D.C., Revised April, 1962.

(63) Varney, B.M.: "Aerological Evidence as to the Causes of Tornadoes," *Mon. Wea. Rev.*, Vol. 54. No. 4, April, 1926, pp. 163-165.

(64) Williams, D.T.: "Instability Lines and Their Environments as Shown by Aircraft Soundings and Quasi-Horizontal Traverses." NSSP Project Report No. 3, February, 1962, 15 pp.

(65) Wolford, Laura V.: "Tornado Occurrences in the United States," *Technical Paper No. 20,* U.S. Weather Bureau, Washington, D.C., Revised 1960.

(66) Wood, P.A.: "Techniques Used in Surface Analysis," U.S. Weather Bureau Library, Kansas City, Mo. (Multilith)

# Appendix A

# GLOSSARY OF SELECTED TERMS

*Adiabatic Chart.* Any thermodynamic diagram plotting temperature against either log p or $p^{0.288}$ and containing dry adiabats, either saturation or pseudo-adiabats, and saturation mixing-ratio curves.

*Autoconvection.* If the lapse exceeds 3.4°C/100 m, density increases with height and the layers will over-turn spontaneously. This situation arises in shallow layers due to surface heating and also develops aloft due to evaporative cooling of virga and hydrometeors into dry air. Such overturning, without other trigger action, is called "autoconvection."

*Bubble; Bubble High.* It frequently happens that precipitation and vertical currents associated with thunderstorms induce small anticyclones (i.e., shallow domes of cooled air) causing slightly higher pressure, complete with clockwise circulation, of the order of 50 to 300 miles across. These transitory small highs have the effect of a different air mass and unstable air overrunning them may form squall lines on their leading edge. Such cells are called "bubbles."

*Chinook.* In the western United States, a foehn wind is commonly called "Chinook," after an Indian tribe of the northwest.

*Convective Condensation Level,* abbreviated "CCL." If surface air is heated from below until adiabatic ascent brings it to saturation, the level at which this occurs is called the "Convective Condensation Level." This may be found on an adiabatic chart by starting at the mean mixing ratio of the surface moist layer (or lowest 150 mb, whichever is most representative) and ascending the constant mixing ratio line to its intersection with the sounding. This point is at the Convective Condensation Level.

*Convection Temperature.* The surface temperature that must be reached to initiate convective currents that will extend high enough to reach saturation. The convection temperature is found on an adiabatic chart by ascending from the mean dew point to the moist layer along the mixing ratio curve to the sounding, then descending along the dry adiabat to the surface pressure.

*Convergence.* When streamlines approach each other, the region is said to exhibit "confluence." When wind speeds diminish downstream, "Speed convergence" is indicated. Both are usually indicative of mass convergence.

*Cross Totals Index.* The 500-mb dry-bulb temperature subtracted from the 850-mb dew point.

*Destructive local storm, abbreviated "DLS."* DLS comprise tornadoes, hail, and thunderstorm gusts over 50 knots at the surface.

*Dew-Point Index.* The difference between the 500-mb temperature and the mean dew point of the moist layer raised along a pseudoadiabat to 500 mb. This index varies less with diurnal surface heating than the Stability Index.

*Diffluence.* The rate at which adjacent flow is diverging along an axis oriented normal to the flow.

*Divergence.* Regions wherein streamlines diverge are said to exhibit "diffluence." Wherever wind speeds increase downstream, "speed divergence" is indicated. Both are usually indicative of mass divergence.

*Downrush.* The strong downward-flowing air currents associated with thunderstorms.

*Downrush Temperature.* The temperature found by lowering the Wet-Bulb-Zero down a pseudoadiabat to the surface pressure. This closely approximates the temperature of downrush currents in thunderstorms when they reach the surface.

*Dry.* Air is considered very dry if its relative humidity does not exceed 50 percent. Air is considered moist if its relative humidity is not less than 65 percent. Intermediate values of relative humidity are moderately moist.

*Dry Instability Index.* The difference between the surface temperature raised along a pseudoadiabat to 600 mb and the sounding at 600 mb. If an inversion exists below 600 mb such that the temperature raised from its top would give a larger index, then this latter value is used.

*Equatorial Air.* An air mass that invades the Gulf Coast region from time to time. It has very high temperature and high moisture content. It is usually conditionally and convectively unstable, without a significant inversion or dry layer.

*Foehn.* A warm, dry wind that descends the leeward side of mountain ranges. Its characteristics are the result of forced ascent, during which it absorbs the heat of condensation of its moisture, then descent, during which it warms at the dry adiabatic rate ("Chinook" of the northwest United States).

*Front.* A surface, line, or zone where one or more meteorological elements vary rather abruptly; a "discontinuity." The primary AFGWC criterion for the identification of a front is its usefulness in forecasting rather than any set of objective criteria.

*Gust.* A sudden brief increase in wind speed. Particularly, the gusts associated with the violent downrush that comes out of the base of a thunderstorm and spreads out horizontally at the surface.

*Hail.* Precipitation in the form of ice. In forecasting, it is assumed that hailstones are spherical and the size is given as the diameter in inches.

*Height.* As used by the AFGWC, heights are those measured on an adiabatic chart, either simply by noting the pressure, or by applying the "ICAO Standard Atmosphere Altitude" scale from the surface pressure upward. For example, the Level of Free Convection may be noted at 650 mb, the depth of the moist layer 3,000 feet, and the wet-bulb freezing level at 8,200 feet. The last two would be determined from the surface pressure without correction for temperature.

*Humidity.* Three measures of humidity are commonly used, according to the purpose:

1. Relative humidity is used in determining whether air is saturated or unsaturated, and the amount of moisture relative to saturation. Air is considered "moist" if its relative humidity is 65 percent or more, "dry" if its humidity is 65 percent or less, and "very dry" if its relative humidity is 50 percent or less.
2. Mixing ratio is used as a measure of the absolute amount of water vapor available.
3. Dew point in severe-weather forecasting is used at the surface only, purely as a matter of convenience, due to its being the only measure of humidity that is reported. It must be compared with the temperature to determine the moistness or dryness of the air and must be compared with the pressure to determine the amount of water vapor available.

*Instability.* The term "potential" is used in MWWC to describe all forms of instability that require an activating mechanism for realization. Thus, "potential instability" includes latent instability, convective instability, conditional instability, and even stable situations that are forecast to become unstable due to anticipated changes. Usually when "instability" is mentioned, "potential" is understood, as indicated by one of the various indexes (Showalter, Lifted, Totals, etc.). It is believed that absolute instability occurs in the natural atmosphere though it may be temporary, and the superadiabatic lapse rates reported in radiosonde observations are often significant. Mechanical instability, leading to autoconvection, exists when the lapse rate exceeds about 10°C/1,000 feet. It is believed this situation arises not only in a shallow surface layer on hot days, but also in the upper air when precipitation falls into and rapidly evaporates within a dry layer.

*Isotach.* Line of equal wind speed.

*Lifted Index.* Measure of potential instability computed by lifting the mean moisture in the lower 3,000 feet of the atmosphere moist adiabatically to 500 mb and subtracting the temperature at this point from the reported 500-mb free-air temperature.

*Level of Free Convection* is the level at which a parcel of air lifted dry-adiabatically until saturated; and saturation-adiabatically thereafter; would first become warmer than its surroundings, in a conditionally unstable atmosphere. Found at the pressure level where the mean wet-bulb temperature of the moist layer, raised along a pseudoadiabat, first intersects the sounding.

*Mean; Average.* Usually taken as the arithmetic mean, i.e., the quotient of the sum of a set of values divided by the number of values in the set. In severe-weather forecasting, the mean is usually estimated by eye (e.g., the mean dew point of the moist layer is normally the dew point in the middle of the moist layer, assuming a linear dew-point laps rate).

*Mesoscale.* That scale of atmospheric motions of characteristic dimensions too small to remain readily identifiable on the macroscale synoptic maps. Results of mesoanalysis reveal systems which have definite order, pattern, and chronological continuity such as *mesohighs* and *mesolows.*

*Saturation Adiabat.* Commonly used for pseudoadiabat, or whatever curve appearing on an adiabatic chart to indicate the lapse rate with upward motion of saturated air (used synonomously with "moist adiabat").

*Severe Weather Threat (SWEAT) Index.* An empirically-derived index used to specify and predict areas of potentially severe convective weather.

*Shear.* The difference in wind velocity between two contiguous air currents generally measured to the right of the jet or maximum wind axis.

*Showalter Stability Index.* The difference between the 500-mb temperature and the wet-bulb temperature of the 850-mb level raised along a pseudoadiabat to 500 mb.

*Significant Moisture.* A 6-degree or less temperature dew-point spread at any level, or a dew point of -17°C or warmer at 500 mb, or 0°C or warmer at 700-mb.

*Smoothing.* The process of eliminating insignificant or unimportant irregularities in isolines of a parameter analyzed on a map or diagram (usually done by eye in ordinary weather analyses). In severe-weather forecasting, irregularities are of the greatest importance; smoothing is minimized.

*Storm.* Short for thunderstorm; or area of thunderstorms and associated severe phenomena, hail, strong gusts, and tornadoes. These are local in nature in contrast to extensive frontal systems and hurricanes.

*Streamline.* A curve whose direction at every point coincides with the instantaneous direction of the wind. Not to be confused with paths or trajectories. Streamlines show the synoptic pattern of the wind direction, which is usually similar to, but not identical with the pressure pattern.

*Structure of the Atmosphere.* Vertical distribution of the magnitudes of temperature, humidity, and stability of a representative air column or parts thereof.

*Surge.* A relatively sudden and vigorous movement, of an air mass, or an air-mass property, in some particular direction. Also used for pressure increases not explained by the more usual meteorological patterns.

*Thunderstorm.* A cumulonimbus cloud that produces thunder and/or lightning, sometimes hail, gusts, and tornadoes; set off by convergence, frontal activity, orographic lift, or surface convection.

*Tornado.* Any destructive wind gust or whirl associated with a pendant funnel or tubular cloud of very limited horizontal extent (when over water, a waterspout).

*Total Totals Index.* The sum of the Vertical and Cross Total Indexes.

*Uprush.* The updraft in a thunderstorm. The speed of the ascending current in a thunderstorm has never been measured directly, but may be estimated from the size of hail produced and from study of a sounding representative of the air producing the thunderstorm.

*Vertical Totals Index.* The 500-mb dry-bulb temperature subtracted from the 850-mb dry-bulb temperature.

*Waterspout.* A tornado over water.

*Wet-Bulb Temperature.* No distinction is made between the wet-bulb temperature, which is the lowest temperature to which a sample of air may be cooled by isobaric evaporation of water into it, and the pseudo-wet-bulb temperature, which is that of a parcel raised dry adiabatically to saturation, then returned pseudoadiabatically to its original pressure. The wet-bulb temperature curse, actually the pseudo-wet-bulb temperature curve, is used to a great extent in severe-weather forecasting.

*Wet-Bulb-Zero.* The height in the environment sounding of the wet-bulb at the intersection of the 32°F (0°C) isotherm on the adiabatic chart. It is assumed that this is an indication of the height of the freezing level, in a storm column, that might develop in the air mass.

*Wind.* The horizontal component of air motion over the surface of the earth.

# Appendix B

# THE SEVERE-WEATHER SITUATIONS 3 AND 4 DECEMBER 1964

## SECTION A—GENERAL

The Vertical and Cross Totals were analyzed for 2-degree intervals on Figure 54. The barbed isolines represent Cross Totals (CT) beginning with a value of 18, and were drawn with regard for the moisture influx and low-level wind flow. Thus, the area of maximum CT over northwest Louisiana extended to the ENE in the strong low-level wind flow (shown by solid black arrows) curving from the western Gulf toward Nashville. Although the 18-CT line enclosed a rather large area, the significant 500-mb moisture (depicted by cross-hatching) was limited over much of the map, and little probability existed that middle-level moisture would be advected into Georgia, Alabama, and South Carolina during the following 18 hours. It was more likely that any thunderstorm occurring over these sections during the forecast period would consist of the remnants of activity forming over the very unstable areas in Arkansas and Louisiana. Since this was an early evening chart, additional surface heating could not be expected to influence thunderstorm development, and the occurrence of activity would be associated with other significant features at the surface and aloft.

## SECTION B—FAVORABLE FACTORS

In the unstable area of the Cross Totals analysis extending from Fort Worth to Nashville and southward into southeast Louisiana there were several significant factors favorable for severe weather.

a. The air mass was very unstable.

b. The air mass was likely to be lifted over a warm-frontal boundary extending from south of Oklahoma City to between Shreveport and Little Rock, on toward the northeast of Jackson, Mississippi.

c. Speed and directional convergence were evident in the low-level wind field — for example, between Little Rock and Nashville and between Shreveport and Little Rock. Also, there was a strong low-level jet (shown by solid black arrow) over Shreveport.

d. A weak wave at 500 mb was located along a Midland, Texas-Oklahoma City axis. This wave caused a significant-moisture tongue at 500 mb, which indicated that considerable vertical motion and positive vorticity advection was moving toward the area of greatest instability.

e. Dryer and much warmer low-level air was evident by the 850-mb dry-line symbols to the southwest of the threat area. This dry-line orientation resulted in a strong moisture and temperature gradient nearly perpendicular to the low-level flow from Houston toward Shreveport. This moisture and temperature contrast is one of the basic ingredients of a severe-weather outbreak.

f. A well-defined mid-level jet was apparent from Midland through southern Arkansas and into eastern Tennessee. Jets of this type are conducive to severe-weather development and indicate a preferred zone for significant vertical motion.

## SECTION C—STABILITY INFLUENCES

The static CT's and VT's indicated considerable thunderstorm activity throughout the area bounded by the 20-CT isopleth. However, for the forecast to be worthwhile, the area had to be reduced. An examination of the VT's (the small crossed circles) showed that they were most signficant in the dry air over south central Texas on an axis through Shreveport to Nashville. This axis lay along the mid-level shear, and a Total Totals area of 50 to 52 was present over northeast Texas, northwest Louisiana and southern Arkansas.

## SECTION D—SEVERE-WEATHER FORECAST

It was unlikely that the Vertical Totals would increase south of northern Louisiana or north of southern Tennessee since the time of day prevented any addition of heat to the lower level, and cold-air advection aloft appeared to be improbable south of a line from Shreveport to Chattanooga. Therefore, the resulting forecast called for a heavy thunderstorm area along an axis from near Memphis to just east of Nashville, and a severe area from northeast Texas toward Memphis.

Since the major criteria for tornadic activity had been or would be reached within the next few hours in the area around Shreveport, tornadoes were forecast for a point near Tyler, Texas to near Eldorado, Arkansas. Also, light thunderstorms appeared most probable over the remainder of Louisiana and eastward

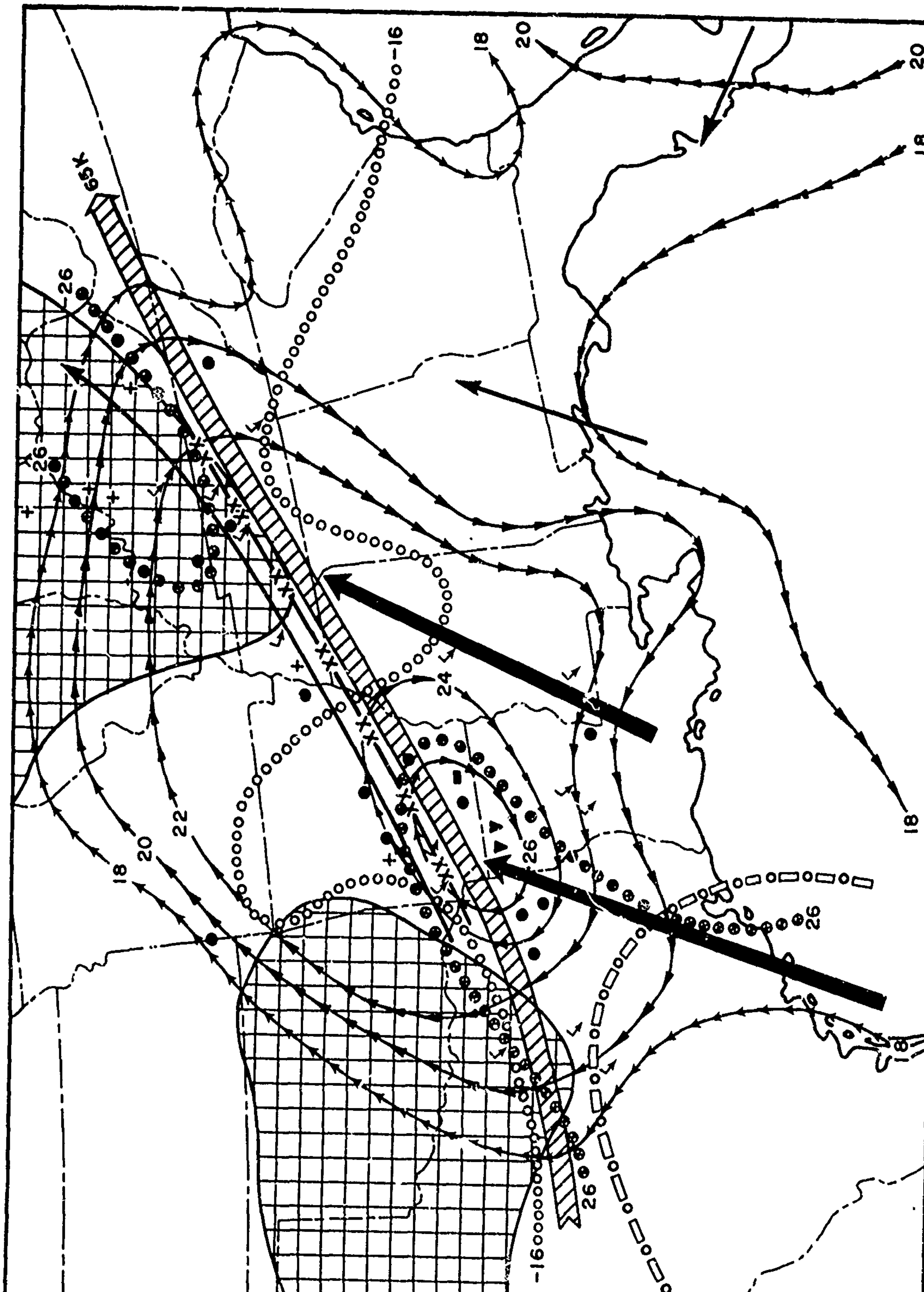



Figure 54. Composite Chart for 0000Z 3 December 1964 showing Cross Totals, low-level wind flow, significant 500-mb moisture, and activity during the period 030000Z to 031200Z.

into Mississippi during the forecast period. These scattered thunderstorms were not likely to develop in a haphazard fashion over the area since the middle and upper levels were quite dry. Development was expected to spread ahead of the outbreak from the northwest and west. Conditions over much of the Florida penisula were quite favorable for convective thunderstorms, but no additional low-level heating would be available. Thus, it was unlikely that isolated activity would occur, but if it should, it would be confined to the coastal waters of southern and southeastern Florida.

## SECTION E—ANALYSIS OF SITUATION ON 3 DECEMBER 1964

Heavy thunderstorms developed rapidly near 0200Z within a 50-mile radius of Shreveport and two tornadoes were sighted. One tornado was sighted 30 miles northeast of Shreveport at 0300Z and another 25 miles north of Shreveport at 0330Z. Thunderstorms spread east and northeast (as shown in Figure 55) with hail reported in southern Arkansas and heavy thunderstorm activity in central Tennessee. Activity over Florida was confined to a few lightning reports during the night at Key West. The severe thunderstorms formed and moved in clusters without an organized squall line developing — typical of a Type A synoptic pattern. The importance of the intersecting low-level jet and the middle-level shear zone was illustrated in this situation since the most intense outbreak occurred at this intersection. A study of the area within a 50-mile radius of Shreveport a few hours prior to severe development, revealed that the synoptic features required for violent thunderstorms were concentrated in that area. That is:

a. The air mass was critically unstable with a Cross Total of 26, Vertical Total of 26, Total Total of 52, and Lifted Index of -6.

b. Low-level moisture was concentrated in a rather finite area.

c. The area was traversed by a strong low-level jet.

d. The area was directly south of a marked middle-level jet.

e. The low-level jet intersected this middle-level wind band within the threat area.

f. There was a steep moisture and temperature gradient to the southwest of the threat area and a low-level wind was blowing across this gradient.

g. The degree of instability was increasing since low-level warm air was running northeastward under progressively colder air at 500 mb.

h. There was evidence of significant positive vorticity advection into the threat area as seen by the 500-mb moisture over Oklahoma and Northern Texas.

It is often the case with Type A synoptic patterns that a low-level dry influx from the southwest aids triggering. In this situation the thunderstorm outbreak continued eastward during the night, but abated in intensity as a result of mixing, which diffused the sharp boundary between the moist and dry air.

## SECTION F—DIFFERENCES IN THE PATTERNS

At 031200Z it was evident that another severe-weather situation was possible (Figures 56 and 57). The primary difference between the patterns on each of the two days was that on the second day the approach of a much stronger 500-mb short-wave trough through western Oklahoma and west central Texas was evident and was associated with a pronounced north-south maritime polar front. This upper-air feature was to be the last short wave in the series, and indications were that the whole system would push south and east out of the country in the next 24 to 36 hours. The general stability pattern was quite similar to the previous day with considerable potential instability evident as far west as the Fort Worth-Dallas area where Total Totals of 52 to 56 were present. With the maritime polar outbreak approaching a line from Fort Worth to San Antonio to Laredo, careful and immediate attention should have been given on the second day to the area around Fort Worth and Dallas. This area under these conditions was a good example of the Type B tornado situation with dryer and warmer air to the southwest of the threat area, and strong low-level flow across this boundary. (The first day was a Type A pattern.) Also, there was an intersecting frontal system moving from the west. Since the developing low-level jet lay to the east of the Fort Worth-Dallas area, and the mid-level jet had become less well-defined, the possibility of tornadoes was remote but serious consideration was given to the possibility of wind and/or hail.

Wind did not appear to be a serious problem for the second day since the thunderstorms that developed shortly after 1200Z were all located over the cold surface layer north of the surface warm front position. Thus, the downrush differential would not be especially effective. Also, there was not much chance of developing a localized mesoanticyclone or bubble since the layer near the surface was already cooler than could be realized from the downrush air. Normally this area would be preferred for hail occurrences but in this instance two conditions were working against it:

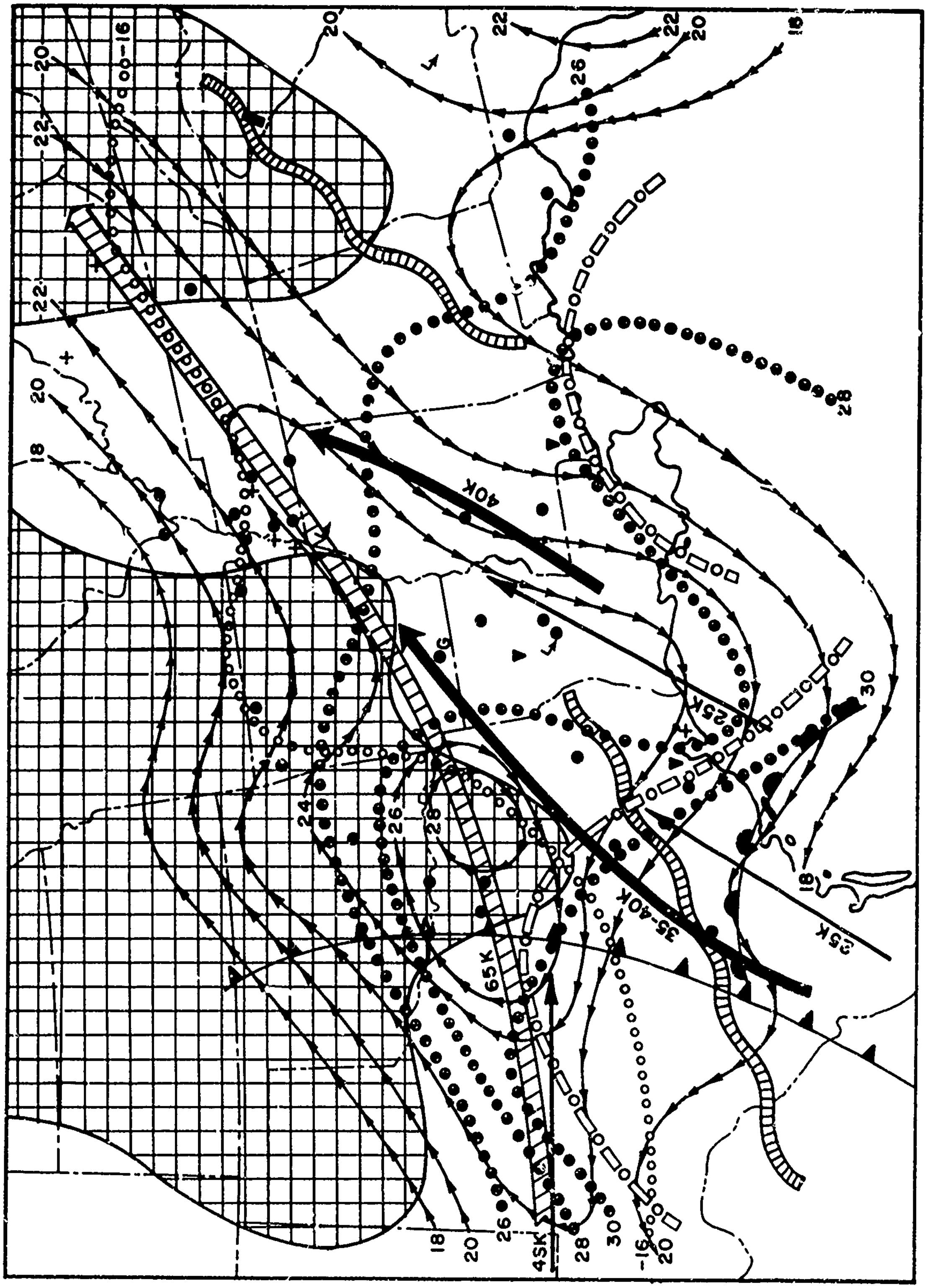


Figure 55. Composite Chart for 1200Z 3 December 1964 showing parameters of interest and activity during the period from 031200Z to 040000Z.

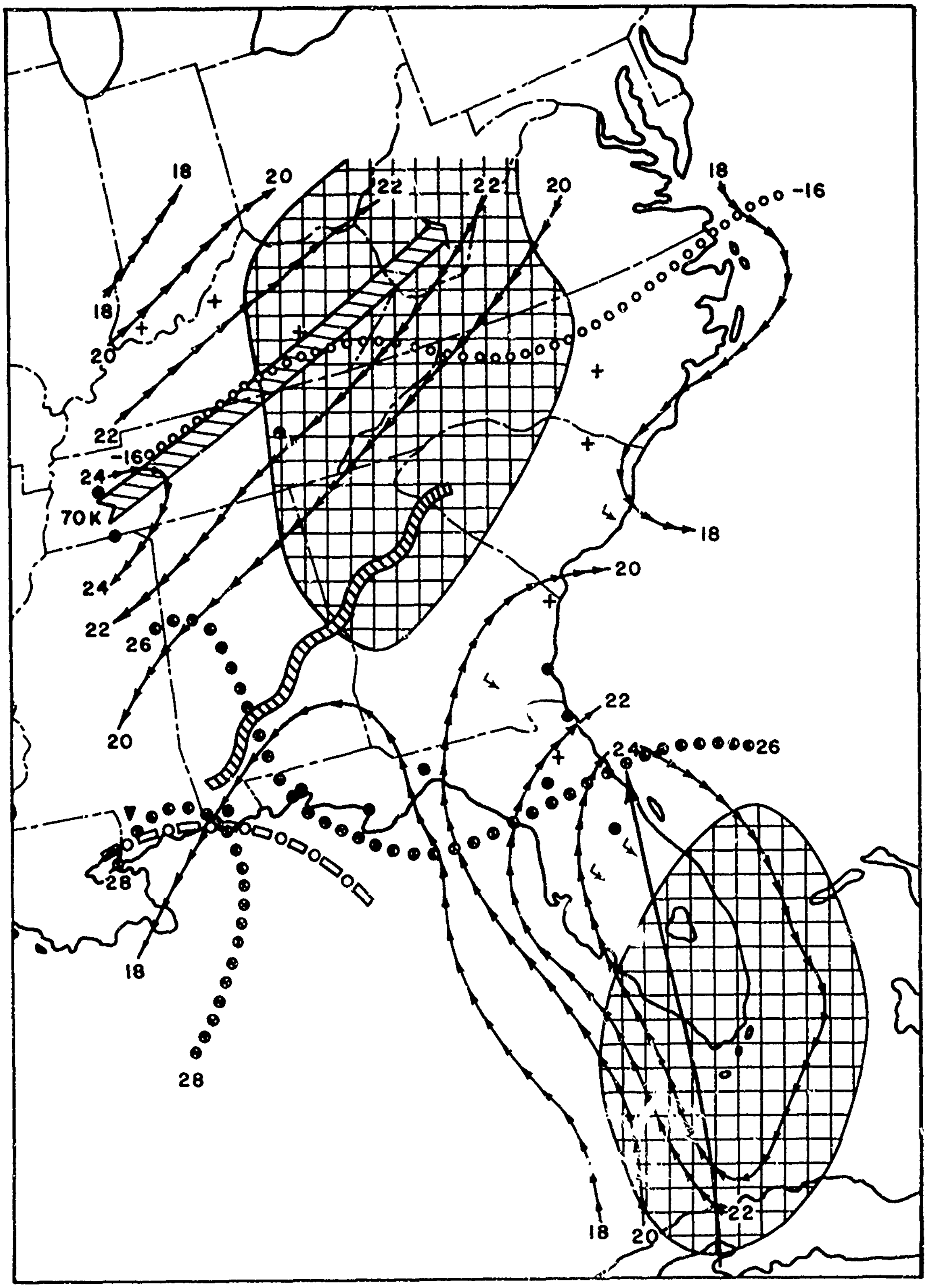



Figure 56. Composite chart for 1200Z 3 December 1964 showing parameters of interest and activity during period 031200Z to 040000Z

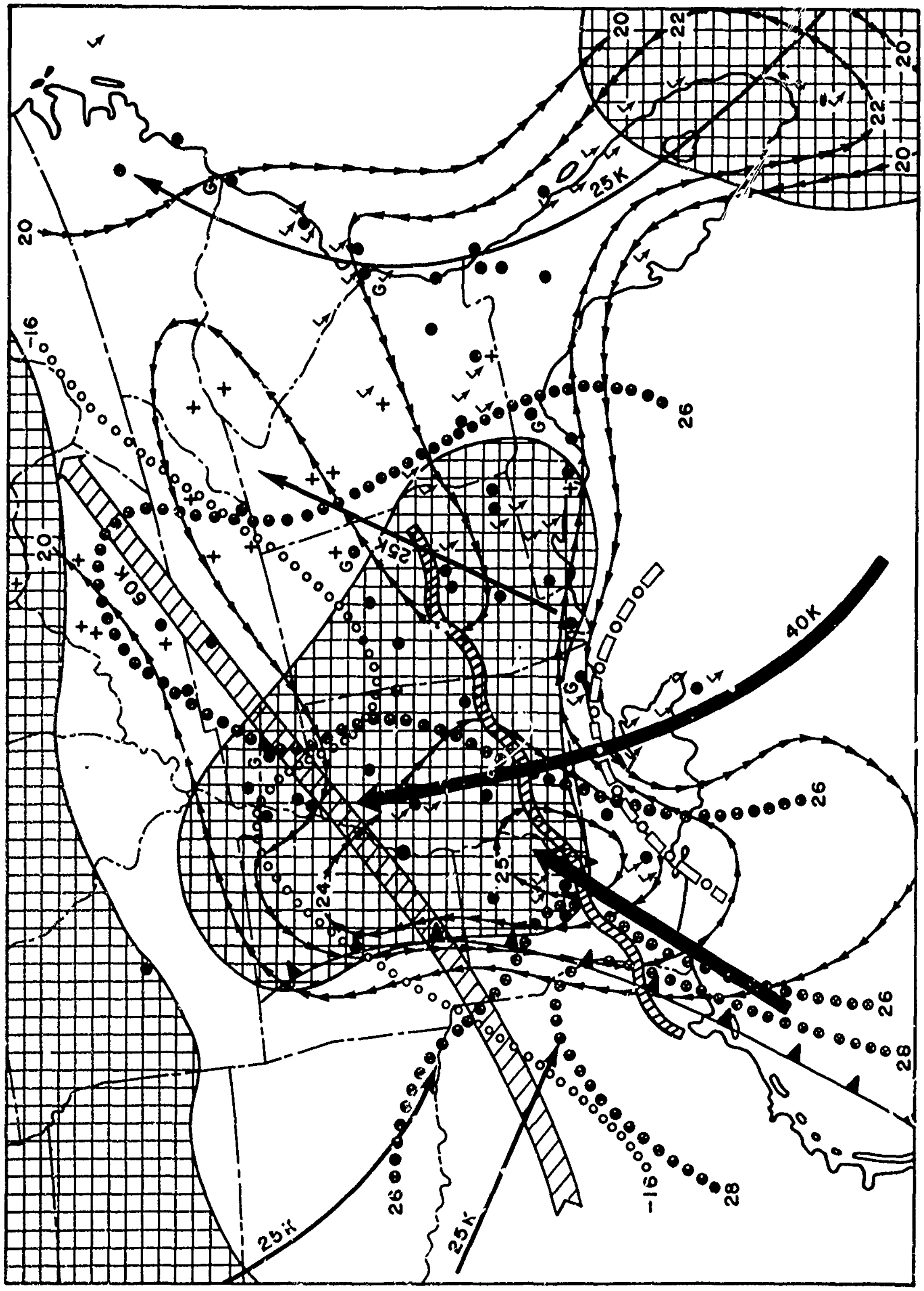



Figure 57. Composite chart for 0000Z 4 December 1964 showing parameters of interest and activity during period 040000Z to 041200Z

a. Time of day; and

b. The wetness of the air column. Extrapolation of the dry air in the middle and lower levels indicated that the important second condition would not be changed before activity moved further eastward. Since the outlook had forecast scattered thunderstorms for south central and southeast Oklahoma, and north central Texas during the morning, no amendment was issued. By 1500Z scattered thunderstorms accompanied by heavy rain formed a well-defined squall line extending from just south of Tulsa, Oklahoma through Sherman, Texas to 30 miles southwest of Dallas. This line was just ahead of the maritime polar front and north of the dry 850-mb boundary. No winds or hail were reported until the squall line reached the Fort Smith-Texarkana-Lufkin line later that afternoon.

