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A MECHANISM FOR ASSISTING IN THE RELEASE OF CONVECTIVE INSTABILITY

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ABSTRACT

A model is proposed as one means whereby an air mass characterized by the "typical" tornado sounding is converted to one described by the type of sounding observed in the vicinity of a tornado. 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.) convergence is surmounted by higher-level (500 mb.) divergence. Thus a model of jet structures is described which assists in, or possibly in some cases effects, the release of convective instability through vertical stretching or lifting. An example is presented to illustrate the use of this model in tornado forecasting and methods of application are outlined.

1. INTRODUCTION

Typical pre-tornado soundings which have been described by various investigators usually have in common the characteristic of pronounced convective instability. At the same time, these soundings also share the property of marked parcel stability for the lower moist layer. It is therefore necessary that the air column, particularly the lower moist layer, be subjected to considerable lifting before the convective instability can be realized. The manner in which the convective instability is released, or set up for release, is perhaps the least understood of the various aspects of severe local storm forecasting. The objective of this study is to describe one means, a model of jet structures, which can assist in the release of convective instability and in some cases possibly effect this release.

The mechanism to be described consists of a pattern of horizontal convergence at low levels surmounted by horizontal divergence at some higher level. The resulting vertical motion thus contributes to the conversion, usually gradual, of the vertical structure of the environment from one of marked convective instability with dry air aloft and an inversion-capped moist layer to one of marked parcel instability in which moisture penetrates to greater heights and the capping inversion is eliminated. The area considered here is much larger than that of an individual thunderstorm or tornado and it is emphasized that the microstructure of the tornado itself is not speculated upon here. This study deals with the environment during the intermediate processes of the realization of convective instability. It will be shown that this model may be delineated synoptically by certain combinations of low and high level jet structures. "Jet" as used here shall refer to a horizontal wind speed maximum.

2. RELATED INVESTIGATIONS

The model postulated agrees with empirical findings of the pioneers in the field of tornado forecasting. Varney [1] in 1926, was one of the first to point out the existence of a temperature inversion with relatively dry air over a layer of about 6,000 feet of moist, warm air as a precedent

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condition for tornado development. A little later that same year, Humphreys [2] stated:

> Mid-air temperature inversions appear to be quite common and the lapse rates next above these inversions [increase] very rapid[ly], often nearly or quite of adiabatic value. In short, so far as one can infer from these few observations [26 observations by sounding balloon or kite], the atmosphere in the neighborhood of a tornado appears to be unusually stratified, and tending to become unstable at one or more levels.

In 1942, Lloyd [3] presented several precedent soundings and was perhaps the first to point out that the soundings were convectively unstable. Like previous investigators, he attributed the release of the great instability to the movement from the west of cold air aloft over a warm, moist layer at the surface.

The importance of convective instability in the development of tornadoes was first illustrated by Showalter [4] in a proposed typical sounding which was based upon many soundings taken prior to tornado development and within the same air mass. He proposed that the convective instability could be released through free convection if mechanical lifting occurred, and the mechanical lifting could be produced by horizontal convergence or frontal lifting. Fawbush, Miller, and Starrett [5, 6] proposed six criteria necessary for tornado development which agreed with earlier investigations. It should be noted here that Fawbush, Miller, and Starrett, Tepper [7, 8, 9], and others suggest that this lifting occurs rather suddenly.

More recently Beebe [10], in an analysis of tornado proximity soundings (tornado occurred within 50 miles of a RAOB station and within the hour following release time), showed that the air mass in which tornadoes develop is no longer characterized by the "typical" sounding. None of these proximity soundings showed the low-level inversion while moisture was noted to great heights. Thus, these proximity soundings more nearly resembled the mean thunderstorm sounding shown by Byers [11]. Further study of these data suggests that the transformation of the "typical" sounding is a gradual process occurring over a period of several hours rather than as a sudden conversion.

3. DEVELOPMENT OF THE MODEL

The hypothesis presented is that the environment preceding tornado activity is acted upon by a dynamic mechanism consisting of horizontal convergence at low levels and horizontal divergence at a height sufficient to produce the modifications noted. This low-level convergence causes vertical stretching of the lower atmospheric layers and, in the environs of tornado inception, produces parcel instability and causes moisture to be carried upward into the middle troposphere.

A valid relationship of observable parameters which will delineate such a structure is the vorticity equation which may be stated:*

$$\frac{d\eta}{dt}=-\eta \operatorname{div}_2 \boldsymbol{V}+S+F \tag{1}$$

where
η = vertical component of absolute vorticity
$\frac{d\eta}{dt}$ = time rate of change of vertical component of absolute vorticity on a particle in motion
$\boldsymbol{V}$ = horizontal velocity
$\operatorname{div}_2 \boldsymbol{V}$ = horizontal divergence
S = torque of horizontal solenoid field
F = horizontal torque of frictional forces

Since this equation may be considered either as scalar, or, to the same effect, as consisting of coaxial vectors, it may be restated:

$$\operatorname{div}_2 \boldsymbol{V}=-\frac{1}{\eta}\frac{d\eta}{dt}+\frac{S}{\eta}+\frac{F}{\eta} \tag{2}$$

A measure of the horizontal divergence may thus be obtained by considering some area at the height desired and noting:

a) the time rate of change of absolute vorticity of particles moving horizontally through the area,
b) the horizontal solenoid field within the area, and
c) the magnitude of the frictional torque within the area.

