SELS

SELS FORECASTING PROCEDURES

By

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FOREWORD

This paper outlines the general methods used by the Severe Local Storm Warning Center (SELS) in forecasting severe local storms as of Feb. 1, 1955. The objective of this paper is to acquaint other forecasters with the charts, tools, methods, parameters, definitions, and techniques that are currently utilized in SELS operations. It would be impossible to describe the SELS techniques in sufficient detail, including the weighting of parameters from one situation to another, to permit the formulation of a severe local storm forecast from a step-by-step listing. Where deemed appropriate, some discussion of the current SELS thinking regarding future research is included. Since the forecasting of severe local storms is intimately associated with the forecasting of many other meteorological phenomenon, an attempt is made here to effect a separation between forecasting in general and the specialized forecasting in SELS. Thus, while other meteorological parameters and concepts are involved in SELS forecasting, and may be mentioned from time to time, that they have not been included here does not in any way discount their importance in SELS work.

The current level of knowledge regarding the cause of severe local storms is somewhat less than in the case of some other types of weather forecasts - temperature forecasts, for example. Considerable research, mostly of an empirical nature, has been accomplished during recent years. Also, the SELS Center has tested many methods, aids, and ideas which have been proposed and has developed some improved, practical procedures in forecasting severe local storms. The SELS philosophy, then, is to utilize all preceding methods until these can be superceded by improved techniques. It may be noted that virtually all of the SELS methods and procedures described here have been either developed or revised during the past year. Data limitations have necessarily restricted the statistical testing, particularly on the revised procedures for hail and turbulence forecasting. These procedures are being prepared in loose-leaf form so that additions and corrections can be substituted as additional study and experience demand. All forecasters, particularly District Forecasters, are solicited and urged to submit comments and suggestions.

At this time, SELS forecasts are concerned with short-range predictions, usually 12 hours or less, of the occurrence of tornadoes and severe thunderstorms over the United States, excepting such storms that occur in connection with hurricanes. Severe thunderstorm forecasts are issued when thunderstorms are expected to result in one or more of the following:

a) Surface gusts of 75 mph (65 knots) or more,
b) Sustained surface winds of 50 mph (44 knots) or more,
c) Hail having a diameter of 3/4 inch or larger,
d) Severe turbulence.

A tornado forecast implies that the area alerted will also have severe thunderstorms.

The size of the severe local storms forecast area is dependent upon the type of weather expected and the season. Severe thunderstorm areas are usually considerably larger than in the case of tornado forecast areas. During winter and spring when family-type tornadoes are most frequent, forecast areas are larger than during summer and early fall when isolated tornado occurrences are more common. Experience has shown that a tornado forecast area during late winter, spring and early summer of 20,000 square miles is an average maximum size. This size has been substantiated to a certain extent by the findings presented in the Weather Bureau's "Research Paper No. 37" [1] which shows the average area cut out by a pressure jump path to be 151-175 miles long by 101-125 miles wide. This report states further that "... the average area swept out by a pressure jump line has the shape of a rectangle almost 50 percent longer than it is wide." Composite charts of the Showalter stability index and deep moist layers from 11 situations in which tornado proximity soundings were found [2] also point to an average area of some 20,000 square miles. It is stressed that all these data are based upon average conditions and there will be variations from these mean values in individual situations.

The objective of SELS forecasters in issuing severe local storm forecasts is to predict the area which is expected to contain the maximum amount of severe weather. Various data restrictions, along with the limitations in our current knowledge of the cause of severe local storms, preclude the prediction on a unique area. Thus, each forecast area is surrounded by an area having an expected lower probability of the occurrence of severe local storms with the probability decreasing with distance from the predicted area. The same is also true with regard to the valid time of the forecast.

In general, the valid time of severe local storm forecasts is limited to a 6-hour period. This time limitation sometimes necessitates the issuance of several forecasts for contiguous or overlapping areas during a particular situation. But for the present, it is felt that for several reasons this is preferable to alerting a much larger area for the necessarily longer time.

TORNADO FORECASTING

INTRODUCTION

The importance of the geographic, seasonal and diurnal distribution of tornado occurrences must not be overlooked in tornado forecasting. In the Weather Bureau "Technical Paper No. 20" [3], Chart 13 shows the occurrences and tracks of all reported tornadoes from 1916 through 1950. From this chart, it may be noted that the area of maximum annual frequency is in the Kansas-Iowa area. While tornadoes have been reported in every state, occurrences are rare west of the Continental Divide and practically unknown in the western mountain areas. Charts 1 through 12 of this same technical paper illustrate the distribution by months during this 36-year period. Of particular interest here is the seasonal progression of the area of maximum frequency from the South and Southeast in winter to the Southern Plains in spring and on to the Central and Northern Plains in summer.

Climatological data on the diurnal distribution by months or seasons are not readily available. Figure 11 of this same technical paper [3] illustrates the diurnal distribution, based upon all occurrences, in the Florida-Georgia-Alabama-Mississippi-Louisiana area. In this area the maximum frequency of occurrence, as may be observed in charts 1-12, is in late winter and early spring. From Fig. 11 it may be noted that the afternoon diurnal maximum from 1300-1900 LST is about double that of the early morning minimum from 0300 to 0900 LST.

On the other hand, in Kansas where the monthly frequency is greatest during late spring and early summer, the afternoon diurnal maximum from 1500-2100 CST is about 20 times greater than during the minimum period from 0400 to 1000 CST. Thus it is evident that the diurnal distribution of occurrences is much more important over the Central Plains than over the Southeast.

The climatological expectancy of a tornado occurring within a specific 20,000 square mile area, within a given month, and during a particular 6-hour period never even approaches the 50% probability level. For example, consider the climatological probability for Kansas (82,000 sq.mi.) during the month of maximum frequency, May (5 tornadoes per month), during the period of maximum diurnal frequency, 1500-2100 CST (64% of all tornadoes occur in Kansas during this period). The climatological expectancy is as follows:

$$20{,}000/82{,}000 \times 5/30 \times .64 = 64/2460 = .026 \text{ or,}$$

less than a 3% probability of verification if the day and area were selected at random within the limits specified above. During the last two years, 1953 and 1954, approximately 4 times more tornado reports are being logged each year as compared with the 36-year period from 1916 through 1950. If this indicated change is correct, then the highest climatological expectancy of a tornado forecast area being verified (Kansas) is 10%. The expectancy in Alabama in March is about ½ of 1%, based upon data from 1916 through 1950. Considering the area east of the Continental Divide, all months, and four 6-hour periods per day, the climatological expectancy of a tornado occurrence within a 20,000 sq. mi. area during a 6-hour period is 1/434. Thus, the tornado forecaster must always deal with situations in which the climatological chance of verification is much lower than is true of most types of weather forecasting.

During the first 10 months of 1954, verification records showed that 20%, or 1 in 5, of all SELS tornado forecast areas contained one or more tornadoes during the valid time. Increasing the areas by 150 miles in each direction and adding 2 hours to the valid time, 40% (including the 20% listed above) of these extended forecast areas contained 1 or more tornadoes. While the expectancy of verification of a tornado forecast 1 in 5, seems unimpressively low, that has been attained against a climatological expectancy of 1 in 434. By comparison, 12-hour precipitation forecasts in most sections of the United States east of the Continental Divide may be expected to verify about 1 time in 2 occurrences. The climatological probability of verification of precipitation forecasts during 12-hour periods varies from about 1 in 4 to 1 in 6.

Air Mass Types

Much research on tornado forecasting has dealt with a "typical" [4] or "mean" [5] sounding as representative of the air mass in which tornadoes occurred. Such soundings are characterized by a dry layer overlaying a moist layer near the surface as well as both conditional and convective instability. More emphasis has been placed on tornado forecasting during the past few years and has resulted in the procurement of many more upper air soundings during the tornado season than were available for study heretofore. Many soundings obtained just prior to or associated with tornado occurrences have been observed to differ markedly from the "typical" or "mean" soundings. A preliminary study in SELS [6] of most of the tornado occurrences in the United States during 1952 and 1953, plus other interesting cases, pointed to 4 broad types of soundings as representative of the associated air mass in which tornadoes form.

Examples of these types of upper air soundings preceding tornadoes are given in figures 1 through 4. Precedent soundings are defined in SELS as those characteristic of the air mass but removed in time and/or space from the vicinity of tornado occurrence. It is emphasized that this identification of types is somewhat tentative. Also, while a Type IV sounding has been identified, it is not certain at this time whether the tornado actually occurs within this air mass or whether it occurs in conjunction with this air mass and that shown as Type I.

The above study also showed, in the case of the Type I air mass, that as the time and site of tornado occurrence was approached, the "typical" inversion gradually disappeared and the moist layer became increasingly deep. Thus it is necessary, when attempting to define or study tornado soundings, to first set some limit in time and/or space since the environment in which the tornado forms is undergoing what appears to be a continuous change. On the basis of the foregoing, a tornado proximity sounding was then defined as one in which all of the following criteria are met:

a) Tornado occurrence within 50 miles of a raob station.
b) Tornado occurrence within the hour following release of the radiosonde instrument.
c) Tornado occurrence within the same air mass as that in which the sounding was taken.
d) Sounding taken ahead of or near the parent thunderstorm but not behind it.

A proximity sounding thus represents the change, over a relatively small area, in an environment previously characterized by the precedent sounding. However, a proximity sounding is not necessarily characteristic of the air mass itself. A proximity sounding of the Type IV air mass is shown in Fig. 5.

In the study of "Tornado Proximity Soundings" [2], 11 examples were found wherein the precedent air mass was classed as Type I. An inspection of these 11 soundings revealed that none of them contained a "typical" inversion but, rather, were characterized by the penetration of the moisture to great heights (averaging 16,000 feet above the surface). All of these 11 soundings were both conditionally and convectively unstable. These soundings were analyzed to determine the various parameters commonly used in severe local storm forecasting. One of the most interesting features brought out in this analysis was the change in depth of the moist layer over the area in which tornadoes developed.

Using data from these 11 cases, a composite chart was prepared by plotting moist layer depths relative to the point of the tornado occurrence. Data from 120 soundings were used in the preparation of this composite chart, shown in Fig. 6. It appears that tornadoes actually occur within areas of deep moist layers which are surrounded by lesser depths.

At the same time that the moist layer deepens over the areas where tornadoes develop, the moist layer becomes more shallow upstream in many cases. Figure 7b is an example of a proximity sounding (a tornado occurred 20 miles south-southeast of Oklahoma City about 1 hour later) while Fig. 7a is an example of a Type I precedent sounding (6 hours before). In this case, the depth of the moist layer increased from 2,700 feet to above 13,000 (humidity data above this level are missing). At the next raob station upstream, Ft. Worth shown in Fig. 8, the depth of the moist layer remained nearly the same during the 12-hour interval while the "typical" inversion became more pronounced. Meanwhile, the depth at San Antonio, Fig. 9, decreased with marked drying aloft. Further upstream, Brownsville shown in Fig. 10, the depth decreased even more markedly, lowering from 4,700 feet to a depth of only 2,700 feet. Initially, the moist layer was of a more or less uniform depth but with time increased markedly in the vicinity of tornado formation while, simultaneously, it lowered markedly upstream.

From the study and analysis of these data, the following conclusions have been drawn:

1) Data available at this time clearly show that at the time and site of tornado occurrence, the "typical" inversion and presence of relatively dry air aloft are not characteristic of the air mass types investigated here.

2) Tornado forecasting in connection with the Type I sounding must take into account the manner in which the conversion from the precedent sounding to the proximity sounding is effected.

3) Attempts to utilize forecast parameters based upon the presence of the "typical" inversion and/or relatively dry air aloft at the time and site of tornado occurrence may be misleading.

Objective Methods

During the past few years, several objective methods of forecasting tornadoes for specified areas have been developed. These include: Armstrong's method for Georgia [7] ; Kraft's method for the Gulf States [8] ; Mook's method for Ohio [9] ; Schmidt's method for Western Kentucky and Western Tennessee [10] ; and the Shuman-Carstensen method for the Mississippi Valley [11] . All of these objective methods provided a typing system of the synoptic charts and in this respect a most useful service was rendered. Unfortunately, these studies did not, or perhaps could not, take the thermodynamic features of the various air masses into account except as grossly implied by the synoptic types.

Another limitation in the application of these methods, is that the size of the areas as well as the time periods involved are entirely too large to be used consistently without adverse public reaction. Rigid utilization of these methods would result in very large areas being alerted to the danger of tornadoes for an unreasonably long time. Of course, this does not preclude their use as a guide in SELS forecasting and this purpose was served very well during the past 2 years.

Tornado occurrence and upper air data available to these researchers was limited so that the "normals" implied in these studies are not strictly applicable to the much improved reporting system (both with regard to upper air soundings and tornado reports) in operation now. Tests conducted by SELS during the past 2 years have shown that some of these studies (Armstrong and Shuman-Carstensen in particular) held up very well while others did not. The parameters and rules now employed in SELS operations take into account not only the synoptic features of individual situations, but the climatological and thermodynamic features as well. Thus the current thinking in SELS is that these studies have been superseded by improved techniques during this developmental stage of tornado forecasting. As in all science, the SELS goal is towards more, not less, objectivity.

THERMODYNAMIC CONSIDERATIONS

Analysis of Soundings

The primary objective of the analysis of soundings is the determination of potential energy of hydrostatic instability that will be available at the time and site of severe thunderstorm or tornado occurrence. This analysis is carried out by the parcel method. The positive areas are dimensioned at present under the following assumptions: (1) the representative parcel is a mean parcel from the lower three thousand feet layer; (2) there is no entrainment; and (3) the upper boundary that is significant is not higher than the 400 mb level. The upper boundary is varied for the particular phenomenon being measured or predicted.

Tentative threat areas are outlined from prognostic positions of: (a) 6- and 12-hour surface fronts, instability lines, and pressure centers; (b) 6- and 12-hour jets, or wind maxima, at either the gradient or 850 mb and 500 mb levels; and (c) instability areas. Following this tentative delineation of possible threat areas, an analysis is made of those soundings taken within and surrounding each area. The raob analysis for parcel instability is largely dependent upon the assumed temperature and moisture distribution through the layer next to the ground. Experience thus far indicates that the depth of the significant layer is around 3,000 feet.

The steps followed in analyzing a sounding are as follows:

1. Temperature of the lower 3,000 feet. Where significant surface heating (or cooling) is expected before probable occurrence time, the actual sounding temperature is modified through this layer. In general, this modification is made on 09Z and 15Z soundings by assuming a dry adiabatic temperature lapse rate (lower 3,000 ft. only) through the predicted afternoon maximum temperature (t). Following the surface temperature forecast, the mean potential temperature of the lower 3,000 feet is determined.

2. The mean mixing ratio of the lower 3,000 feet ($\bar{w}$) is determined graphically (equi-areal method) from the plotted sounding.

3. Lifting condensation level (LCL). The intersection of the mean mixing ratio and the mean potential temperature define the LCL. Above this level, it is assumed that parcels from the lower 3,000 feet will rise along a moist adiabat without entrainment.

4. Level of free convection (LFC). Following along a moist adiabat through the LCL, the LFC is defined as the level above which the parcel is buoyed upward by its lesser density than its environment. Normally, this level will be determined at the point where the parcel trajectory, along a moist adiabat from the LCL, crosses the actual sounding.

5. Lifted index (LI). The parcel trajectory is continued upward along a moist adiabat from the LFC to the 500 mb level. The 500 mb temperature thus determined might be considered as the parcel or updraft temperature within the thunderstorm cloud, if one develops. The algebraic difference between the updraft temperature and the environment temperature (computed updraft or parcel temperature minus observed temperature) at the 500 mb level defines the LI as used in SELS. It will be noted that the evaluation of the LI is similar to that of the Showalter stability index (SI) with the difference being in the determination of the lower moisture and temperature values. In dealing with severe local storms, LI values will usually be larger negative than SI values.

Raob Analysis Chart

Values from these analyses are plotted on base maps, using the following station model:

(Level of free convection)	LFC	LI	(Lifted index)
(Mean mixing ratio)	$\bar{w}$	$\bar{\theta}$/t	(Mean potential temperature) (Forecast surface temperature)

($\bar{\theta}$ and t are used primarily as forecast check points after the analysis and have no further prognostic value.) Examples of the analysis of soundings are shown in Fig. 11a (actual sounding) and 11b (prognostic sounding).

With convective activity that results in severe local storms, it is reasonable to expect that the LFC would lower in time and may become coincident with the LCL at the time of thunderstorm development. In those cases of a low-level moisture injection, the LCL will also be lowering. This acts to increase the positive area as well as to decrease the negative area.

The LCL is dependent upon the values of $\bar{\theta}$/t and $\bar{w}$. Assuming that the temperature forecast, or other assumed value, of $\bar{\theta}$/t is valid, the change in the LCL is determined by the change in $\bar{w}$. Thus the upwind gradient of $\bar{w}$ or moisture injection, is of considerable importance in the final forecast. Surface dewpoints during late morning and afternoon permit an hourly check on the change in $\bar{w}$. That is, local heating and convection acting on the surface layer of a convectively unstable air mass will normally decrease the surface dew point through layer mixing. Therefore, rapid or continuous increases of the surface dew point, from hourly reports, over threat areas are of particular significance.

The Prognostic Sounding

Much of SELS routine operations is aimed at the production of a prognostic sounding which is intended to be representative of the air mass within the threat area under consideration before severe local storms develop. The prognostic sounding provides an important basis for the determination as to whether or not a severe local storm forecast will be issued. Also, if one is issued, it will provide the principal basis for forecasting hail size, level and class of severe turbulence, and maximum surface wind gusts.