The forecast for the 1800Z outlook was simplified since an active squall line was already in existence. The area of primary concern again appeared to be in southern Arkansas and northern Louisiana, since most parameters previously mentioned as necessary for severe activity were forecast to converge in that particular zone. The low-level jet appeared to be developing along the San Antonio-Shreveport-Nashville line with the only change likely to be a shift eastward of the maritime polar front. The front and squall-line forecast movement indicated that the low-level jet should back slightly and move into a position over Lake Charles, through Monroe, Louisiana and northward toward Memphis by evening. The dryer warmer air to the southwest of the area was expected to persist until pinched off by the maritime polar front, which would permit a cross-gradient flow to continue into Louisiana and southern Arkansas. Stability was forecast to decrease over these areas since significantly warmer low-level air would be advected into the area while the 500-mb temperature field would remain essentially unchanged. The middle-level jet, while not well-defined, seemed to be trying to organize itself along the Midland-Fort Worth-Nashville line. The short wave at 500 mb continued ENE creating a strong vertical-motion field over the threat area during the late afternoon and evening. With these considerations, it seemed reasonable to forecast severe thunderstorms and a few tornadoes along an axis from Lufkin, Texas to near Greenville, Miss. This axis fits the region of climatological tornado maximum for December for this area.

A second area of high climatic frequencies for December tornadoes is near Houston. This is of particular interest since the Houston area on this date is very close to the boundary of the warm dry air and the moist air to the east. Extrapolation of the squall line placed the hot-dry boundary by late afternoon in the vicinity of Houston, where a Total Totals of at least 52 was expected. Also, if the middle-level jet formed along the predicted axis, it was probable that the 500-mb shear zone would lie further south along the Houston-Lake Charles line. Thus, the southwest portion of the tornado area included Houston and curved eastward toward Alexandria, Louisiana. The warm dry air in the lower levels over southeast Louisiana did not appear significant at this time, but required consideration since the low-level jet was expected to shift eastward and since more moist and cooler low-level and middle-level air was present north of the area.

## SECTION G—ANALYSIS OF SITUATION OF 4 DECEMBER 1964

The Total Totals just north of the surface warm front were observed to be near 47 in the morning. The 18-Cross Total line covered a large territory, but the absence of 26 or even 24 Vertical Totals over much of this area appreciably reduced the thunderstorm probabilities. Thus, much of the area can be eliminated from consideration except for western and southern Alabama, southern Georgia, the Carolinas, and Virginia. It was unlikely that any major change in stability would occur over these areas during the 12-hour outlook period. Also, it was unlikely that thunderstorms from the west would spread into these sections before 0600Z.

Along the Gulf Coast through southern Georgia and northern Florida (Figure 54), the Vertical Totals were favorable for convective activity but 700-mb and 500-mb moisture was lacking. It was discussed in Chapter 8 that when this region had dry air aloft, activity was not necessarily prohibited, but that development was restricted to widely scattered cells. Further south, over southern Florida, upper-level moisture was available, hence scattered thunderstorms were forecast. Isolated thunderstorms were not forecast along the Gulf Coast and over northern Florida, but should have been in view of the Total Totals of 46 to 50 over much of this area. Thunderstorms did occur as shown on Figure 54. Further west heavy thunderstorms were forecast through southern Arkansas into western and northern Mississippi, and through Louisiana and east Texas — surrounding the tornado and severe thunderstorm area previously mentioned.

The position of the squall line by 2100Z was from 100 miles north of Little Rock to Texarkana to just east of Houston. Heavy activity was reported along the line with strong gusty winds, heavy rain and hail southwest of Texarkana, west of Shreveport, and in the vicinity of Lufkin, Texas. A tornado was observed (near 1900Z) four miles north of Ellington AFB, Houston, while the air base reported thunder and wind gusts to 32 knots. Tornadoes were reported between 2200 and 2300Z forty to seventy miles ESE of Shreveport, and at 0200Z in the vicinity of Alexandria. Also, heavy thunderstorms were reported near Memphis during the evening with the last reported at Anniston, Alabama about 0800Z. By 0600Z the thunderstorms had spread to near the Nashville, Tennessee-Burwood, Louisiana line, and had continued eastward ahead of the frontal system during the night and next morning.

An unforecast tornado was reported northwest of Gulfport, Mississippi at 2100Z. This storm was associated with a group of isolated convective cells. The occurrence of this storm is an important clue since the post-analysis of the 0000Z data disclosed that the tornado most likely occurred in conjunction with the primary low-level jet just north of the hot/dry 850-mb warm front, in an area of increasing instability, and in the vicinity of the middle-level wind shear to the south of the jet.

An examination of the next chart, 040000Z, confirmed the predicted changes in the 031200Z pattern. The maritime polar front extended from just past Shreveport to east of Galveston. The hot dry air had been modified and cut off by the advancing front which helped to explain the cessation of tornadic activity after that reported near Alexandria at 040100Z. The low-level jet had shifted eastward with the main branch almost north-south through Louisiana and Mississippi and another branch from the southwest over Lake Charles then toward Alexandria. The middle-level jet developed and was well-defined from Midland through Texarkana to Nashville. The middle-level shear zone was from south of San Antonio to Lake Charles to Jackson, Mississippi and on toward Montgomery, Alabama. It should be noted that the Alexandria report was in close proximity to the intersection of the southwesterly low-level jet with the shear zone, and was in an area of well-defined low-level convergence. The isolated tornado northwest of Gulfport occurred very close to the intersection of the low-level jet and the edge of the middle-level shear zone. Also, the activity around Memphis and Jackson, Tennessee was near the intersection of the main low-level jet and 500-mb jet.

The 42-knot thunderstorm report after midnight in the Anniston, Alabama area was near the shear zone and it seemed likely that the low-level jet had shifted eastward by this time to cover the Anniston area. In fact, the low-level winds for 0600Z showed that Montgomery's wind had increased to 45 knots from the SSW at 400 feet. No further reports of significant weather were received after this report probably because there was an increase of stability in the air mass ahead of the system. Also, the cold air aloft developed a more northerly track, and the low-level and middle-level dry sources were overtaken by the squall line or cut off by the cold front.

# Appendix C

# THE SEVERE STORMS OF 11 FEBRUARY 1965

## SECTION A—GENERAL

On 11 February 1965 a major outbreak of severe thunderstorms, tornadoes and damaging windstorms occurred over a 14-hour period along a line extending from just WSW of College Station, Texas into north central Alabama. This situation is an excellent example of the use of the Totals indexes as well as other prediction parameters available to the forecaster. The tornado pattern was essentially Type B with an active squall line moving ahead of an almost north-south maritime polar front, and intersecting a well-defined warm-frontal boundary along a line from near Austin, Texas to Shreveport to Memphis, and ENE into North Carolina. At 1200Z the squall line was active from eastern Oklahoma to west of Tyler, Texas and southwestward to Cotulla, Texas. Thunderstorms were occurring all along this line, with a few reports of heavy rain and moderately gusty winds. The squall line and its parent cold front were moving eastward at about 22 knots with the thunderstorm cells moving more than twice that speed toward the NNE. Surface dew points were dropping substantially in the westerly flow to the rear of the cold front. An examination of the 1200Z composite chart showed that the squall line was moving into an area increasingly favorable to the production of severe thunderstorms and the time of day was becoming more favorable for the production of such activity.

## SECTION B—FAVORABLE PARAMETERS

Many of the favorable parameters usually associated with violent thunderstorms had already or would shortly be ahead of the squall line over portions of east Texas and the northern half of Louisiana. The stability analysis showed the Cross Totals to be a very unstable 26 in a corridor extending along the San Antonio-Shreveport axis, with a probable maximum of 29 or 30 over the central portions of eastern Texas. These CT's suggested that the development of tornadic storms was likely especially when coupled with the Vertical Totals of 28 to 30 for an extremely unstable Total Total of 60. The Lifted Index at San Antonio was 6 and Shreveport 0. It was interesting that the Total Totals pattern, even at 1200Z, quite accurately predicted the major path of activity even into northwestern Alabama. Since the position of the first significant southerly low-level flow appeared to be along an axis extending from McAllen, Texas through College Station toward Tyler, it was reasonable to expect squall-line intensification along this axis, and further intensification in the vicinity of the low-level jet located from Brownsville through Shreveport. The area of instability as well as the low-level jet was expected to show some eastward movement during the day.

At 500 mb the southern and eastern periphery of a strong band of middle-level winds was evident from Del Rio, Texas to San Antonio to Tyler, Texas, and then northeastward through northwestern Arkansas creating an effective horizontal shear zone near the most unstable area. Cold air was available at 500 mb with the -16°C isotherm intruding into northwestern Louisiana and southwestern Arkansas from central Texas. At 850 mb a strong contrast between the warm moist air over the threat area and the hot and much dryer air to the southwest was apparent, since temperatures of 17 to 21°C and dew points of -3 to +5°C were common to the southwest of the surface warm front as compared with values of +15 and +12°C to the northeast of the front. Also, there was a well-defined cross-gradient low-level flow across this boundary.

## SECTION C—THE SEVERE-WEATHER FORECAST

The prediction was based on the expectation that the air column over the threat area would become more unstable along the axis of the low-level flow, and that mesolow development would likely take place where the squall line intersected the warm frontal boundary in the area of strong low-level wind flow. Positive vorticity advection and vertical motion were evidenced not only by the 500-mb moisture at Shreveport but also by the thunderstorms already developing along the squall line.

Considering the above, the forecast was for severe thunderstorms, tornadoes, and locally damaging winds 60 miles either side of a point about 30 miles north of College Station, Texas along an axis into the Tupelo, Mississippi area. This decision meant accepting a risk that the surface warm front would edge northward out of the area displacing the zone of activity more to

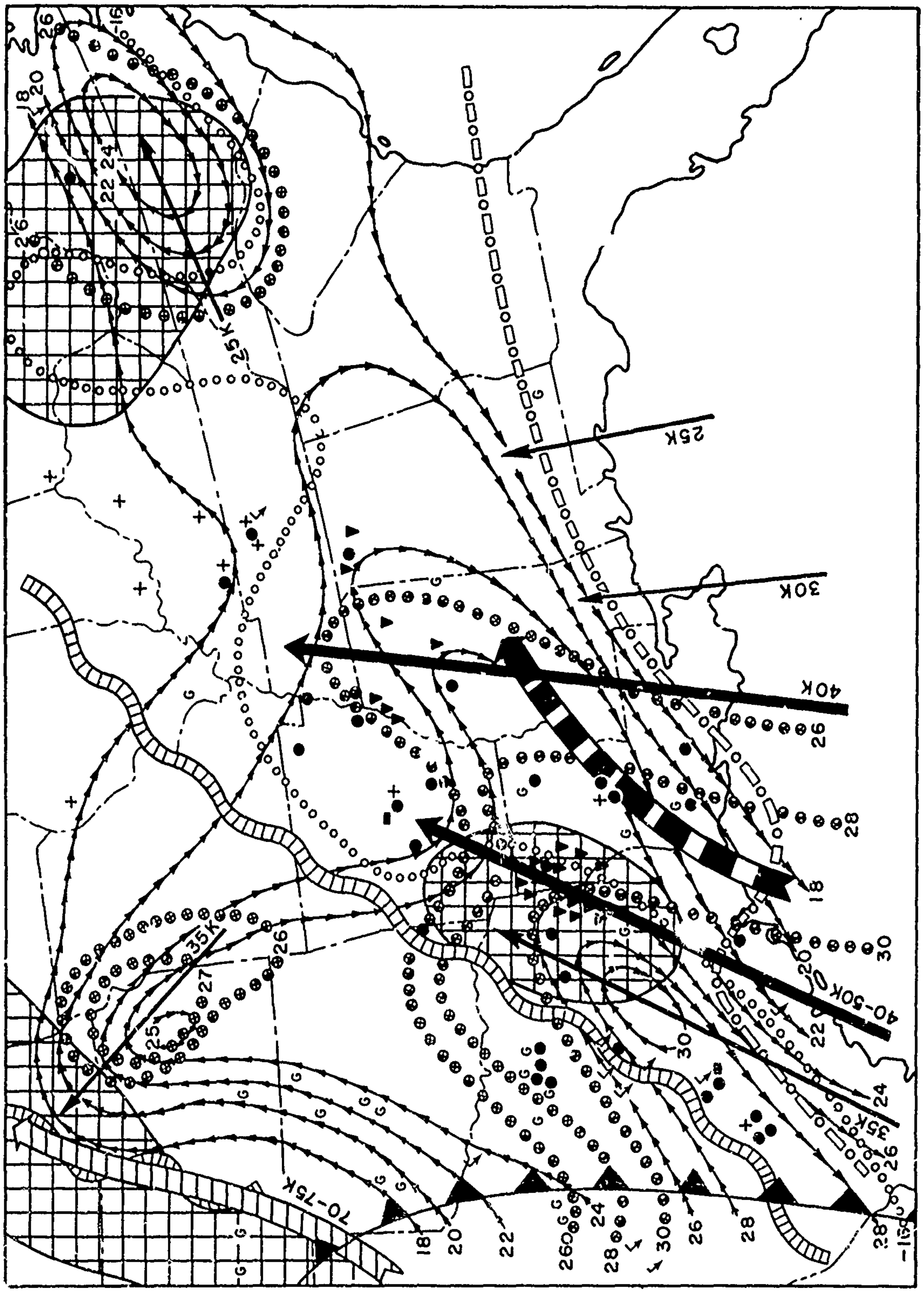



Figure 58 Composite Chart of major features fo. 1200Z 11 February 1965. Includes the Activity During the Period from 111200Z to 120000Z.

the northeast. However, thunderstorms and moderate to heavy rain would probably continue along the north of the front keeping the lower layers relatively cool and discouraging any significant warm-frontal advance northward. The long axis seemed justified in view of the regular movement of the front and squall line, the general pattern of instability, and the low-level wind and moisture field. Also, the time of day was favorable, and the middle-level jet and its horizontal shear zone was expected to drift eastward. While the Total Totals pattern indicated that thunderstorms would continue during the day and spread eastward with the squall line, there was little or no activity through the Gulf Coastal States. There were two good reasons for this:

a. Supporting 700-mb and 500-mb moisture for convective activity was not in evidence to the south of the warm front.

b. The Vertical Totals were well below the critical value of 26, and the Cross Totals were below the threshold value of 18 over Florida and the coastal sections of Georgia, Alabama, and southeastern Louisiana.

The situation was different over North Carolina and southern Virginia. Vertical and Cross Totals were high with Total Totals of 50. The Moisture was apparent at 500 mb in both the Huntington and Greensboro soundings. Thunderstorms which occurred in the low-level convergence of the warm front before daylight in eastern Tennessee and extreme western North Carolina, were expected to redevelop and spread eastward. While the Totals indexes indicated "green"-type thunderstorms, the coolness of the air near the surface tended to inhibit gusts, and extrapolation placed the activity off the coast before significant surface heating would occur. The intrusion of strong totals northward from Oklahoma into northern Kansas was of considerable interest. This nose of unstable air with a Total Total of at least 52 presented a strong stability gradient over a relatively short distance. The Omaha sounding showed Vertical Total values of 20 and Cross Total values of 19. The strongest southeasterly low-level winds in this region were perpendicular to the horizontal stability-index gradient in north central Kansas and southeastern Nebraska. Also, this region was under the influence of a well-defined middle-level jet of 70 to 75 knots with the horizontal shear to the right of the jet on the order of 20 to 25K/90 nm.

## SECTION D—RESULTS AND POST ANALYSIS

The combination of unstable overrunning coupled with the favorable vertical-motion field and deep moisture resulted in 15 to 22 inches of snow on an axis extending from near Concordia, Kansas to Omaha. Most snow accumulation occurred between 110900Z and 111800Z.

The severe activity shown on Figure 58 occurred from 111200Z through 120600Z—a period of 18 hours. The squall line continued eastward and southeastward after the last severe report from Tuscaloosa, Alabama, but weakened rapidly as the squall line moved further away from the parent cold front and into less unstable air. By 121500Z the activity had diminished into rain showers.

# Appendix D

# THE TYPE B SEVERE-WEATHER OUTBREAK OF 26 NOVEMBER 1965

## SECTION A—GENERAL

On 26 November 1965 a strong Type B severe-weather outbreak occurred over Illinois and portions of south central Missouri and northeastern Arkansas. The activity consisted of tornadoes, locally damaging windstorms and isolated large hail which spread east and northeast during the later afternoon and evening from the Bradford, Illinois—Harrison, Arkansas line into southern Michigan, Indiana, and portions of Arkansas, Kentucky, and Ohio. This outbreak was unusually strong for the time of year and was considered worthy of a detailed analysis.

The classification of this storm system as a Type B pattern was determined by a close examination of the 261200Z upper-air charts. Warm and rather dry air was evident over Kansas, Oklahoma and Texas and was being advected to the ENE on a 50- to 55-knot jet in the lower levels (Figure 59). This dry tongue was adjacent to a well-defined pocket of moist air lying over Missouri, eastern Iowa and Illinois. A more southerly low-level jet was evident in this moist air, and extended from Shreveport to Little Rock into western Illinois. A strong cold front was located from southeastern Colorado into east central Nebraska and eastern South Dakota. Dry air over Kansas, Oklahoma, and western Missouri was colliding with cooler and more moist air to the ENE, and was being carried by strong WSW flow at 700 mb (Figure 60). There was a major 700-mb trough moving from the northwest toward the threat area. Strong cold-air advection at 500 mb (Figure 61) was in evidence by an analysis of the isotherms, height, and temperature falls. This analysis indicated that a strong short wave was moving out of the western plains.

All the above factors coupled with the associated 850-mb and 700-mb features suggested a Type B outbreak, with a squall line forming ahead of a moving major surface system and with little likelihood of air-mass recovery, and the repetition of activity usually associated with a Type A pattern.

## SECTION B—FAVORABLE PARAMETERS

The parameters associated with the development of severe thunderstorms and tornadoes were present in both number and strength on the 1200Z charts. In addition to the strong convergence in the 850-mb flow between these dissimilar air masses and the approaching cold front, the low-level temperature ridge was lying well to the west of the moisture ridge. Checking this parameter against Table 1 classified this particular feature as *strong*. The low-level jet in both the dry and moist air also was classified as strong. While the low-level moisture barely meets the *moderate* criteria at the 850-mb level, some moisture increase was likely during the day.

The secondary 850-mb dry line extending from southeastern Oklahoma through northwestern Arkansas and central Kentucky south of the Ohio river was also of considerable importance. Its location and future movement determined a southern limiting boundary for activity and a zone of intersection once a squall line developed. Also, intersection of this particular feature with the 850-mb warm front and the low-level jet was a favored area for mesolow development.

At 700 mb the dry-air intrusion was upwind of the threat area and dry and moist air were positioned adjacent to each other from north central Arkansas eastward through Kentucky over the secondary 850-mb dry line. Since the wind flow paralleled this feature over these areas little displacement north or south was expected. The 700-mb no-change line associated with the western trough was well-defined from eastern South Dakota to Topeka, Kansas to central Oklahoma. A second 700-mb no-change line from southern Michigan to the east of Dayton, Ohio to northwest of Nashville was associated with a weakening line of nocturnal thunderstorms. Table 1 classified the western no-change line as *strong* and the wind flow crossed the line at an angle of greater than 45 degrees.

Another important factor to be considered was the strong band of 700-mb winds in the dryer air over Kansas, Oklahoma, and Missouri. This orientation placed the strongest intrusion of dry air against the mid-level moist air west of the Mississippi River in Missouri, and indicated that the zone of steepest moisture gradient and most rapid rate of advective moisture change during

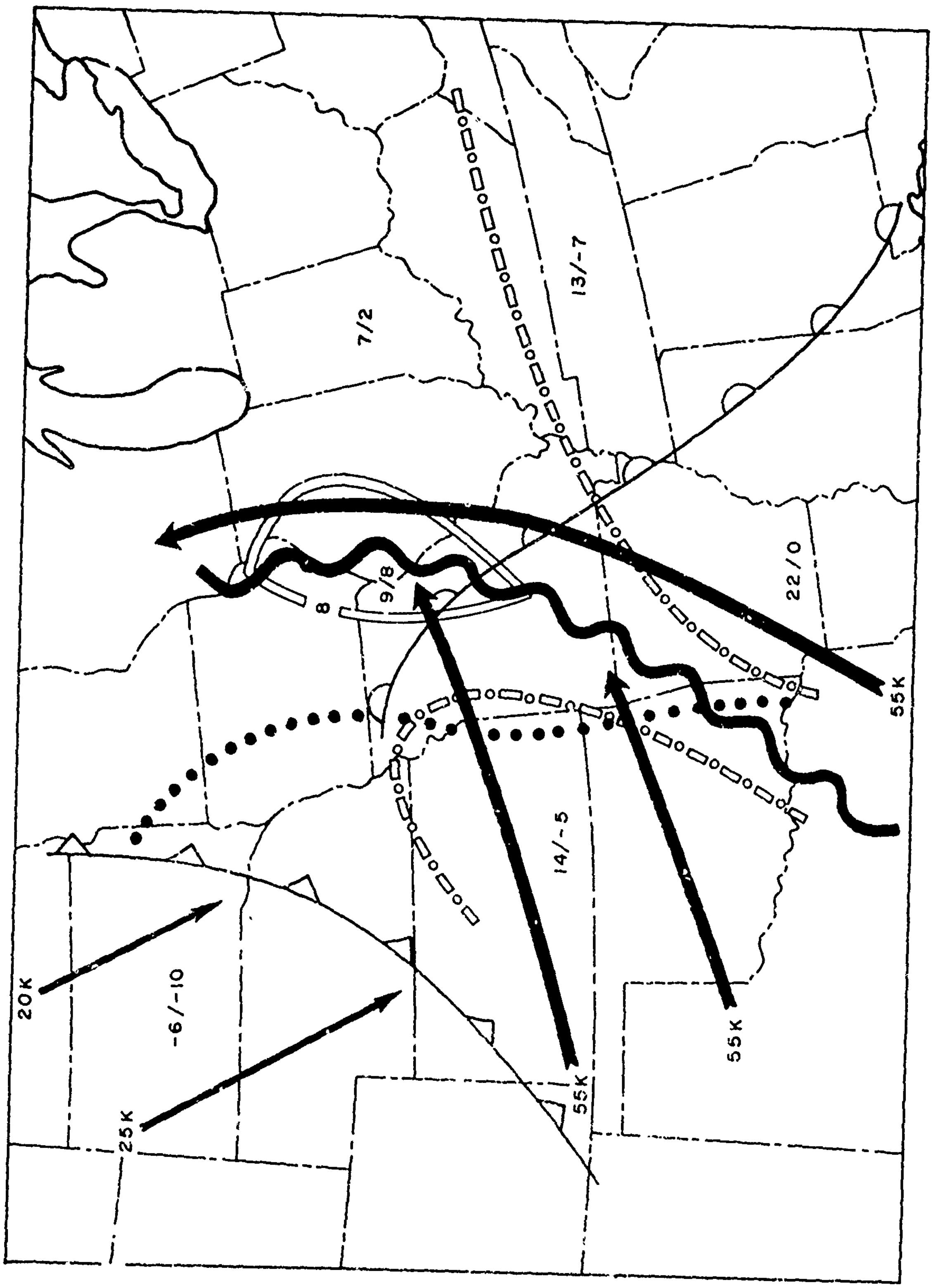



Figure 59. Major features of the 850-mb chart at 1200Z 26 November 1965.

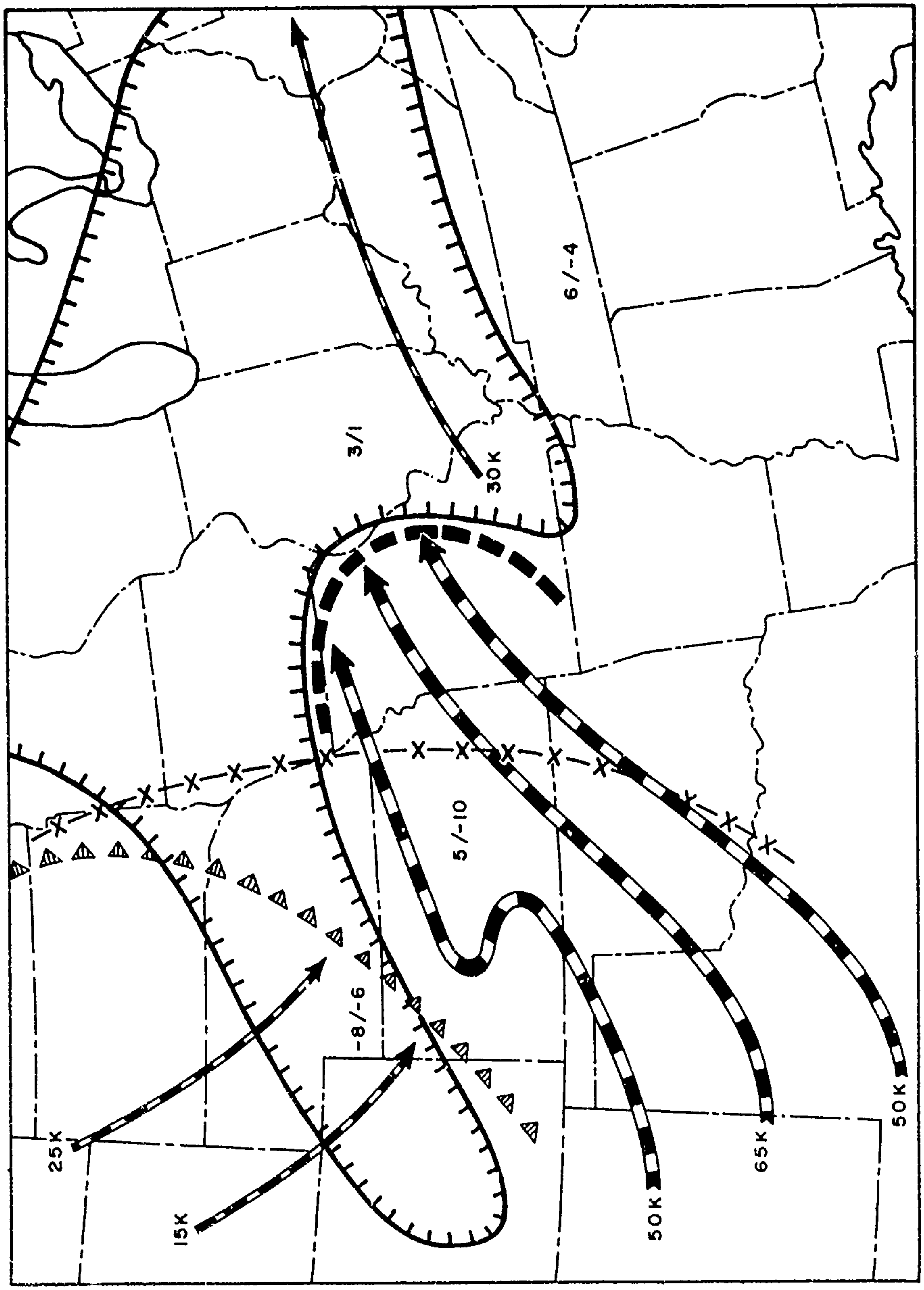



Figure 60. Major features of the 700-mb chart at 1200Z 26 November 1965.

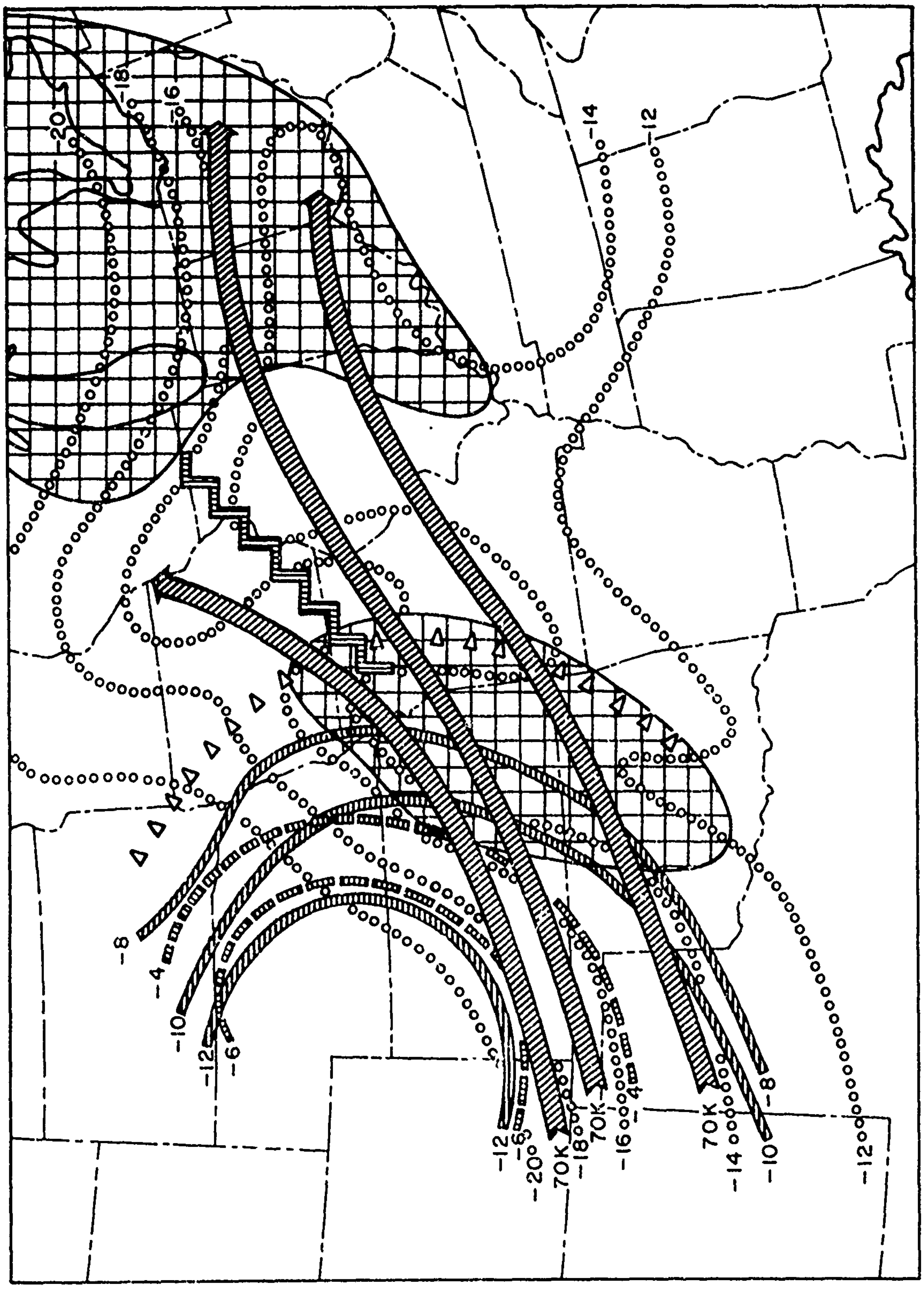



Figure 61. Major features of the 500-mb chart at 1200Z 26 November 1965.

the day would probably lie along the Illinois border southwest of the Springfield-Peoria area.