For an order of magnitude estimate of the values of horizontal divergence required to significantly modify an environment, an approximate computation may be made. Insofar as the atmosphere may be approximated by an incompressible fluid, the equation of continuity may be stated:

$$\frac{\partial w}{\partial z}=-\operatorname{div}_2 \boldsymbol{V} \tag{3}$$

where w is the vertical component of velocity. Assuming a distribution of horizontal divergence with height such as that shown in figure 1, it may be stated:

$$\operatorname{div}_2 \boldsymbol{V}=\operatorname{div}_2 \boldsymbol{V}_0 \cos\frac{\pi z}{6000}, \ (z \text{ in meters}) \tag{4}$$

where subscript 0 refers to surface $z=0$. Combining (3) and (4) and integrating with from $z=0$ to arbitrary height z,

$$w_z=-\frac{6000}{\pi}\operatorname{div}_2 \boldsymbol{V}_0 \sin\frac{\pi z}{6000}, \ (\text{m/sec.}) \tag{5}$$

A value for $\operatorname{div}_2 \boldsymbol{V}_0$ may now be inserted in (5). This value is computed from the value for $\operatorname{div}_2 \boldsymbol{V}_z$ at a height of about 1500 meters, or 850 mb., near the Flint, Mich. tornado as obtained by Cressman [12], viz: -10^{-5} sec.$^{-1}$

$$\operatorname{div}_2 \boldsymbol{V}_0=\operatorname{div}_2 \boldsymbol{V}_z \sec\frac{\pi z}{6000}=-10^{-5}\, 1.4 \text{ sec.}^{-1} \tag{6}$$

*The term representing the interchange of vorticity between the horizontal and vertical is omitted. A qualitative evaluation of this neglected term indicates that it acts to modify the distribution of the vertical motion within the regions identified by the other terms, but that it does not act to reduce the maximum vertical motion or to shift this point or area of vertical motion from the significant regions.

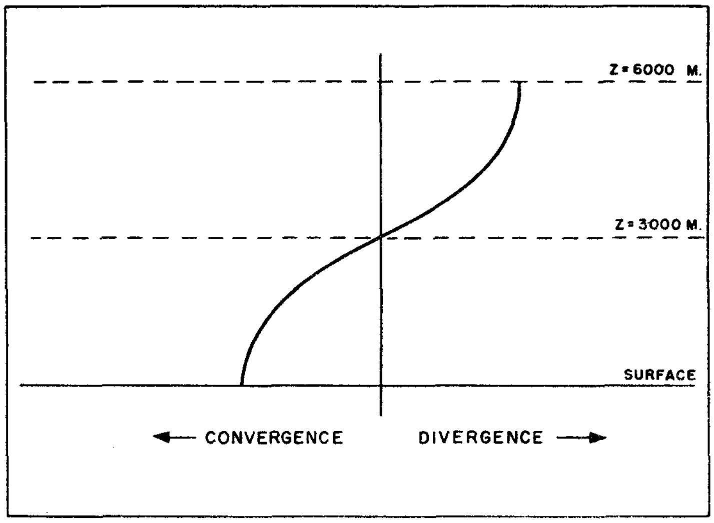

FIGURE 1.—Distribution of horizontal divergence with height assumed for computational purposes.

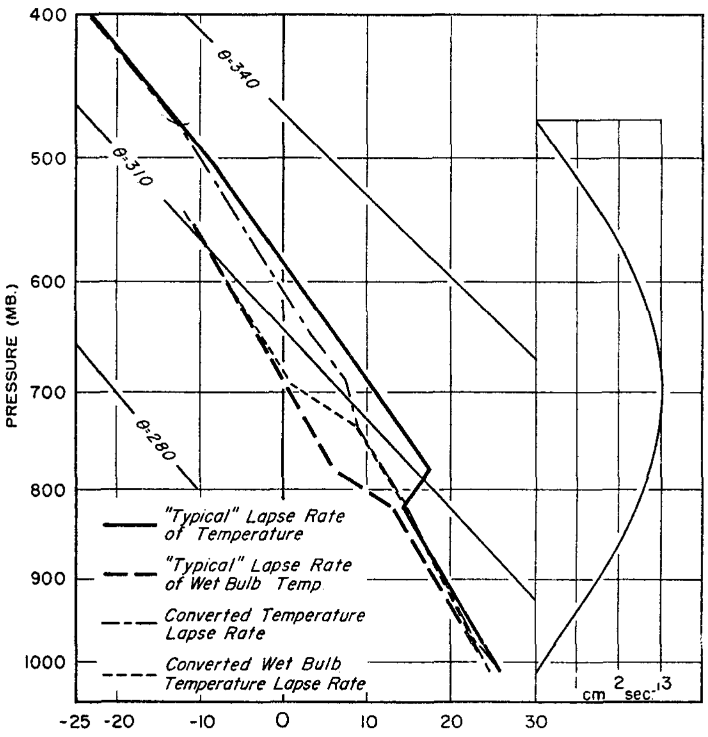

FIGURE 2.—A "typical" sounding shown before and after modification by lifting. The vertical motion field acting is shown at right.