The preparation of a prognostic sounding involves the prediction of temperature and humidity at selected levels above a given point at some future time. The levels involved usually include the surface, 850, 700, and 500 mb levels as well as the base and top of the low-level inversion when it is present. The following 4 processes are involved in changing the temperature at a given point:

1. The horizontal advective change. The shear-stability chart (to be described later) involves this as the primary basis, being actually a field of two-point predicted soundings in its projected form. The horizontal advective change is usually evaluated only for the 850, 700 and 500 mb levels. Advective change as used here refers to the trajectory of air parcels. Thus, temperatures are moved with the expected horizontal trajectory of air parcels but these values are modified for the three other processes involved in temperature changes listed below.

2. The dynamic change. A recent paper on the conversion of convective instability [13] stresses the importance of the dynamic change. This change is a consequence of lifting or vertical stretching and involves adiabatic temperature changes as well as those resulting from the release of the latent heat of condensation. The significance of this change, particularly when dealing with an air mass containing a low-level inversion, may usually be estimated by simply lifting all points which lie above the base of the inversion or above the 3,000 feet layer. The amount of this lift varies with the situation, being greatest in the case of pronounced and favorable jet structures or other indices of low-level convergence and high-level divergence. A lift of 50-100 mb is usually used to estimate this change but it should be understood that this is a tentative figure at this time and further study on this problem is continuing in SELS.

3. Local heating (or cooling). The modification of the surface and low-level temperature is determined largely by the surface temperature forecast. This has already been taken into account to a certain extent in the analysis of the actual soundings. However, further consideration must be given to a surface temperature forecast for the time and site of possible occurrence.

4. The latent heat change. Heating due to the release of the latent heat of condensation is taken into account in the preparation of prognostic soundings in the evaluation of the temperature change resulting from lifting described above.

   Isobaric evaporational cooling at low levels, due to rain falling through non-saturated air, is sometimes an important factor in the determination of the temperature through the lower 3,000 feet. This effect is most frequently taken into account in the prediction of the surface temperature and also in the mean potential temperature of the lower 3,000 feet which is used to calculate the LCL. Also, there are occasional instances in which evaporational cooling at, say 700 mb, due to rain falling from some higher level, effectively lowers the height of the LFC. The lowest temperature to which non-saturated air parcels can be cooled through evaporation alone is represented by the wet bulb temperature of the air.

Humidity Change.

1. The horizontal advective change. An adequate low-level moisture supply is currently considered by SELS forecasters to be a necessary condition prior to the formation of severe local storms. The horizontal low-level advective moisture change is estimated from the surface map, the 850 mb chart and plotted soundings. Moisture values are moved with the expected trajectory of air parcels and modified as indicated in the two processes listed below.

2. The vertical change. While the change in moisture values on the constant pressure charts is usually considered in most forecasting operations as resulting mostly from horizontal advection, it is important to remember that moisture also moves along the vertical axis. Indeed, it is this movement that is of paramount importance in the development of convective activity. In the prognostic sounding, this vertical change, or pull-up, of moisture is taken into account through the same lifting process described under the dynamic temperature change above.

3. The evaporation-condensation change. The moist adiabatic lapse rate may be used to evaluate mixing ratio or dew point changes under saturated conditions during lifting or sinking. Humidity increases due to the evaporation of rain falling through non-saturated air at low levels are occasionally important in lowering the LFC.

These steps are discussed in general terms rather than as point-by-point steps. As in the case of the preparation of prognostic surface maps, a general outline of the factors involved can be presented whereas the relative importance of the various factors will necessarily vary from one situation to another.

Showalter Stability Index.

The stability index (SI) as developed by Showalter [12] and transmitted regularly both via teletypewriter and Facsimile has proven to be a very useful tool in SELS operations. Although it is a very simple parameter, it does contain a considerable amount of information about the air mass structure. Negative or small positive values of this index might be considered as a normal necessary condition prior to the development of severe local storms (there are occasional important exceptions), but it should be noted, as Showalter has stated, that such values certainly do not constitute a sufficient condition. Plotted values of this index on a map will very quickly and easily delineate most suspect areas and this is the principal use currently made of the SI by SELS forecasters. Also the SI, where used in conjunction with the LFC, is a tool for making a rapid check upon thunderstorm potential but not for making the forecast itself. There are some severe local storm outbreaks which may not be indicated by a typical analysis of static, low-valued areas of the SI in such cases. The forecasting problem is one of anticipating the time rate of change of stability.

DYNAMIC CONSIDERATIONS

Jet Structures

A rather recent development [13] in tornado forecasting has been the utilization of low and high-level jet relationships as an important factor in the conversion of an air mass from that represented by the precedent sounding to one characterized by the proximity sounding. By considering certain indications of the vorticity equation, it is possible to analyze configurations of jet axes and jet maxima such that low-level (850 mb) horizontal convergence is surmounted by higher level (500 mb) horizontal divergence. These jet structures may act upon an air mass that is both conditionally and convectively unstable to create, or help create, areas of parcel instability where maximum thunderstorm activity and tornadoes occur. The models of jet structures to be described constitute one means which assists in or, possibly in some cases, effects the release of convective instability through vertical stretching or lifting. Jet, as used here, refers to a horizontal wind speed maximum.

In general, the jet axis or wind maxima at the 500 mb level that is of concern here is that which lies to the southeast of the major axis. These secondary jets may often constitute little more than the southern or southeastern boundary of a plateau of high wind speed extending to the right (usually southeast) of the major jet axis. (An exception to this generalized case exists in the situation illustrated in Fig. 15 where the 500 mb jet of interest is usually the major jet at that level.) The intensification of this secondary jet is frequently noted on 500 mb charts prior to tornado occurrence and the wind maximum at the time and site of occurrence is generally quite apparent. It is stressed that the interest here is that divergence and wind shear at the 500 mb level may often be used to delineate a vertical motionfield.

The use of the following models in tornado forecasting is based primarily upon a careful analysis of jet, or wind maxima, axes at the 850 and 500 mb levels. The prognosis of these jet axes may be accomplished through the application of contour prognoses, extrapolation, and anticipated reactions of thickness fields. The low level jet is also closely related to surface developments and displacements.

Figure 12 illustrates an example in which an anticyclonically curved upper jet axis is orientated at an angle of 45 degrees or less with respect to the lower jet axis. With this structure, the significant area is related to a line from the point of intersection (or the extended intersection point if the jets do not actually intersect) southwestward, bisecting the angle between the two jets. The reasoning here is that undelineable fine structures branch from the main jet axes and interact very nearly along the bisecting line. The probability of such interaction is a function of the spatial separation of the jets and, thus, of the angle between them. Occurrences usually break out first in the south and move northward along the line bisector. This pattern is frequently quasi-stationary and attends many major family outbreaks. A typical predicted tornado area is outlined in Fig. 12 (no movement is shown).

Figure 13 illustrates an example of a right angle intersection without curvature. A configuration of jet axes is predicted for a given point and this intersection is further predicted to move across the field shown. Since the fine structure of the jet is not amenable to treatment, the area chosen for the prediction of tornado occurrence is centered upon the line of movement of the jet intersection and embodies an area of uncertainty, due to lack of detailed data, on either side of this line. The occurrences will usually be found very close to the intersection and seldom consist of more than one or two tornadoes.

Another example, Figure 14, is that of an anticyclonically curved jet axis aloft which intersects the low level jet at an angle of more than 45 degrees. The reasoning and extrapolation of the intersection point is similar to that in the case above (Fig. 13). The principal difference is the weighting of the area to the south of the upper jet and to the west of the lower jet axis for the probability of occurrence. (For an explanation of why the weighting of the areas is different in Figs. 12, 13 and 14, see the referenced paper [13] .) The limits of error in positioning the jet axes requires inclusion of the intersection point and some area to the north and east. A typical area for tornadoes with such a configuration is outlined in Fig. 14.

A fourth case, Figure 15, is that of the intersection of a cyclonically curved jet aloft with a low level jet. This situation is also similar to the second example but weight is given to the area to the north and west of the upper jet. This type is representative of the elusive "cold" type occurrences, such as the Hartford, Conn. storm of May 10, 1954. In these situations, the low level jet is not necessarily well defined but surface indices place the occurrence in a region of pronounced low-level convergence.

Variations in these convergence-divergence patterns are, of course, possible Quantitative calculations of the magnitude of horizontal convergence or divergence from these patterns have not been attempted. However, qualitative estimates of the divergence, based principally upon the strength and orientation of the jets, are considerations in most SELS forecasts.

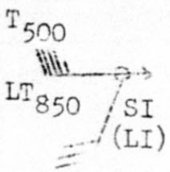
As previously mentioned, these models constitute only one means of effecting vertical stretching, or lifting, of an air mass. Other mechanisms such as cold fronts, warm fronts, terrain features, etc., exist and must be given consideration. Thus, the lack of prior existence of these jet structures does not preclude the expectancy of severe local storms, i.e., a low-level jet may not be in evidence but result from marked deepening of a low center. Particularly in summer, the 500 mb jet may not be indicated by winds aloft measurements but subsequently develop as a result of low-level convergence and increasing mean temperature (thickness) through this layer.

Shear-Stability Chart

The purpose of the shear-stability chart is to obtain an estimate of prognostic areas of maximum hydrostatic instability and to indicate a rate of change of stability. The measure of stability used here is the Showalter stability index (SI) [12] . Shear refers to the vector difference in wind between the gradient and 500 mb levels. Otherwise, of course, SI areas could be advected without change. This chart consists of a superposition of 500 mb temperatures and winds upon the gradient winds and temperatures of the 850 mb parcels lifted to the 500 mb level (850 mb lifted temperatures). Gradient winds are considered to be more representative of the moisture flow in the lower 3,000 feet. In SELS operations, the gradient wind is arbitrarily defined as the strongest speed that is noted in the first 5 groups of the coded pibal message (no more than 4,000 feet above the station). Data for this chart are compiled and analyzed only within and surrounding threat areas which may have been determined from other considerations.

Prognostic areas, and magnitude, of instability are obtained by simply advecting point values of both the 500 mb temperature and 850 mb lifted temperature with the winds at the appropriate levels. A constant compensation for non-adiabatic effects is applied by advecting these values with only 60% of the indicated wind speeds. Graphical subtraction of prognostic 850 mb lifted temperatures from prognostic 500 mb temperatures yields prognostic values of the Showalter stability index. An interpolation between the initial SI field and the prognostic SI field will represent the magnitude of the change in this stability parameter with time as well as the areas over which the change occurs. These prognostic values may not be observed if convective activity occurs between soundings.

Data are plotted on a base map according to the following station model:



where T_{500} = observed 500 mb temperature
= 500 mb wind direction and speed
LI = Lifted index
SI = Showalter stability index
= gradient wind speed & direction
LT_{850} = 850 mb lifted (to 500) temperature

This chart is used in conjunction with the analyzed 850 and 500 mb charts so that an initial analysis of these data is not necessary. A 6 to 12-hour forecast of the 500 mb temperature field is made by advecting the 500 mb temperatures downstream with 60% of the indicated winds. It is sometimes necessary to modify these advected values due to expected dynamic influences such as deepening or filling, flattening or sharpening of troughs, etc. An analysis is then made of these 500 mb forecast temperatures.

The next step is to make a forecast of the 850 mb lifted temperature values. Since $T_{500} - LT_{850} = SI$, and $LT_{850} = T_{500} - SI$, the observed 500 mb temperature minus the observed SI is equal to the 850 mb lifted temperature. These LT_{850} values are then computed for those stations within and surrounding a threat area. A tentative 6 to 12-hour forecast of LT_{850} is made by advecting these values with 60% of the reported winds at that level. Adjustments are then made for anticipated changes in the pressure, temperature and moisture field, frontal movements, etc. Extreme care must be exercised in this operation to avoid overlooking very cold values (positive SI values) of the lifted temperature which are a result of dry air at the 850 mb level but with high dew points just below this level. In such a case a lifted temperature computed from the LI value obtained from the raob analysis is used as a more representative condition. The LI is a better index of latent instability and is often used instead of the SI in and around threat areas. An analysis is then made of these prognostic 850 mb lifted temperatures.

With these 2 sets of lines on the chart, a graphical analysis of SI (or LI) values through intersections may be quickly and easily effected. For example, when the forecast 500 mb temperature is equal to the 850 mb lifted temperature, the SI is zero. Or, when the forecast 500 mb temperature is colder (larger negative) than the 850 mb lifted temperature, the SI is negative.

The 700 mb "no-change" line

An approach to the prediction of squall line formation is found in the 700 mb "no-change" line technique. Basically, this consists of the delineation of a low-level isentropic trough (approximates a warm tongue at 850 mb) and an advected thermal ridge at 700 mb (a temperature "no-change" line). If the prognosis shows the "no-change" line to be shearing over the low-level isentropic trough (other factors being favorable), squall line inception is predicted along the line of and at the time of coincidence.

This procedure is empirical in its basic derivation. However, several physical bases have been offered to account for its validity.

One of these relates to air mass modification. In general, the low-level isentropic trough (850 mb warm tongue) will be found to be coincident with a southerly low-level jet axis. The region to the left of this axis is favorable for convergence due to "chimney effect", frictional torque, and the horizontal solenoid field. In addition, in the deceleration zone of the jet a packing of mean isotherms with anticyclonic curvature will tend to create a favorable jet pattern for divergence at some level aloft over an extent of the convergence field to the left of the jet axis at low levels.

The depth of the vertical motion field so produced may not be deep enough to significantly modify the stability of the air mass. However, when a mean thermal ridge is advected into coincidence with this pattern at intermediate heights (the 700 mb "no-change" line is an index to this), the favorable divergence pattern is projected to greater heights. The modification of the air mass may then proceed to critical instability limits, with consequent outbreak of activity in the favorable region.

Another physical basis is found in the concept of hydrodynamic instability in isentropic surfaces. Insofar as the action of shearing into coincidence of the "no-change" line and the isentropic trough is representative of an increase in slope of isentropic surfaces to the rear of the isentropic trough, a tendency toward hydrodynamic instability in these surfaces is denoted. In general, there exists a critical slope of isentropic surfaces

surfaces for hydrodynamic instability. The flow pattern at 700 mb is usually such that, given the exceeding of this critical limit, a component of motion in the isentropic surfaces is available as an impulse.

Thus, at some point near coincidence, the critical limit of hydrodynamic instability for the isentropic slope of the isentropic surfaces to the rear of the isentropic trough is exceeded. An impulse, which may be highly linearized in configuration, then travels eastward into the isentropic trough, acting as a squall line initiating mechanism.

A combination of the above leads to a complex of (1) the creation of a region of favorable air mass for intense thunderstorm activity which may be linearly triggered by (2) an impulse created by an attendant increase to critical isentropic slope.

It is to be observed that a linearized impulse such as that described above can be expected to have associated with it a coincident linearized perturbation of the surface pressure. It is felt by many forecasters with experience in handling severe storms, on a basis of synoptic experience, that the surface pressure perturbations noted prior to and attendant to squall line formation (and, sometimes, tornado inception) may be structurally accounted for by such a mechanism.

Pressure Jumps

The pressure jump concept is not amenable to treatment on the forecast desk and is not used as a tool to forecast either tornadoes or the beginning of convective activity. As stated in "Pressure Jump Lines in Midwestern United States" [1] , "83 percent (of the 65 tornadoes whose time and location were available) fell inside the area swept out by a pressure jump line and of these, 82 percent corresponded within 1 hour to the pressure jump line isochrone." While 68 percent of these 65 tornadoes were associated with pressure jump line isochrones, data on the number of pressure jump line situations that were not associated with tornado situations were not presented. Most of the pressure jump lines studied had a life of 4 hours or less. Also, most of the severe local storms occurred during the first half of the life of a pressure jump line. Thus the time between the development of a pressure jump line and tornado formation is much too short to be of forecasting value. Indeed, as pointed out in a later paper [14] , a tornado occurrence may actually precede the formation of a pressure jump line.

The principal use that is made of pressure jump reports in SELS is to verify the development of or location of an instability line that was expected within that general area and time. Thus, pressure jump reports at this time are primarily an analysis tool rather than a forecasting tool

Synoptic Charts

The following guidance list is intended to describe synoptic conditions which are usually associated with tornado occurrence. However, it is emphasized that, in particular instances, all of these conditions are neither necessary or sufficient. The following conditions are generally considered to be favorable for tornado development or to delineate areas in which tornadoes occur.

Surface Map

1. The warm sector of a wave cyclone.
2. Intersections of warm fronts and instability lines.
3. Instability lines.
4. Cold fronts.
5. Areas having a surface dew point of 53°F or greater [15] .

850 mb Chart

1. Trough to the west of a threat area.
2. Moisture injection. That is, a southerly jet within an area of high moisture values. While a lower limit on the depth of the moist layer has tentatively been set at 3,000 feet, it is imperative that a strong moisture injection be in evidence in such situations. Otherwise, if the moisture is distributed through a depth comparable to the vertical extent of Cumulonimbus clouds, the low-level supply would be appreciably lowered, the LFC would increase to greater heights, and convective activity would be of only transitory duration. Thus the location and position of the low-level moisture injection is one of the most important aspects in severe local storm forecasting.
3. Warm air advection.
4. Coincidence, or near-coincidence of temperature and dew point ridge.

700 mb Chart

1. Trough to the west of a threat area.
2. "No-change" lines. (See description.)
3. Areas with increasing local change of moisture values are most favorable.

500 mb Chart

1. Jet intersections with low level jet or low level convergence region.
2. Cold temperature advection from a westerly direction.
3. Evidence of dynamic cooling.