The 500-mb thermal trough from southwestern Minnesota through central Iowa and central Missouri was favorably oriented to be advected eastward. The cross-isotherm flow was quite strong and indicated continued moist cold-air advection into the warmer tongue to the east. The jet band at this level was broad but well-defined and showed diffluence from north central Missouri into northern Illinois. There was horizontal speed shear to the south of this jet zone which extended from Amarillo to Oklahoma City into southern Illinois and southeast Indiana. The 12-hour temperature and height falls to the rear of the leading thermal trough at 500 mb were indicative of strong active vorticity acceleration. Also, the presence of significant 500-mb moisture at Topeka, Columbia, and Oklahoma City could only be accounted for by vertical motion, since moisture was not advected into the area. Table 1 placed the mid-level jet in the *strong* category and the 500-mb positive vorticity advection from the 1200Z NMC barotropic prog was classified as *strong.*

Considering the remaining parameters from Table 1, the Totals Index (Figure 62) was calculated to be 52 to 54 over south central Iowa as early as 1200Z with a larger area covered by 50's as analyzed. The Lifted Index was calculated to be on the order of minus six. Thus, the available instability met the *strong* criteria.

The 12-hour surface pressure change over southeastern Minnesota and central Iowa amounted to a 12-millibar fall which placed it in the *strong* category. The axis of the Wet-Bulb-Zero heights taken from the 1200Z soundings and shown on the Composite Chart, Figure 63, extended from Dodge City, Kansas to Peoria, Illinois with values near 9,000 feet above the earth's surface. This height is in the *strong* classification as well.

An examination of the 850/500-mb thickness chart showed the thickness ridge to be well-defined from southeastern North Dakota through southwestern Minnesota into central Iowa, central Missouri, and northwestern Arkansas. The ridge was located in the zone of maximum anticyclonic thermal wind shear, the squall-line formation would be close to this ridge line as the line of no 12-hour thickness change (which overlays the 700-mb no-change line) approaches.

## SECTION C—POST ANALYSIS OF FORECAST AND OBSERVED ACTIVITY

The surface chart for 1800Z shows the major surface features associated with the morning upper-air patterns. This chart was one hour prior to the first indication of squall-line development picked up on radar. A line of thunderstorms and rainshowers, began forming along the maritime polar front along the Ottumwa, Iowa—Kirksville, Missouri—Sedalia, Missouri line at 1900Z, and by 2200Z an active and severe squall line was located from southwest of Rockford, Illinois to east of Peoria, Illinois through Springfield, Illinois and southwestward to a point northwest of Harrison, Arkansas. The first severe reports were the destructive tornado northeast of Peoria and a windstorm near St. Louis at 2200Z, and 35-40-knot thunderstorm gusts at many stations along the squall line.

By 270800Z the squall line had moved to a position from eastern Ohio, through eastern Kentucky, to Tuscaloosa, Alabama, to Lafayette, Louisiana, and had degenerated into a line of heavy showers accompanied by strong northwest gusts.

The salient features, from the 1200Z charts discussed above, are shown on the Composite Chart Figure 63, along with the reported activity for the 26th of November. A check of the 1800Z surface pattern showed that the initial squall-line development occurred very close to the maritime polar front from the low center southward through Iowa and north central Missouri. This development was very close to the 1200Z position of the 850/500-mb thickness ridge and ahead of the morning position of the 700-mb and 850-mb lines of no-temperature change. Intense low-level convergence was expected between the advancing dry low-level air and the moist air further east since the low-level jet and moisture ridge will tend to hold, or even curve cyclonically, because of the position of the deep surface low. This convergence was expected to cause a strong moisture gradient close to the surface front shortly after noon. The 700-mb dry intrusion was leading the low-level dry tongue which is a favorable condition for severe activity. The result of all of these features, coupled with the apparent cooling in the thermal trough at 500 mb, was expected to result in eastward displacement of the area of greatest instability to a position just west of the 1200Z position of the low-level jet.

The broad middle-level jet pattern and the availability of the middle-level dry air upwind, over a rather broad north-south front, indicated that once the squall line developed it would affect a large area in its eastward movement. The large instability area also indicated a widespread pattern of severe weather. Since the most favorable location for family-type tornado outbreaks with the Type B pattern is usually

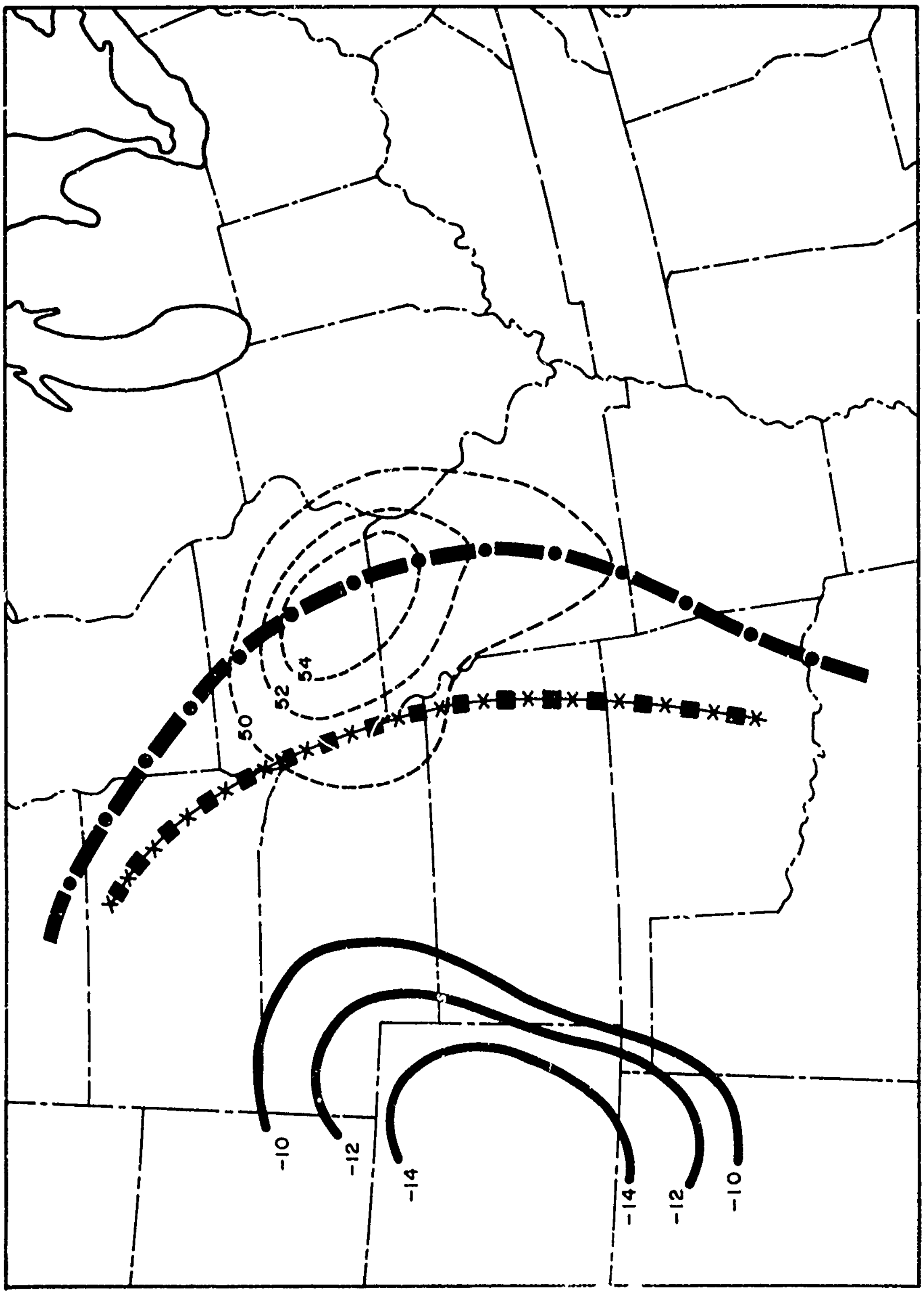



Figure 62. Total Totals analysis and 850/500-mb thickness change at 1200Z 26 November 1965.

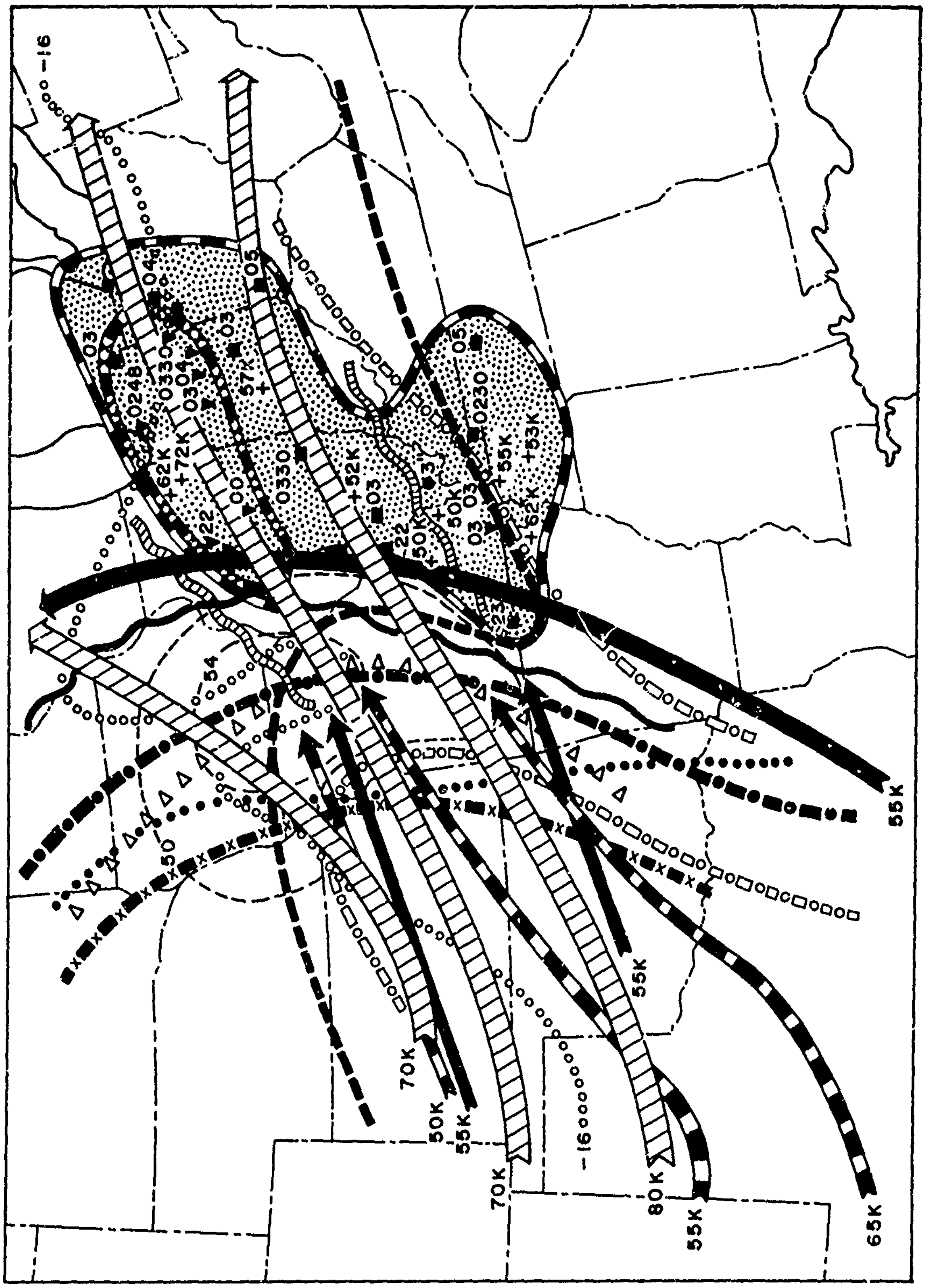


Figure 63. Composite Chart of the 1200Z 26 November 1965 data. Includes the severe activity during period 260000Z to 261200Z.

associated in a narrow zone in the vicinity of a surface intersection, first consideration was given to the warm-frontal zone extending east and southeast from the surface low. This front was not likely to move northward any appreciable distance since the low was forecast to move eastward and the air to the north of the front was quite cool. In addition, the lower levels to the south of the front were cooled significantly by the passage of the nocturnal squall line previously mentioned. The remains of this old squall line were still apparent at 1800Z to the south of the warm front and were acting as a boundary zone. Since squall-line development usually takes place near and south of the low, the most likely area for tornadoes was along an axis from near Quincy, Illinois toward Detroit, Michigan. The inception point was expected to be close to the intersection of the low-level moist ridge and low-level southerly jet axis with the middle-level jet. This area of intersection was also the most favored point for mesocyclone formation. As the squall line moved eastward and continued to develop southward in the moist air, consideration was given to severe thunderstorms or tornadoes further to the south. Tornadoes were not likely for several reasons, the primary one being the absence of a well-defined surface boundary necessary to intersect the squall line and cause subsequent mesoscale developments. Severe thunderstorms along with damaging wind gusts and hail were likely to be widespread along the remainder of the squall line. Activity in the north was expected to be limited because of the cooler low-level air north of the warm front. Activity in the south was expected to be limited because of the presence of dry air south of the 700-mb dry line and the shallow low-level moisture indicated by the position of the 850-mb dry line. These boundaries were effective as shown on the Composite Chart.

# Appendix E

# THE TOPEKA, KANSAS, TORNADO OF 8 JUNE 1966

## SECTION A—GENERAL

The Topeka, Kansas tornado of 8 June 1966 is an interesting study of the feasibility and value of the forecast parameters of Table 4 over a rather restricted area. The use of the forecast parameters resulted in a successful operational tornado forecast for the morning of the 8th. The forecast was based on the 08/1200Z surface and upper-air data, and 09/0000Z data presented a point in time midway between the first tornado occurrence in central Kansas and the last in northwest Missouri. The destructive storm at Topeka began almost at 09/0000Z.

## SECTION B—STORM HISTORY

The first tornado was reported shortly after 08/2100Z just south of Great Bend in central Kansas and the last near 09/0230Z north of Kansas City. Evidence indicates that there were two major tornado tracks associated with the storm system (Figure 77). The first track extended from south of Great Bend, Kansas, across Topeka and ended at the southwest corner of Midcontinent Airport, 15 miles north of Kansas City. The second was from north of Salina, Kansas, across Manhattan, Kansas, to just southwest of St. Joseph, Missouri. Also, a third storm track of lesser intensity extended from Hutchinson, Kansas, to just southwest of Olathe, Kansas. The number of tornadoes involved is unknown but examination of the various tracks indicated the probability of 6 to 8 individual storms within the system. The Topeka tornado began on the ground from about 30 miles WSW of Burnett's Mound on the southwest edge of Topeka, continued across the city, and went aloft at the northeast corner of Topeka. The storm then moved eastward in a skipping fashion with the last visible damage at Midcontinent International Airport in northwest Missouri. This track would indicate a path of total and intermittent destruction of some 65 miles.

The Topeka storm is a particularly good example of the Type B tornado pattern. Figures 64 through 77 show the salient features of the surface and upper-air analyses including a plot of the activity reported. The isolated windstorm shown southwest of Lincoln, Nebraska was associated with the northern portion of the squall line (Figure 77), and under an area of diffluence at the jet level (Figure 68). This activity was short-lived since it was well north of the surface warm front. The activity in central Oklahoma occurred along the western edge of the 850-mb and 700-mb moist tongue where strong moisture was present in an area of moderate horizontal speed shear just east of the 500-mb cold trough. Also, a large angle of intersection existed between the strong low-level jet and the speed shear zone.

The single hailstorm east of Quincy, Illinois, occurred near the surface warm front under the strong eastern 700-mb dry intrusion, and reasonably close to the upper jet.

The Quincy storm cell was moving rapidly under the influence of the strong middle-level flow, and the tornado reported northeast of Rantoul, Illinois, was associated with this system. The early morning outbreak on the 9th in Chicago and the activity in northwest Missouri of the previous evening were most likely connected with the Topeka storm complex. A study of the movement of the upper jet indicated that the storm impulse steered along the track of the upper jet (Figure 75). The speed of translation was about 37 knots which is compatible with the strength of the middle- and upper-level flow.

## SECTION C—DISCUSSION OF THE PARAMETERS

Table 5 summarizes the parameters affecting the threat area at 08/1200Z and 09/0000Z. From the 08/1200Z data it is apparent that only two weak parameters (instability and a high Wet-Bulb-Zero height) would have to be more favorable in order that severe thunderstorms or tornadoes could be confidently forecast. Most parameters usually appear weak in the early morning data so the severe-weather forecaster has to carefully and correctly assess the changes to be expected in space and time to arrive at an accurate forecast of the threat area and the start of activity. However, in the Topeka case, the 1200Z data indicate that nearly all of the parameters favor the development of severe weather. Early morning thunderstorms modified the Topeka sounding resulting in a moist and quite stable air structure. A careful study of the 1200Z Composite Chart (Figure 70), in

**Table 5 - Summary of Topeka Parameters**

| | 1200Z VALUE | 1200Z Rating | 0000Z VALUE | 0000Z Rating | SOURCE OF DATA |
|---|---|---|---|---|---|
| 500-mb Vorticity | Yes | S | Yes | S | Barotropic or Baroclinic Prog |
| Lifted Index | ±0 | W | -6 | S | Plotted Sounding |
| Totals | 35 | W | 54 | M | Thickness Chart |
| Mid-Level Horizontal Shear Zone | 45K/90 nm | M | 55K/90 nm | S | 500-mb Chart |
| High-Level Horizontal Shear Zone | 100K/90 nm | S | 95K/90 nm | S | Jet Chart |
| Low-Level Jet | 45K | S | 35K | S | 850-mb Chart |
| Low-Level Moisture (Dew Point) | 10°C | M | 15°C | S | 850-mb Chart |
| 850-mb Max-Temp Field | West of Moist Ridge | S | West of Moist Ridge | S | 850-mb Chart |
| 700-mb No-Change | 40°/35K | M | 80°/35K | S | 700-mb Chart |
| 700-mb Dry Intrusion | 40°/40K | M | 60°/35K | S | 700-mb Chart |
| 12-hr Sfc Pressure Falls | - | - | 6.3-mb | S | Sfc Chart |
| 500-mb Height Change | -50M | M | [illegible]M | M | 500-mb Chart |
| Height of Wet-Bulb-Zero | 11,600 ft | W | 9,800 ft | M | Plotted Sounding |
| Sfc Pressure Threat Area | 1009.3 mb | M | 1003 mb | S | Sfc Chart |
| Sfc Dew Point | 64°F | M | 70°F | S | Sfc Chart |
| Winds Veer With Height | Yes | | Yes | | Composite Chart |
| Speed Differential | No | | Yes | | Composite Chart |
| Intersecting Upper & Lower Jets | Yes | | Yes | | Composite Chart |
| Increasing Sfc Temp | Yes | | +11°F | | Surface Chart |
| Falling Pressure | Yes | | -6.3 mb | | Surface Chart |
| Increasing Dew Point | Yes | | ±6°F | | Surface Chart |
| Thickness Ridge Apparent | Yes | | Yes | | Thickness Chart |
| Thickness No-Change | Yes | | Yes | | Thickness Chart |
| Level of Free Convection | 770 mb | | 790 mb | | Plotted Sounding |
| Favorable Synoptic or Mesopattern | Yes | | Yes | | Surface Chart |

conjunction with the surface map (Figure 64), definitely placed the eastern half of Kansas and northern Missouri in the primary threat area. The surface low was progged to move ENE at 20 knots. This movement would cause the axis of maximum pressure falls to traverse the area and the warm front would provide a boundary of intersection for any squall line. The warm front was not expected to move northward rapidly because the early morning squall line (Figure 64) had cooled the air over much of eastern Kansas and western Missouri slowing the northward spread of warm air at the surface. The positions of the 500-mb, 700-mb and thickness no-change lines, and the location of the thickness ridge, indicated favorable conditions for squall-line development. Also, deep cold advection was moving into the area of increasing temperature, dew point, and instability over central Kansas and western Oklahoma during the afternoon (Figure 69). As shown on the surface chart the squall line formed from northwest of Salina to southwest of Hutchinson, Kansas, about 2000Z, and gradually grew to the north and south (Figure 64).

As shown in Table 5, the parameters at 0000Z had intensified. Tornadic storms had been occurring for three hours prior to 0000Z and the Topeka tornado occurred at 0015Z. At 1200Z a summary of the parameters showed 4 strong, 7 moderate, and 2 weak compared with 12 strong, 3 moderate and none weak at 0000Z. These are the static values taken directly from the data with no adjustments for anticipated changes. In actual forecast practice both sets of data would be further adjusted. For example, the 1200Z data would be adjusted for the threat area at the expected time of development. Such an adjustment should bring the parameters more in line with the actual conditions at 0000Z. The two weak parameters would be modified by the addition of heat and moisture in the low levels, coupled with dryer advection in the middle levels, and cooling in the upper levels. Other considerations of the surface and upper-air patterns would indicate several of the moderate-rated parameters should increase in intensity. In addition, the 12-hour surface-pressure fall forecast would be rated moderate to strong based on the track and forecast pressure near the low center. A similar procedure would be used for the remaining parameters. All values shown are for the Topeka area which was the center point of the most destructive activity.

## SECTION D—SUMMARY

The Composite Chart at 09/0000Z (Figure 76) is an excellent example of the concentration of the important and varied tornado-forecast parameters in a geographically restricted area. The primary area of instability represents Total Totals of 54. The moist ridge at 850-mb and the low-level jet are in perfect alignment. The 850-mb temperature ridge is west of the moist tongue and dry air is available upstream to the west and southwest of the threat area. At 700-mb dry air is available upwind of the threat area and is being advected into the area at 35 knots by WSW winds. The 700-mb no-change line is well-defined and near the surface squall line. The thickness ridge has moved to the east of the area and the squall line is located about 100 miles behind it. The upper-level jet tranverses the threat area and is significantly stronger than the low-level jet. The two jets intersect at a large angle. The presence of so many of the forecast parameters of strong intensity over a large area is no more unusual than the frequency of destructive tornadoes associated with family-type storms. It is when these parameters are concentrated over a particular area that the more widespread and violent outbreaks occur.

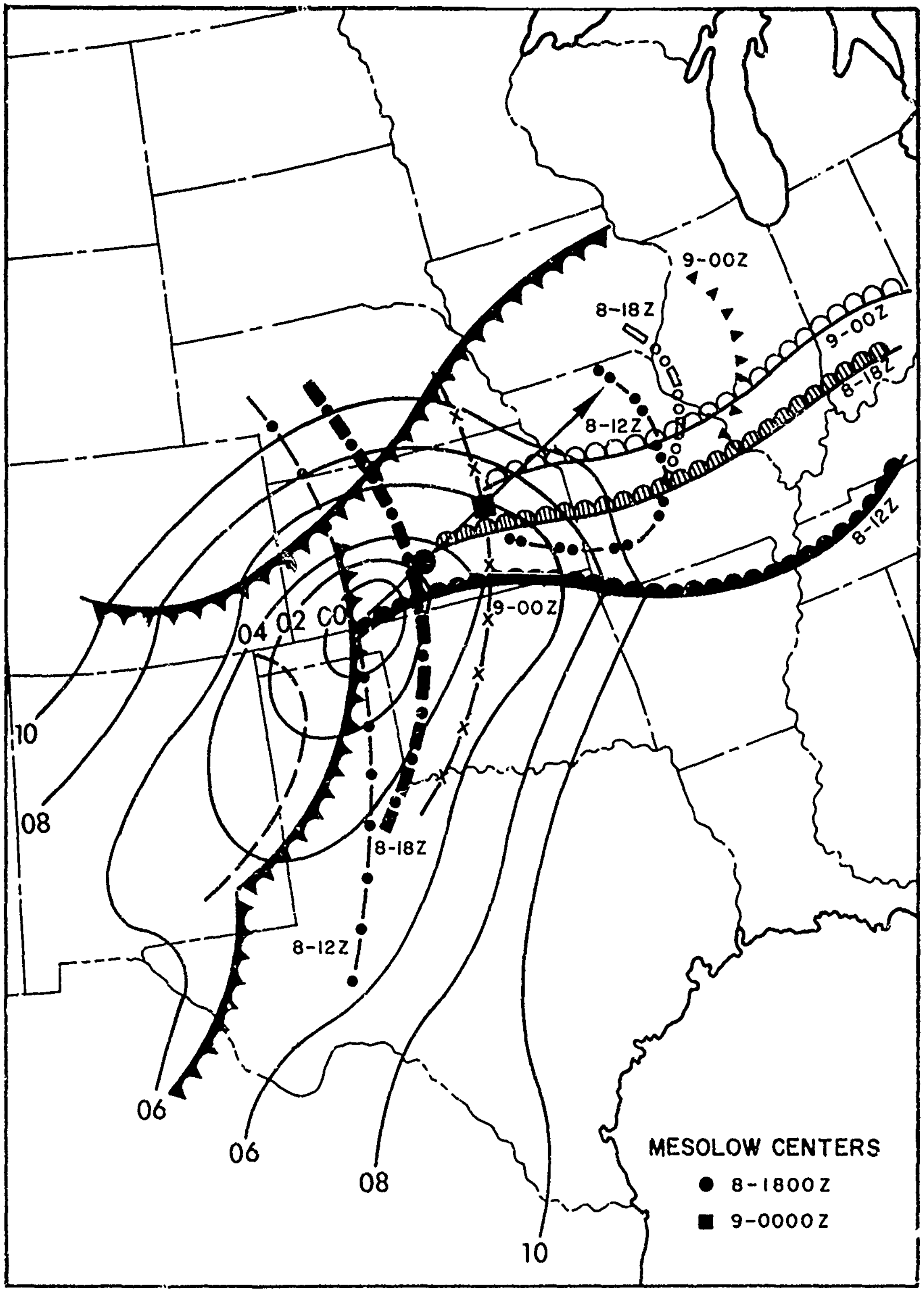



Figure 64 Location of major surface features during period 08/1200Z to 09/0000Z. Isobar analysis is for 08/1200Z.

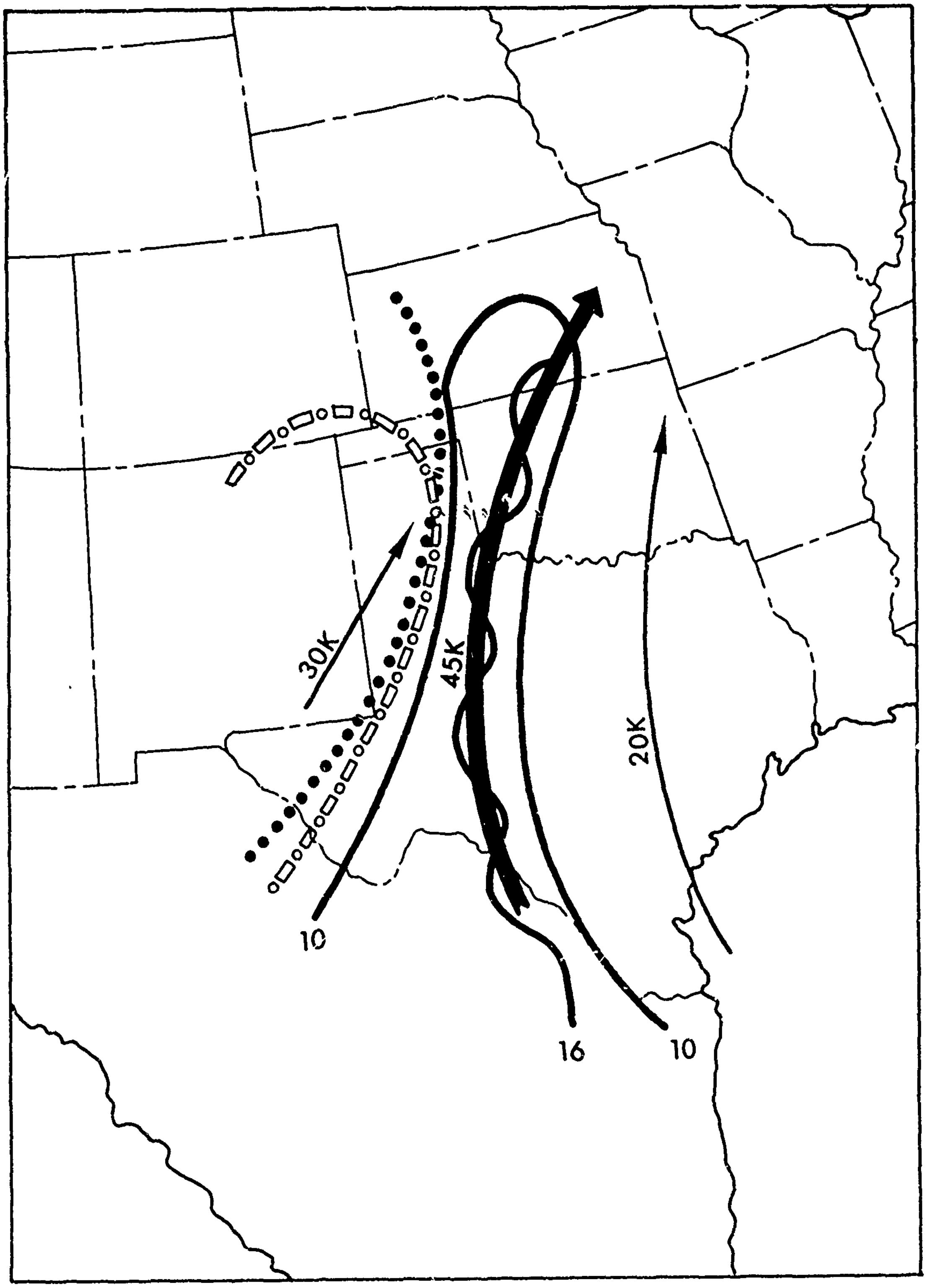



Figure 65. Major features of 850-mb chart for 08/1200Z.
Solid-line isopleths are dew points.

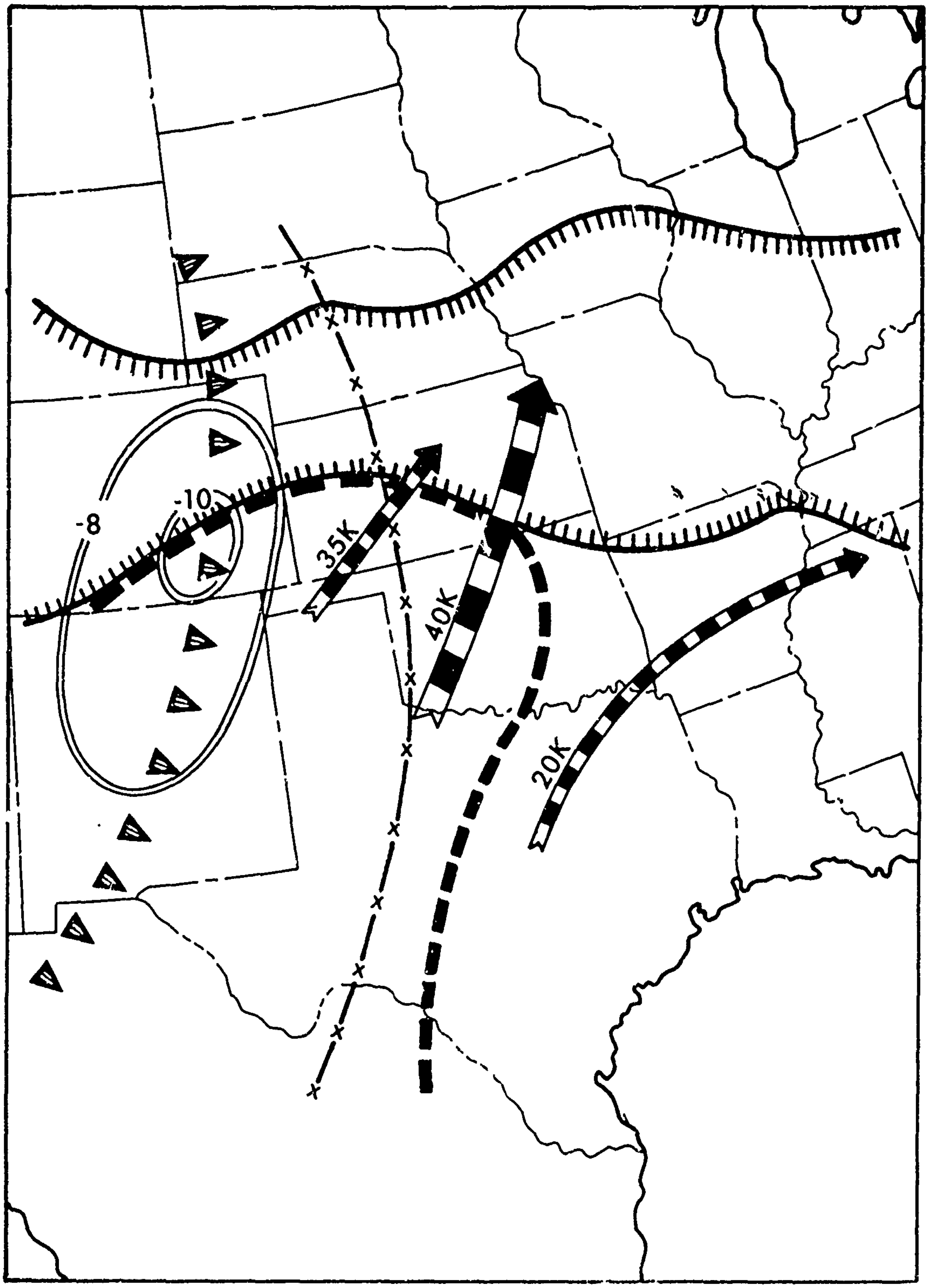



Figure 66. Major features on 700-mb chart for 08/1200Z

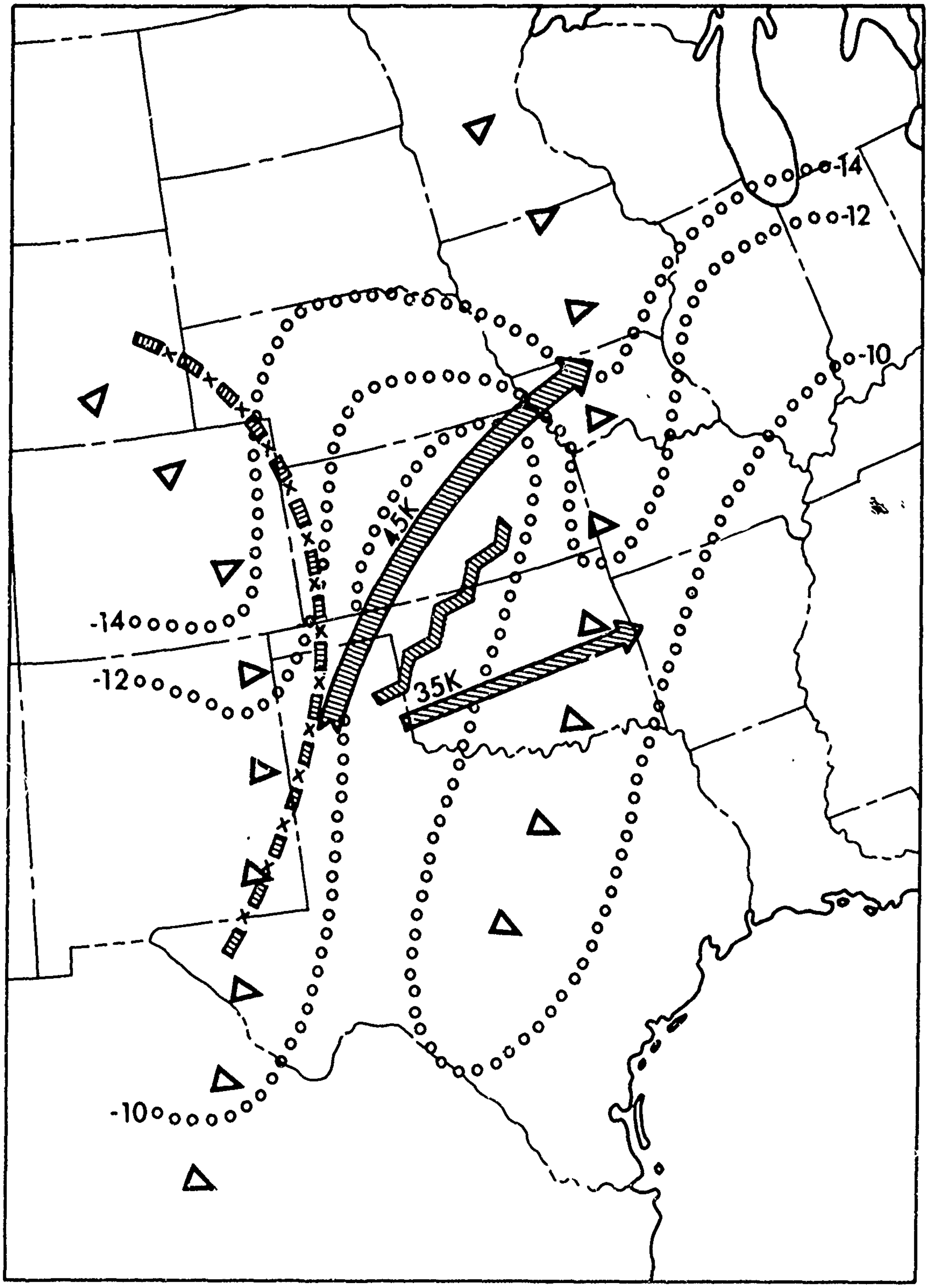



Figure 67. Major features on 500-mb chart for 08/1200Z.

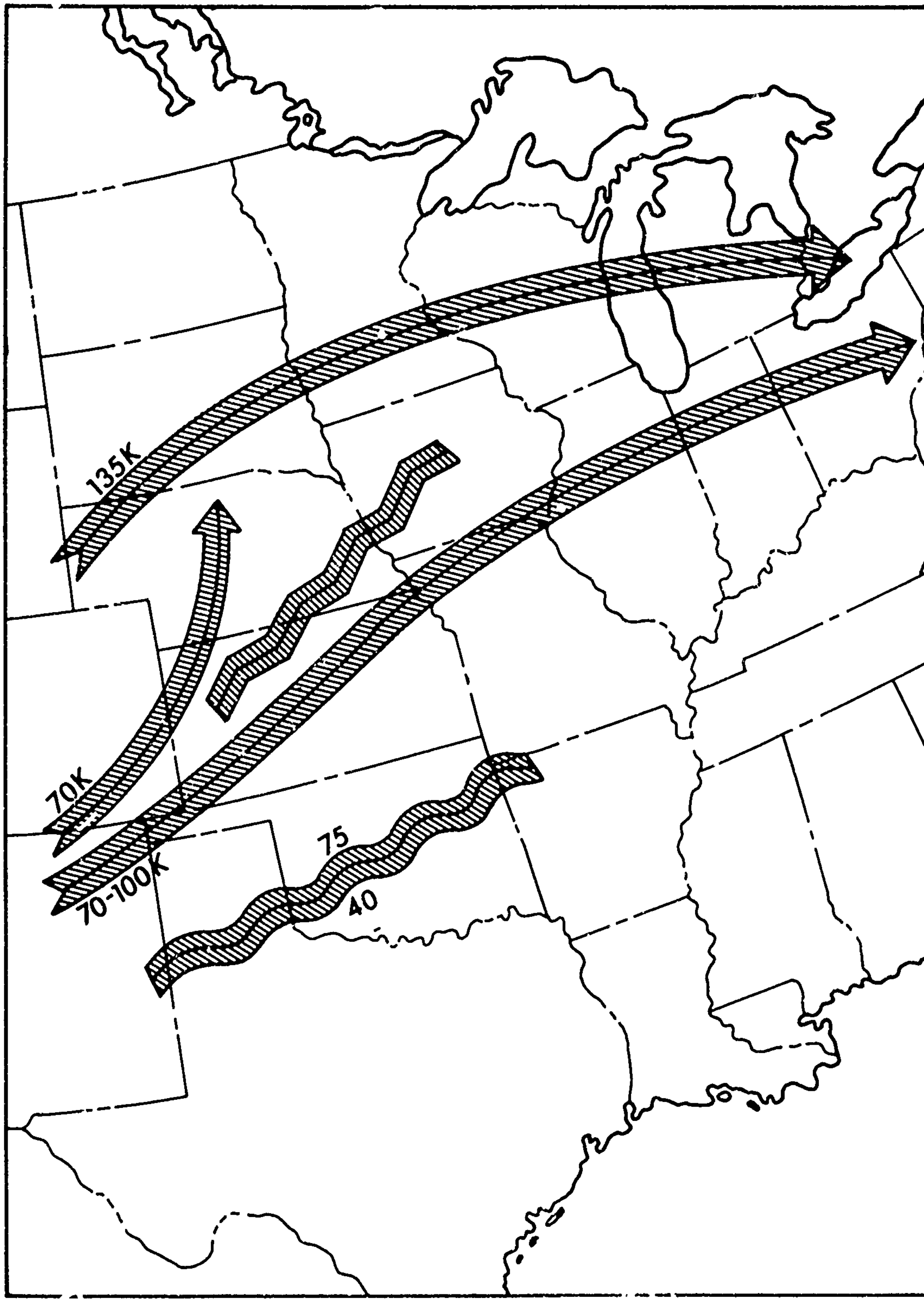



Figure 68. Upper-level jet features at 08/1200Z.

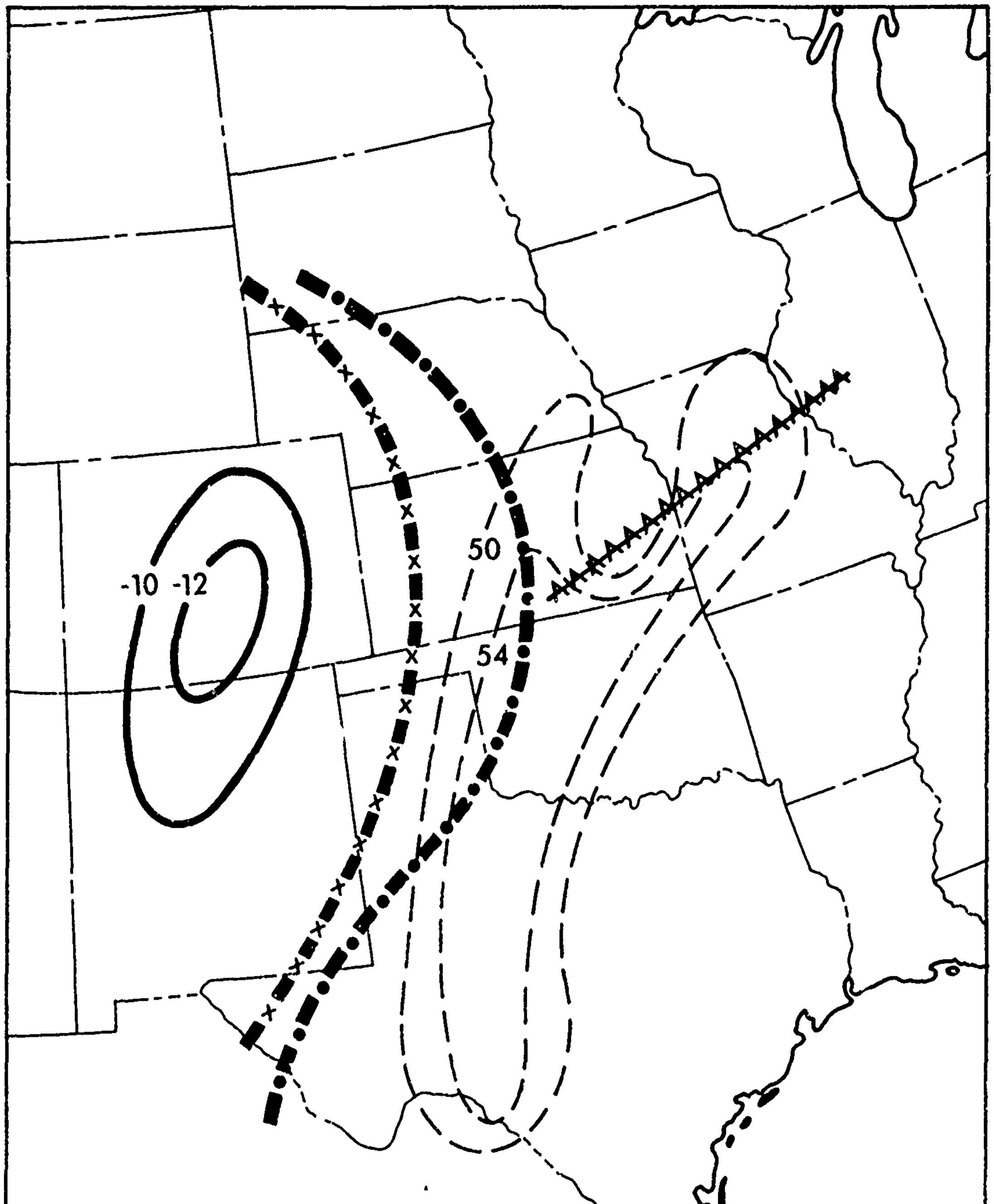



Figure 69. Thickness change, no-change line, thickness ridge line, and Total Totals at 08/1200Z. Also shows zone of anticyclonic wind shear.

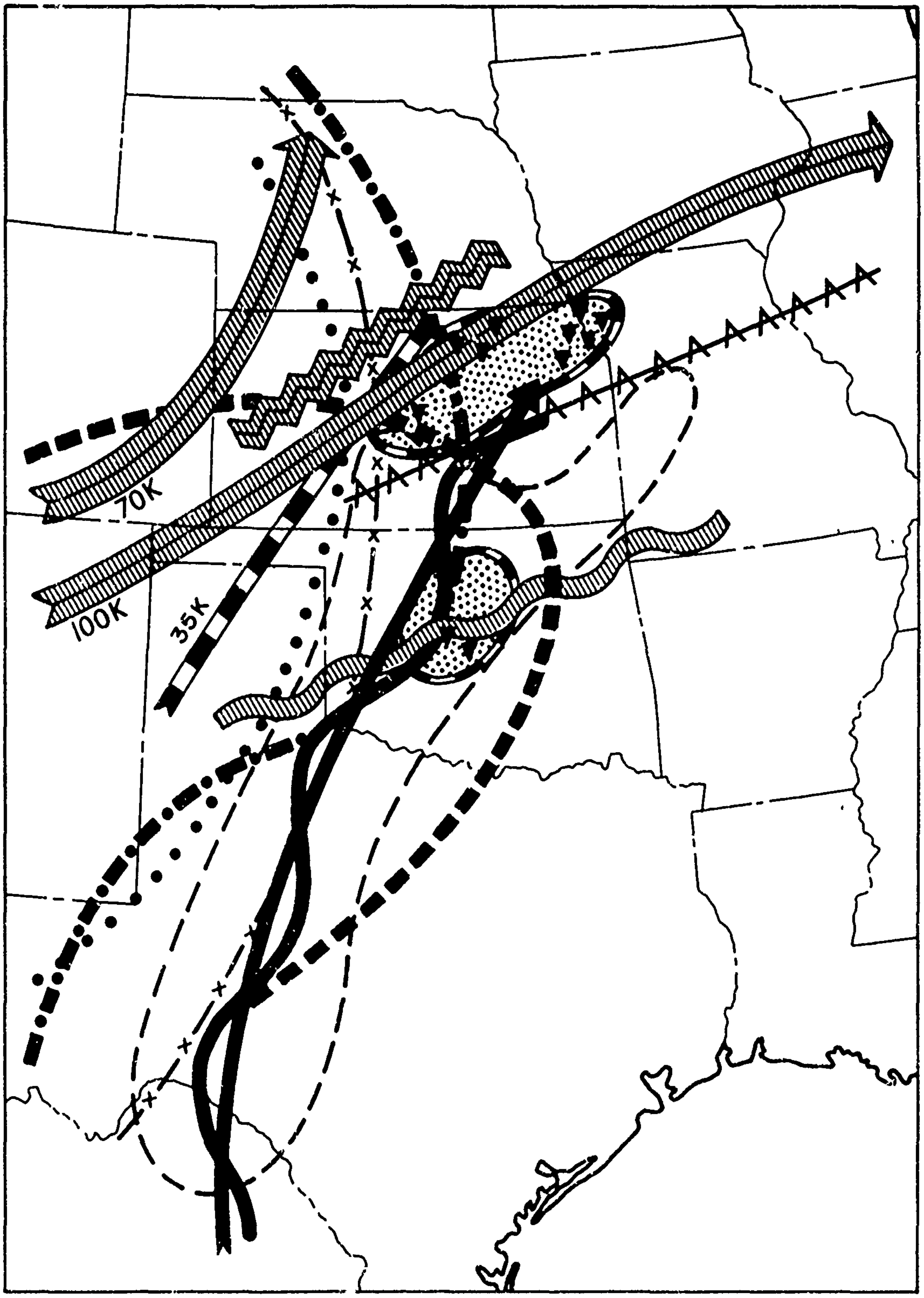



Figure 70. Composite chart for 08/1200Z. Stippled areas show activity during period 08/1200Z to 09/0000Z.

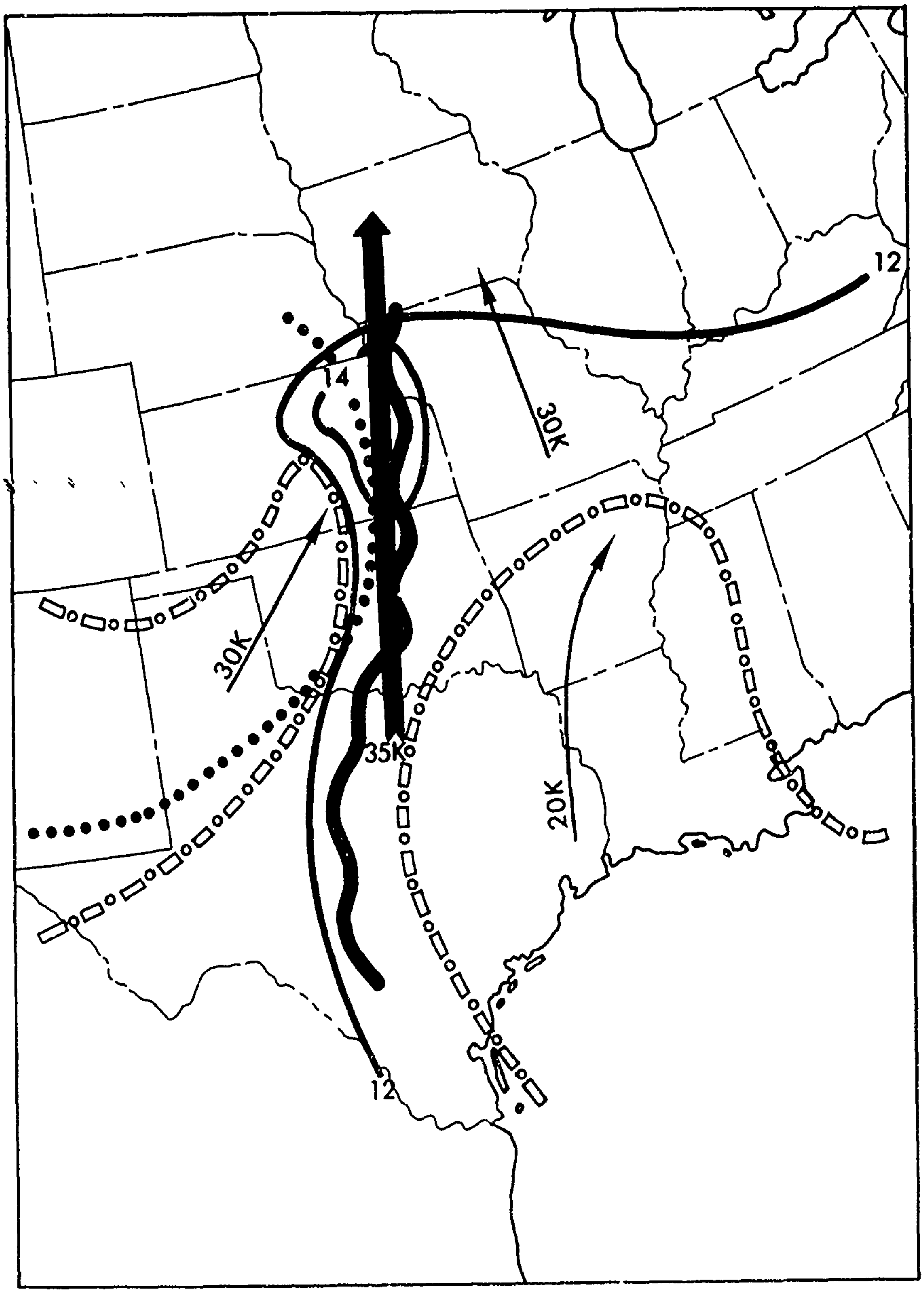



Figure 71 Major features of 850-mb chart for 09/0000Z. Isopleths are 850-mb dew points.

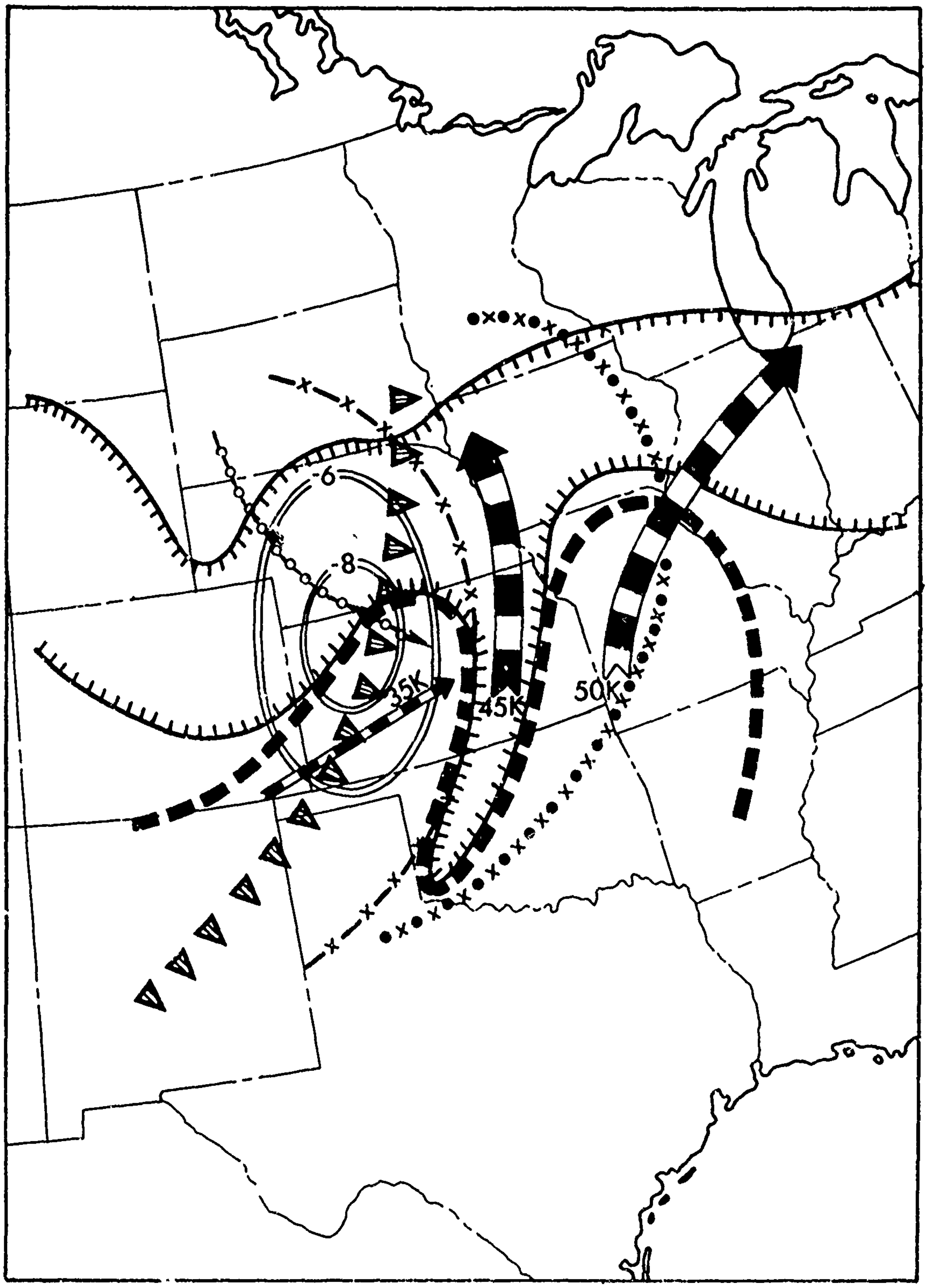



Figure 72. Major features of 700-mb chart at 09/0000Z
Arrow is the direction of the axis of cold air advection.

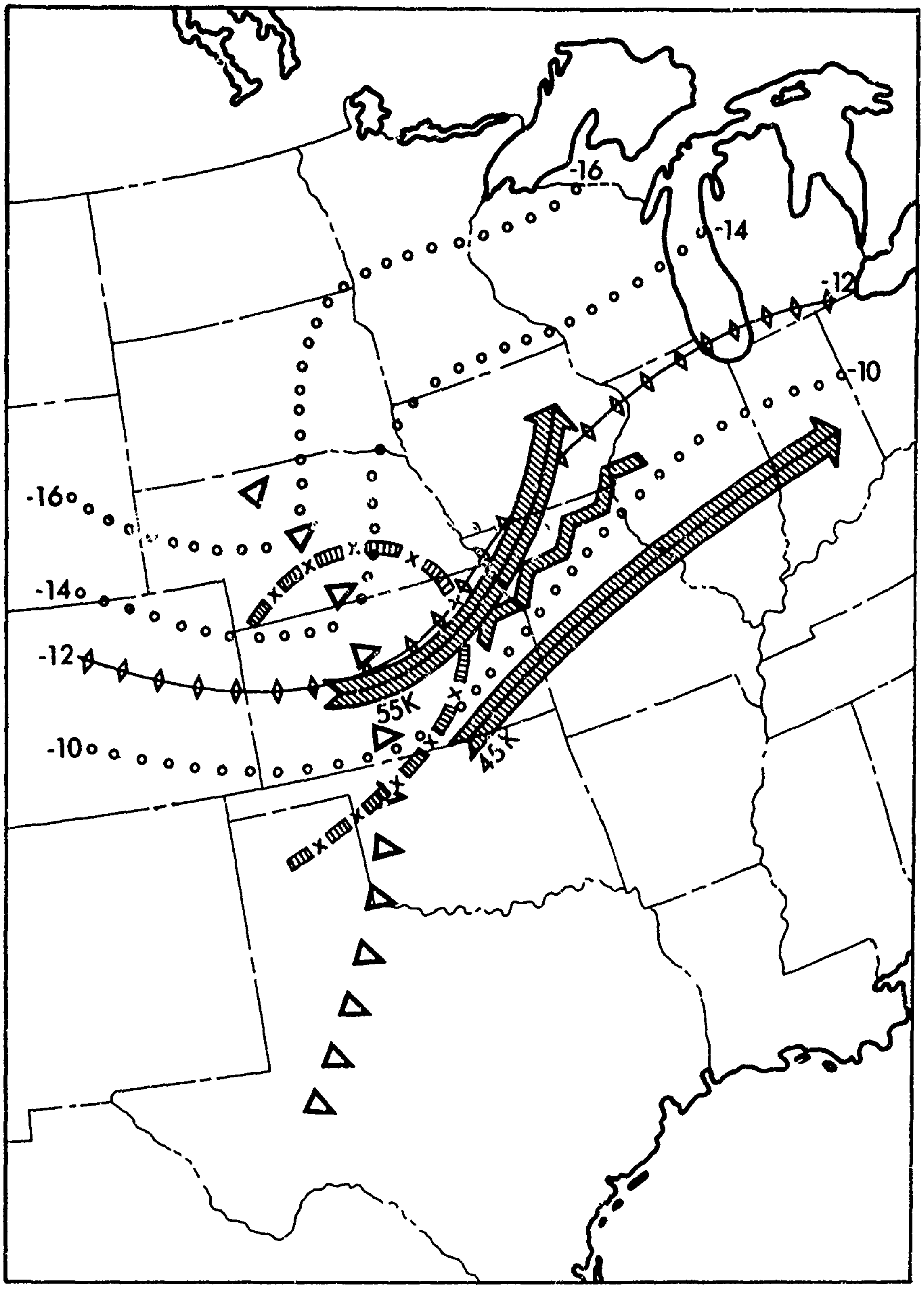



Figure 73. Major features on 500-mb chart at 09/0000Z
Note the -12°C critical temperature line

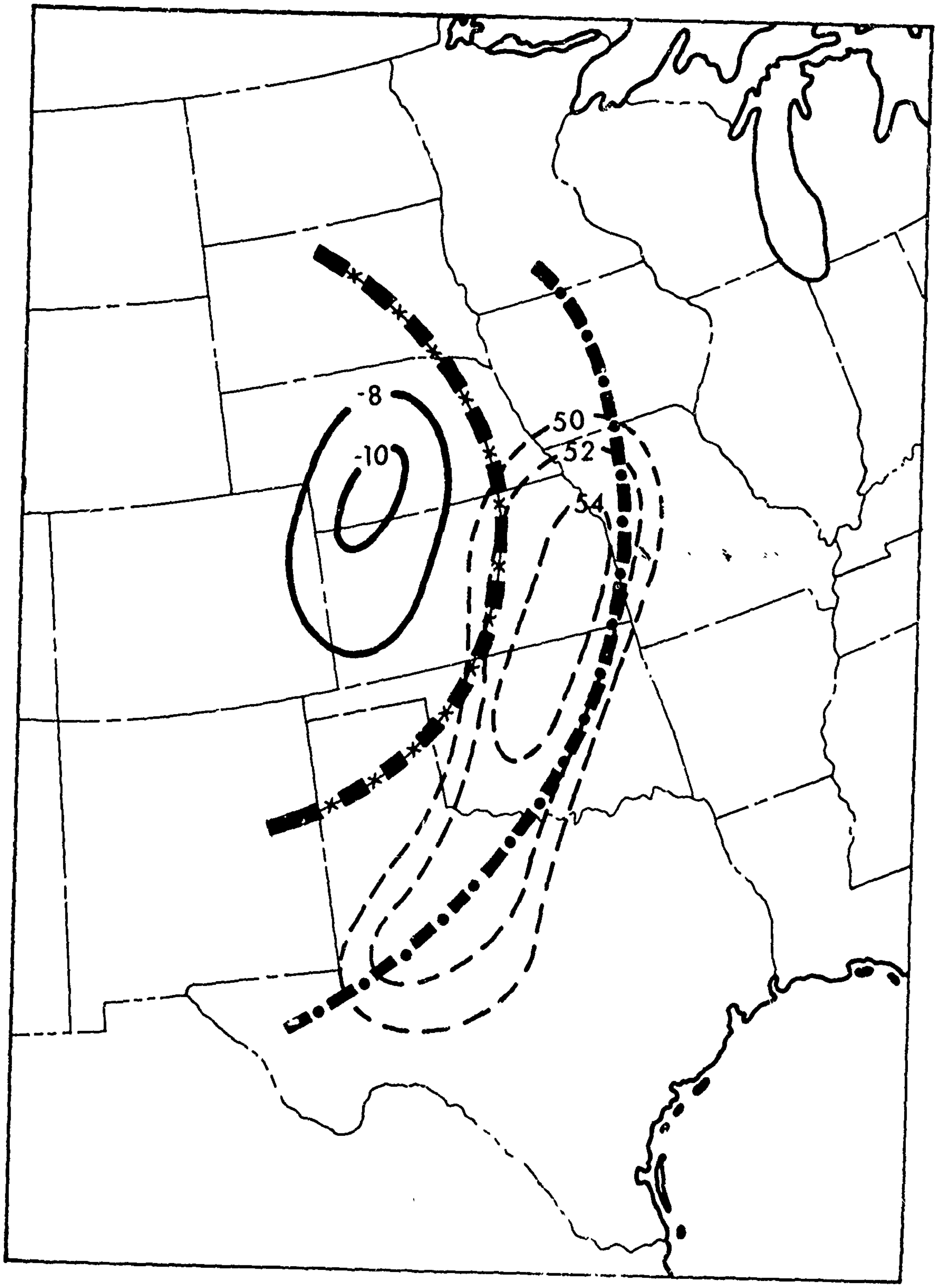



Figure 74. Thickness parameters and Total Total analysis for 09/0000Z.