Radar Plotting Chart

At the present time little has been confirmed as to the appearance of a tornado on the radar scope. The following echo patterns are suspected of being indicative of severe local storm activity:

1. Echoes which indicate vertical shear (hooks, s-bands, 6-shaped echoes, etc.).
2. Intersection of two or more bands of echoes.
3. Areas of maximum vertical development.
4. Areas of marked convergence of echo paths.
5. Well defined bands of strong convective echoes.

However, until the subject has been studied more rigorously, the radar reports must be used principally to position areas of current activity and to determine the velocity and vertical extent of the echoes.

Formulation of the Forecast

In common with other types of weather forecasting, the formulation of a tornado forecast does not entail a simple weighing of parameters or direct application of rules. Instead, the SFLS forecaster must arrive at some decision, or series of decisions, in each individual situation regarding the combined relative importance of the climatological, thermodynamic and dynamic features previously discussed. At the present time these decisions are based upon subjective considerations and are necessarily subject to the capacity of the human brain to accurately evaluate the importance of all parameters in all cases. So, until these parameters, as well as others that will be developed, can be measured and combined in a more objective manner, tornado forecasting must rely heavily upon experience itself.

The development of a set of rules which would be applicable in any area, any season, or any of the 4 air mass types previously described has not been attempted. Nevertheless, the following discussion will attempt to portray, in a generalized manner, the methods used in SELS to formulate a tornado forecast. For lack of specific knowledge to the contrary, it is currently assumed that the tornado develops through the conversion of potential to kinetic energy along with the release of instability. Thus, the tornado forecast method may be used in the prediction of hail, turbulence, and surface wind gusts.

The formulation of SELS severe weather forecasts is a function of both dynamic and thermodynamic considerations. There are occasional instances in which all of the thermodynamic considerations are pronounced and, at the same time, all dynamic considerations are strong and well-marked. In such cases (e.g. the tornado situation of March 21-22, 1952), nearly all criteria for forecasting tornadoes are fulfilled. However, these situations are not representative of those which most frequently confront the SELS forecaster. Experience has shown that, in general, dynamic considerations are the more important during late fall, winter and spring. This is, as is well known, the season when the more severe outbreaks occur. On the other hand, thermodynamic considerations seem to have a more dominant role during summer and early fall when pressure patterns are usually weaker and less well-defined.

A first approximation to the section of the United States in which a threat area may be suspected can be made upon the following considerations:

1. SI. Areas of negative values, particularly large negative values, become tentative suspect regions for further analysis.
2. Shear-stability chart. By advection of LT_{850} and T_{500} values from this chart further refinement to the suspect region can be made.
3. A quick estimate is made of the conditions discussed under "Synoptic Charts."

The above gross considerations thus outline a region, perhaps as large as several states, for further refinement by the following:

Dynamic considerations

1. A 6- and 12-hour prognostic surface chart, including fronts, instability lines, and pressure centers.

2. 6- and 12-hour prognostic positions of 850 and 500 mb jets. The jet structures, as previously described should, in general, be in evidence or predicted over the threat area.

3. Deepening. Deepening surface lows, or waves, are considered to be favorable for tornado formation. This is particularly true of the family-type outbreaks in winter, spring and early summer. Deepening of a low center, or wave, is necessarily taken into account in the preparation of the surface prognostic chart. It should be noted that there are also many tornado occurrences without prior evidence of surface deepening. The deepening referred to here is not to be confused with the development of micro-lows, or "tornado nests" as described by Means [16] . Such micro-lows seem to develop only a very short time prior to, or even concurrent with, tornado formation.

4. 700 mb no-change line. In the usual situation during winter, spring and early summer, it should be expected that the 700 mb no-change line will be coincident or nearly coincident with the low level isentropic trough at the time of instability line development. While there are exceptions, this guide should be considered as more of a necessary condition rather than as a sufficient condition.

These 4 dynamic considerations will usually further limit the tentative region to a threat area in which tornadoes may be possible but not necessarily probable.

Thermodynamic Considerations

1. Initial analyses of observed soundings should in general show LFC values that are below 600 mb within threat areas. Analyses of prognostic soundings should show LFC's around the 850 mb level. Other things being equal, the expectancy of severe local storms is directly proportional to higher pressure values (lower elevations above the ground) of the LFC. Both convective and conditional instability should exist, or be predicted, at the time and site of tornado occurrence.

2. LI values, within a threat area, should be negative and the probability of severe local storms is proportional to increasingly large negative values of the LI. In most cases, LI and LFC values will dimension the positive area.

3. Moist layer. In general, the moist layer should be at least 3,000 feet deep but in cases where the minimum is only slightly exceeded there must be evidence of a strong moisture injection within this layer to replenish the supply if and when convective activity occurs. Those cases of moist layer depths of 3-8,000 feet that suddenly increase to above the 700 mb level are believed to constitute direct observational evidence that conversion of convective instability is under way. Convective instability is either being released at sounding time, or will be released very soon. Therefore,

such areas are "hot" and quick forecast action is advisable. In general, SELS forecasters attach little significance, per se, to the existence or non-existence of a relatively dry layer overlying the lower moist layer, except as an index to convective instability.

4. The prognostic sounding(s) is intended to represent the air mass structure within the threat area(s). Thus, it constitutes the final thermodynamic consideration as to whether or not a tornado forecast will be issued. Also, computations of hail size, severe turbulence, and thunderstorm surface wind gusts are made from this sounding.

   An exception to these considerations has been noted in the case of the jet structures shown in Fig. 15. In these cases there may be moisture to great heights over a very large area and static SI values may be positive (but becoming negative at the time and site of the beginning of activity). Also, surface dew points may be in the 40's. In these cases, the instability is assumed to result almost entirely through dynamic modifications of the air mass.

HAIL SIZE FORECASTING

At the present time, hail size forecasts are of more value to aviation than other interests. Experience has shown that hail stones of a size smaller than 3/4 inch do not often cause important damage to commercial aircraft in operation today. So, in predicting severe thunderstorms, SELS forecasters are concerned with hail size only when hail stones having a diameter of 3/4 inch or larger are expected. At present, no attempt is made to pinpoint the exact time and location of large hail occurrences. As in the case of tornado forecasting, a prediction is made of the probability of large hail occurrence over a given area, say 100 by 200 miles, during a specified time period. Such a prediction does not carry any implication regarding the areal extent of the hail, large or small, that might be damaging to other interests, such as agriculture.

A technique for predicting hailstone size has recently been developed within SELS [17] and is in current use. This method was derived under the following assumptions: a) hail size is proportional to the updraft velocity within a thunderstorm; b) the updraft velocity derives from parcel buoyancy: and c) the updraft may be approximated from positive area measurements on a thermodynamic diagram. The use of this technique is based upon forecasts of thunderstorms made in conjunction with other considerations than positive areas or other thermodynamic indices alone.

Entrainment has been neglected here. In the case of the intense thunderstorms which produce large hail sizes, the parcels may be affected but little by entrainment at the core of strong updrafts of large cross-section where the larger stones are visualized to form. However, entrainment may, in part, account for the spectrum of hail sizes observed over an area due to a spectrum of entrainment rates in a complex of thunderstorm cells. Undoubtedly, entrainment must account for an important number of failures experienced with any hail forecasting technique that cannot account for its effects (and none in application do). In general, it should be expected that the effect of entrainment in reducing the size of the positive area would be greatest in the case of widely scattered thunderstorm activity, and least in an area of numerous, intense thunderstorms, such as along pronounced instability lines. There is no basic observational material on which to base a definite evaluation of the effect, however; and no operationally feasible procedure for including the effect at present.

Data from proximity soundings were used in the development of the SELS method so that, operationally, it is advisable to prepare a prognostic sounding representative of the centroid of a threat area in cases where no real sounding is sufficiently representative. It is also necessary to make a prediction of thunderstorm occurrence within the threat area. This forecast of thunderstorms must be made through other considerations (expected "kickers", favorable synoptic patterns, etc.) since the parameters utilized in hail size forecasting are not necessarily related to the probability of thunderstorm occurrence, beyond the availability of the potential energy of hydrostatic instability.

The updraft velocity is estimated from a measure of the positive area on a thermodynamic diagram (WB form 1147). This positive area usually approximates a triangle and the measurements used here are H (height of the triangle) and ΔT (base of the triangle in degrees C.) Available data point to a temperature of -10°C as the mean level of hail formation. Thus, the height of the triangular positive area, H, is measured from the level of free convection (LFC) to the -10°C level on the predicted parcel lapse rate. The base of the triangle, ΔT, is the temperature difference between the parcel and its environment. That is, the algebraic difference of -10°C minus the temperature of the actual environment or forecast sounding (forecast environment) at this same level. For this value to be significant, the parcel must be warmer than the environment. In those cases where the positive area is not approximately a triangle due to an irregular observed or predicted temperature lapse rate, a smooth line is drawn to represent the mean lapse rate (equi-areal bisection). Actually, in working with prognostic soundings, such cases would not usually appear.

An overlay, shown in Fig. 16, is used to quickly evaluate the positive area. This overlay is placed with the zero point coincident with the -10°C point on the parcel lapse rate and the coordinates parallel to the appropriate coordinates on the WB 1147 base. Initial hail size is read at the intersection of the isotherm corresponding to the environment temperature at the -10°C parcel temperature level and the isobar corresponding to the level of free convection. If the level of the -10°C parcel temperature is different from 400 mb. (and it usually is) a correction for air density effect is made from the chart shown in Fig. 17. The hail size initially obtained from the overlay and the actual pressure of the -10°C parcel temperature level are used to enter this graph for the corrected hail size. It will be noted that the higher the actual pressure of that level, the greater the hail size.

An example (graphical) of the use of this technique on a hail proximity sounding is shown in Fig. 18.

SEVERE TURBULENCE FORECASTING

Severe turbulence may be visualized as a field of intense vertical drafts and eddies (gusts) of such dimensions, orientations, and strength that aircraft traversing the field are subjected to stresses that may do structural damage.

A technique has recently been developed within the SELS Center 18 based on (1) a correlation of drafts with "positive areas" analyzed on a pseudoadiabatic diagram of a sounding representative of the air mass of occurrence; (2) a correlation of effective gusts with drafts obtained in the Thunderstorm Project 17 ; and (3) a definition of the turbulence predicted in terms of the effective gusts.

The effective gust has been utilized as a defining parameter since it may be used to estimate the effect that may be produced on any given aircraft by turbulence.

The severe turbulence predicted by SELS corresponds to the meteorological definition "severe" and the pilot definition "extreme", in each case the most intense turbulence currently defined. The technique employed by SELS in no way affects the official definition as elsewhere stated.

Severe turbulence is predicted when the positive area analyzed below 400 mb. is sufficient to give a hail size of 3/4" at the 400 mb. level, i.e. when draft velocities as computed from the approximative triangular area method equal or exceed 80 fps at any level below 400 mb. (The 3/4" hail size isopleth at 400 mb. is equivalent to a draft velocity of 83 fps - sufficiently close to 80 fps to be equated without significant error.)

The overlay for hail size is reversed and the zero height line laid parallel to the pressure isopleth (WB Form 1147) coincident with the level of free convection. It is then moved along this isopleth while the temperature difference between the parcel trajectory and the lapse rate at various levels is compared with the temperature difference indicated by the distance between the 3/4" hail size isopleth and the zero temperature axis of the overlay, at the same levels. Where the lapse rate-trajectory temperature difference is larger than the overlay temperature difference at any point below or at 400 mb., a severe turbulence forecast is indicated, given the occurrence of thunderstorms.

Usually no restriction on height of severe turbulence is made. In cases where very stable air is indicated at low levels, "severe turbulence aloft" will be forecast.

Revised 6/1/55. Replaces pages 21 and 22 of "SELS Forecasting Procedures".

THUNDERSTORM SURFACE WIND GUSTS FORECASTING

The empirical method of Fawbush and Miller [20] continues to serve as the basis for the evaluation of maximum surface gusts in SELS operations. The procedure is as follows:

1. The zero wet bulb is located on the sounding and the moist adiabat through that point is followed to the surface.

2. The difference between this temperature (at the surface) and the representative surface temperature is used as an index to expected maximum surface gusts.

3. This index, in degrees C., is then related to expected maximum surface gusts. A temperature difference of 12°C corresponds to surface gusts to 75 mph. or 65 knots; 16.5°C corresponds to gusts to 100 mph; and, 7°C corresponds to gusts to 50 mph.

An apparent positive consistent error has been observed by SELS forecasters in values obtained by this method. Some forecasters utilize a constant correction of about -25 knots, while others utilize a subjectively variable correction based upon consideration of the wind field at intermediate heights (10-15,000 feet) and/or the rate of motion of instability lines or fronts.

Research on forecasting thunderstorm surface gusts is continuing in SELS. These gusts are tentatively attributed in SELS to: (a) the downward acceleration arising from the action of the buoyant force within the rain area on parcels in moist adiabatic descent, and (b) the attendant vertical advection of horizontal momentum, particularly in the squall line or frontal type thunderstorm.

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LEGEND

Figure 1. Example of Type I upper air sounding, Barksdale AFB, La., 0900 CST, March 21, 1952. The severe outbreak of tornadoes over Arkansas and Tennessee on March 21-22, 1952 began 6 hours after this sounding and the first tornado in this series was reported 100 miles north of Shreveport, La. Tornadoes with this type of precedent sounding most often occur in the South during late winter and early spring, and over the Midwest during spring and early summer.

Figure 2. Example of a Type II upper air sounding, Atlanta, Ga., 2200 EST, March 27, 1948. Tornadoes occurred about 60 miles northwest of Atlanta 4 hours after this sounding. This warm, moist precedent sounding is most often noted in connection with tornadoes in the Southeast and also with tornadoes associated with hurricanes. Occurrences in this type of air mass are rather infrequent.

Figure 3. Example of a Type III upper air sounding, Mitchel AFB, N. Y., 1000 EST, May 10, 1954. Tornadoes occurred 100 miles north of Mitchel AFB about 3 hours after this sounding. Occurrences in this cold, moist air mass are also rather infrequent and often consist of reports of funnel clouds aloft rather than destructive funnels reaching the ground..

Figure 4. Example of a Type IV upper air sounding, Dodge City, Kan., 0900 CST, June 24, 1953. A tornado was reported 45 miles south-southwest of Dodge City 7 hours after this sounding.

Figure 5. Example of Type IV upper air sounding (6 hours later), Dodge City. Kan., 1500 CST, June 24, 1953. A tornado was reported 45 miles south-southwest of Dodge City one hour after this proximity sounding. This type of sounding (termed the "inverted V" in SELS) is noted in connection with many of the long, narrow, rope-like funnel clouds that occur during the summer months over the higher Plains States. Of particular interest here is the complete absence of either a stable layer or a pronounced lower moist layer. The diurnal variation in these occurrences is very pronounced with the maximum occurring near, or just after, the normal time of maximum temperature.

Figure 6. Composite chart showing depths of the moist layer in eleven Type I cases. Isopleths of the average depth of the moist layer for these cases are shown.

Figure 7a. Upper air sounding at Tinker AFB, Okla., Febr. 19, 1951, 1600 CST.

Figure 7b. Upper air sounding at Oklahoma City, Febr. 19, 1951, 2100 CST. A tornado was reported 20 miles south-southwest of Oklahoma City one hour later

Figure 8a. Upper air sounding at Ft. Worth, Tex., Febr. 19, 1951, 0900 CST.

Figure 8b. Upper air sounding at Ft. Worth, Tex., Febr. 19, 1951, 2100 CST.

Figure 9a. Upper air sounding at San Antonio, Tex., Febr. 19, 1951, 0900 CST.

Figure 9b. Upper air sounding at San Antonio, Tex., Febr. 19, 1951, 2100 CST.

Figure 10a. Upper air sounding at Brownsville, Tex., Febr. 19, 1951, 0900 CST.

Figure 10b. Upper air sounding at Brownsville, Tex., Febr. 19, 1951, 2100 CST.

Figure 11a. Example of an initial analysis of a sounding.

Figure 11b. Example of a final analysis of a sounding (prognostic). Values of hail size, turbulence class, and surface wind gusts are noted.

Figure 12. Example of an anticyclonically curved upper jet and cyclonically curved lower jet intersecting at an angle of less than 45°. Note the threat area positioned along the bisector line. Actually, a lower jet without curvature would usually result in about the same predicted tornado area.

Figure 13. Example of a normal (90°) intersection of upper and lower jets without curvature.

Figure 14. Example of an anticyclonically curved upper jet intersecting a lower jet, without curvature, at an angle of 45° or more.

Figure 15. Example of a cyclonically curved upper jet intersecting a lower jet without curvature.

Figure 16. Overlay for WB Form 1147 for estimating hail size for the -10°C parcel temperature at 400 mb.

Figure 17. Correction graph for parcel temperature of -10°C at a level other than 400 mb.

Figure 18. Upper air sounding at Altus, Okla., April 29, 1954, 1500 CST. Hail size was computed to be $2\frac{1}{4}$ inches. Hail up to 2 in. diameter fell 95 miles north of Altus, Okla. between 1530 CST and 1830 CST.

Figure 19. Upper air sounding at Ft. Smith, Ark., Oct. 11, 1954, 1500 CST illustrating an example of an analysis for severe turbulence. The overlay lines are drawn on this sounding and condition for severe turbulence, as defined, is fulfilled at 18,000 feet. Severe turbulence was reported on the Oklahoma City-Little Rock route at 1603 CST between 18,000 and 28,000 feet msl.

Figure 20. Overlay for WB Form 1147 for estimating the maximum surface wind gusts due to thunderstorm downdrafts.