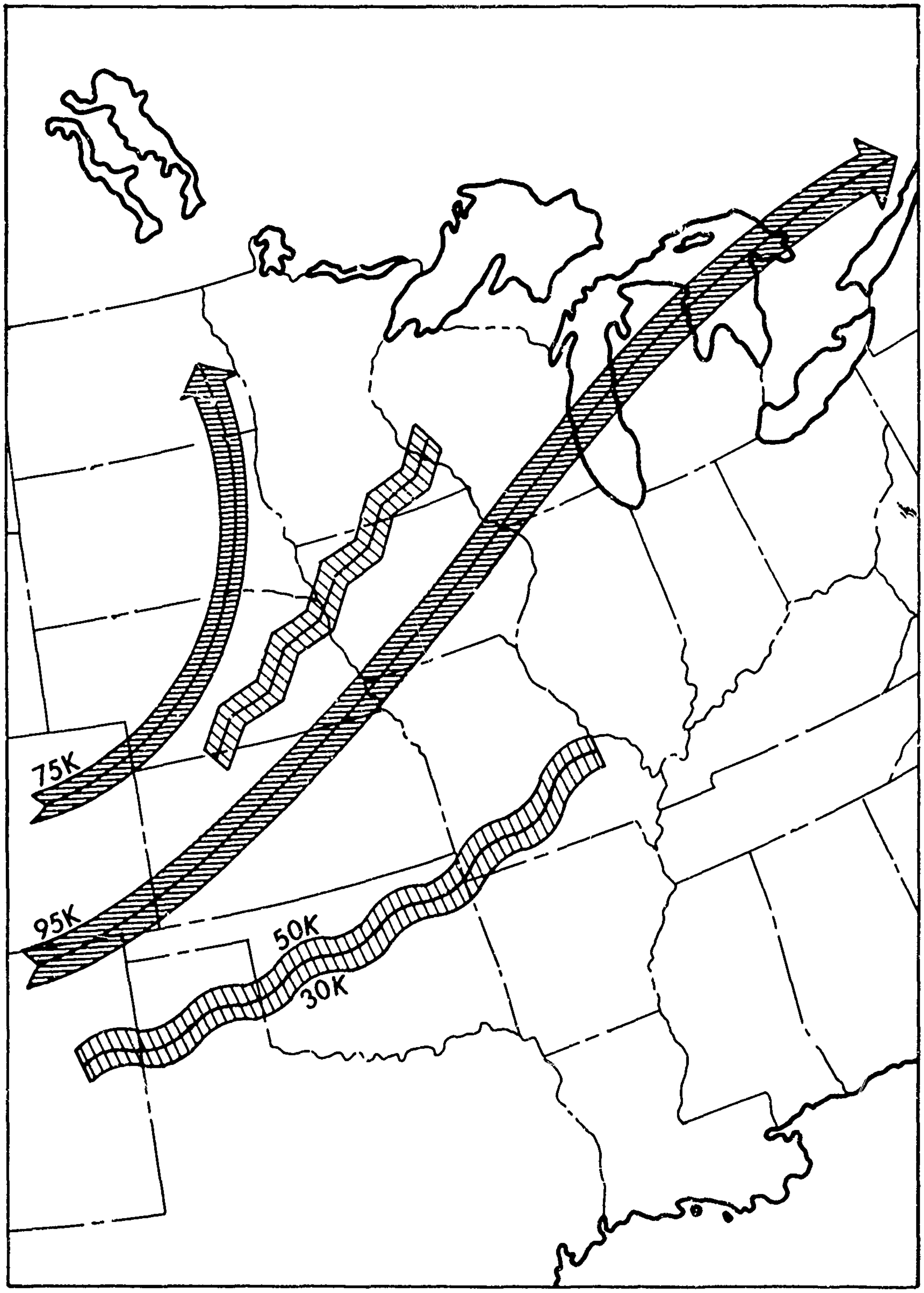



Figure 75. Upper-level jet features at 09/0000Z.

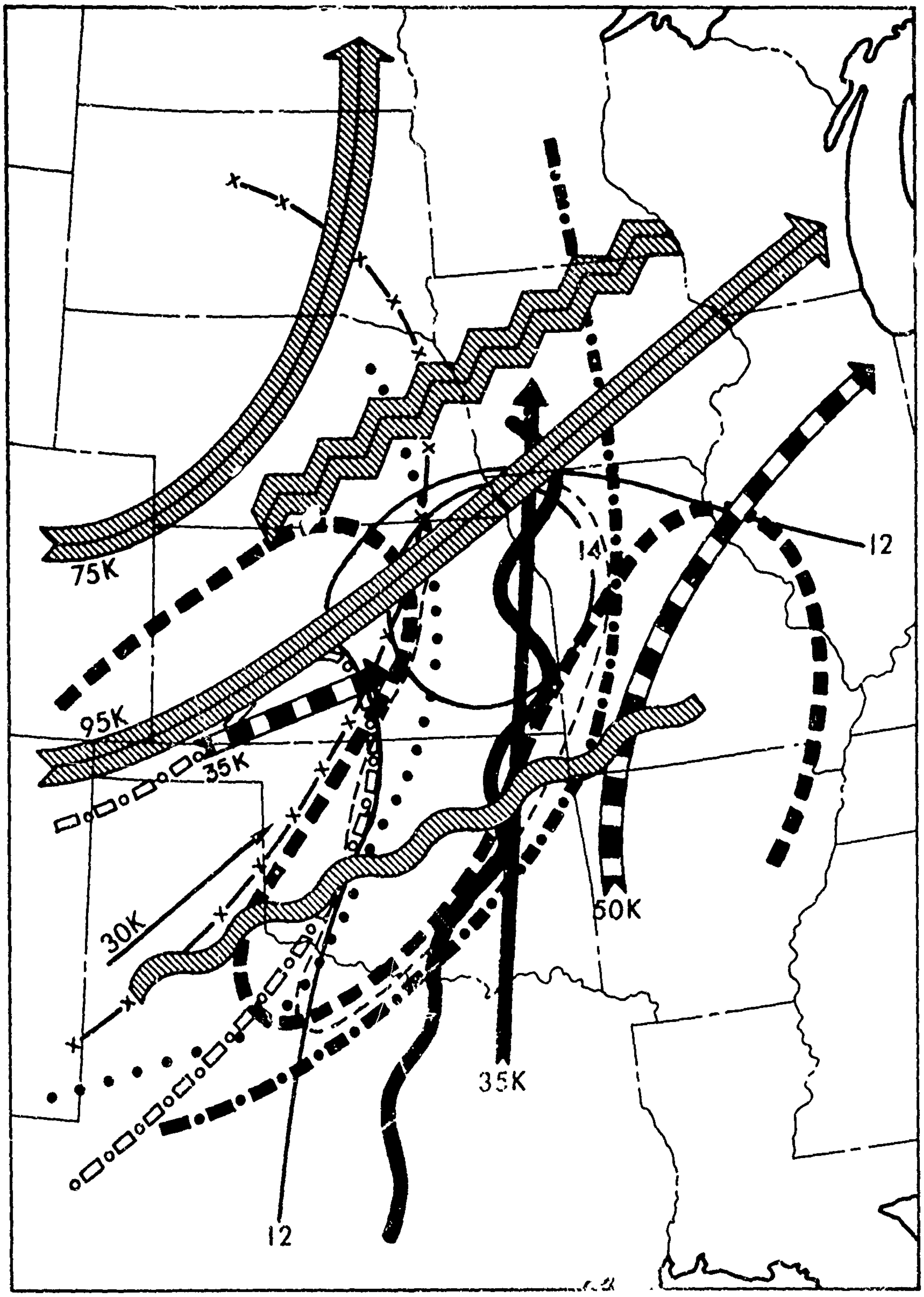



Figure 76. Composite Chart for 09/0000Z.

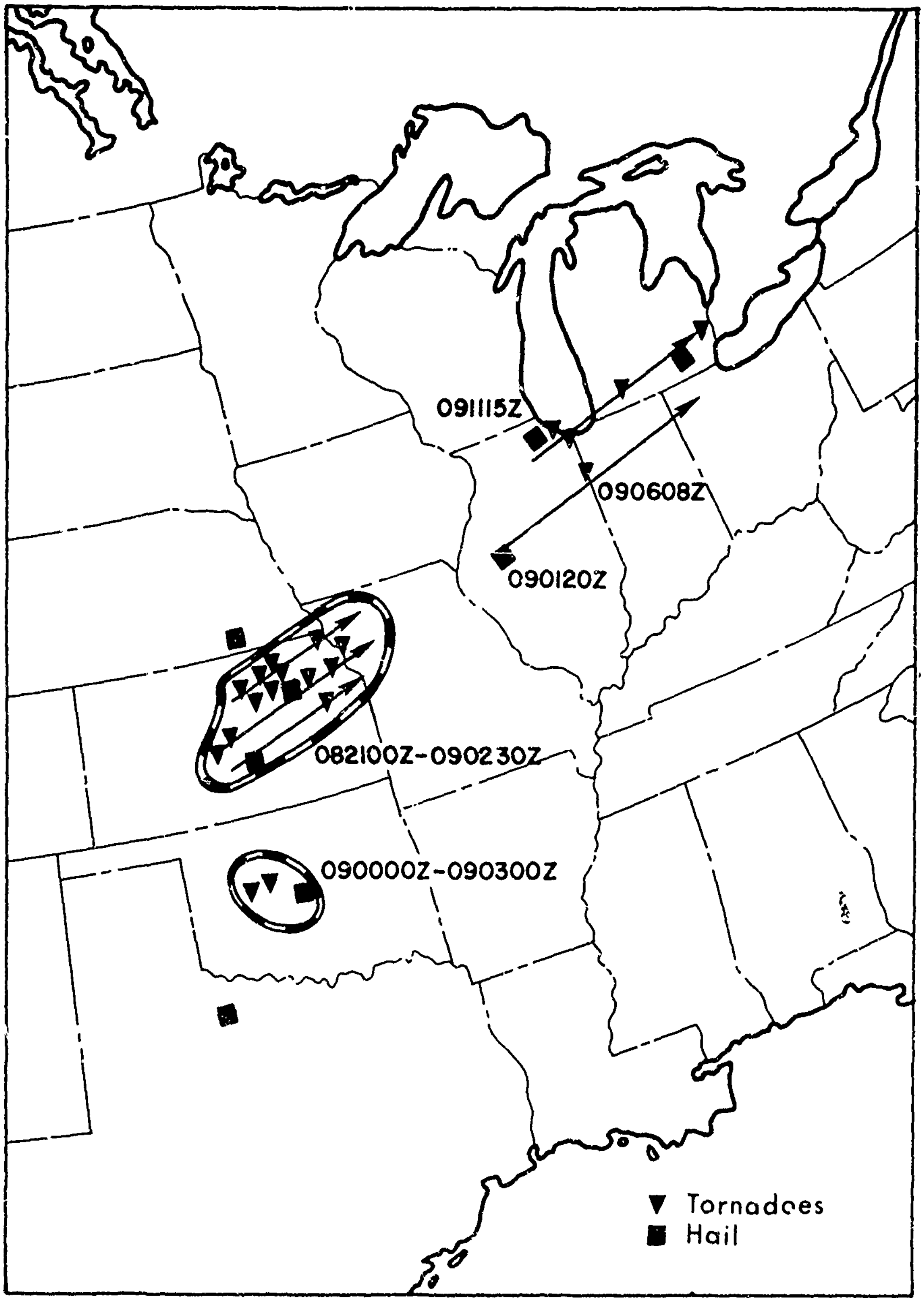



Figure 77. Activity Chart for period 08/2100Z to 09/1200Z.

# Appendix F

# THE USE OF AUTOMATED PRODUCTS IN SEVERE WEATHER FORECASTING

## SECTION A—GENERAL

The availability of AFGWC computers coupled with the concentration of highly competent programmers, specialized technicians in electronic display, skilled forecasting personnel, and the vast, continuously updated AFGWC data base provides severe weather forecasters with far more timely and accurate forecast tools than previously available. Current and prognostic fields of those surface and upper-air parameters described in detail in this report are in the hands of the severe weather forecaster in sufficient time for full consideration in producing the Military Weather Warning Advisory. These products negate the former need for time-consuming, manual prognoses of the various important parameters in space and time and naturally result in a more uniform appraisal of the future severe weather potential over the conterminous United States by forecasters with varying degrees of experience in this highly specialized field.

## SECTION B—AUTOMATED PRODUCTS

Fine mesh 12-, 24-, and 36-hour prognoses of the 850-, 700-, and 500-mb fields are available at two hours plus 20 minutes after receipt of the early SLAM data. These prognoses are available on standard 1:15,000,000 upper air charts computer printed and displayed through the AFGWC Selective Display Model (SDM). Currently, these charts display gridded values approximately 100 miles apart of temperature, dew point spread, wind direction and speed. It should be emphasized that the values chosen for display are limited only by the availability of data at any given level and there are many other display options open to the forecaster.

The AFGWC Boundary Layer Model (BLM) provides advisory forecasters with fine mesh 12- and 24-hour prognoses of temperature, dew point, pressure contours, and winds for selected levels from 50 through 1600 meters above ground level (AGL) to supplement the upper-air prognoses. The BLM 50-meter chart is used as primary guidance for the surface prog. It depicts the D value and wind fields providing sufficient information to analyze the pressure field and locate the forecast position of fronts and troughs. This chart is supplemented by 50-meter temperature and dew point and maximum and minimum temperature progs. AFGWC also utilizes the BLM 600-meter wind prog fields as an aid in forecasting strong gradient gusts, and the 900-meter temperature and dew point progs to better assess the stability of the air columns.

Current fine mesh analysis of the 850-, 700-, and 500-mb charts also are available through the SDM at 1 hour plus 25 minutes after the SLAM data. These charts consist of contoured temperature fields and wind direction and speed. In addition, computer plots of data for each upper air station are available for hand analysis of important parameters, including 24-hour changes in heights, temperatures, and dew point spreads Any chart described in this report is available from the AFGWC data base — including, for example, the 850-/500-mb thickness and totals chart described in Chapter 8.

AFGWC resources also made it possible to develop a unique index designed specifically for indicating the most probable area or areas of tornado and severe thunderstorm potential. This index, termed the Severe Weather Threat Index or SWEAT, is available to AFGWC forecasters in fine mesh gridded form and consists of a current analysis plus 12-, 24-, and 36-hour prognostic fields. The 36-hour fields are fine mesh interpolation of coarse mesh 36-hour progs. The SWEAT Index is described in detail in Section C.

## SECTION C—THE SEVERE WEATHER THREAT INDEX

The requirement for an index to specify and predict areas of potentially severe convective weather has long been recognized by the AWS and civilian meteorological community. The need for such an index stems from the following limitations:

a. Operationally reliable dynamic models capable of forecasting very small scale features such as tornadoes, or even small parent cyclones, are not currently available.

b. The forecast procedures which were used by the Military Weather Warning Center (MWWC) at Kansas City, Missouri, limited the forecast period to approximately 12 hours because most of the effort was expended on analyses. Centralized forecasts of unique severe weather predictors were not available on facsimile circuits; therefore, additional efforts were required to prepare manual forecasts. Automated production of operational forecasts at Kansas City was limited by the capabilities of the computer available there. The same constraint prevented expansion of severe weather forecasts outside the conterminous United States.

c. Most procedures described in this report are only semi-objective. The constant turnover of forecaster personnel, usually concentrated in the summer months, resulted in the loss of almost irreplaceable expertise in this esoteric area of forecasting. An ever-present and very intensive training effort was required to keep the severe weather forecasts at a consistently high level of quality. A new approach was needed to augment experience with objectivity.

The transfer of the MWWC function to the AFGWC provided the opportunity to apply unique resources to the problem. For the first time, the proper combination of ingredients was available — a vastly improved current and predicted environmental data base, together with required meteorological know-how, programming expertise, and computer hardware.

## SECTION D—DERIVING THE SWEAT INDEX

Case studies collected through the years at the MWWC provided the foundation for developing a Severe Weather Threat (SWEAT) Index. A study of 328 tornadoes and experience gained in daily forecasting determined which parameters to consider and the relative weights to be assigned to each parameter. Several constraints were imposed:

a. The index must be computed from U.S. selected-level radiosonde (SLAM) data available approximately one hour after observation time. This allows an automated plot of the SWEAT Index available about one hour and 15 minutes after observation time and gives a means of rapidly appraising the current air-mass potential.

b. The index must be computed from fields currently stored in the AFGWC prediction data base. This facilitates automated prognoses of the SWEAT Index without a major revamping of the data base.

c. The parameterization must use reported and predicted values directly, rather than relying on derived parameters or complex pattern recognition.

Under the above constraints, using our empirically derived weighing factors, the SWEAT Index was developed to the present form [6].

$$I = 12D + 20(T-49) + 2f8 + f5 + 125(S+0.2)$$

where

I = SWEAT Index

D = 850-mb dew point in degrees Celsius (if D is negative, the term is set to zero)

f8 = speed of 850-mb wind in knots

f5 = speed of 500-mb wind in knots

S = Sin (500-mb - 850-mb wind direction)

T = "Total Totals" in degrees Celsius (T is the sum of the 850-mb temperature and dew point, minus twice the 500-mb temperature; if T is less than 49, the term 20(T-49) is set to zero)

The entire shear term, 125(S+0.2), is set to zero if *any* of the following conditions are *not* met: 850-mb wind direction in the range 130 through 250 degrees, 500-mb wind direction in the range 210 through 310 degrees, 500-mb wind direction minus 850-mb wind direction positive; and both the 850- and 500-mb wind speeds at least 15 knots. Note that no term in the formula may be negative.

Application of this formula to past tornado and severe thunderstorm cases resulted in the distribution of SWEAT Index values versus observed weather shown in Table 6. The cumulative distribution of SWEAT Index values versus observed weather is shown in Table 7. A severe thunderstorm, as defined here, is one which is accompanied by gusts of at least 50 knots and/or hail at least 3/4-inch in diameter. A tornado case is defined as the occurrence of five or more tornadoes in the same general area. A severe thunderstorm case is defined as the occurrence of a combination of five or more severe thunderstorms and/or tornadoes (0-4 tornadoes) in the same general area. The cases are mutually exclusive; i.e., no tornado cases are also included as severe thunderstorm cases, although in some instances both kinds occurred on the same day but in different areas. SWEAT Index fields were analyzed from station data for the synoptic hour (0000Z and 1200Z) closest to the occurrence; hence, values were interpolated in space but not in time.

**Table 6 - Distribution of SWEAT Index values versus observed weather**

| | SWEAT Index Value | | | | | | |
|---|---|---|---|---|---|---|---|
| | 200 | 2-300 | 3-400 | 4-500 | 5-600 | 6-700 | 7-800 |
| Tornado Cases | 0 | 0 | 1 (a) | 23 | 27 | 5 | 1 |
| Severe Thunderstorm Cases | 0 | 4 (b) | 27 | 36 | 30 | 4 | 1 |

(a) Actual value 375 (b) Lowest value 272

**Table 7 - Cumulative Distribution of SWEAT Index Values Versus Observed Weather**

| | SWEAT Index Value | | | | | | |
|---|---|---|---|---|---|---|---|
| | ≤200 | ≤300 | ≤400 | < 500 | < 600 | ≤700 | ≤800 |
| Tornado Cases | 0 | 0 | 1 (a) | 24 | 51 | 56 | 57 |
| Severe Thunderstorm Cases | 0 | 4 (b) | 31 | 67 | 97 | 101 | 102 |

(a) Actual value 375 (b) Lowest value 272

From Tables 6 and 7, it appears that the SWEAT Index threshold value for tornadoes is about 400, and for severe thunderstorms about 300. Remember, only cases where severe weather was *known* to have occurred were considered. Nothing can be inferred about "false alarm" rates. It must be emphasized, however, that the SWEAT Index is only an indication of the potential for severe weather. A high SWEAT Index for a given time (either observed or predicted) does not mean that severe weather is occurring or will occur. Some type of triggering action is necessary to realize the potential. Experience has shown that, although high SWEAT values can occur in the United States during the morning (1200Z) without concurrent severe convective weather, the potential is usually realized if the predicted value for the afternoon and evening is also high. Although low observed values of the SWEAT index almost certainly mean there is no severe weather occurring, values sometimes increase dramatically during a 12-hour period. For example, at 1200Z, 8 June 1966, Del Rio, Texas (DRT), had a SWEAT Index of 508 while Topeka, Kansas (TOP), showed 293. Twelve hours later (0000Z, 9 June 1966) the value at DRT dropped to 232 with no activity occurring while the value at TOP jumped to 573. One of the most powerful and destructive tornadoes on record slashed through Topeka, starting about 0000Z, 9 June 1966. (See Appendix E.)

The SWEAT Index should not be used to predict ordinary thunderstorms. Use of the shear term and minimum values for the stability (Totals) and wind speed terms were specifically designed to discriminate between ordinary and severe thunderstorms. For the prediction of ordinary thunderstorms, a stability index such as the "Lifted Index" or "Totals" is more applicable.

In addition to the early SWEAT analysis and prognoses mentioned above, AFGWC forecasters are provided with a modified SWEAT Index based on the BLM current analyses, and 12- and 24-hour prognoses. This procedure substitutes data at a terrain following level for the 850-mb lower reference level used in the early SWEAT. By using the BLM analysis and forecast data, the 850-mb temperature, moisture, and wind are replaced with BLM data for 900 meters above ground level (AGL). An adjustment is made to the "Totals" term to compensate for the varying thickness of the 900-meter AGL/500-mb layer. This results in a floating index (over the terrain) which has proved more reliable in high terrain areas. The early SWEAT has been retained for use with SLAM data, as well as for areas where BLM forecasts are not available. Several examples of SWEAT analyses and prognoses are shown in Figures 78 through 80.

A further refinement was added to the BLM SWEAT package in the fall of 1971. This consists of a single chart which depicts the forecast *maximum* SWEAT value for each grid point for the 24-hour period following the 1200Z and 0000Z data base times. Also depicted is the Z-time this maximum value is expected. This chart has proven very successful in real-time operation and its application to a specific case is shown in Figure 81.

## SECTION E—AN OPERATIONAL CASE

On the 21st of February 1971, a series of destructive tornadoes moved through portions of extreme northeastern Louisiana and over most of western, north-central, and northern Mississippi. The number of tornadoes reported exceeded fifty, but subsequent air and ground investigation indicated only three primary, nearly parallel, paths of damage (Figure 82). The first of this violent series of tornadoes was reported at Delhi, Louisiana, shortly after 2100Z. The last report, at 0123Z, 22 February, was from the second and longest track, which covered approximately 120 miles. Several reports of multiple funnels were received along portions of the three tracks. These storms were the most concentrated of a series of tornadoes which occurred during the three-day period 21-23 February 1971 in the Gulf Coast states eastward into the Carolinas and Virginia.

The tornado forecast parameters used by both the AFGWC and the Severe Local Storms Unit (SELS) of the National Weather Service at Kansas City were evident in profusion on the surface and upper air charts for 1200Z on the 21st. A telephone discussion and exchange of information between the AFGWC and SELS forecasters resulted in agreement that the primary threat area would include the northwest portion of Louisiana and most of Mississippi, and that the activity would start during the early afternoon. Figures 83 through 90 graphically portray the most important features at the 850-, 700-, and 500-mb levels for data base times of 1200Z, 21 February, and 0000Z, 22 February 1971, including composite charts used by the AFGWC for these times.

Figure 91 depicts the composite chart valid for 0000Z, 22 February, made from 12-hour prognoses from the data base for the 850-, 700-, and 500-mb levels. A comparison with the verifying composite chart made from actual 0000Z observations (Figure 90) clearly shows the accuracy of the fine-mesh forecasts in this instance.

The early 12-hour forecast SWEAT Index field valid 0000Z, 22 February (Figure 92), showed values exceeding 650 over northern Missisippi. These values were well over the tornado threshold value of 400 and the highest yet seen up to that time on prognoses using the present form of the SWEAT Index formula. Utilizing the forecast composite chart and the progged SWEAT Index values plus the favorable surface synoptic pattern, the AFGWC Advisory Forecaster indicated tornadoes and severe thunderstorms over the threat area during the afternoon and evening of the 21st. The 24-hour SWEAT forecast indicated eastward and southward movement of the threat area, with values just above 500, by 1200Z on the 22nd. Tornadoes occurred over the southern half of Alabama and Georgia during the night and continued into the early morning of the 22nd.

The relative strength of the parameters at 1200Z, 21 February, and the forecast values for 0000Z, 22 February, derived from AFGWC products are shown in Table 8. This is a modified version of the tornado parameter worksheet depicted in Table 5, Appendix E. Note that the SWEAT Index has been added to this worksheet with values of less than 350 considered weak, 400 to 500 moderate, and greater than 500 strong. The rating of the other key parameters is shown in Table 1, Chapter 5.

Table 8

SEVERE THUNDERSTORM AND TORNADO PARAMETER WORKSHEET

| AREA | ADVISORY NUMBER | DATE | ADVISORY VALID |
|---|---|---|---|
| LA-MS-AL | 86 | 21 FEB 71 | 21 / 18 Z to 22 / 06 Z |

| PARAMETER | 1200Z ANAL VALUE | 1200Z ANAL RATING | 0000Z PROG VALUE | 0000Z PROG RATING | REMARKS/VERIFICATION |
|---|---|---|---|---|---|
| SWEAT | 500-550 | S+ | 500-666 | S | MAX PROGGED OVER CNTRL & NRN MS |
| TOTALS | 58 | S+ | 58-60 | S | |
| LIFTED INDEX | -5 | S+ | -7 | S | |
| PVA | 30° | M+ | 40° | S | |
| 500 MB HT FALLS | -200M | S | -200M | S | |
| 500 MB JET | 95K | S- | 90K | S | |
| 850 MB MOISTURE | 11° | M+ | 13 | S | |
| 850 TEMP RIDGE | W OF MOIST RIDGE | S | W OF MOIST RIDGE | S | |
| LO-LEVEL JET | 45-55K | S | 50K | S | |
| 700 MB DRY INTRUSION | — | S | — | S | |
| 700 MB NO-CHANGE TEMP | WINDS CROSS ∠ 20° | W+ | WINDS CROSS 20-40° | M | 0000Z DATA ACTUALLY STRONG S |
| WINDS VEER WITH HEIGHT | YES | — | YES | — | |
| WINDS INCREASE WITH HEIGHT | YES | — | YES | — | |
| INTERSECTING UP AND LO JETS | YES | — | YES | — | |
| SFC DEW POINT | 62° | M+ | 66° | S | |
| SFC PRESSURE THREAT AREA | 1008 | M+ | 1002 | S | |
| FALLING PRESSURE | YES | — | YES | — | |
| INCREASING SFC TEMP | YES | — | YES | — | |
| INCREASING DEW POINT | YES | — | YES | — | |
| THICKNESS RIDGE | YES | — | YES | — | |
| THICKNESS NO-CHANGE | YES | — | YES | — | |
| MESO OR SYNOP PATTERN | FAVORABLE | | FAVORABLE | — | |

REMARKS

MARKED DIFLUENCE OVER THREAT AREA AT 1200Z AND PROGGED FOR 0000Z.

NUMEROUS TORNADOES OCCURRED FROM N.E. LA INTO MS AFTN AND EVNG.

AFGWC FORM AUG 71 0-25

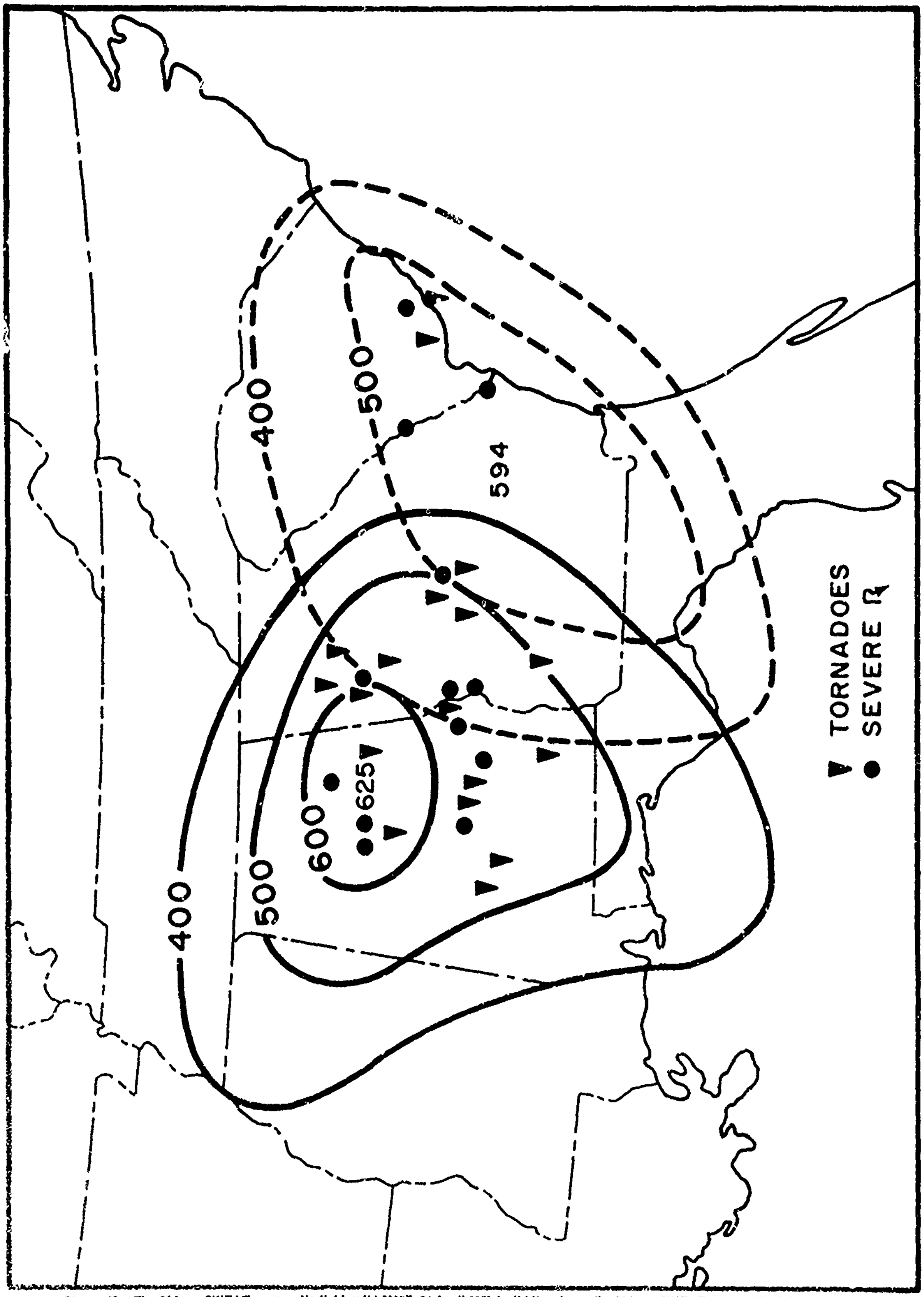



Figure 78. The 36-hour SWEAT prognostic field valid 0000Z, 24 April 1971 (solid lines) and the 24-hour SWEAT prognostic field valid 1200Z, 24 April 1971 (dashed lines) and locations of tornado and severe thunderstorm occurrences. Activity began at 1335Z, 23 April in northeast Alabama and spread east and south into Georgia and southern South Carolina with the last report near Charleston at 0925, 24 April.

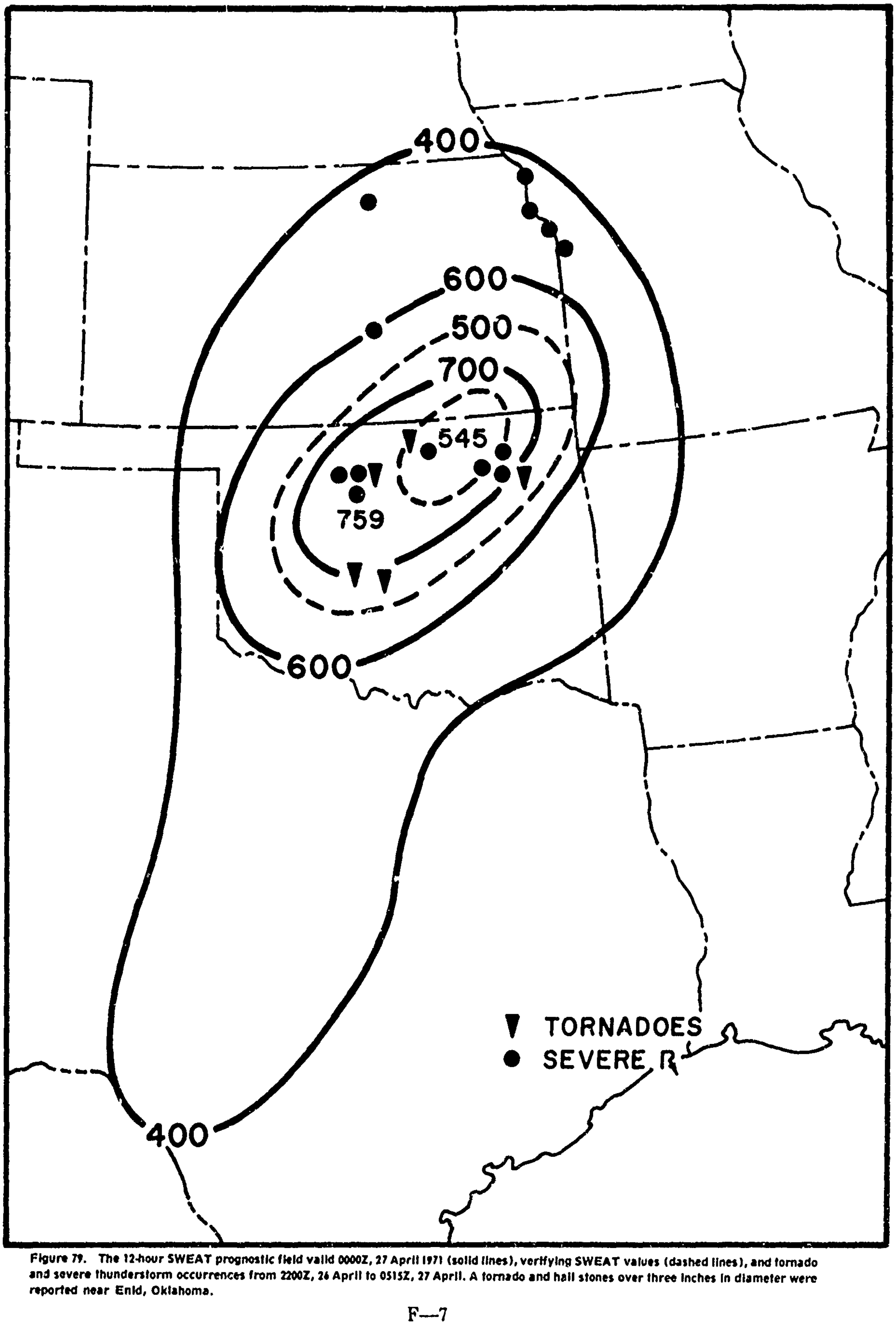



Figure 79. The 12-hour SWEAT prognostic field valid 0000Z, 27 April 1971 (solid lines), verifying SWEAT values (dashed lines), and tornado and severe thunderstorm occurrences from 2200Z, 26 April to 0515Z, 27 April. A tornado and hail stones over three inches in diameter were reported near Enid, Oklahoma.

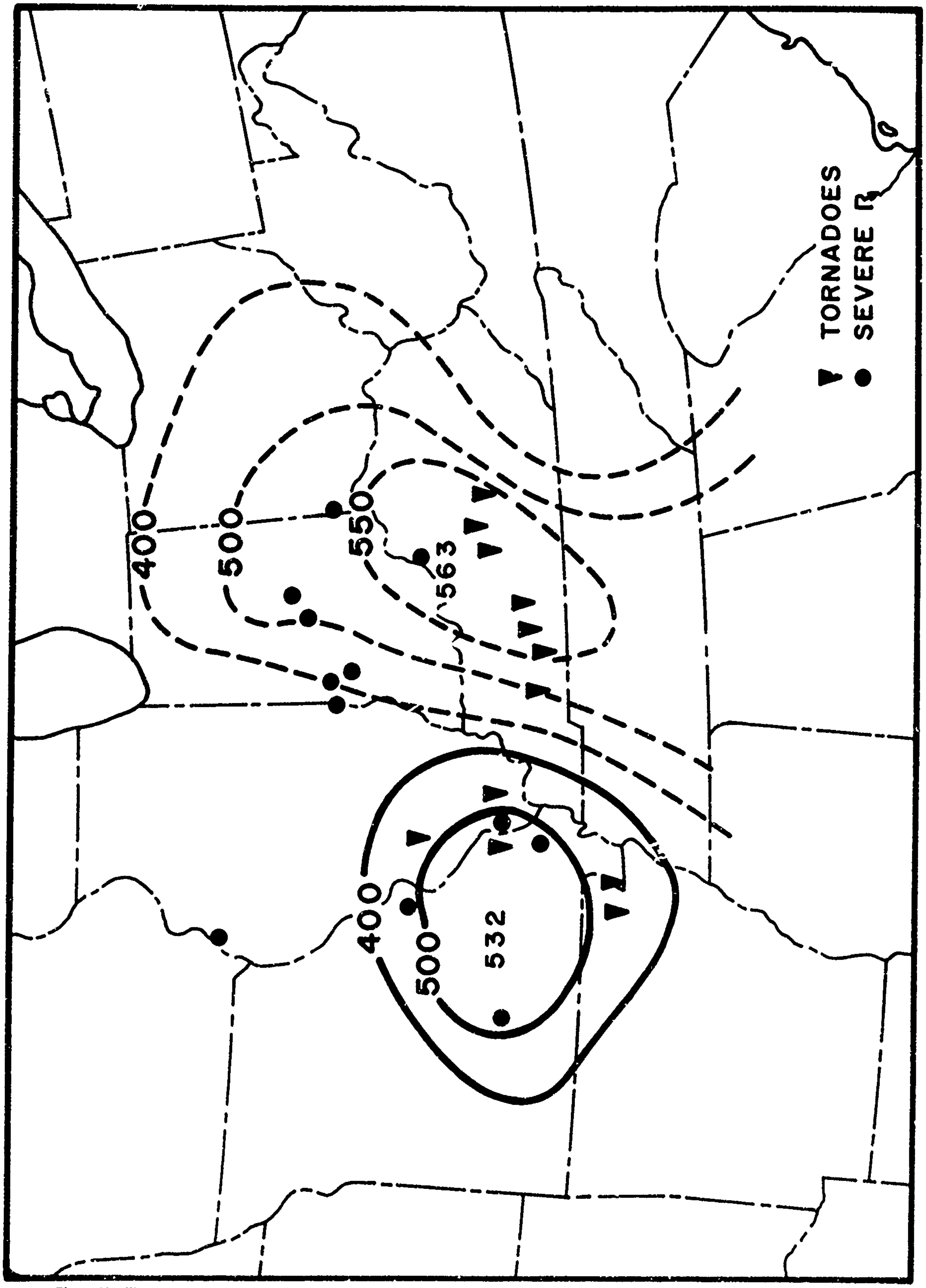



Figure 80. The 12-hour SWEAT prognostic field valid 0000Z, 28 April 1971 (solid lines) and the 24-hour SWEAT prognostic field valid 1200Z, 28 April 1971 (dashed lines) and tornado and severe thunderstorm occurrences. Severe weather first occurred near Fort Leonard Wood, Missouri at 2022Z, 27 April and spread eastward with the last report near 0500Z, 28 April south of Lexington, Kentucky.

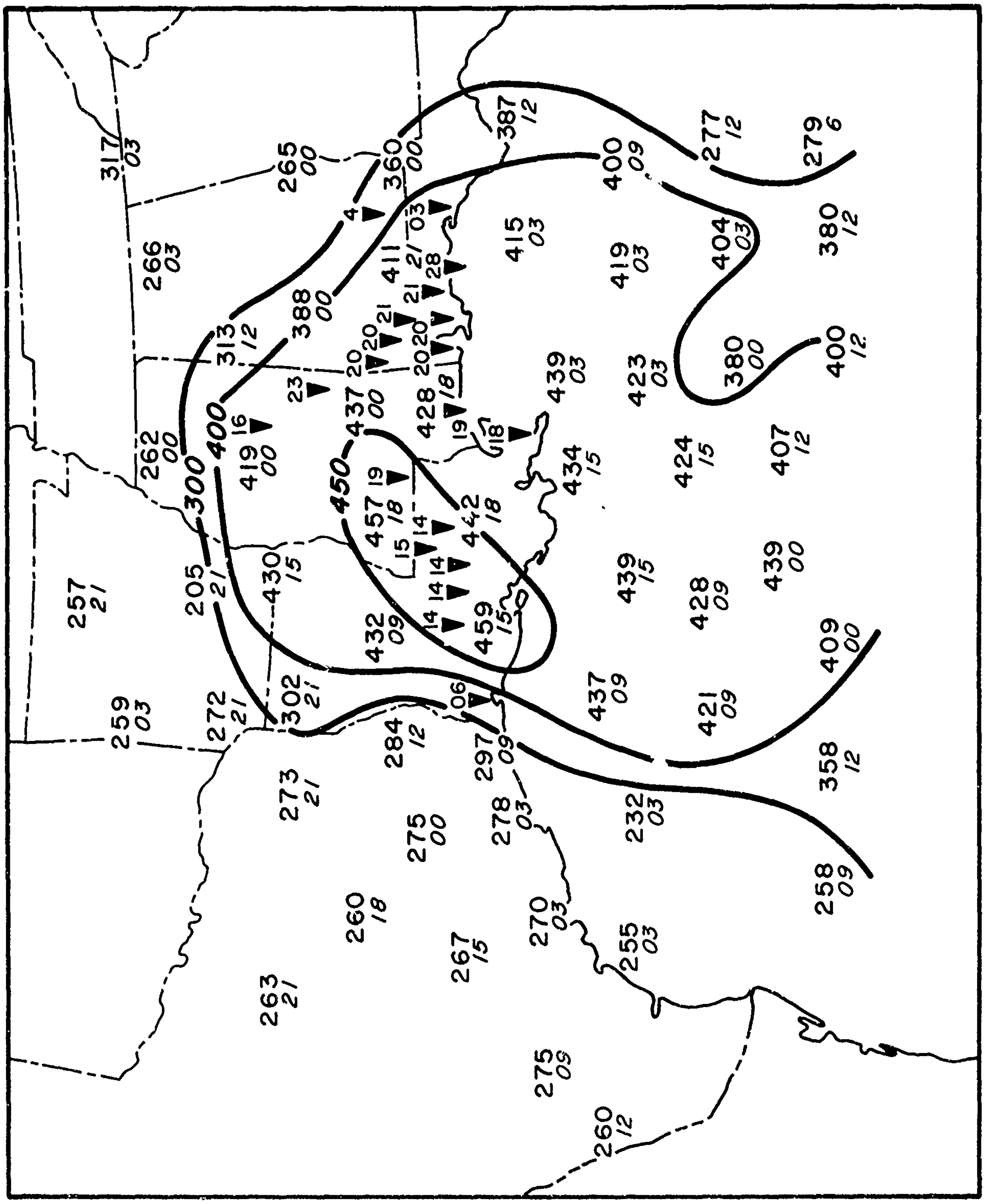


Figure 81. The AFGWC BLM maximum SWEAT index value (top number) and forecast Z-time of the maximum (bottom number) for selected grid points for the 24-hour period beginning 0000Z, 16 September 1971. Also shown is an analysis of the maximum SWEAT values and the location and Z-time of tornado occurrences.

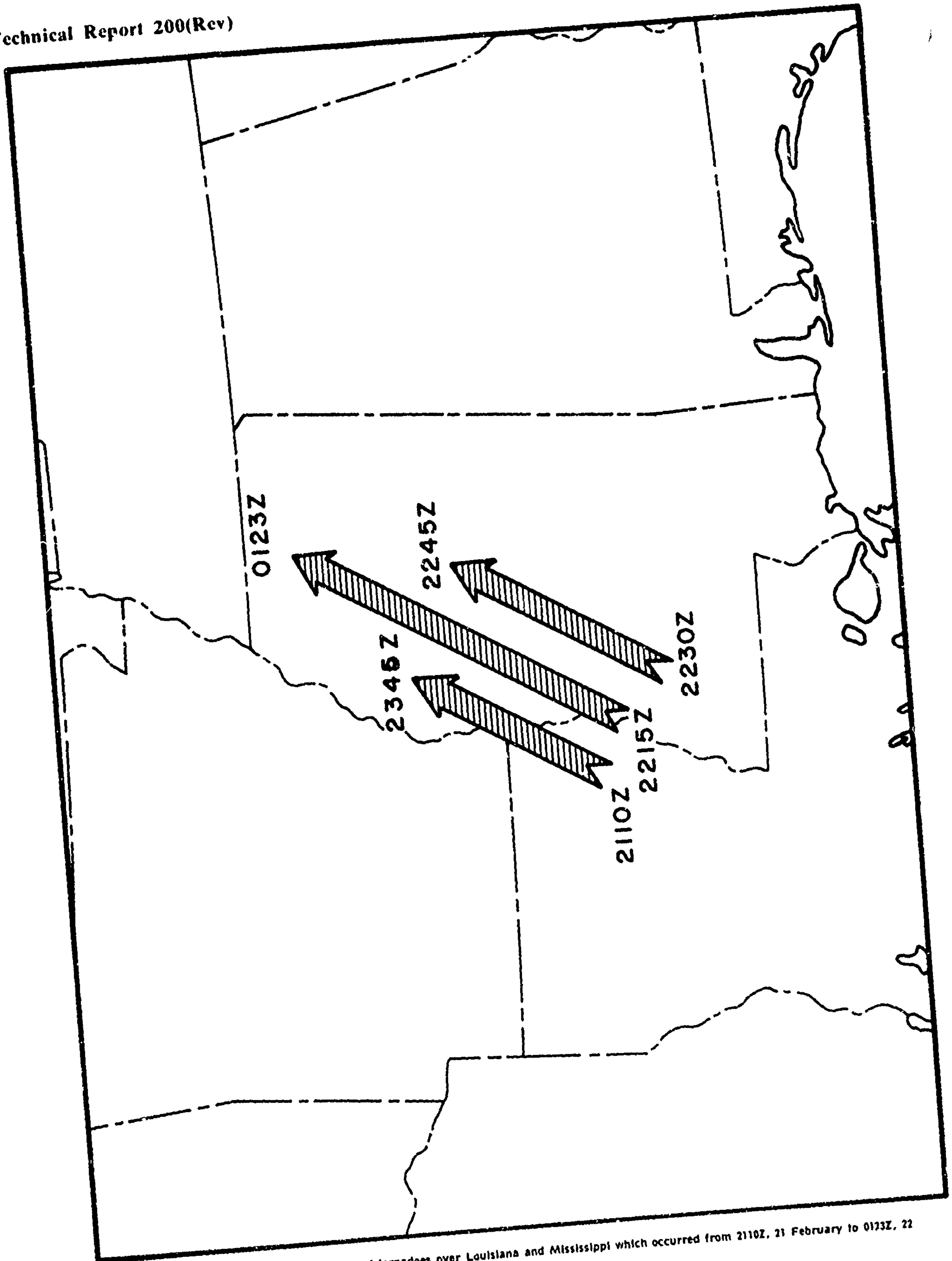



Figure 82. Primary damage tracks of tornadoes over Louisiana and Mississippi which occurred from 2110Z, 21 February to 0123Z, 22 February 1971.

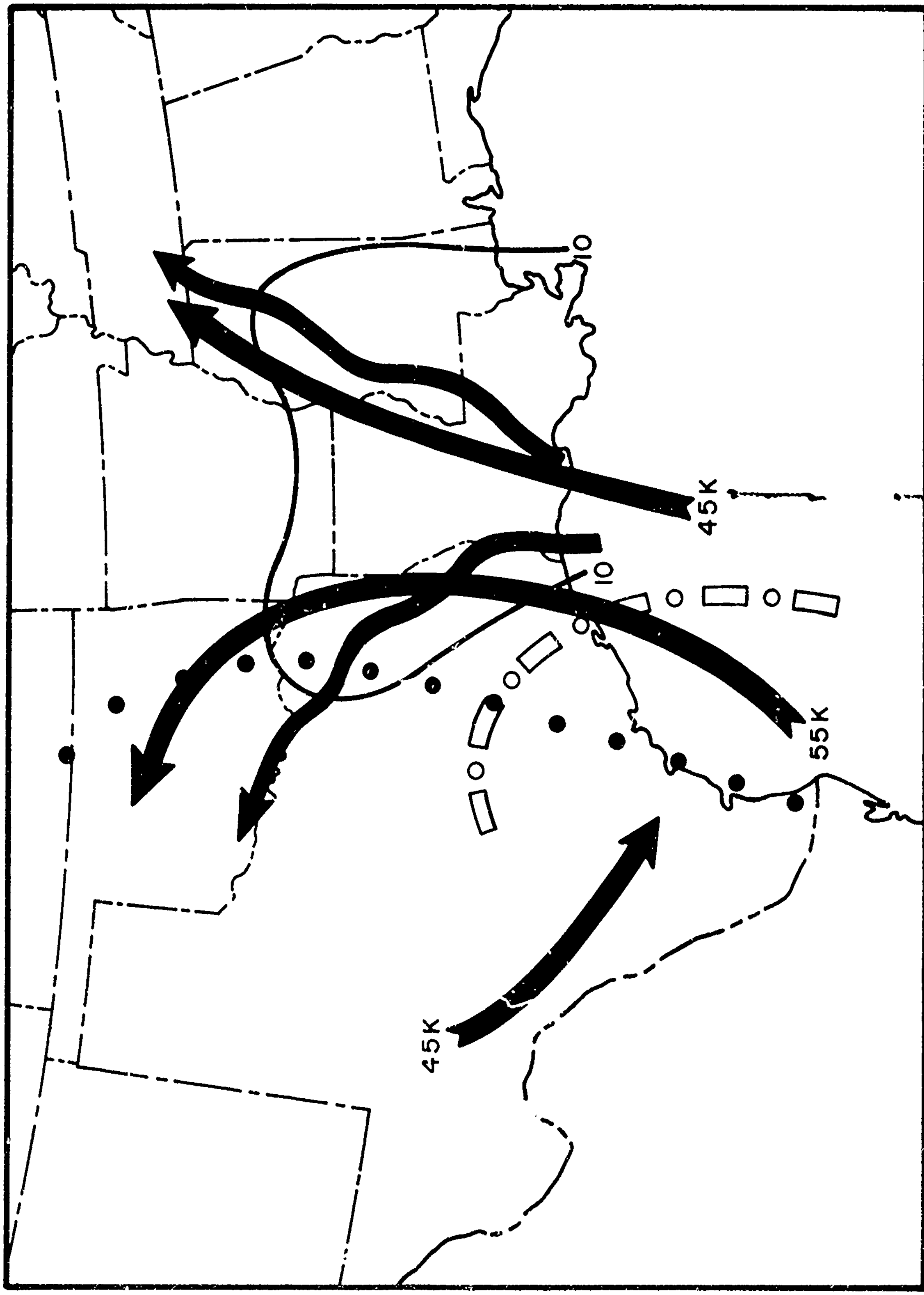



Figure 83. Major features of 850-mb chart at 1200Z, 21 February 1971.

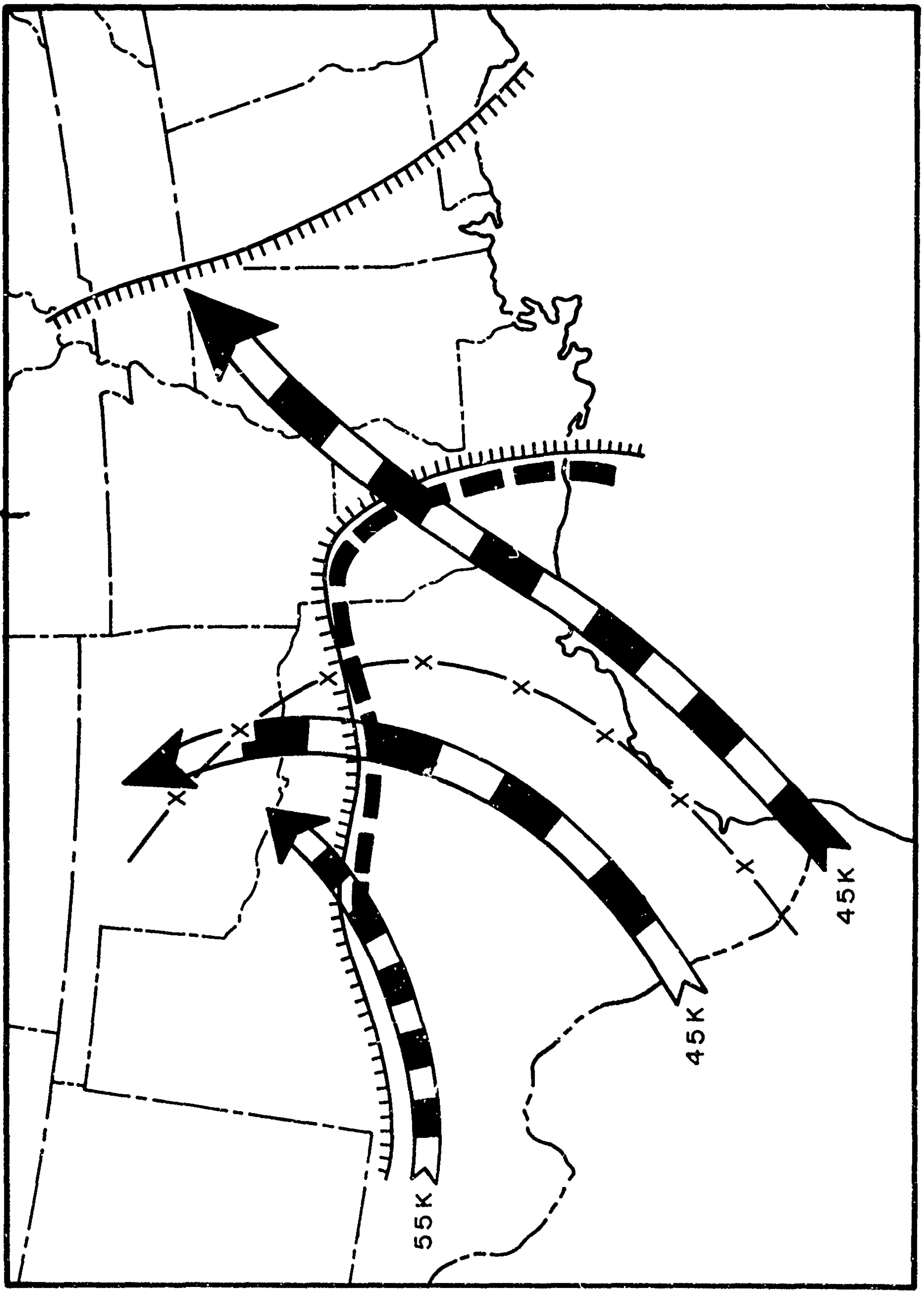



Figure 84. Major features of 700-mb chart at 1200Z, 21 February 1971.

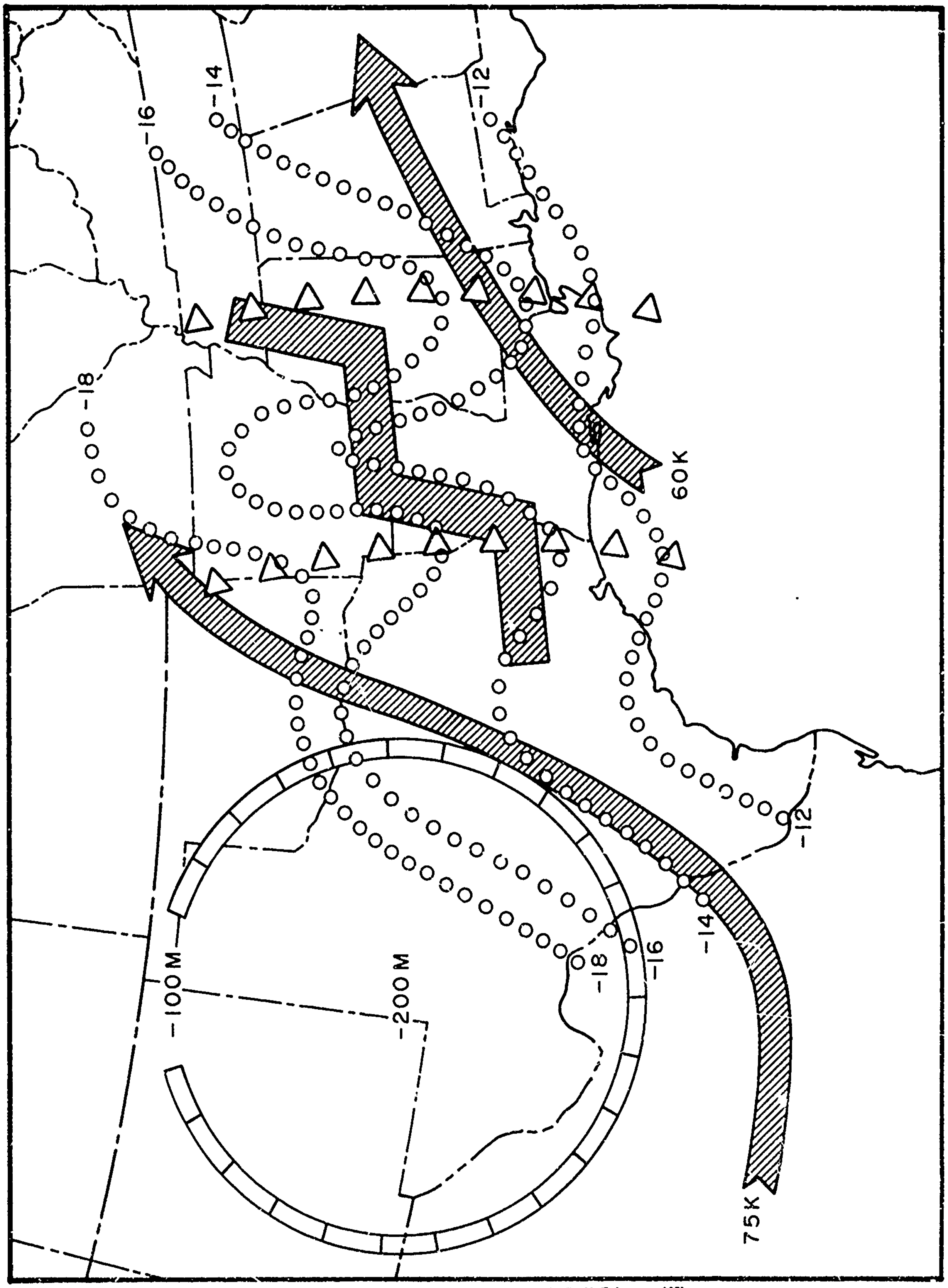



Figure 85. Major features of 500-mb chart at 1200Z, 21 February 1971.

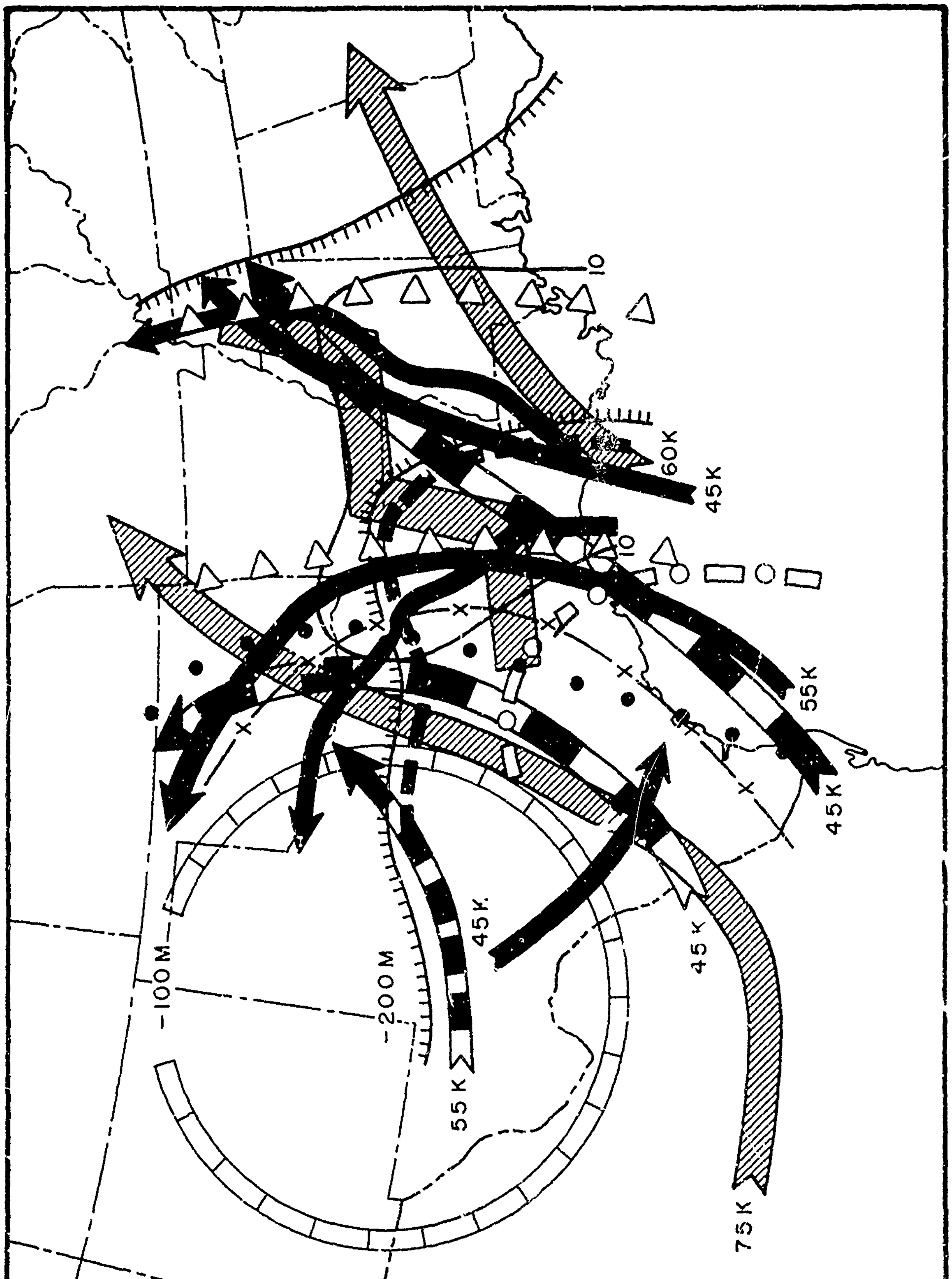



Figure 86. Composite chart for 1200Z, 21 February 1971

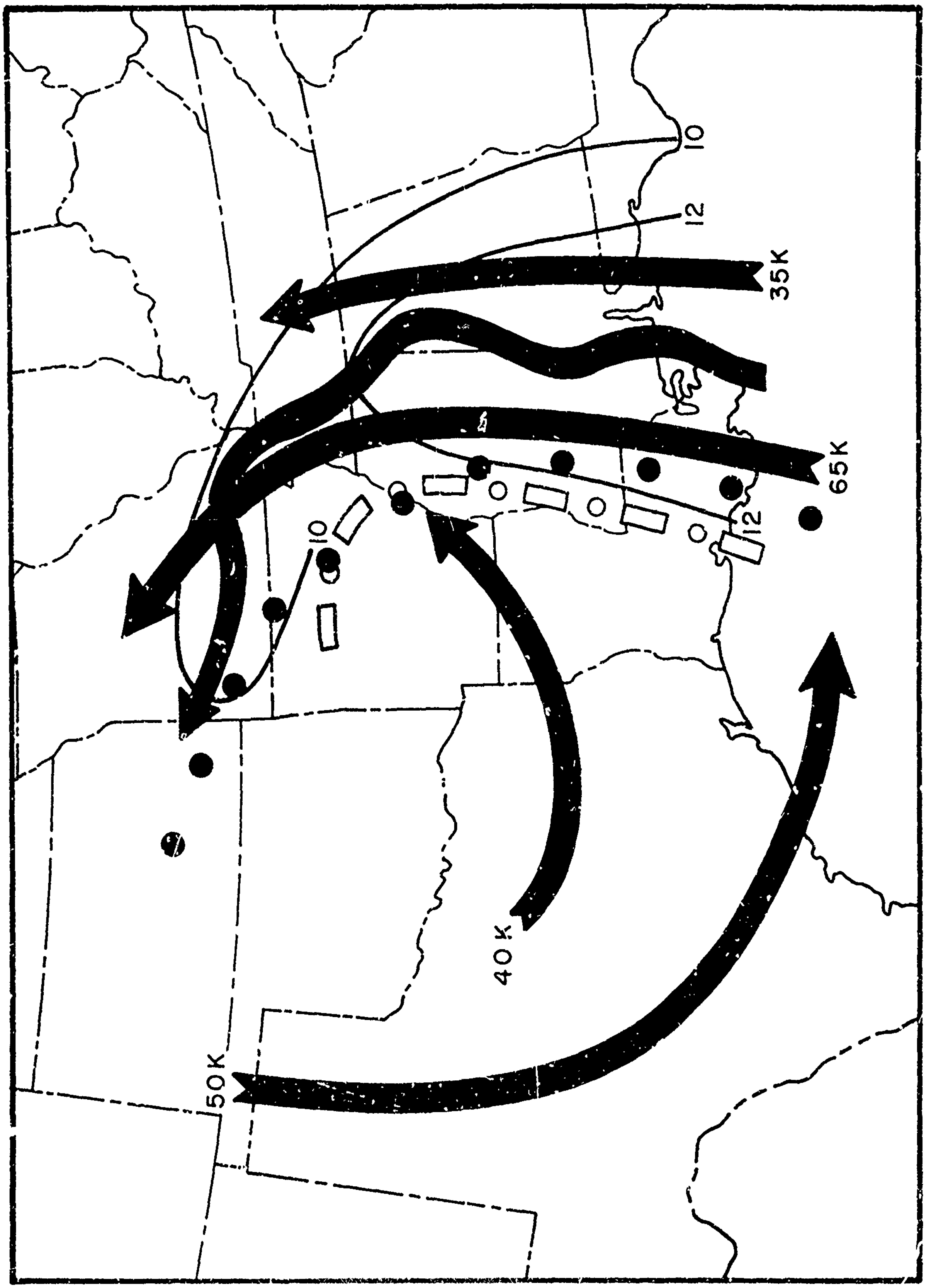



Figure 87. Major features of 850-mb chart at 0000Z, 22 February 1971.