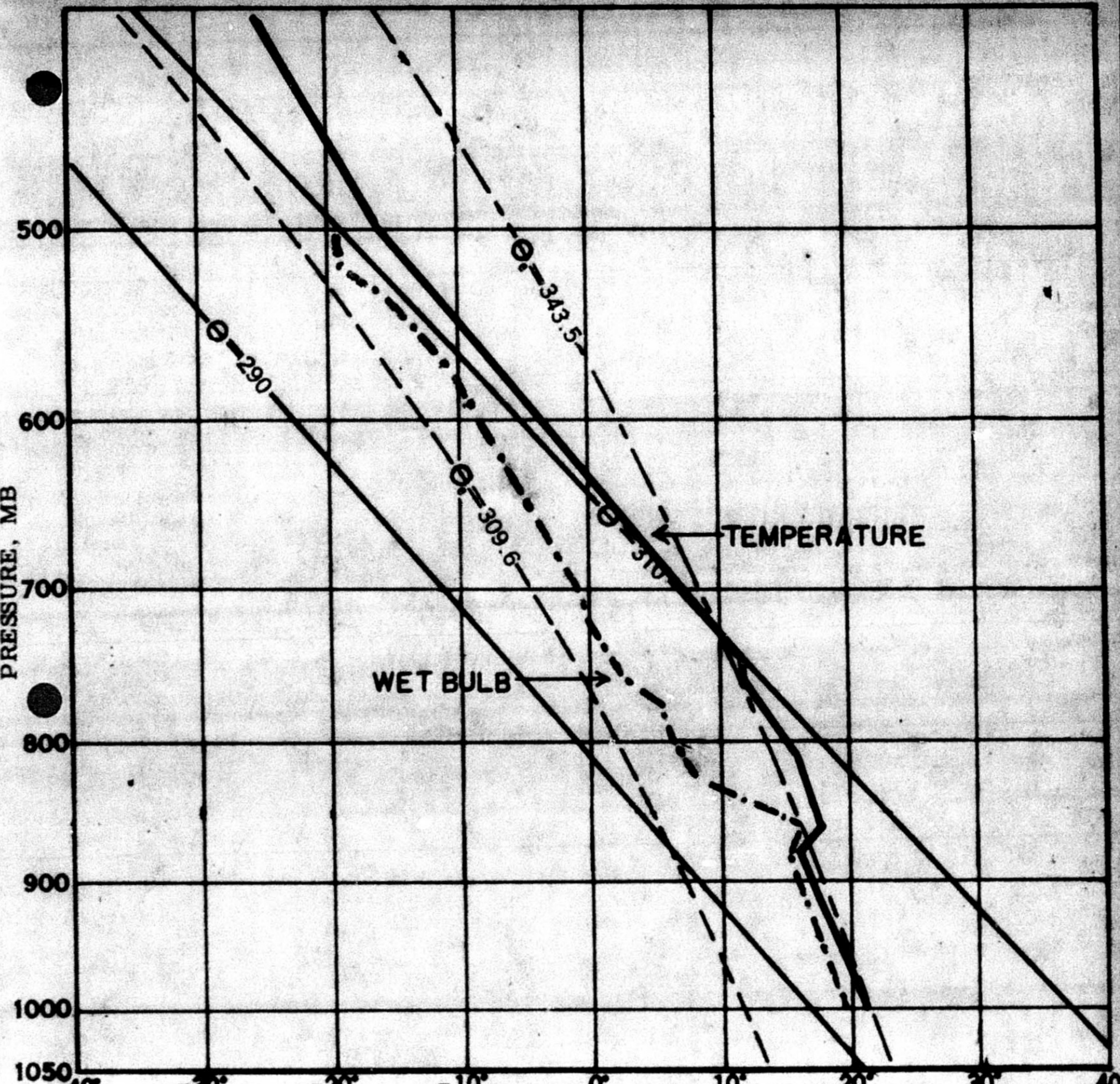
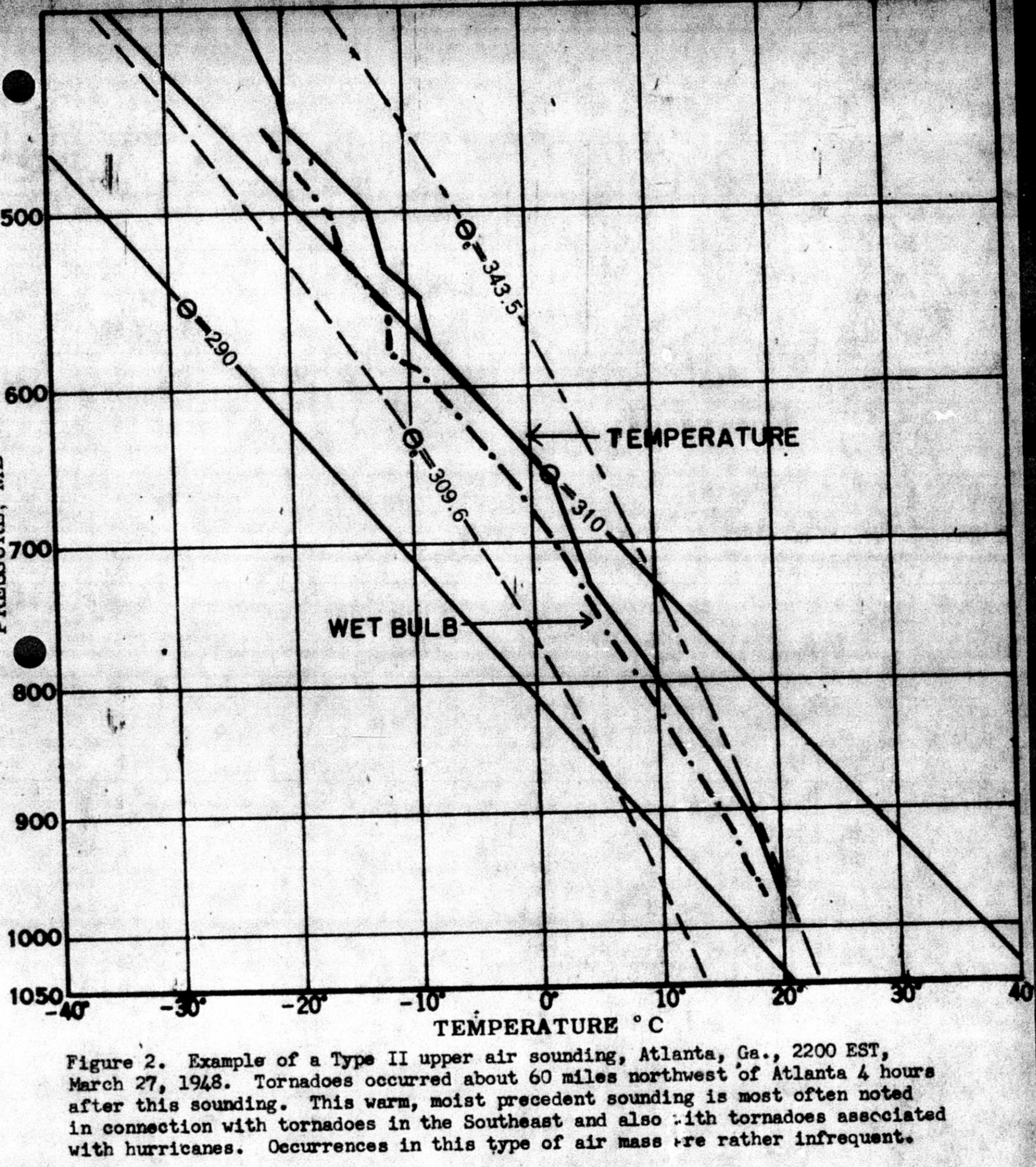


Figure 1. Example of Type I upper air sounding, Barksdale AFB, La., 0900 CST, March 21, 1952. The severe outbreak of tornadoes over Arkansas and Tennessee on March 21-22, 1952, began 7 hours after this sounding and the first tornado in this series was reported 100 miles north of Shreveport, La. Tornadoes with this type of precedent sounding most often occur in the South during late winter and early spring, and over the Midwest during spring and early summer.



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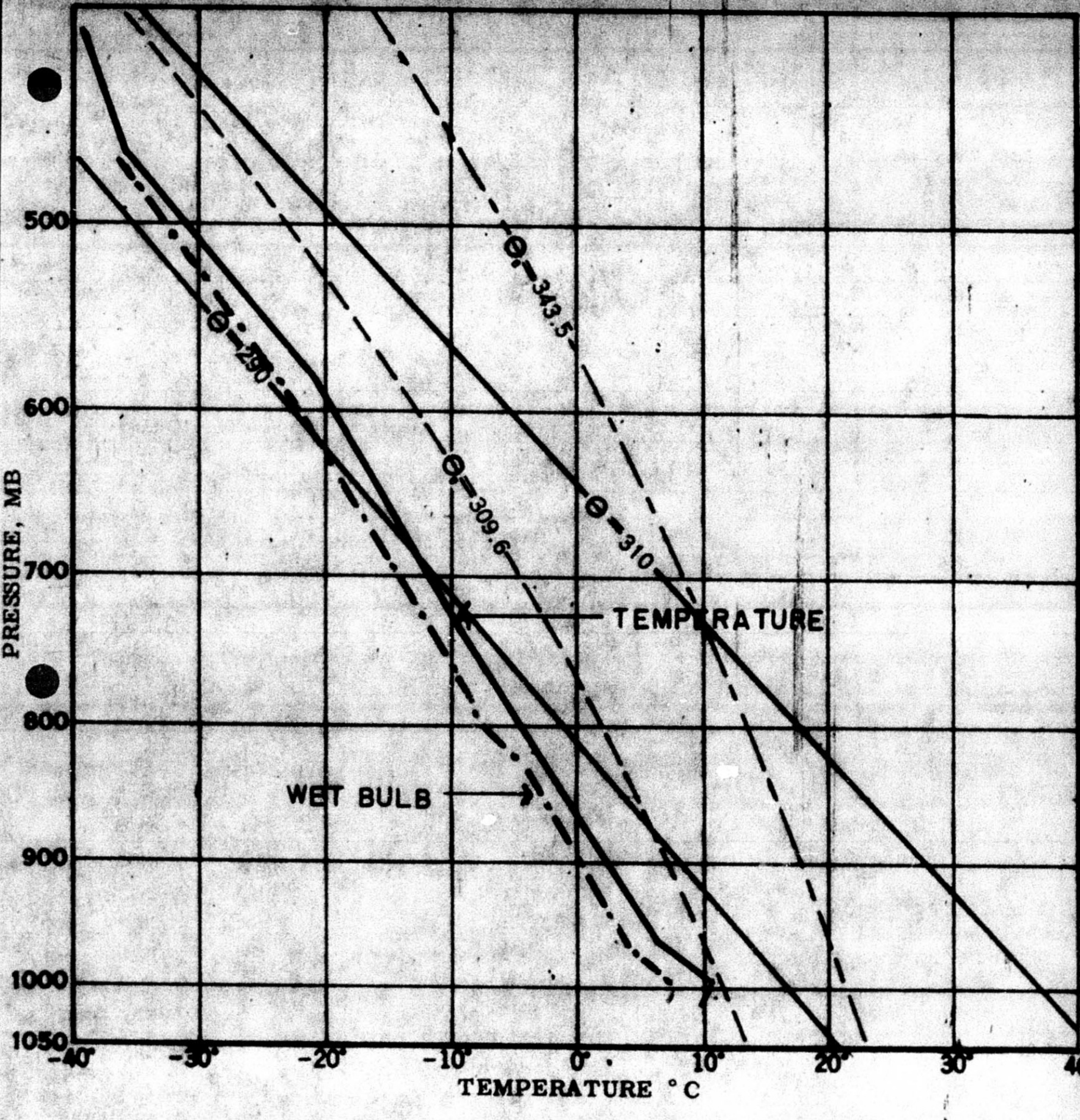

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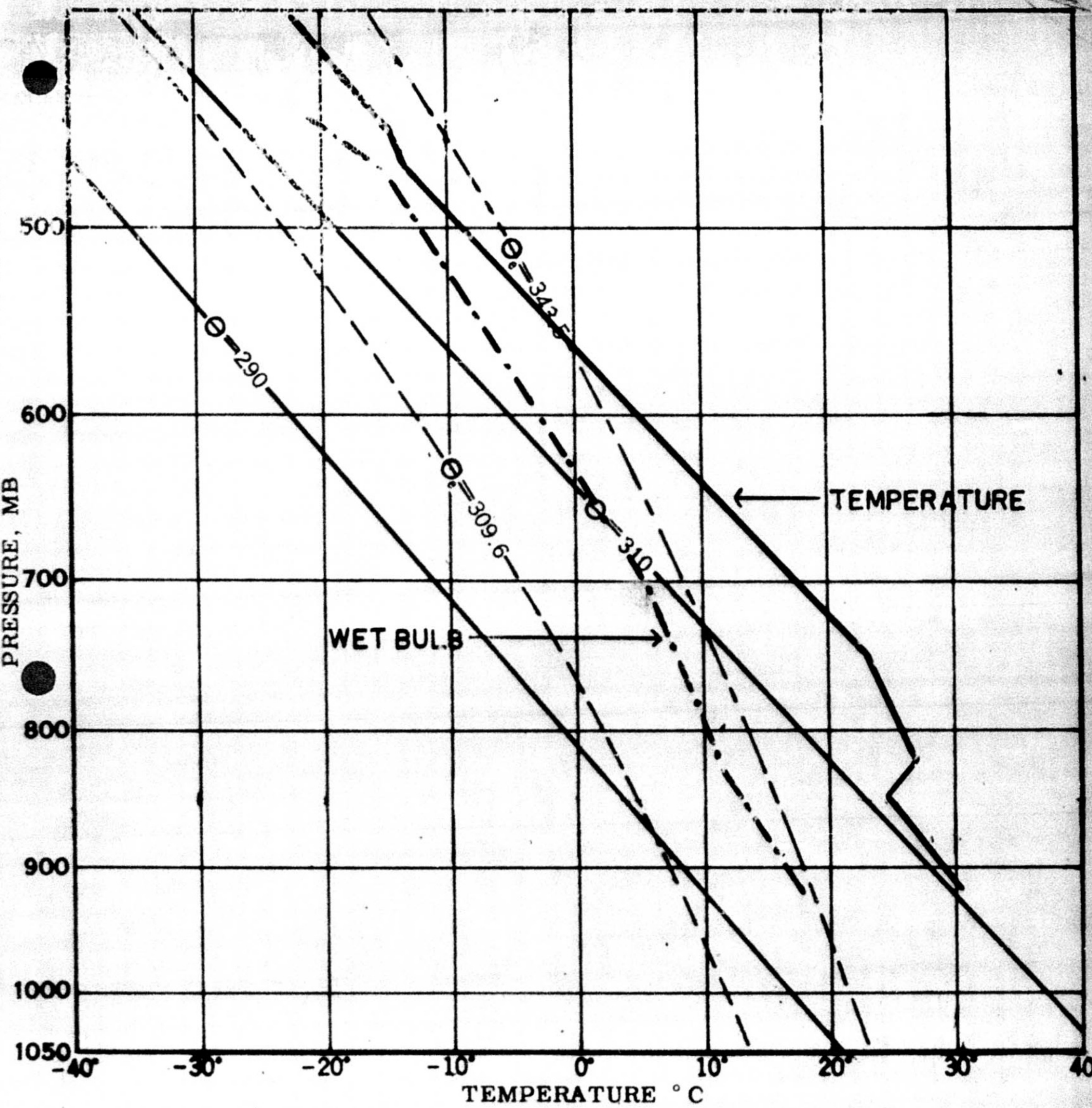

Figure 4. Example of a Type IV upper air sounding, Dodge City, Kan., 0900 CST, June 24, 1953. A tornado was reported 45 miles south-southwest of Dodge City, Kansas 7 hours after this sounding.