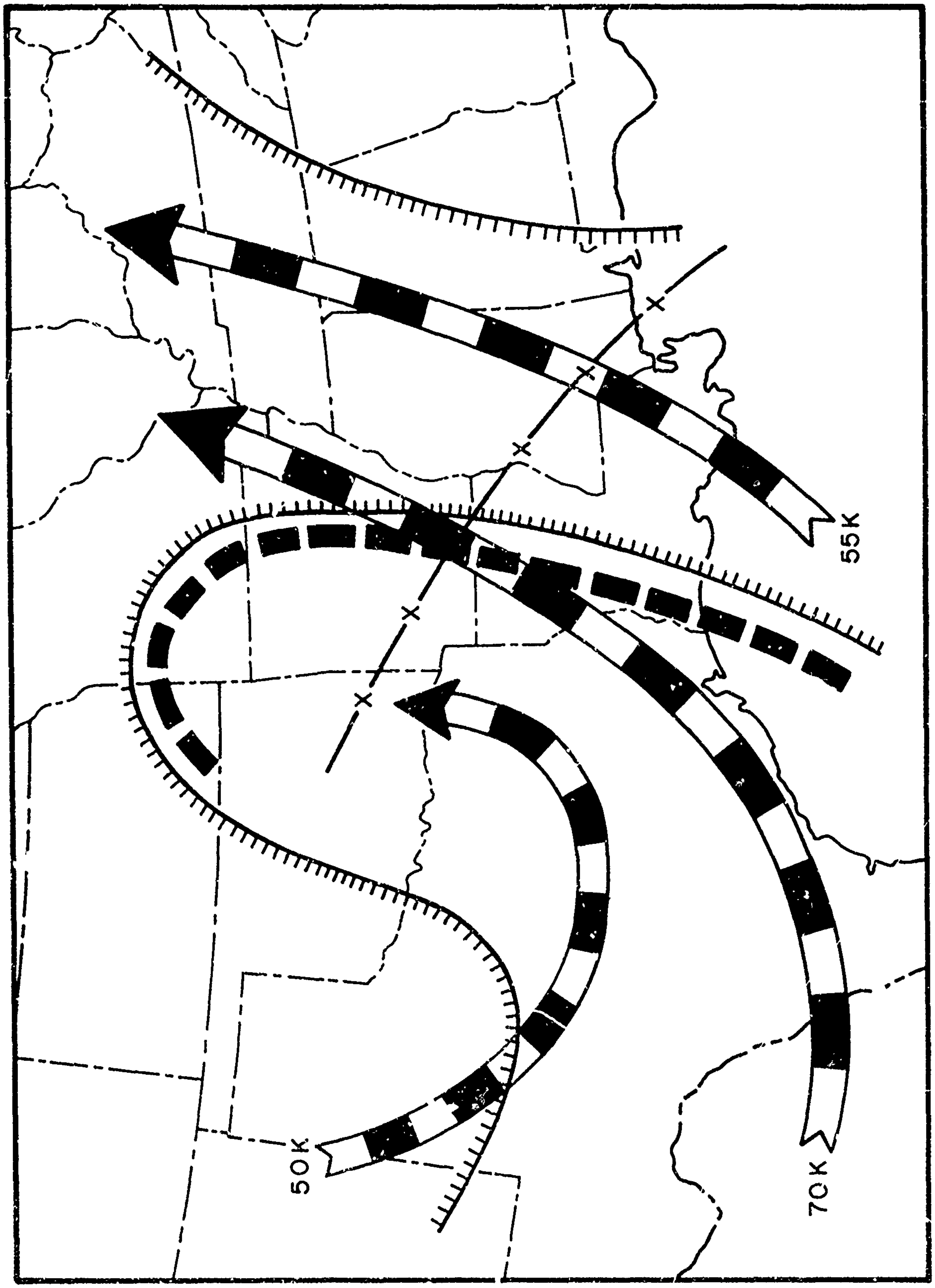



Figure 83. Major features of 700 mb chart at 0000Z, 22 February 1971.

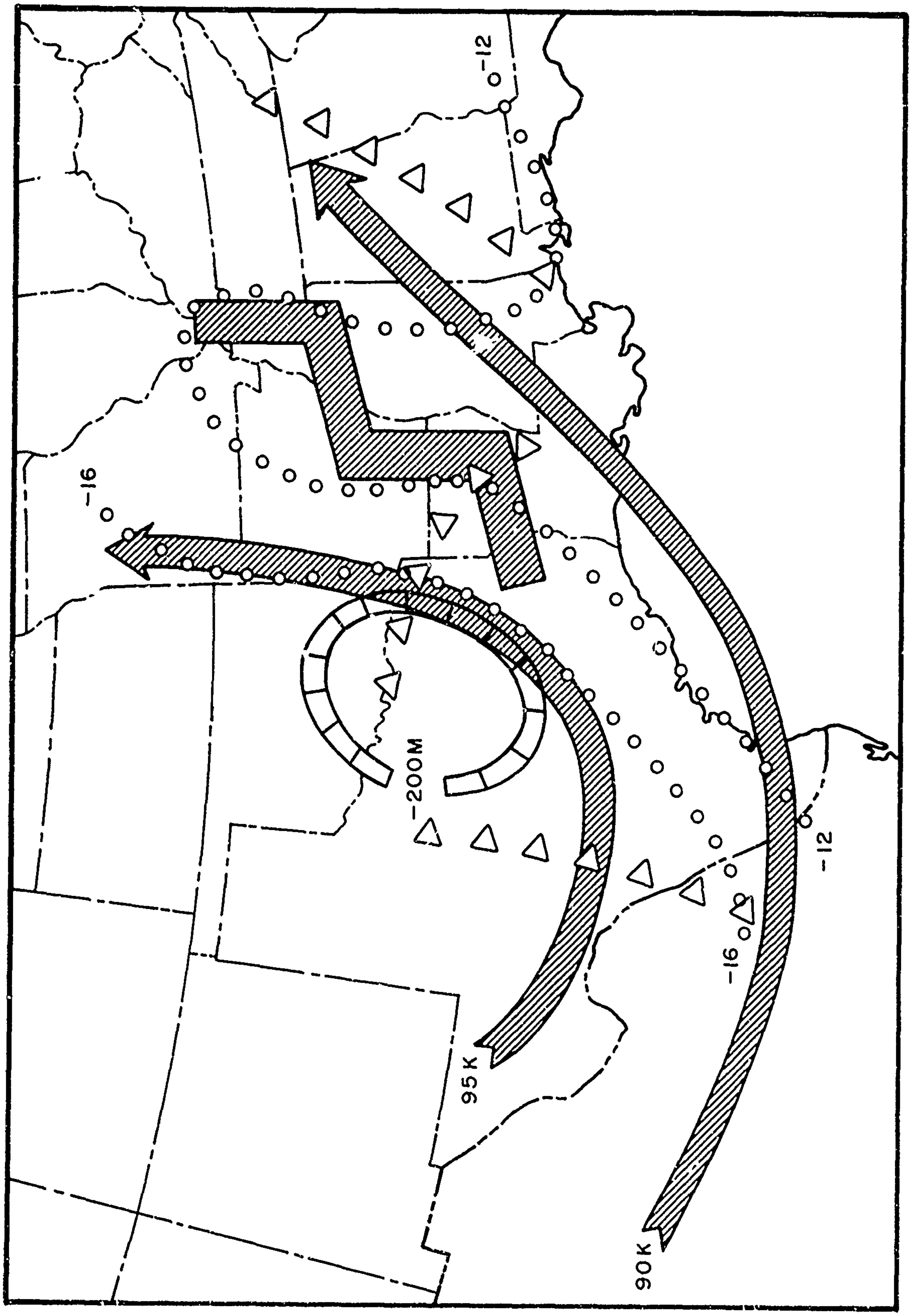



Figure 89. Major features of 500-mb chart at 0000Z, 22 February 1971

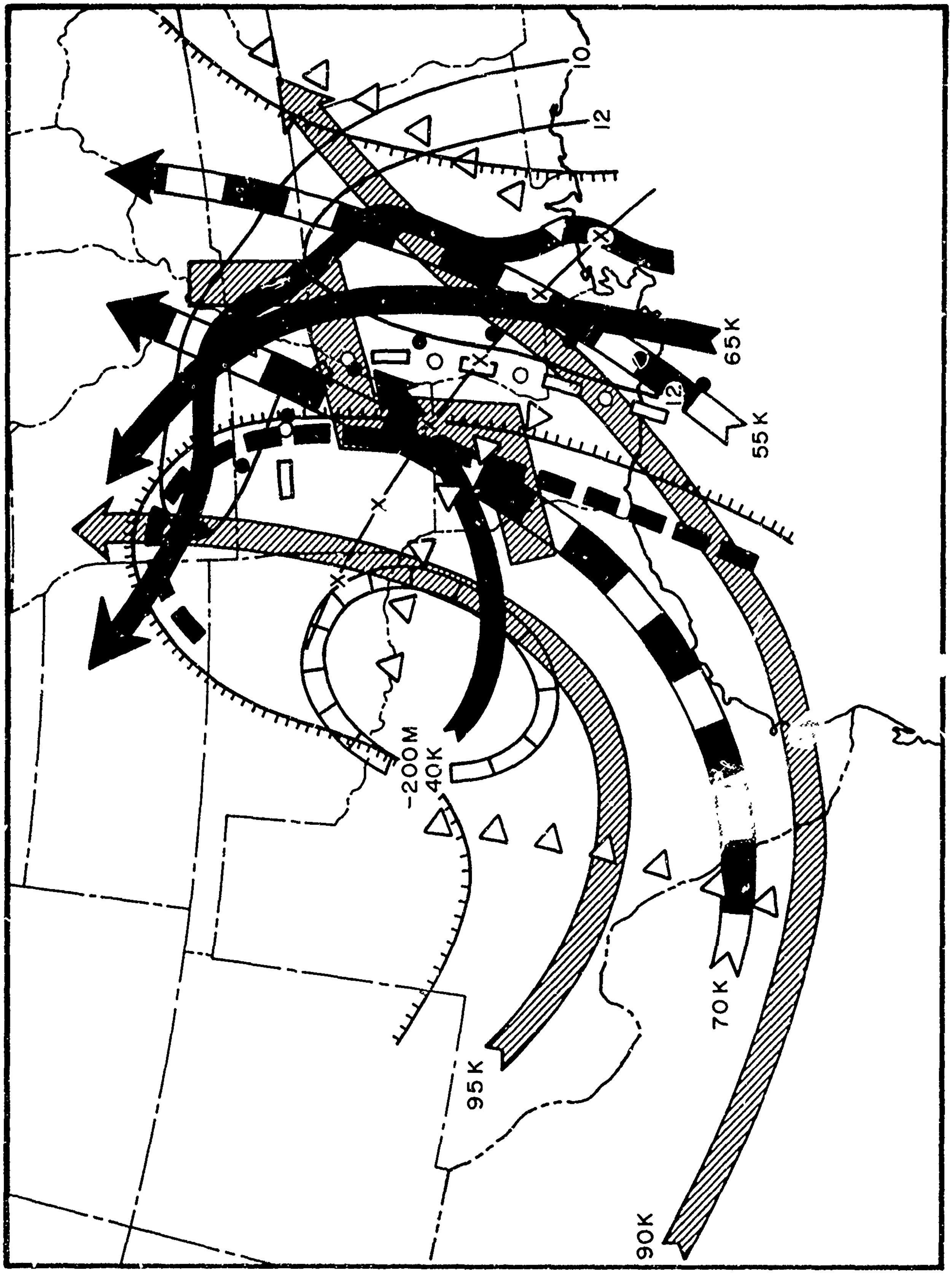



Figure 90. Composite chart for 0000Z, 22 February 1971

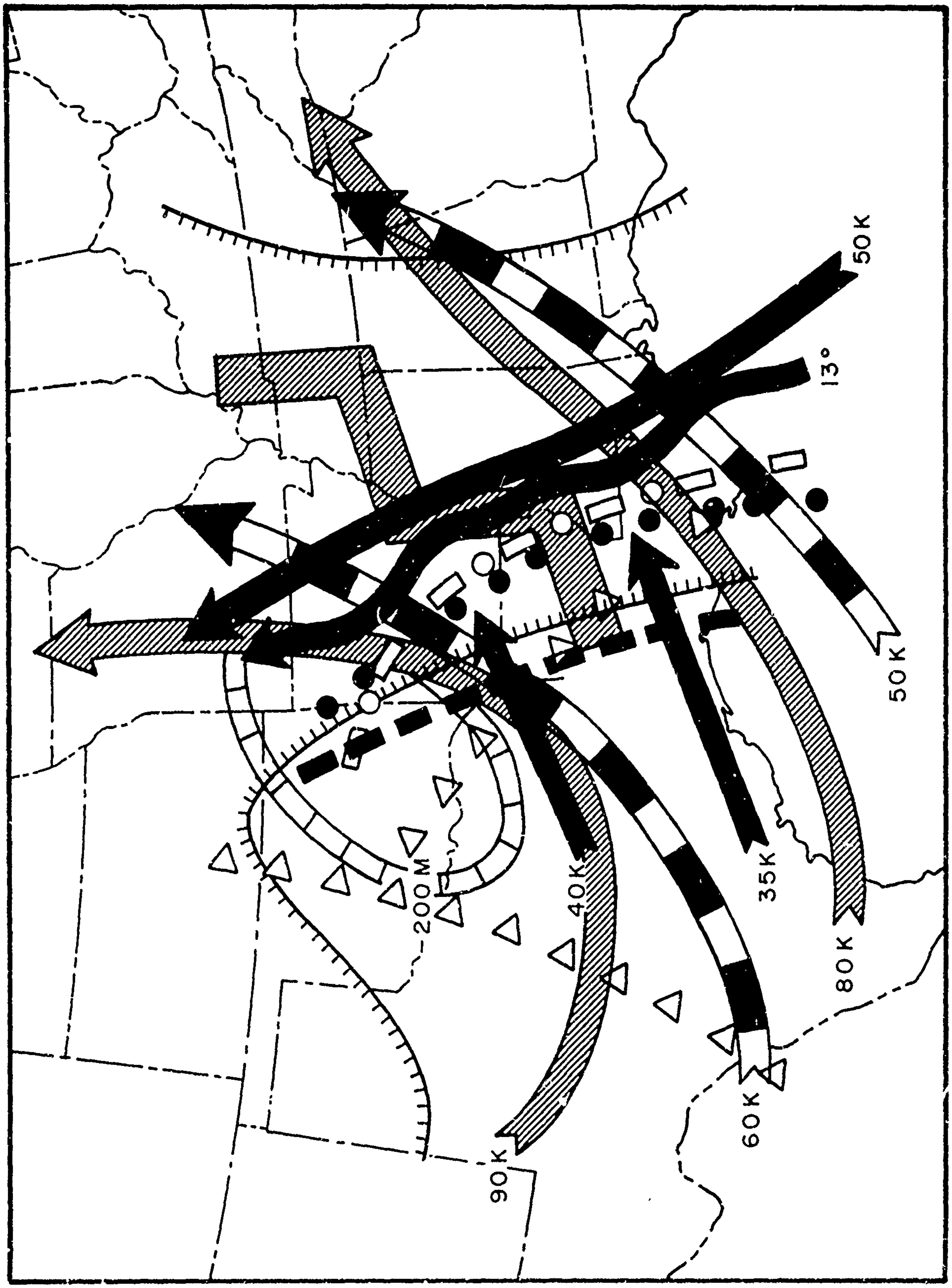



Figure 91 Composite chart valid at 0000Z, 22 February 1971 based on 12 hour prognoses.

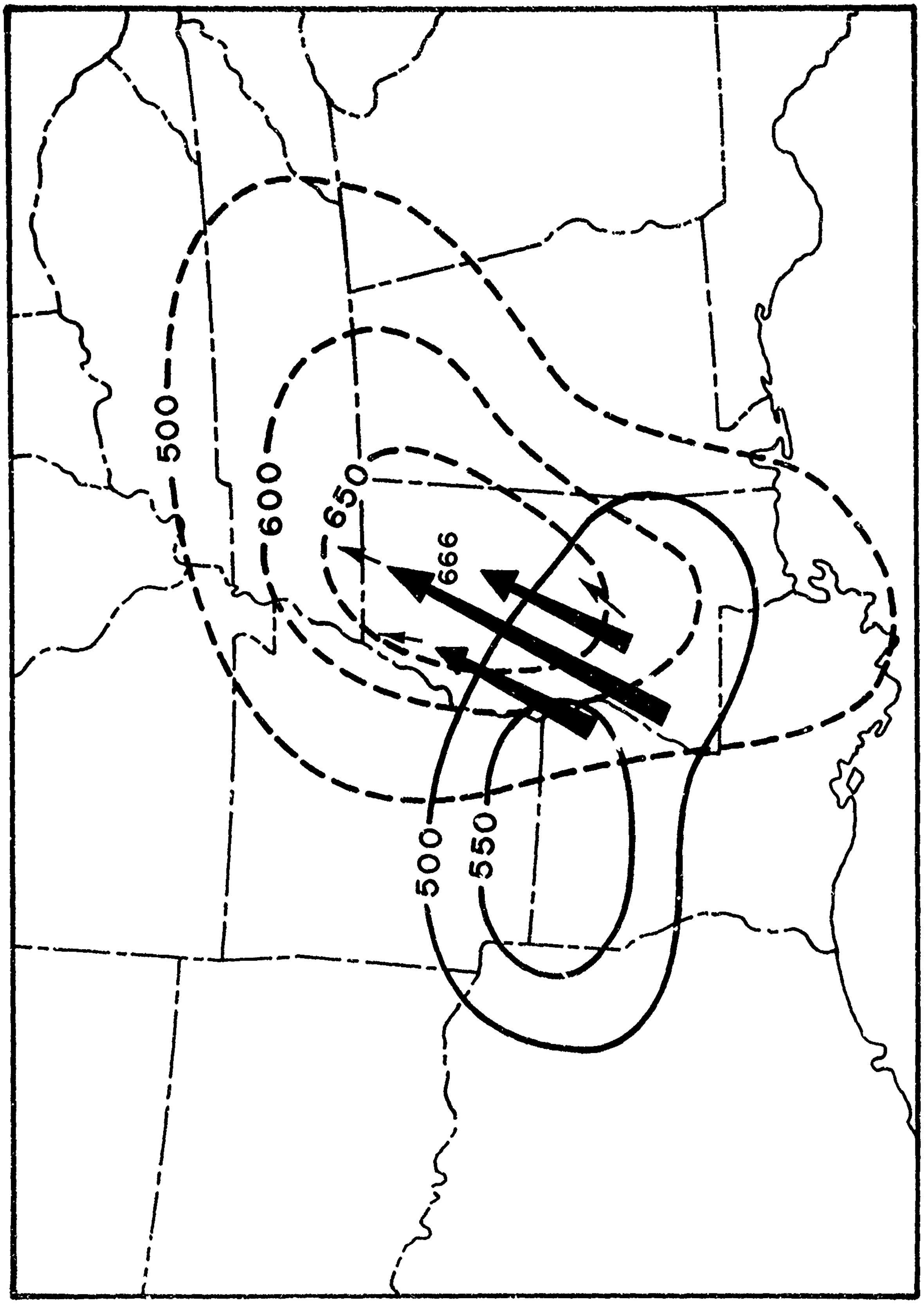



Figure 92 Fine mesh gridded SWEAT analysis for 1200Z, 21 February 1971 (solid lines) and the 12-hour SWEAT prognostic field valid 0000Z, 22 February 1971 (dashed lines) The three major tornado tracks from Figure 82 are superimposed on the figure.

## Appendix G

# THE FORT RUCKER, ALABAMA TORNADO OF 13 JANUARY 1972

### SECTION A—GENERAL

At 0725Z, 13 January 1972, a destructive tornado struck the Enterprise-Ozark area in the southeast corner of Alabama. Several million dollars in damage, which included total destruction of a number of helicopters, was inflicted at Fort Rucker, Alabama; major damage was also suffered in the nearby Ozark area. This tornado was one of a series that hit southeast Alabama, northwest Florida, Georgia, and South Carolina on 13-14 January 1972. This case study is included because this type of tornado is the most difficult to forecast, i.e., they are not associated with identifiable synoptic or even mesoscale features such as lows, organized squall lines, warm fronts, etc. In these instances, we are trying to forecast microscale phenomena using a macroscale network. This case study also illustrates the usefulness of the SWEAT Index in identifying areas of rapidly increasing instability.

### SECTION B—SYNOPTIC SITUATION

At 1200Z, 12 January 1972, a decaying warm front was evident along the Gulf Coast extending from near New Orleans across northwest Florida and off the east coast near Savannah, Georgia. This boundary became progressively diffuse during the day allowing tropical air from the Gulf of Mexico to spread inland. Figure 93 shows the surface chart for 0000Z, 13 January. Southerly flow of air from the Gulf dominates the entire southeast United States with the closest frontal system located in the Missouri-Oklahoma area. Isolated thunderstorms occurred over the southeast United States during the period from 12/1200Z to 13/0000Z but no severe weather was reported.

The composite chart for 13/0000Z (Figure 94) delineates the important parameters at that time. At 500 mb, the thermal trough extending from western South Carolina through central Georgia into northwest Florida was probably a contributing factor to the thunderstorm activity which occurred during the day and into the evening of 12 January over portions of the southeast United States. A second and stronger 500-mb thermal trough associated with a 30 m/12 hour height fall area extended from northeast Arkansas into northwest Louisiana and on southwestward. Close examination of the 500-mb wind field revealed a relatively weak short wave over southwest Mississippi and southeast Louisiana just ahead of the thermal trough. The 500-mb numerical prognosis indicated this minor short wave would move rapidly eastward and be located over western Georgia by 13/1200Z. This minor short wave triggered the initial outbreak of tornado activity, the first tornado occurring nine miles north of Pensacola, Florida at 13/0340Z and the Fort Rucker tornado at 13/0725Z. The last tornado report in this initial outbreak occurred at 13/0743Z. At 13/0000Z, several parameters favorable for severe weather were either in existence or progged to be present within the next 12 hours. These parameters (Figure 94) consisted of a low level jet over the threat area, the presence of dry air upwind, a moderate 500-mb jet, and increasing low level moisture. Parameters not favorable at this time included low level (850 mb) flow parallel to the low level and mid level (700 mb) dry/moist boundary, Severe Weather Threat (SWEAT) Index values less than critical, lack of a strong trigger, sparse RADAR detected activity, and the complete absence of a surface boundary or organized pressure fall pattern.

The composite 12-hour prognostic chart valid at 13/1200Z (Figure 95) indicated that nearly all the parameters would fall into place by this time. The SWEAT Index values were forecast to increase over the threat area with values over 400 at 13/1200Z reaching the northwest Florida coast (SWEAT values isopleths valid at 13/1200Z not shown in Figure 95 to reduce cluttering). In addition, the AFGWC Boundary Layer Model forecast maximum SWEAT values for the 24-hour period from 13/0000Z to 14/0000Z showed a dramatic increase with values exceeding 400 occurring over a large area of the southeast United States and a peak value of 573 occurring along the northwest Florida coast. A fairly strong 500-mb short wave was progged to be over eastern Mississippi. Increasing low level moisture was apparent and both low level and 500-mb jets were forecast to continue over the threat area. While the low level dry/moist boundary was present, flow patterns were not favorable for its eastward progression. This was off-set, however, by the

**Table 9**

| SEVERE THUNDERSTORM AND TORNADO PARAMETER WORKSHEET | | | | | |
|---|---|---|---|---|---|
| AREA SRN AL — FL PNHNDL — NW FL-SW GA | ADVISORY NUMBER 48-49 | DATE 130000Z JAN 72 | | ADVISORY VALID 13/ 00 z to 13/12 z | |
| PARAMETER | 0000Z ANAL VALUE | 0000Z ANAL RATING | 1200Z PROG VALUE | 1200Z PROG RATING | REMARKS/VERIFICATION |
| SWEAT | 343 | W + | 350-400 | W M + | BLM MAX 450-573 21-00Z(5) 1200Z 400-468(M) |
| TOTALS | 52 | M + | 52 | M | 1200Z 51-54 (M) |
| LIFTED INDEX | -5 | M + | -5 | M | 1200Z -5 (M) |
| PVA | W | W + | M | M | 1200Z (M) |
| 500 MB HT FALLS | -30 | M | -40 | M | 1200Z -40(M) |
| 500 MB JET | 50K | M | 50 | M | 1200Z 60K (S) |
| 850 MB MOISTURE | 8' | W + | 10° | M | 1200Z 13° (S) |
| 850 TEMP RIDGE | OVR MOIST RIDGE | M | W OF MOIST RIDGE | S | 1200Z WEST OF MOIST RIDGE (S) |
| LO-LEVEL JET | 30K | M | 30K | M | 1200Z 40K (S) |
| 700 MB DRY INTRUSION | CROSSTHERMS AT 10° ANGLE | W + | CROSS AT 40° 45K | S | STRONG DRY INTRUSION UPSTREAM 1200Z (S) |
| 700 MB NO-CHANGE TEMP | NOT EVIDENT | — | NOT EVIDENT | W | 1200Z EVIDENT (S) 40K AT 50° ANGLE |
| WINDS VEER WITH HEIGHT | YES | — | YES | — | 1200Z YES |
| WINDS INCREASE WITH HEIGHT | YES | — | YES | — | 1200Z YES |
| INTERSECTING UP AND LO JETS | YES | — | YES | — | 1200Z YES |
| SFC DEW POINT | 66° | S | 66° | S | 1200Z 68° (S) |
| SFC PRESSURE THREAT AREA | 1013 | W | 1011 | W | 1200Z 1010 BECAME MORE FVRBL FORENOON (W) |
| FALLING PRESSURE | YES | M | YES | M | 1200Z YES (M) |
| INCREASING SFC TEMP | LITTLE CHANGE | — | LITTLE CHANGE | — | COOLED SLIGHTLY DUE TO R ACTIVITY |
| INCREASING DEW POINT | SLIGHT | — | YES | — | YES 1200Z |
| THICKNESS RIDGE | NOT EVIDENT | — | — | — | NOT EVIDENT |
| THICKNESS NO-CHANGE | NOT EVIDENT | — | — | — | NOT EVIDENT |
| MESO OR SYNOP PATTERN | POOR | — | POOR | — | BECAME MORE FVRBL DURING FORENOON |

REMARKS

FIRST TORNADO 130725Z ENTERPRISE-OZARK AREA AL.
20 MORE TORNADOES DURING PERIOD 131200Z TO 141125Z ACROSS SRN AL-NW FL-W CNTRL AND SRN GA INTO CNTRL S.C.

forecast position of the 700-mb dry/moist boundary accompanied by strong cross flow from dry to moist air. It is also significant to note that by this time the low level temperature ridge would no longer coincide with the low level moisture ridge, but would retrogress westward causing a more volatile situation.

The composite chart made from the actual 13/1200Z data, shown in Figure 96, indicates all parameters in the moderate to strong category. A summary of the severe weather parameter values from the 13/0000Z analysis, the 13/1200Z prognosis, and the verifying values at 13/1200Z are shown in Table 9. After the initial outbreak of tornadoes from 13/0340Z to 13/0743Z, including the one which hit Fort Rucker at 13/0725Z, the tornado activity ceased for approximately 4 1/2 hours and then resumed again at 13/1215Z and continued throughout the remainder of the 13th and into the early morning hours of the 14th. A map showing the location and time (to the nearest hour) of the tornado and severe thunderstorm occurrence is included as Figure 97.

## SECTION C—RADAR ANALYSIS

Analysis of data from five weather radars in the area supports the contention that a weak 500-mb short wave trough, passing through Alabama and the Florida panhandle into Georgia, triggered the initial tornado outbreak between 13/0340Z and 13/0743Z. The trough triggered intense thunderstorm activity as it moved eastward. Radar echo tops in the area of the trough were consistently higher than surrounding tops throughout this period. Furthermore the trough-induced favorable development area propagated eastward at the same speed as the trough itself.

Figure 98 shows selected examples of scope photographs taken every ten minutes at the Apalachicola, Florida, WSR-57 radar. The photo series covers the period 13/0320Z to 13/0720Z (times are approximate because the camera clock and interval timer malfunctioned). In all photographs, Fort Rucker is indicated by an open circle at 338 deg/100 nm. In the first two photos, Pensacola, Florida, is indicated by an open circle at 292 deg/123 nm.

The photo series shows that the Pensacola tornado (0340Z) and the Fort Rucker tornado (0725Z) came from the *same parent thunderstorm complex*; or more precisely, the Fort Rucker tornado was spawned from a thunderstorm which *had converged with the Pensacola storm*. The 0320Z photo shows the Pensacola parent thunderstorm echo, which, with tops in excess of 40,000 ft MSL, moved northeastward with a speed which gradually increased from 12 knots at 0320Z to 25 knots at 0600-0640Z. At 0520Z, a new thunderstorm complex began to form south of the mature system. Subsequent photographs show the new system intensifying and converging with the mature storm. The echo convergence is apparent in the 0640Z photo, and the 0720Z photo seems to indicate the new thunderstorm complex grew at the expense of the old system. At the time of echo convergence, the Centreville, Alabama, WSR-57 radar indicated tops of 51,000 ft MSL for this complex. Apalachicola reported 40,000 ft, and the truth is likely to be somewhere between these values. In any case, this echo complex had either reached or was penetrating the 40,000 ft tropopause by 0640Z. Its antecedent, the Pensacola storm has echoes at, near or slightly exceeding the tropopause throughout most of the period 0340-0640Z. Interestingly, at the time of echo convergence, the Pensacola thunderstorm complex, which had been moving at an average of 21 knots for more than three hours, accelerated to 40 knots, a more characteristic speed for severe weather echo systems. No change in the direction of motion was noted. The merged thunderstorm complex continued northeastward with tops penetrating the tropopause until at least 0812Z. It was this complex which spawned the Enterprise-Fort Rucker tornado.

This photo series shows no hooks, protrusions, pendants, weak echo regions or other echo signatures signifying severe convective weather. This is not surprising since none of these echoes was closer to the radar than 100 nm. Furthermore, the 250 nm PPI range was used for photography and the receiver was operated at full gain. Considering the echo range alone, at 100 nm, a beam at zero degrees elevation would be positioned 6,600 ft above the ground and would have a diameter of more than 21,000 ft. Under these circumstances, hooks and weak echo regions cannot be expected; therefore, a combination of radar reflectivity factor, tops and movement should be used to identify severe storms.

In this case, tops, movement and the *previous history of the storm* were the prime radar indications. As indicated by Darkow in papers presented at the 14th Radar Meteorology Conference (1970) and at the 7th Conference on Severe Local Storms (1971), and as reported in AWSTR 243, a parent thunderstorm complex that produces one tornado is quite likely to produce another. In fact, the probability of multiple tornadoes from a single parent storm is sufficiently high that meteorologists should routinely assume "more tornadoes are on the way," provided the parent storm shows no marked signs of dissipation or decay.

## SECTION D—SUMMARY

This study illustrates the synoptic situation accompanying the occurrence of tornadoes in a Type II air mass which occurred (at least the initial outbreak) without a well-defined triggering mechanism. The tornadoes resulted from increasing instability throughout the period and the passage of several short wave troughs at 500 mb. The initial outbreak of severe weather occurred with a relatively minor short wave; this was followed by a repeat of severe activity associated with the following stronger short wave. Even though the synoptic features were not well defined and the triggering mechanisms were diffuse in this case, the analyzed and forecast SWEAT Index values were quite useful in pinpointing the potential area for severe weather activity.