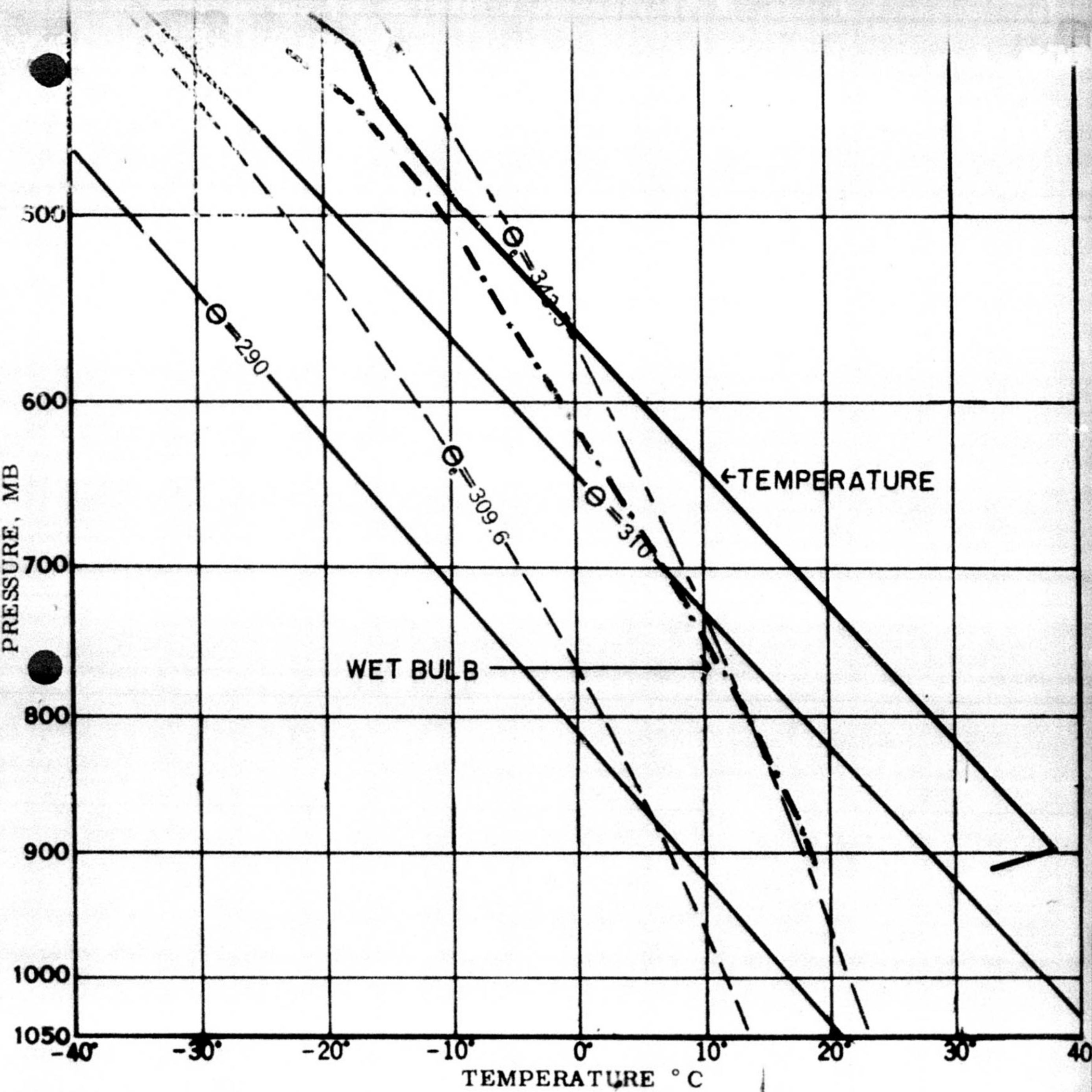

Figure 5. Example of Type IV upper air sounding, Dodge City, Kansas 1500 CST, June 24, 1953. A tornado was reported 45 miles south-southwest of Dodge City, Kansas one hour after this proximity sounding. This type of sounding (termed the "inverted V" in SELS) is noted in connection with many of the long, narrow, rope-like funnel clouds that occur during the summer months over the higher Plains States. Of particular interest here is the complete absence of either a stable layer or a pronounced lower moist layer. The diurnal variation in these occurrences is very pronounced with the maximum occurring near, or just after, the normal time of maximum temperature.

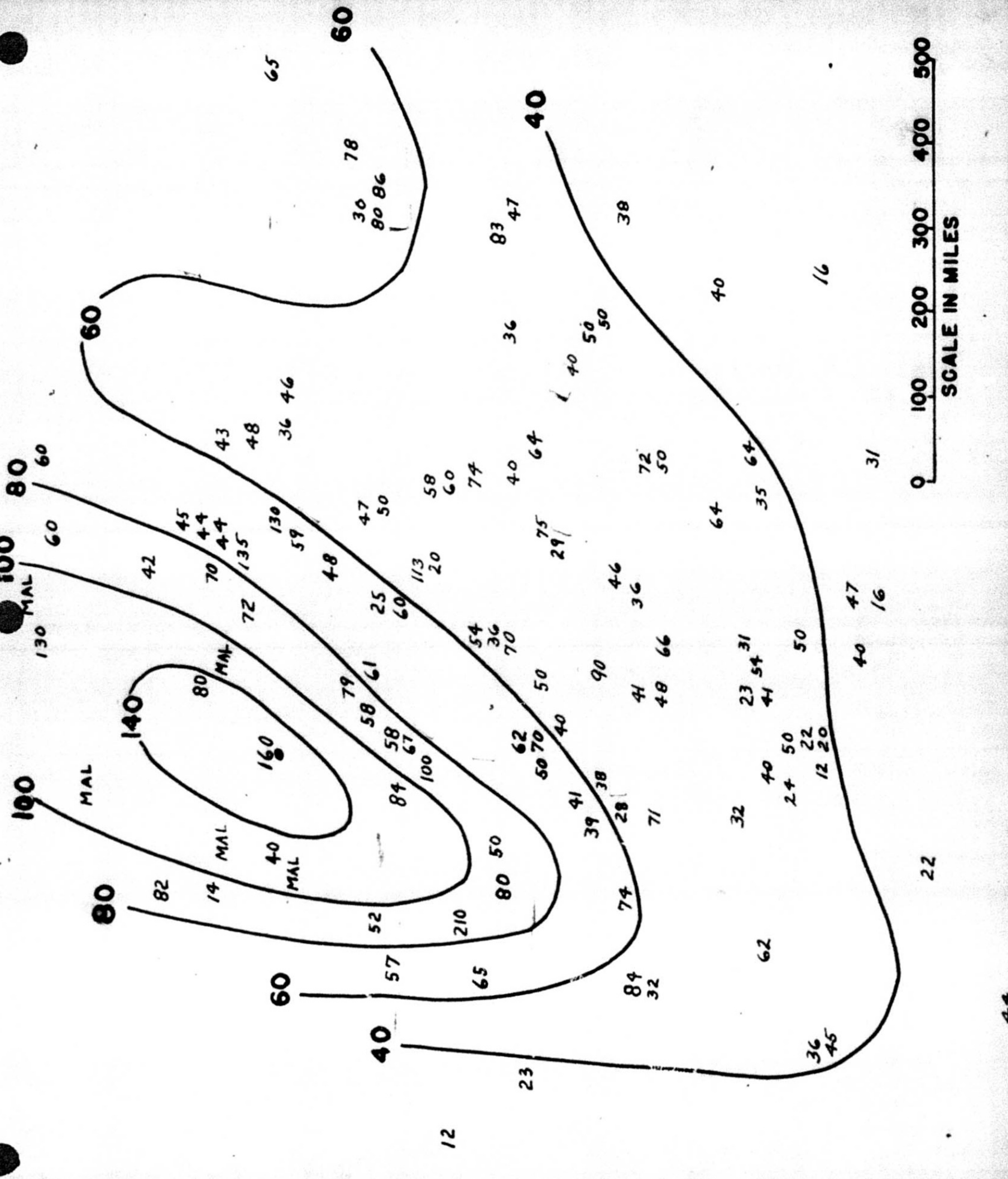

Fig. 6. Composite chart showing depths of the moist layer in 11 Type I cases. Isopleths of the average depth of the moist layer for these cases are shown.

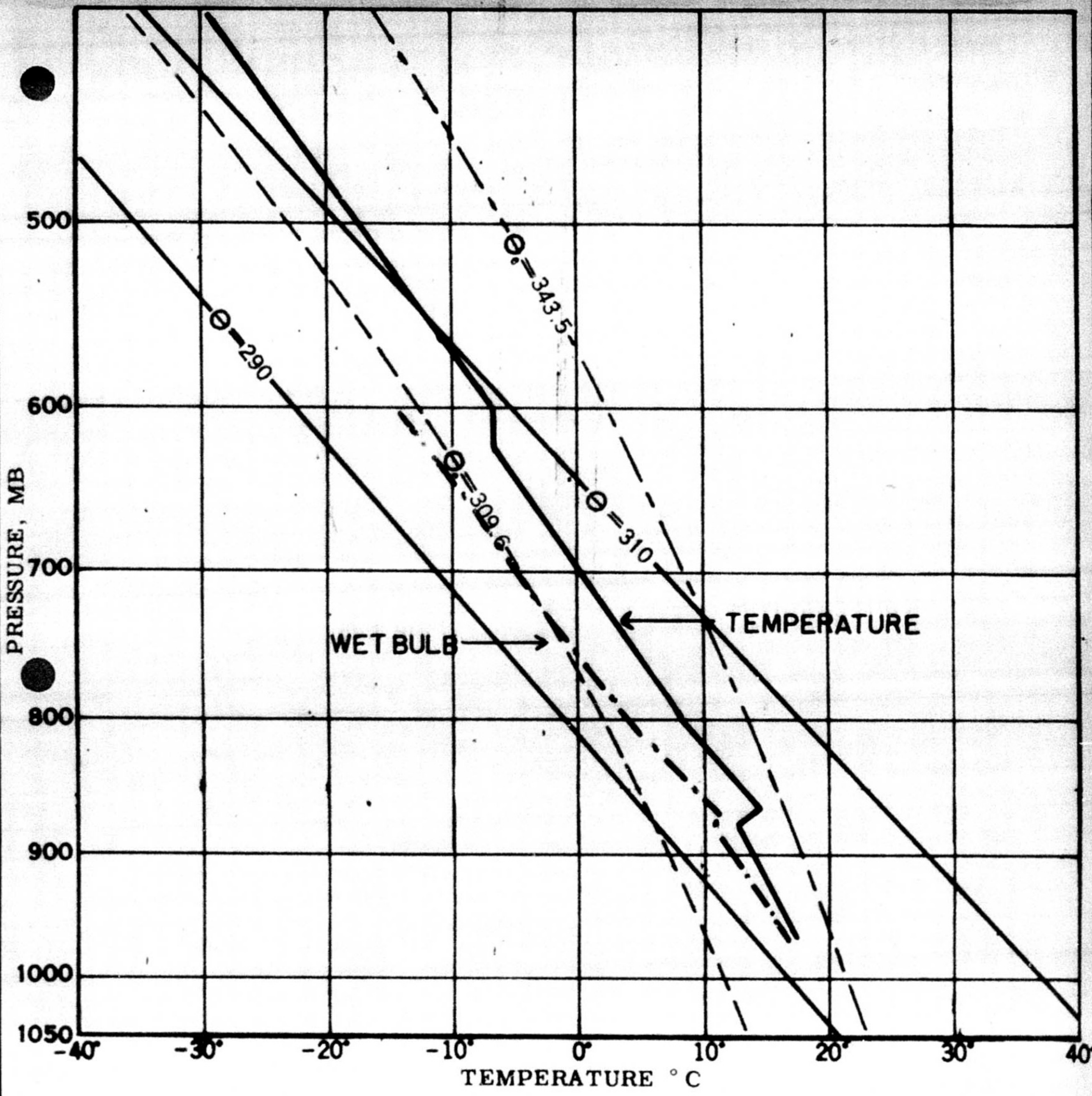

Figure 7a. Upper air sounding at Tinker AFB, Okla., February 19, 1951, 1600 CST.

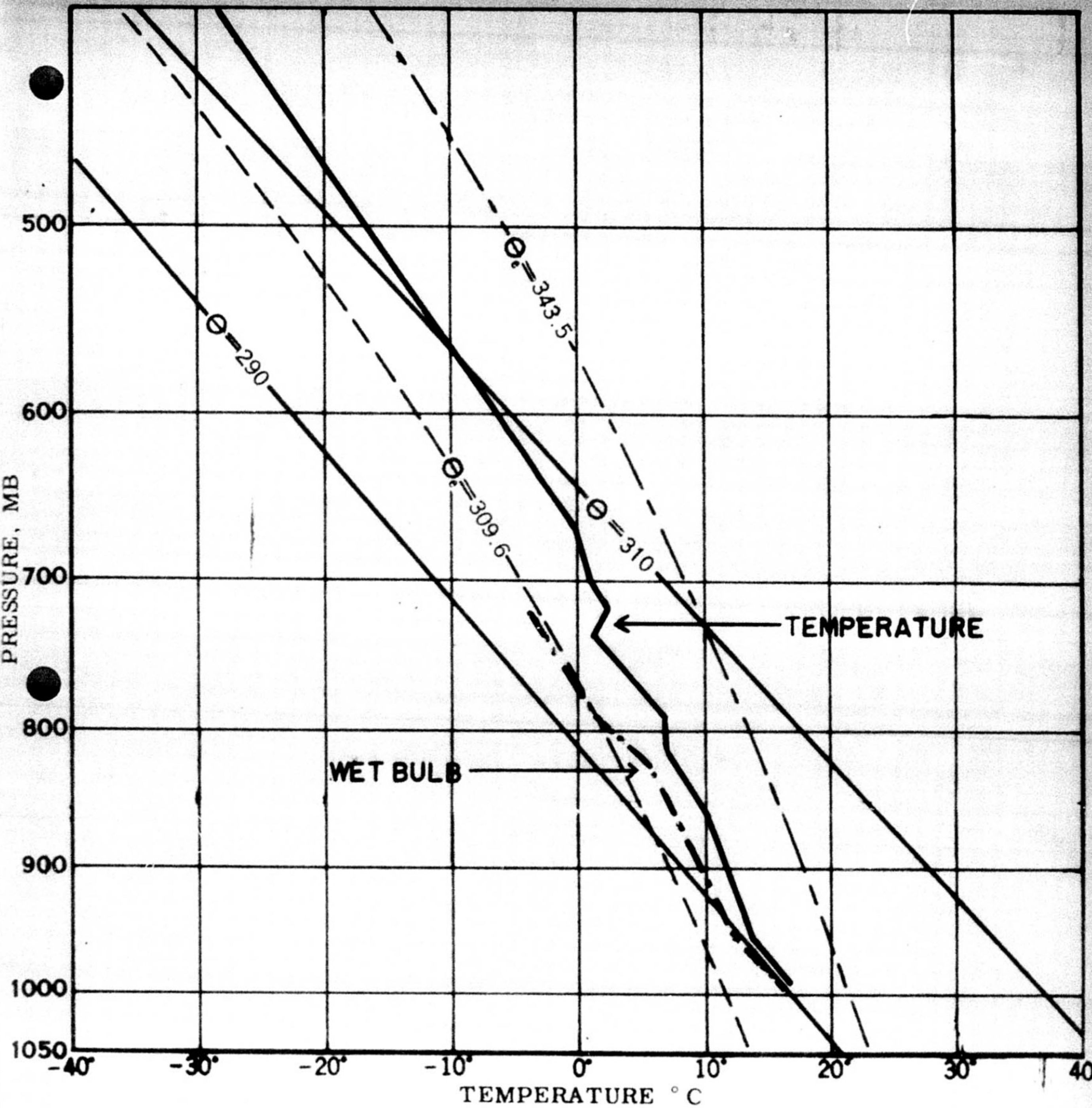

Figure 8a. Upper air sounding at Ft. Worth, Tex., Feb. 19, 1951, 0900 CST.

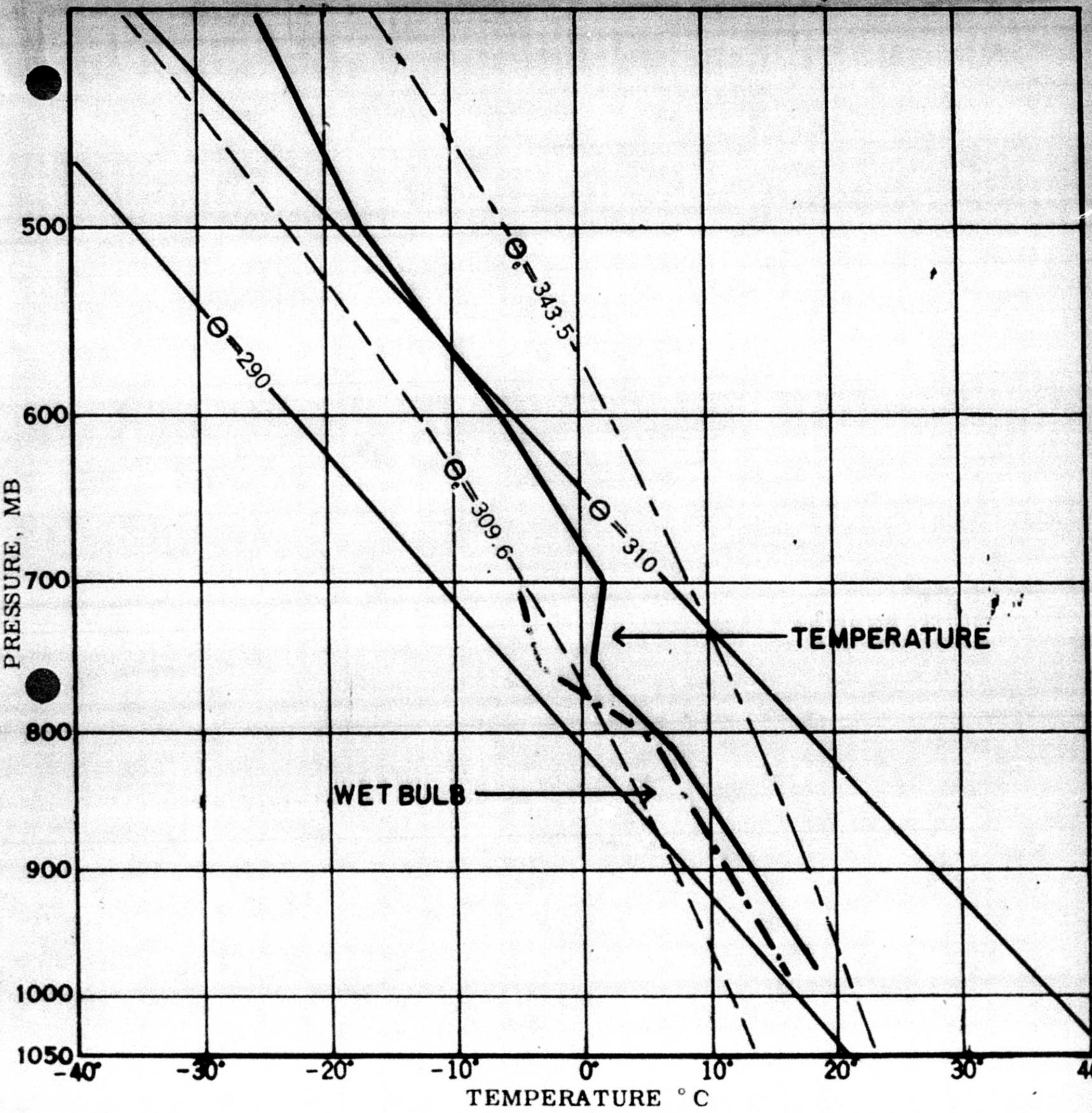

Figure 8b. Upper air sounding at Ft. Worth, Tex., Feb. 19, 1951, 2100 CST.