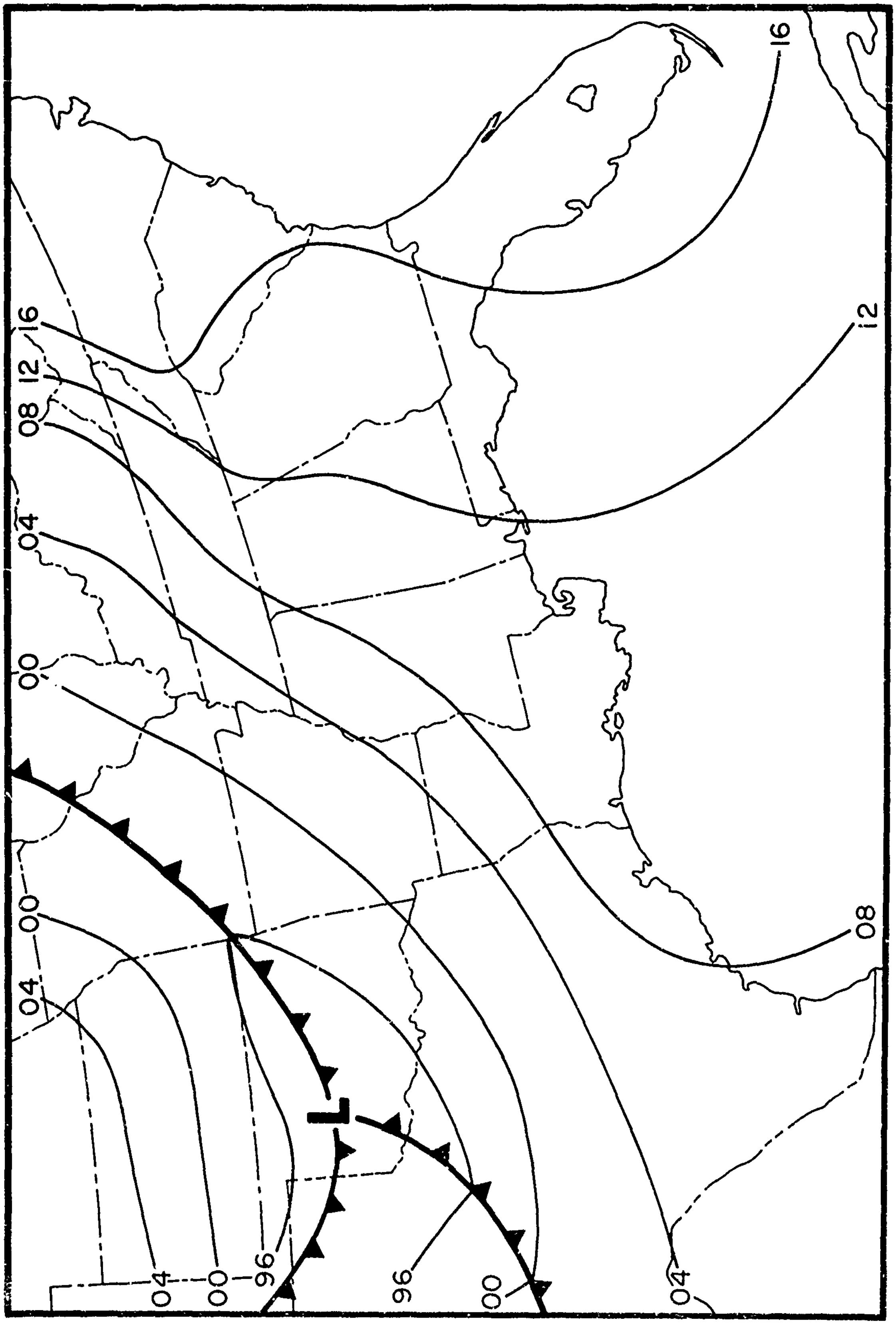



Figure 93 Surface chart for 0000Z, 13 January 1972

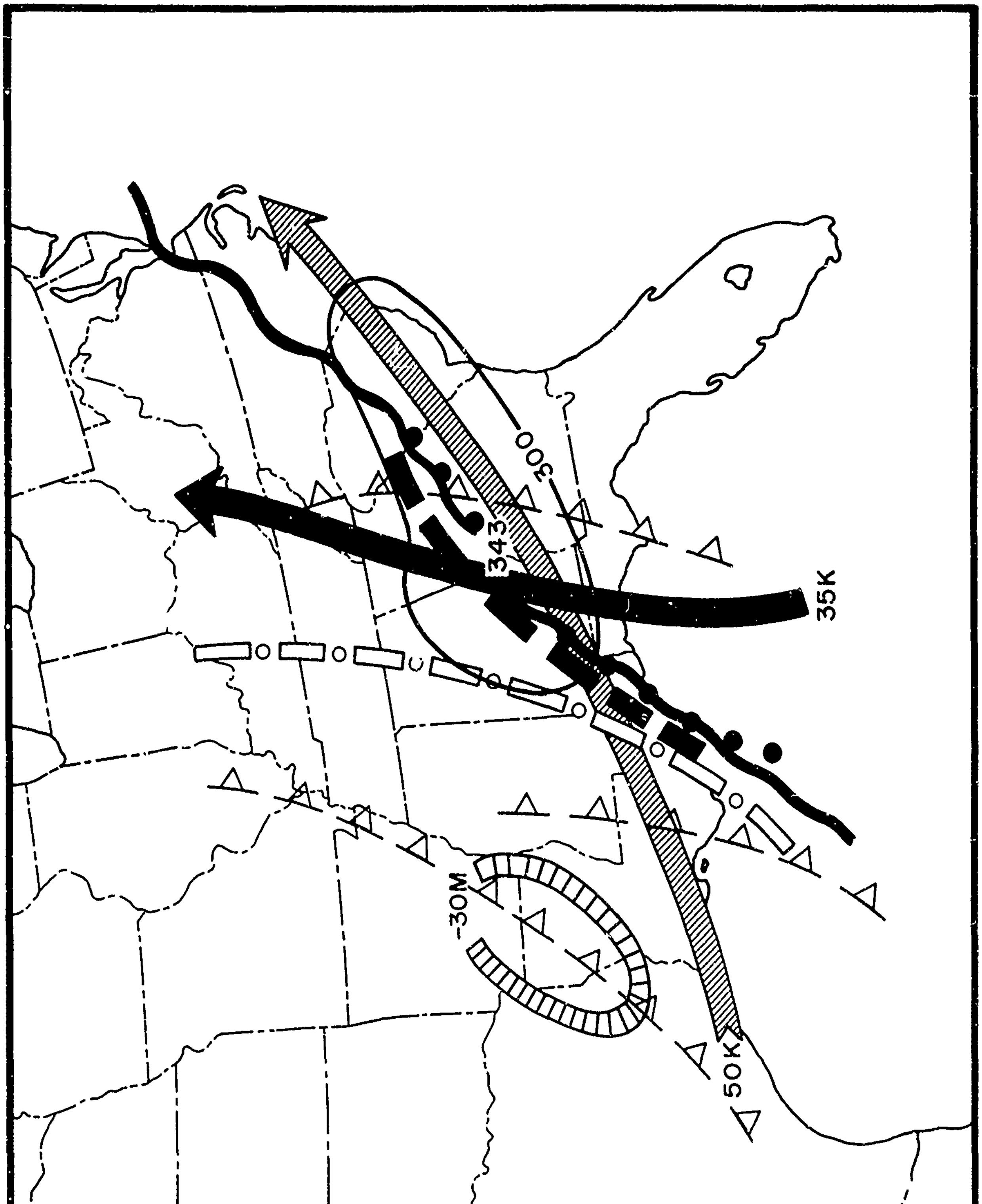



Figure 94. Composite chart for 0000Z, 13 January 1972

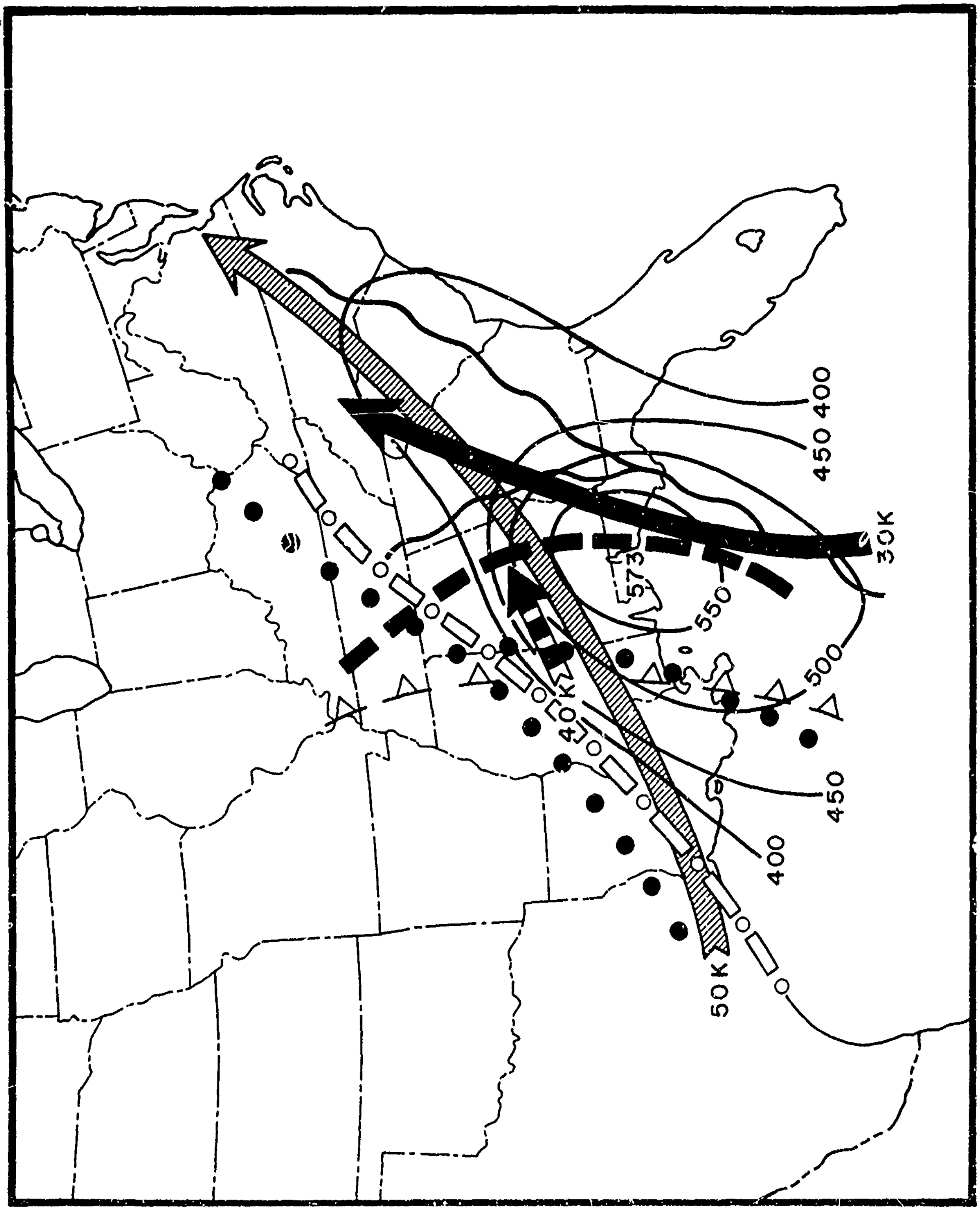



Figure 95. Composite prognostic chart valid 1200Z, 13 January 1972. Maximum forecast SWEAT index values for 24 hour period beginning 0000Z, 13 January 1972 shown by solid isopleths.

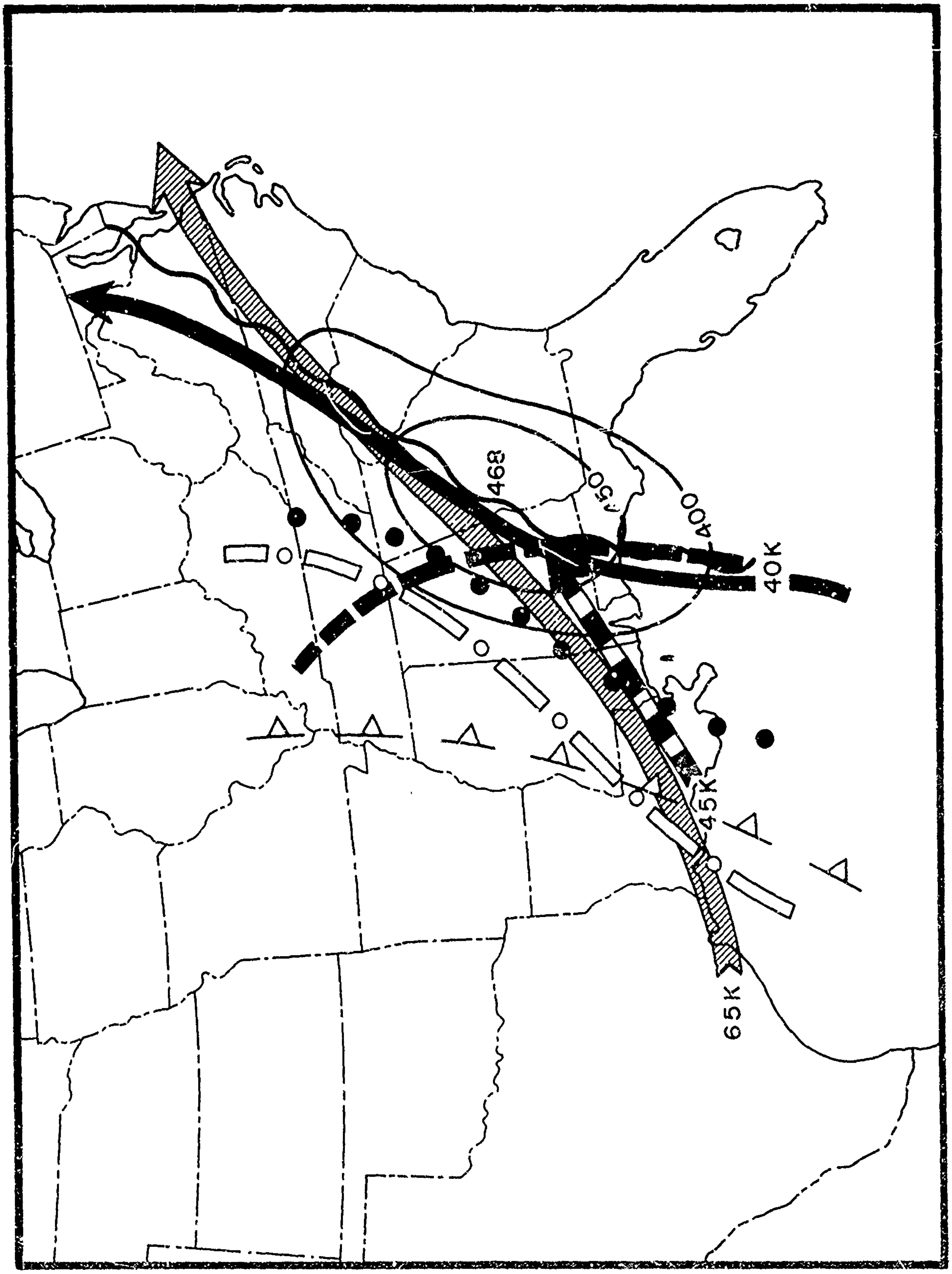
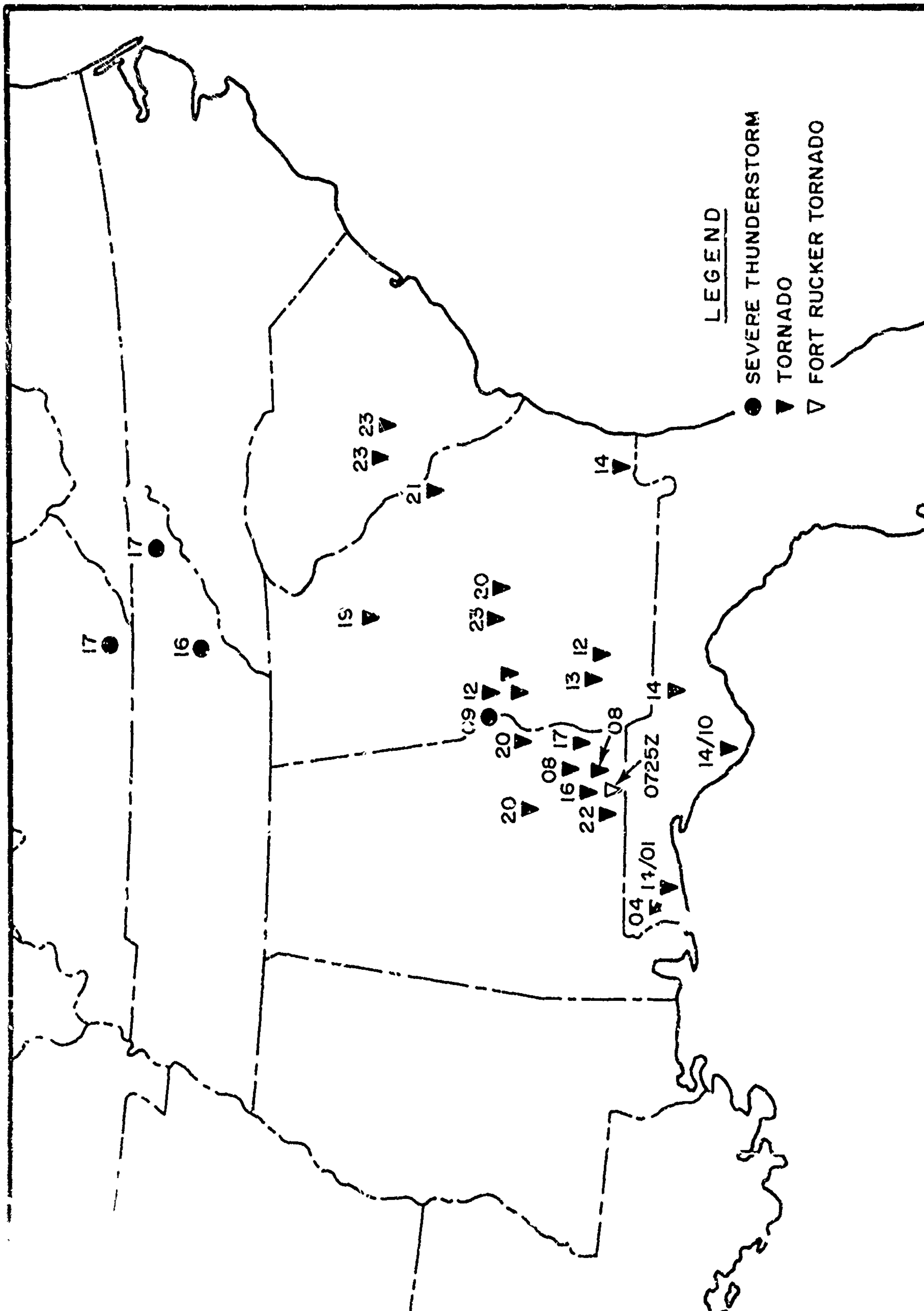



Figure 96. Composite chart for 1200Z, 13 January 1972. SWEAT Index values observed at map time shown by solid isopleths




...earest hour of Z time) of tornado and severe thunderstorm occurrences on 13-14 January 1972 (all ... where 14 precedes Z time)

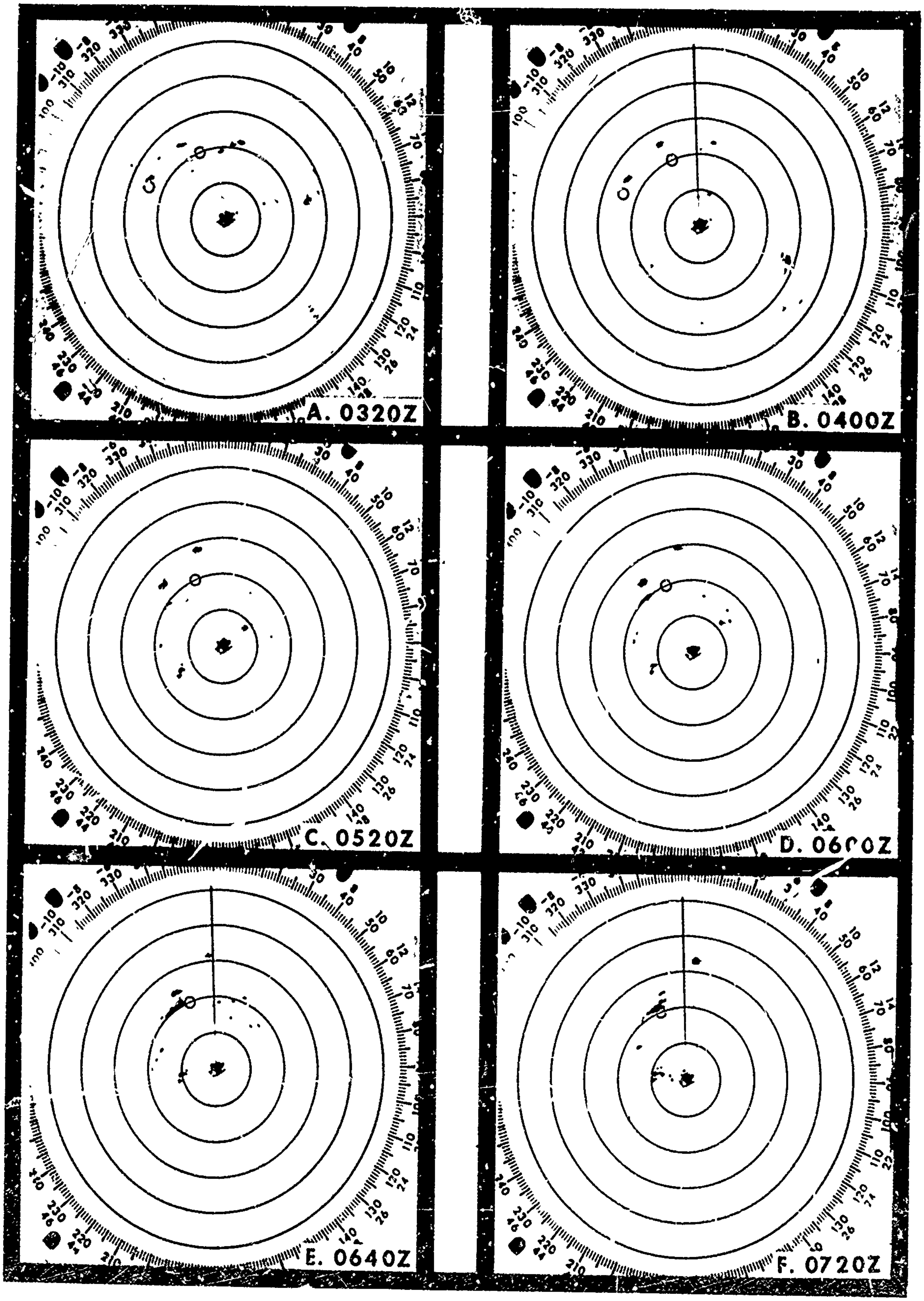



Figure 98 Photographs of the PPI scope of the WSR 57 storm detection radar at the Apalachicola, Florida Weather Service Office on 13 January 1972 Scope range is 250 n mi, range marks are at 50 n. mi intervals

# Appendix H
# CHART SYMBOLOGY

## SECTION A—GENERAL

The number of levels and the variety of parameters needed to analyze a typical severe-weather situation require special symbols and color schemes to organize the information analyzed on the manuscript chart.

## SECTION B—PROCEDURES, SYMBOLS, AND COLOR SCHEMES

The following procedures, symbols, and color schemes are used in actual practice, and Figure 99 is a handy guide which can be unfolded to be referred to as the report is being read.

a. The surface chart is completed in black pencil with frontal systems and other lines of discontinuity depicted by standard printed map symbols. The major 12-hour pressure fall centers are entered using the symbol "Δ P."

b. The positions of significant dry lines and dry prods (tongues) at 850 mb are entered in red using an alternating dashed line and circle representation.

c. Shears and convergent zones in the low-level flow are indicated by solid red arrow-tipped lines, and low-level jets are shown by double-line shaded arrows. Jet speeds are often shown near the upwind end of the arrows.

d. The axes of low-level moisture areas are indicated by solid green arrows, and axes of areas of major moisture advection are shown as double-lined, shaded, green arrows. Often moist tongues are outlined as double green-shaded lines.

e. Principal 850-mb temperature ridges are denoted by a line of solid red dots.

f. Frontal positions and other lines of discontinuity at the 850-mb level are entered in red.

g. Significant areas of moisture at 700 mb are shaded lightly in brown.

h. Dry-air tongues at 700 mb are outlined in dashed heavy brown lines.

i. Well-defined lines of 12-hr no-temperature change associated with significant troughs at 700 mb are denoted by brown solid X's and dashes.

j. Frontal positions and troughs at 700 mb are entered in brown using standard printed map symbols.

k. Significant wind flow at 700 mb is entered using brown arrows with the axes of maximum-wind flow denoted by double-line arrows. Special attention is given to the wind flow between the dry and moist areas, and the location of near-by jet axes.

l. Temperature ridges or other desired features of the 700-mb temperature field, are entered in brown using heavy-shaded circles. Thermal troughs are often shown as brown open triangles.

m. The positions of thermal troughs at 500 mb are entered on the Composite Chart as open blue triangles, and a sufficient number of isotherms necessary to define the 500-mb thermal field are entered as dashed blue lines.

n. The 500-mb Critical Temperature for the season of the year is often shown as a heavier shaded dashed blue line. The Critical Temperature is that temperature during a month or season which, if exceeded in the direction of cooling, is highly correlated with thunderstorm occurrences.

o. Significant wind flow in the middle levels, including the jet band, is depicted by a solid heavy blue arrow, horizontal zones of speed shear by open blue wavy lines, and zones of diffluence by jagged blue lines.

p. Significant height fall areas at 500 mb are shown as solid blue double lines and temperature fall areas as broken double blue lines.

q. Similar features at the 200-mb level are frequently entered using the same symbols as shown for the middle levels except the shaded areas are purple.

r. The 850/500-mb thickness ridges are depicted as solid black dashed lines and the 12-hour no-change thickness line by solid black X's and dashes.

s. Thickness falls are shown as solid black double lines.

t. The Total Totals analysis for 50° and greater, by 2° or 4° isopleth intervals, are entered as dashed orange lines.

u. The Lifted Index determined from the analyzed raobs is often entered as open black dashes.

v. The 500-mb barotropic or baroclinic progged areas of maximum vorticity for the forecast period are outlined and shaded in yellow.

w. The SWEAT Index is entered for values of 400 or greater, using solid orange lines.

## SECTION C—PARAMETER SYMBOLS

A number of symbols are used on activity charts to denote the severe weather observed.

a. Thunderstorms are entered as solid circles;

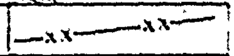
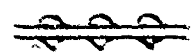
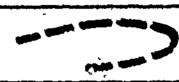
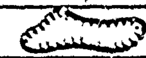
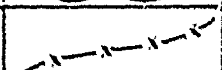
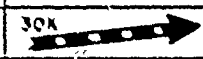
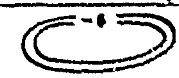
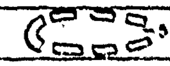
b. Tornadoes are solid triangles;

c. Lightning is an arrow with the shaft bent at a 90° angle.

d. Damaging winds are a "plus" symbol; and

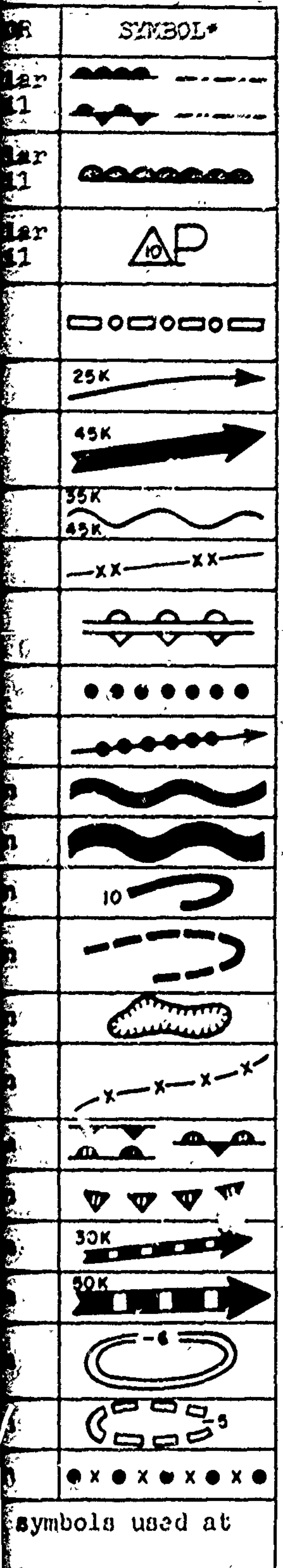
e. Hail occurrences are entered as solid squares.

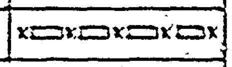
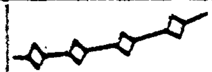
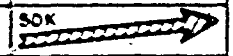
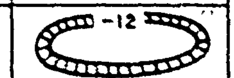
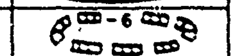
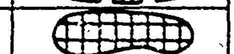
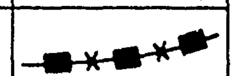
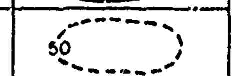
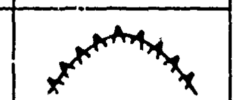
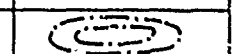
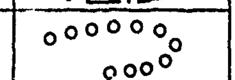
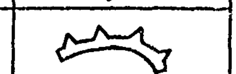
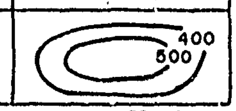
Figure 99 is a fold-out aid to be used while the reader studies the many figures in this report.

| CHART | PARAMETER | ENTRY | COLOR | SYMBOL* |
|---|---|---|---|---|
| Surface | Fronts, Isobars, Transitory Discontinuities | Already on Base Map | Regular Pencil |  |
| | Hot/Dry Prod | Same | Regular Pencil |  |
| | 12-Hour P Falls | Same | Regular Pencil |  |
| 850 MB and/or Low-Level Wind and Moisture Field | Dry Lines or Dry Prods | Mandatory | Red |  |
| | General Flow | As Required | Red |  |
| | Low-Level Jets Max-Wind Values | Mandatory | Red |  |
| | Horizontal Speed Shears | Optional | Red |  |
| | Convergent Zones | As Required | Red |  |
| | Fronts, Troughs, Squall Lines | Optional | Red |  |
| | Temp Ridges | Mandatory | Red |  |
| | Axis of Cold Advection | Optional | Red |  |
| | Axes of Moisture | Mandatory | Green |  |
| | Max-Moisture Influx | Optional | Green |  |
| | Moist Tongues | Optional | Green |  |
| 700 MB | Dry Tongues, Prods or Intrusions | Mandatory | Brown |  |
| | Moisture | As Required | Brown |  |
| | 12-Hr No-Change Lines | Mandatory When Well Marked | Brown |  |
| | Fronts/Troughs | Optional | Brown |  |
| | Thermal Troughs | Optional | Brown |  |
| | General Wind Flow | As Required | Brown |  |
| | Max-Wind Axes | Mandatory | Brown |  |
| | Significant Height Falls | Optional | Brown |  |
| | Significant Temp Falls | Optional | Brown |  |
| | Temp Ridges | Optional | Brown |  |

* These symbols are for black and white charts. A few color symbols used at MWWC differ slightly from what is presented here.

**Figure 99** List of the parameter symbols used in the figures of this report.




| CHART | PARAMETER | ENTRY | COLOR | SYMBOL* |
|---|---|---|---|---|
| 700 MB | Convergent Zones | As Required | Brown |  |
| | Axis of Cold Advection | Optional | Brown |  |
| | Diffluent Zones | Mandatory | Brown |  |
| 500 MB and/or Mid-Levels | Thermal Troughs | Mandatory | Blue |  |
| | Isotherms | Mandatory | Blue |   |
| | Critical Seasonal Temperature | Optional | Blue |  |
| | General Wind Flow | As Required | Blue |   |
| | Jet Flow | Mandatory | Blue |   |
| | Diffluent Zones | Mandatory | Blue |  |
| | Horizontal Speed Shears | Mandatory | Blue |  |
| | Significant Height Falls | Optional | Blue |   |
| | Significant Temp Falls | Optional | Blue |   |
| | 500-mb Moisture | Optional | Green |  |
| Jet and/or Trop Chart | Jet Flow | As Required | Purple |  |
| | Speed-Shear Zones | As Required | Purple |  |
| | Diffluent Zones | As Required | Purple |  |
| | Jet Max | Optional | Purple |  |
| 850/500 MB Thickness Chart | Thickness Ridges | Mandatory | Black |  |
| | 12-Hr No-Change Thickness Line | Mandatory | Black |  |
| | Significant Thickness Falls | Mandatory | Black |   |
| | Total Totals | Mandatory 50 and Above | Orange |   |
| | Zones of Marked Anti-Cyclonic Wind Shear | Optional | Black |  |
| RAOBS | Lifted Index | Optional | Black |  |
| | Level of Free Convection | Optional | Black |  |
| Vorticity Progs | Max Positive Vorticity Advection | Optional | Yellow |  |
| SWEAT Analysis Prognosis | Severe Weather Threat Index | Mandatory | Orange |   |