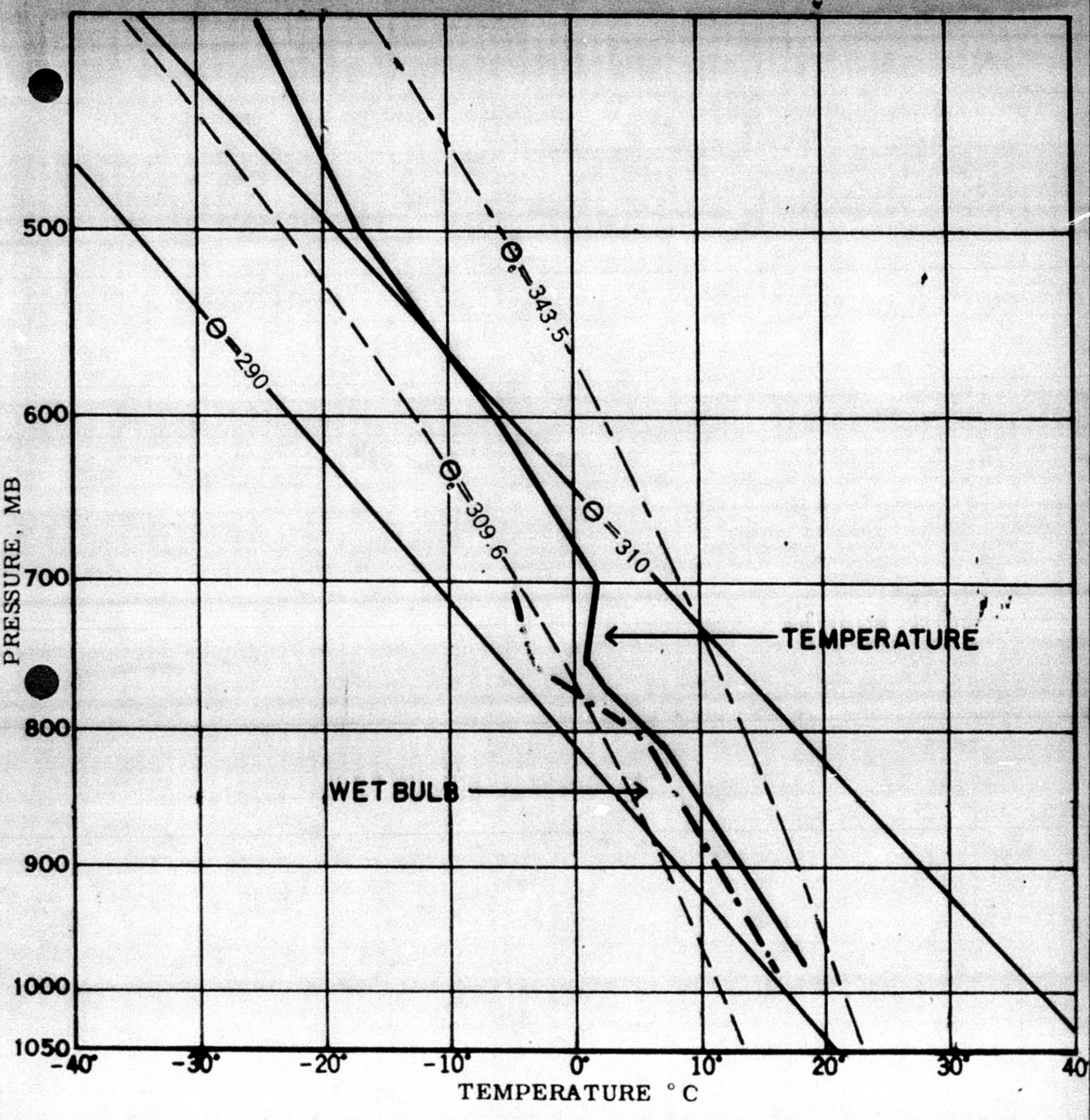

Figure 8b. Upper air sounding at Ft. Worth, Tex., Feb. 19, 1951, 2100 CST.

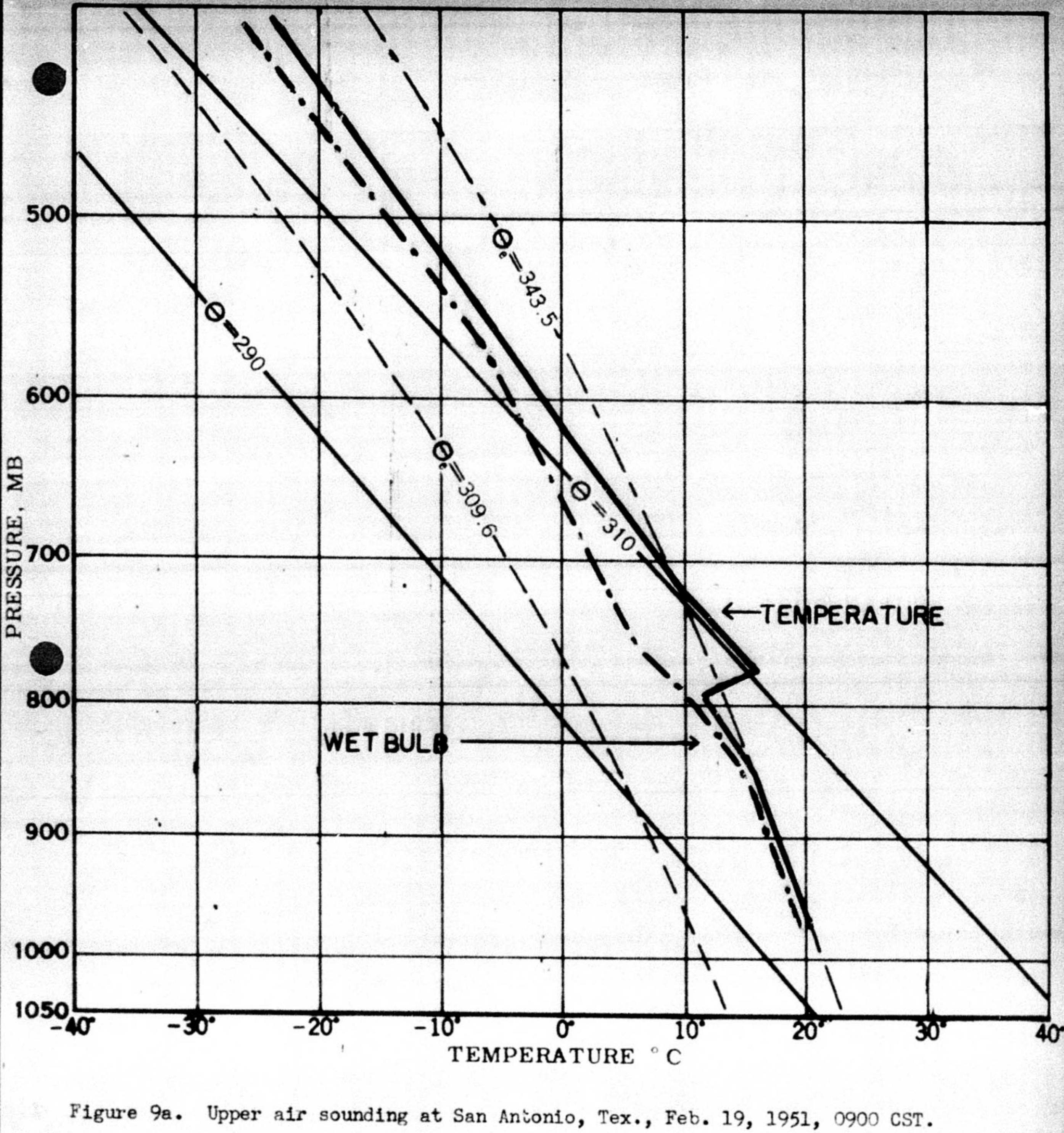

Figure 9a. Upper air sounding at San Antonio, Tex., Feb. 19, 1951, 0900 CST.

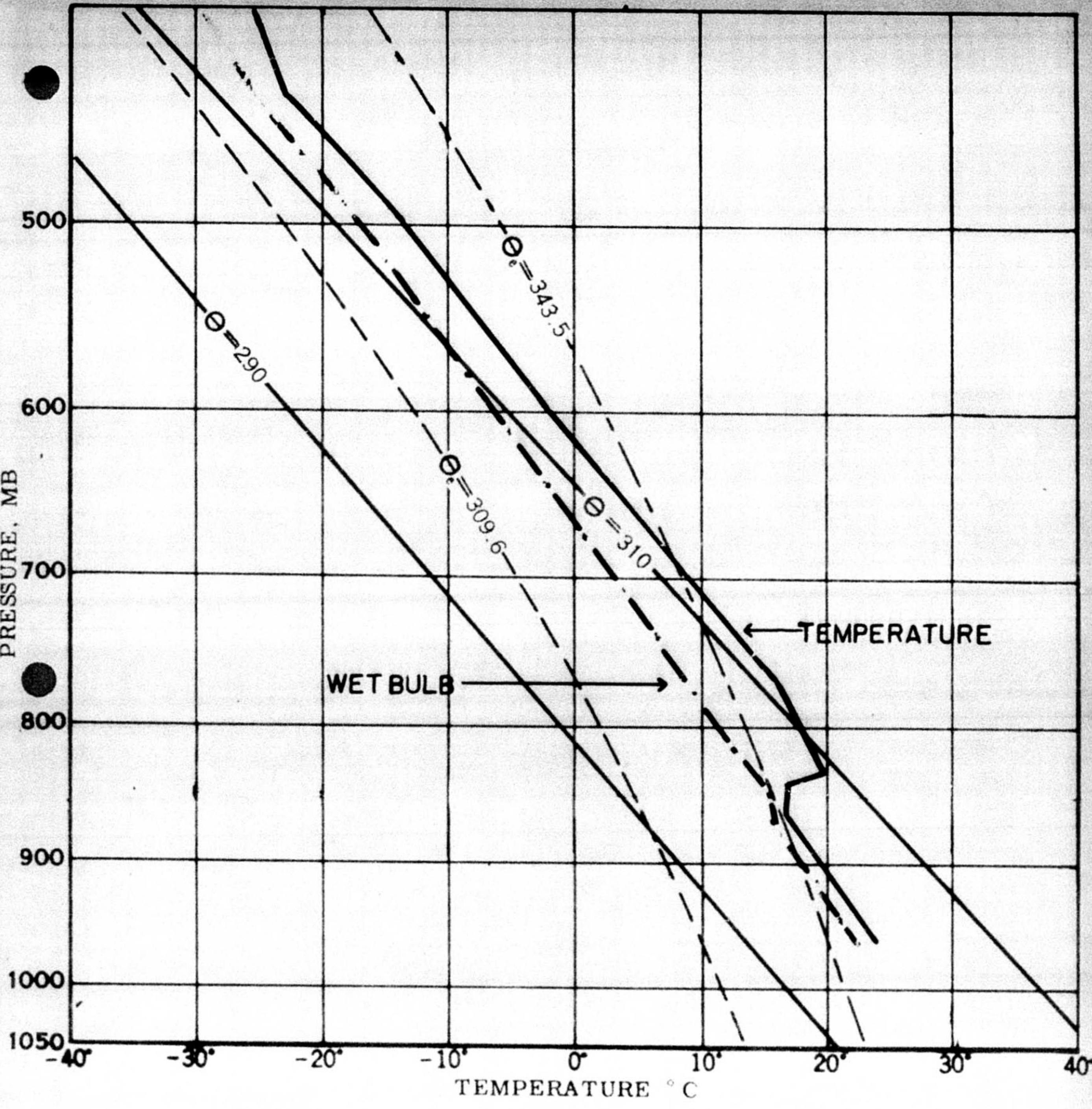

Figure 9b. Upper air sounding at San Antonio, Tex., Feb. 19, 1951, 2100 CST.

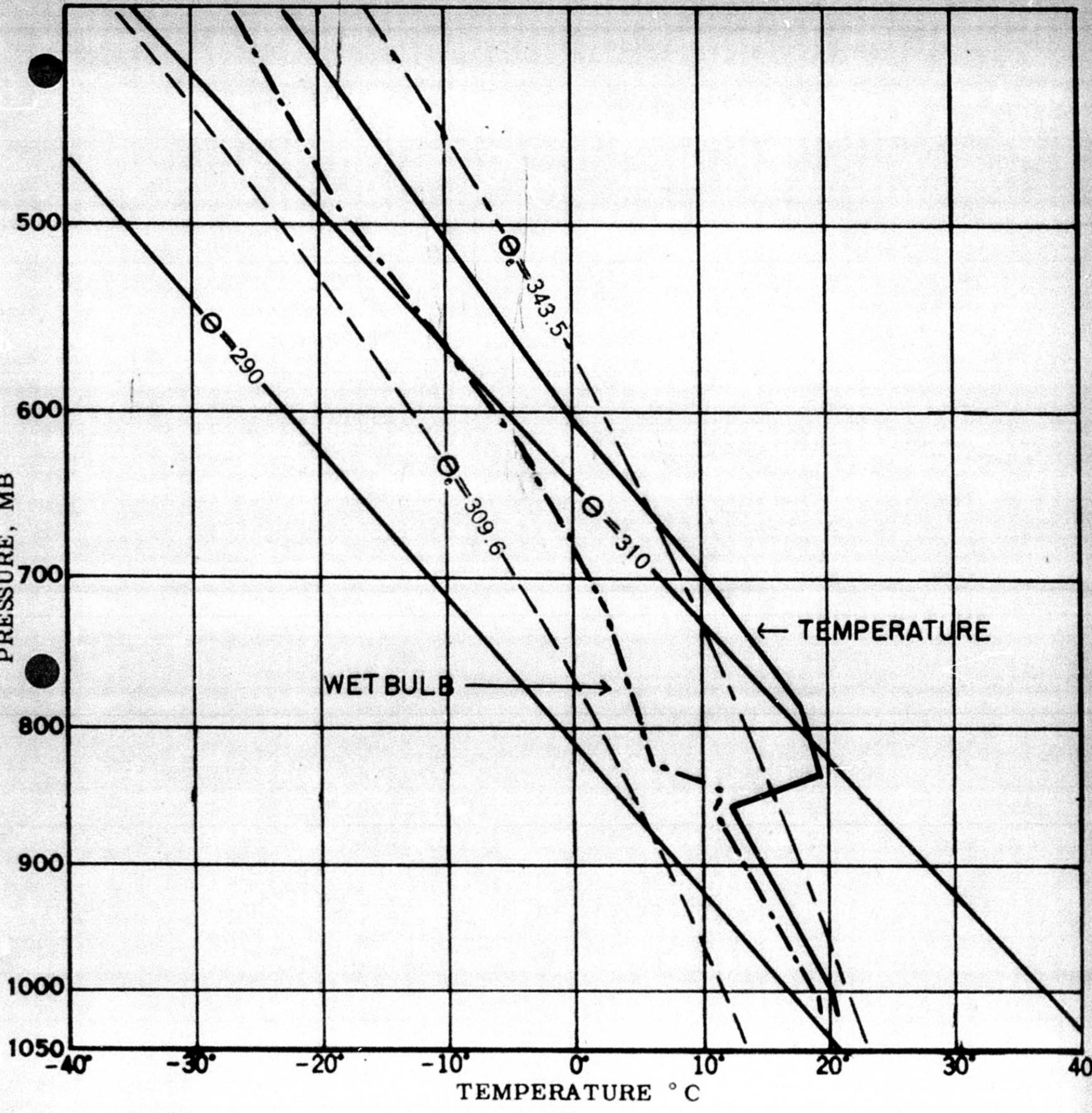

Figure 10a. Upper air sounding at Brownville, Tex., Feb. 19, 1951, 0900 CST

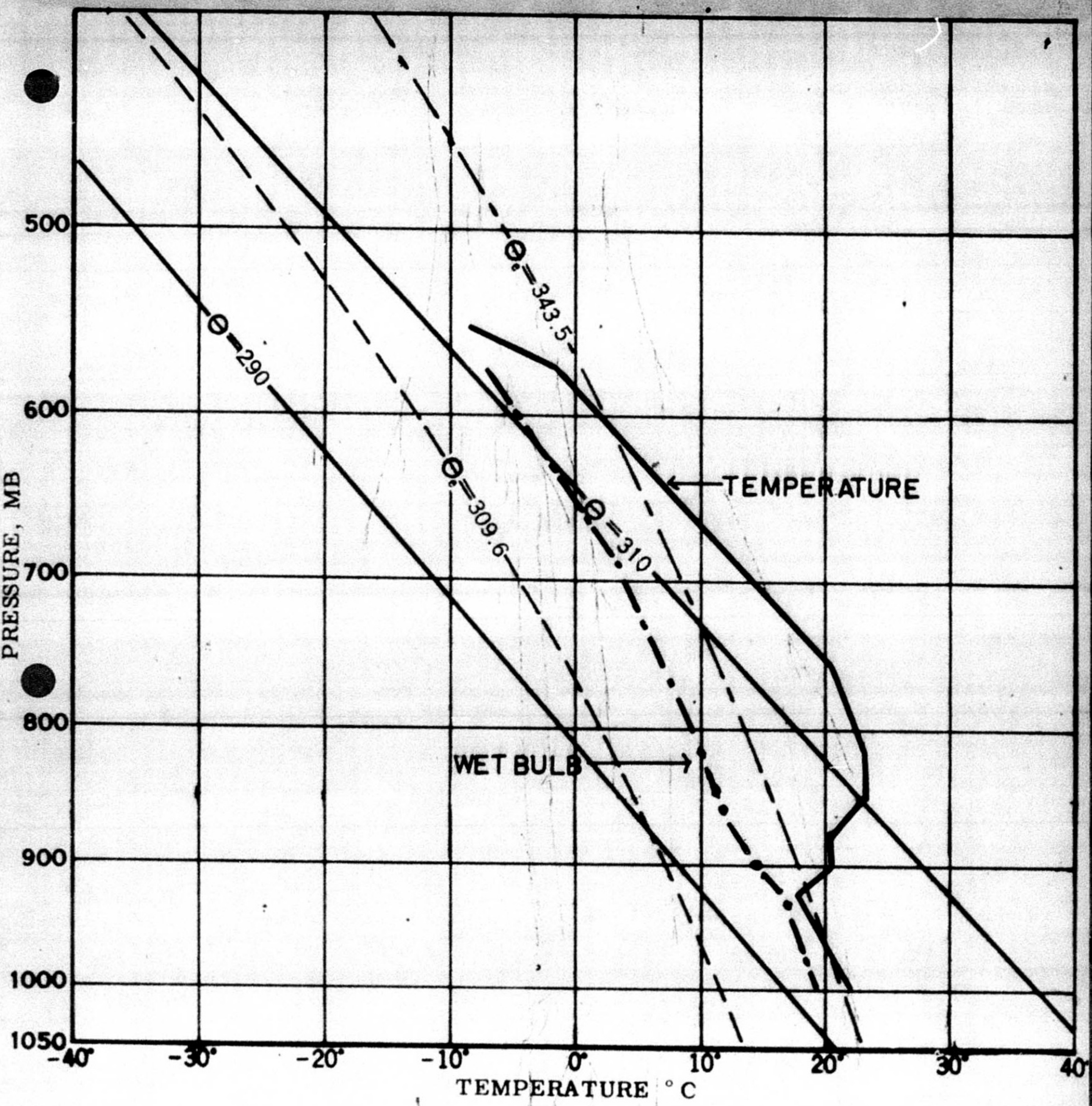

Figure 10b. Upper air sounding at Brownsville, Tex., Feb. 19, 1951, 2100 CST

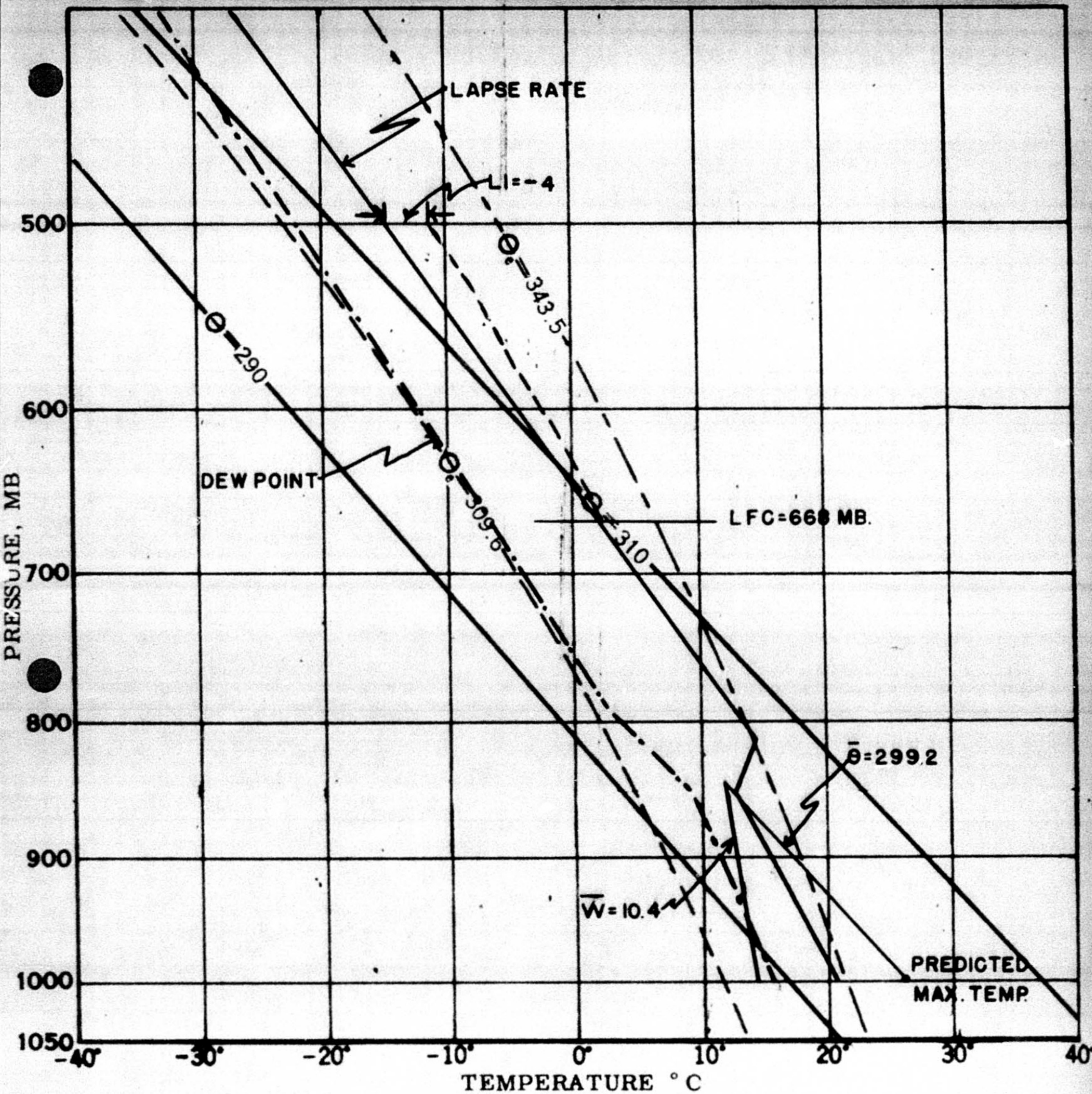

Fig. 11a, Example of an initial analysis. Significant values and graphical procedures are indicated.

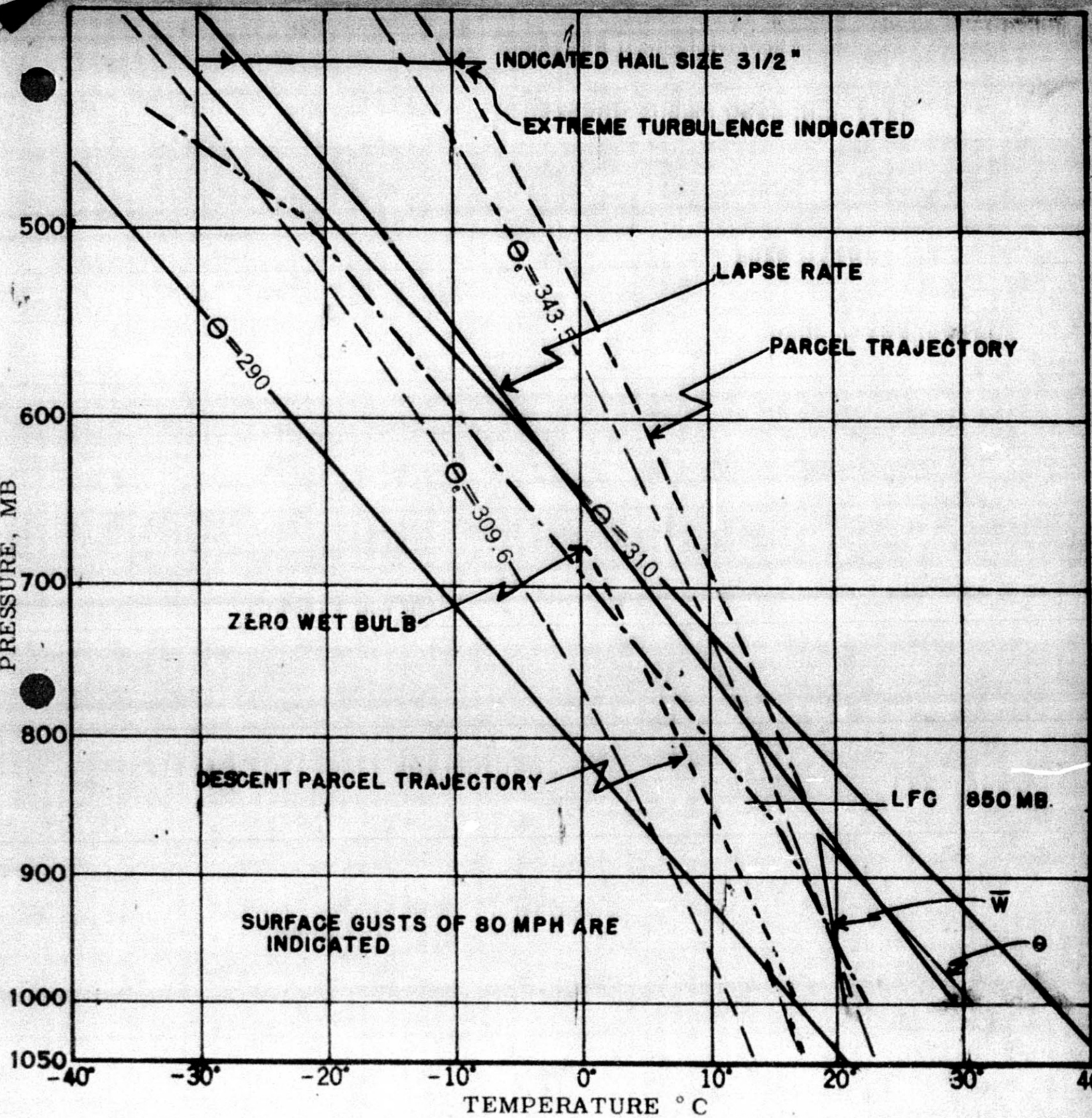

Fig. 11b. Example of a final analysis. Values of hail size, turbulence class, and surface gusts indicated are noted. Graphical procedures are indicated.

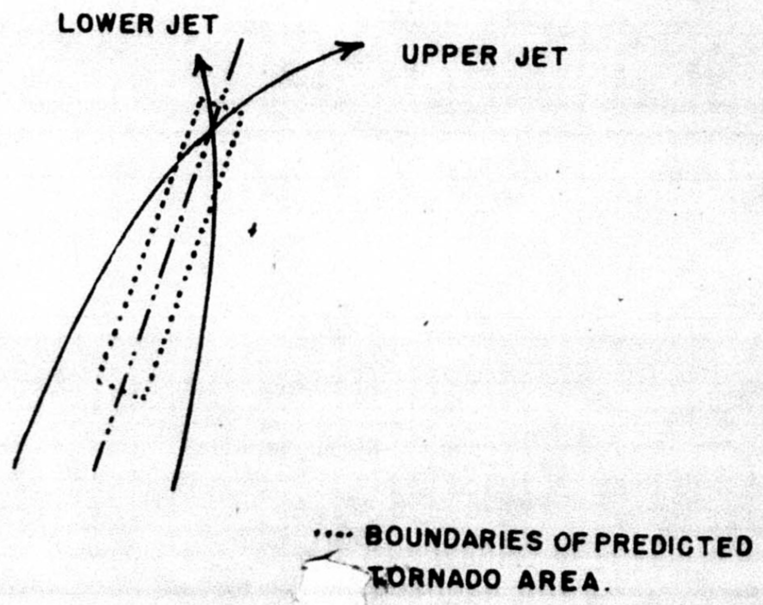
LOWER JET
UPPER JET
.... BOUNDARIES OF PREDICTED TORNADO AREA.

FIG. 12

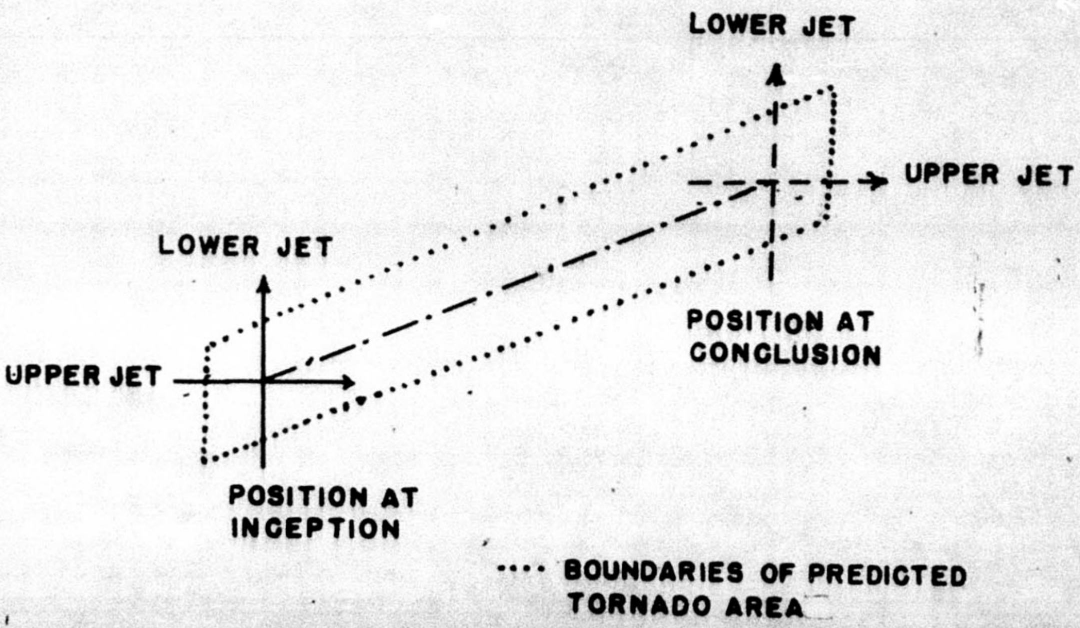
LOWER JET
UPPER JET
LOWER JET
POSITION AT CONCLUSION
UPPER JET
POSITION AT INCEPTION
.... BOUNDARIES OF PREDICTED TORNADO AREA

FIG. 13

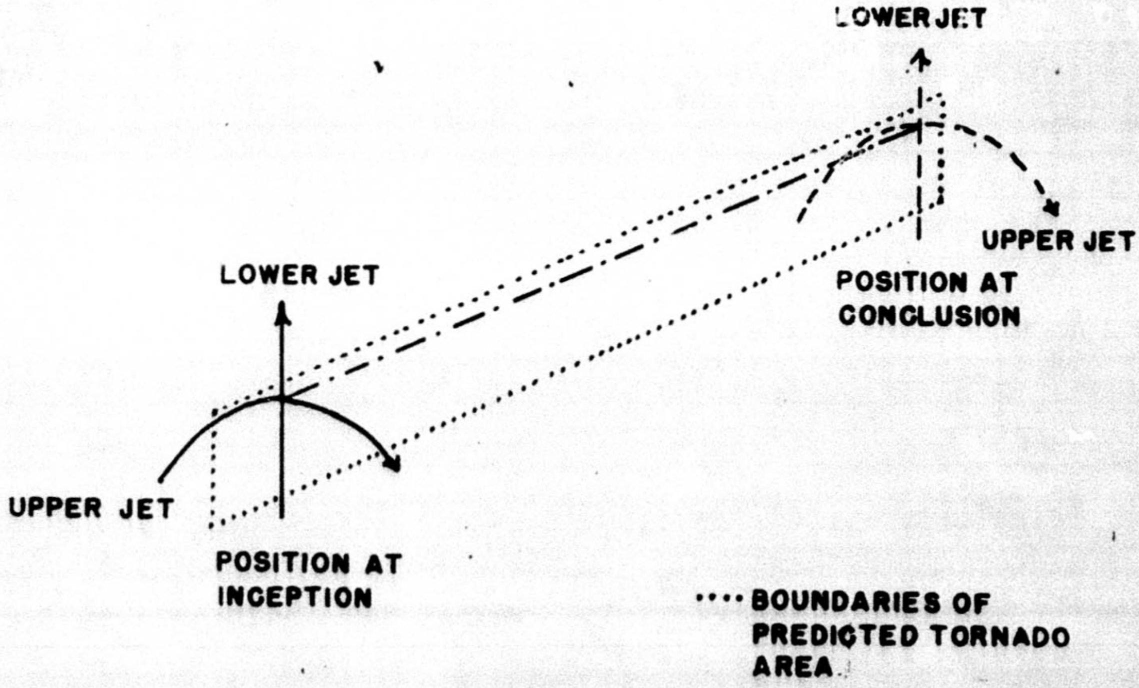
LOWER JET
UPPER JET
POSITION AT CONCLUSION
LOWER JET
UPPER JET
POSITION AT INCEPTION
···· BOUNDARIES OF PREDICTED TORNADO AREA.

FIG. 14

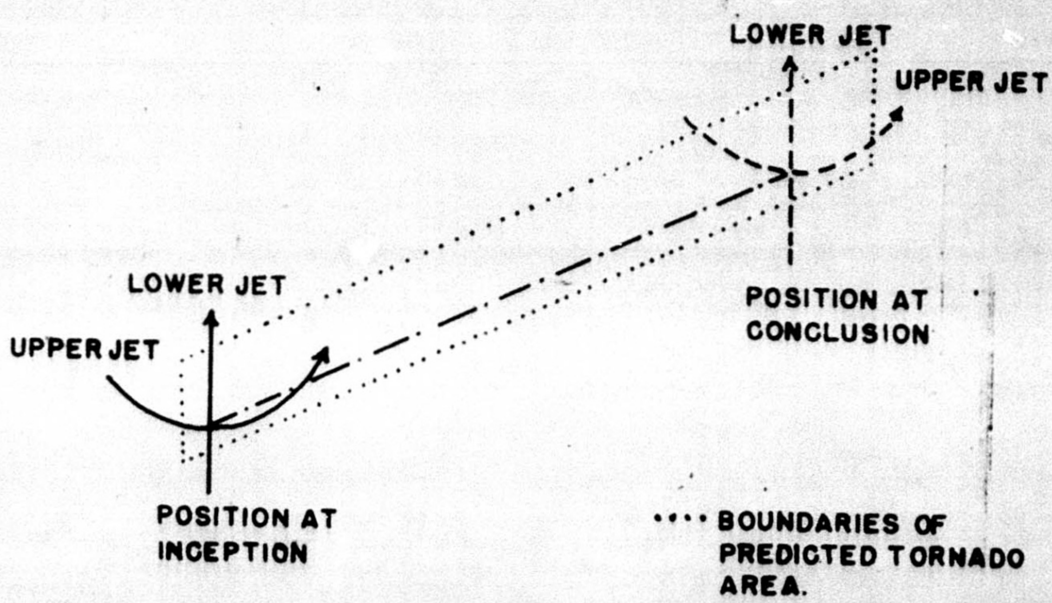
LOWER JET
UPPER JET
POSITION AT CONCLUSION
LOWER JET
UPPER JET
POSITION AT INCEPTION
···· BOUNDARIES OF PREDICTED TORNADO AREA.

FIG. 15

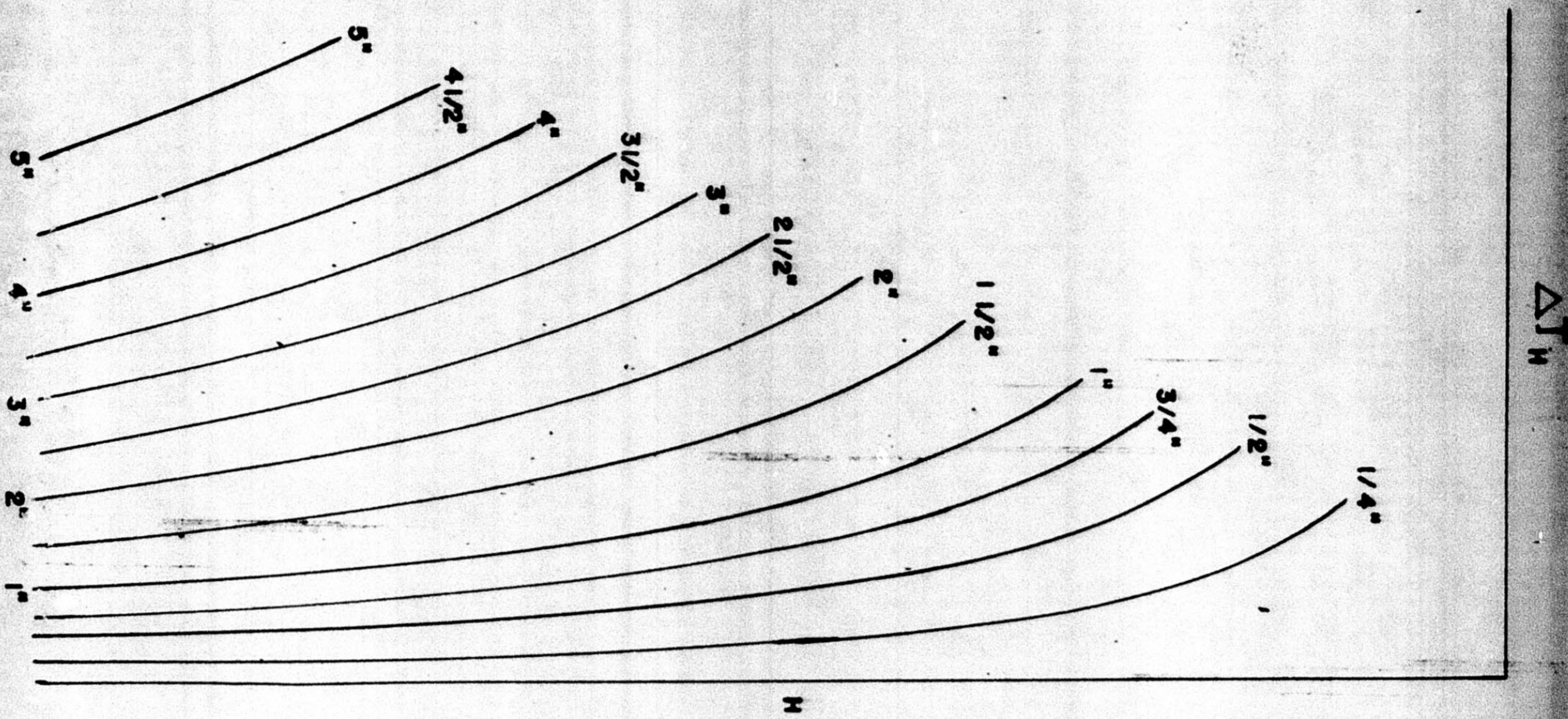

Fig. 16. Overlay for WB Form 1147 for estimating hail size for the -10°C parcel temperature at 400 mb.

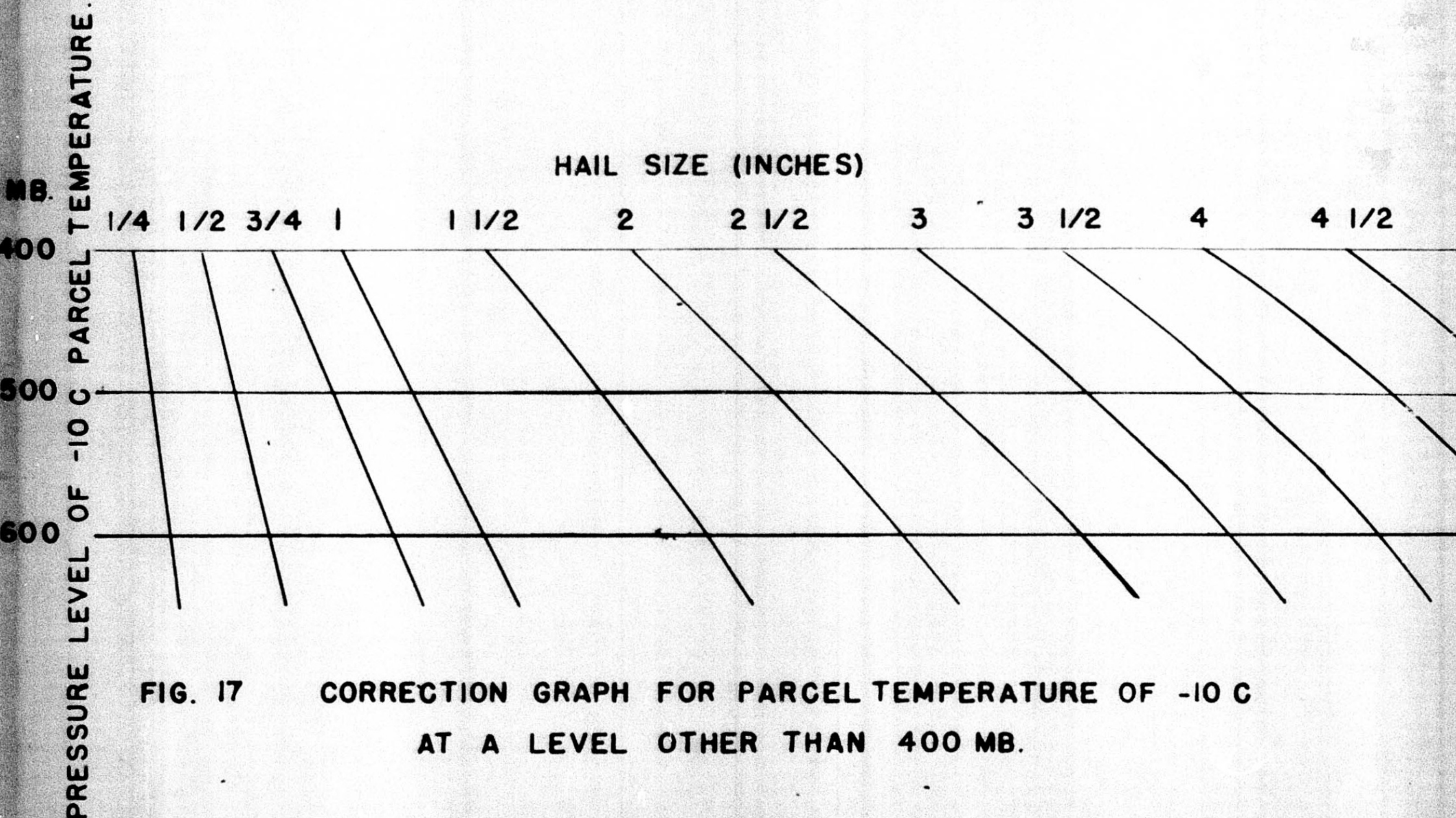

FIG. 17 CORRECTION GRAPH FOR PARCEL TEMPERATURE OF -10 C AT A LEVEL OTHER THAN 400 MB.

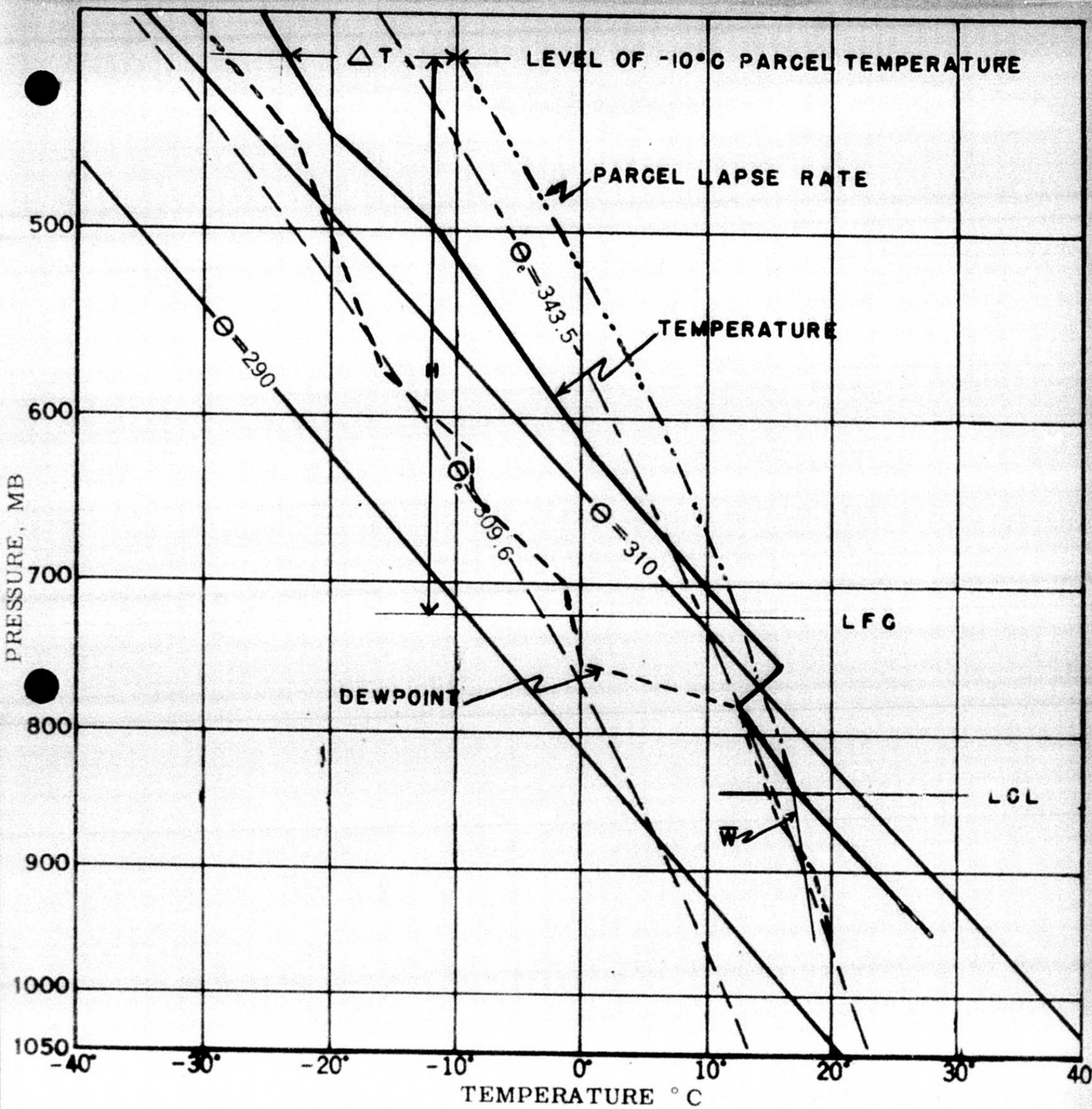

Figure 18. . Upper air sounding at Altus, Okla., April 29, 1954, 1500 CST. Hail size was computed to be 2¼ inches. Hail up to 2 inches diameter fell 95 miles north of Altus, Okla., between 1530 CST and 1830 CST.

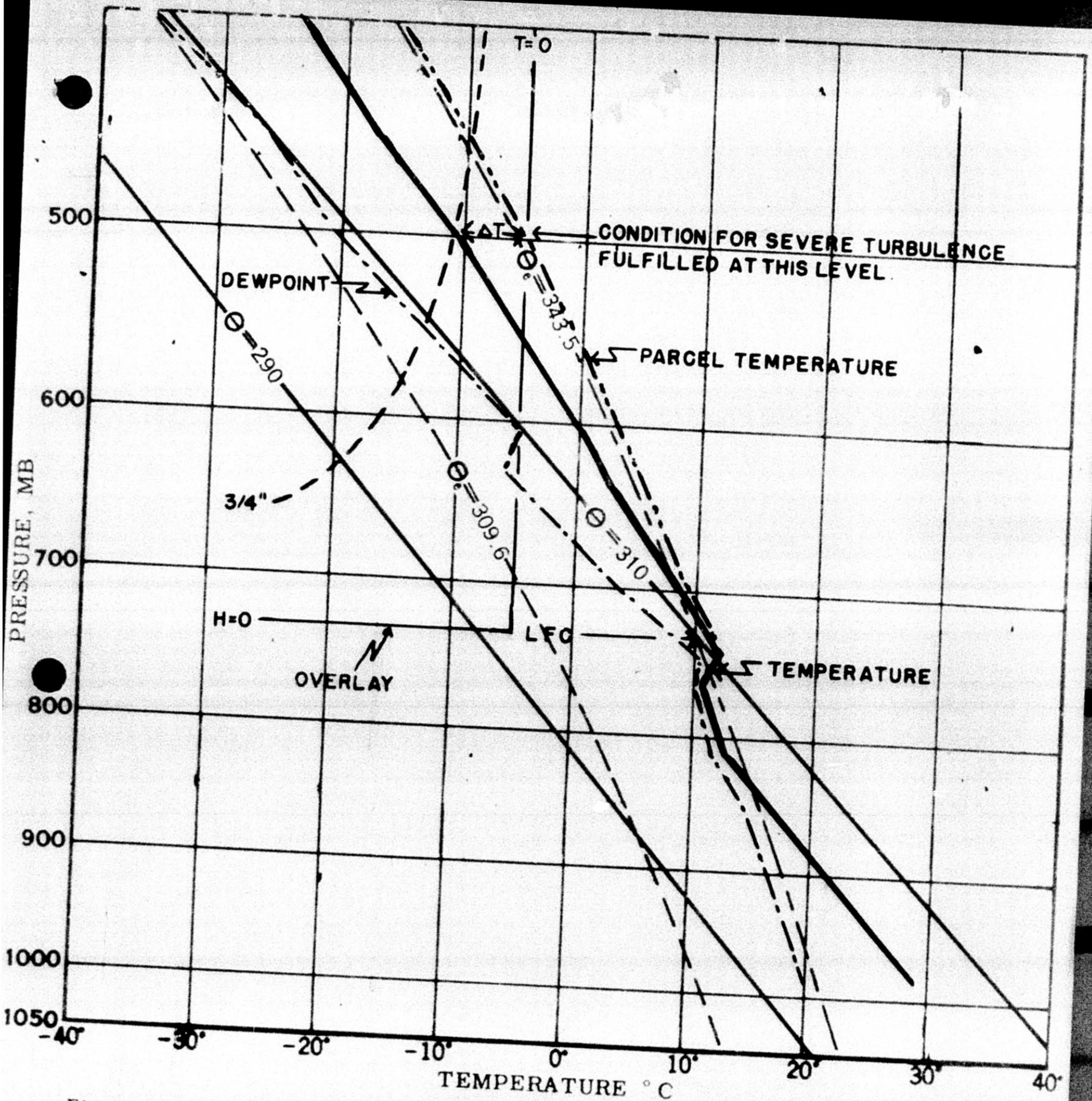

Figure. 19. Upper air sounding at Ft. Smith, Ark., Oct. 11, 1954, 1500 CST illustrating an example of an analysis for severe turbulence. The overlay lines are drawn on this sounding and the condition for severe turbulence, as defined, is fulfilled at 18,000 feet. Severe turbulence was reported on the Oklahoma City-Little Rock route at 1603 CST between 18,000 and 28,000 feet msl.