Inserting this value in (5), a pattern of vertical motion is obtained:

$$w_z \simeq 3 \sin \frac{\pi z}{6000}, \text{ (cm sec.}^{-1}) \tag{7}$$

This distribution of w is shown on the right side of figure 2. Permitting this pattern to act on the Fawbush-Miller typical tornado sounding [13] for a period of 10 hours yields the result shown in figure 2.

This time period of action was frequently observed in cases of modifications of environment studied, but it is probably near the maximum significant time interval. It may be that modification by such means is effected occasionally in as short a time interval as one hour (10^4 sec^{-1}). Since Cressman's data were based upon a relatively large grid, such an order of magnitude is not excessive for small areas. This sets the following limit:

$$|\text{div}_2 V_0| \geq 10^{-5} \text{ sec.}^{-1} \tag{8}$$

Since, except in some unusual circumstances, particularly at low levels, $\left|\frac{S}{\eta}\right| \ll 10^{-5}$ sec.$^{-1}$, it is necessary that the first and third terms on the right in (2) make the contributions of the proper magnitude. This can be the case usually only in the vicinity of marked wind maxima, or jets. It is necessary, then, to determine which configurations of such features will delineate the mechanism sought. Restating (2)

$$\text{div}_2 V = -\frac{1}{\eta}\frac{\partial \eta}{\partial t} - \frac{V}{\eta}\frac{\partial \eta}{\partial s} + \frac{S}{\eta} + \frac{F}{\eta} \tag{9}$$

where s is distance and V is speed along the trajectory.

In order to utilize (9) in a practical manner, the following assumptions are made:

a) the condition is steady state, i. e. $\frac{\partial \eta}{\partial t} = 0$

b) the trajectory of a particle moving through the field may be approximated by a streamline, and

c) η is always positive.

Equation (9) may then be expanded in finite difference form as follows:

$$\text{div}_2 V = -\underset{\text{(I)}}{\frac{VK}{\eta}\frac{\Delta V}{\Delta s}} - \underset{\text{(II)}}{\frac{V^2}{\eta}\frac{\Delta K}{\Delta s}} + \underset{\text{(III)}}{\frac{V}{\eta}\frac{\Delta}{\Delta s}\left(\frac{\Delta V}{\Delta n}\right)} - \underset{\text{(IV)}}{\frac{\beta v}{\eta}} + \underset{\text{(V)}}{\frac{S}{\eta}} + \underset{\text{(VI)}}{\frac{F}{\eta}} \tag{10}$$

where V = speed of particle along the streamline
K = streamline curvature
s = distance along streamline
n = distance along normal to streamline—positive to left of flow
v = north-south component of velocity—positive for south wind
β = Rossby parameter = rate of change of coriolis parameter northward $= \frac{2\,\Omega \cos \phi}{a}$ where Ω is angular velocity of the earth and a is radius of the earth.

Utilizing (10), it is possible to analyze various geometrical and geographical configurations of jet axes and jet maxima for regions of action of the dynamic mechanism. Directing attention to the first three terms on the right, consider:

a) A jet axis with curvature but without maxima. Here only term II is significant since $\Delta V = 0$. Figure 3 shows the characteristic divergence

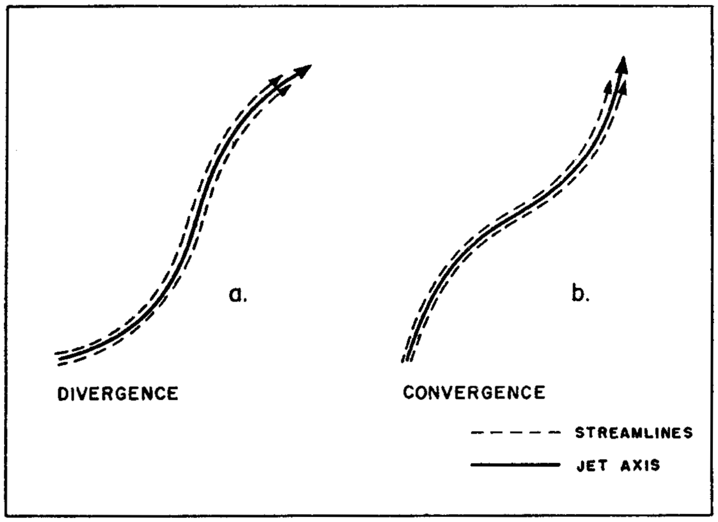

FIGURE 3.—Horizontal divergence patterns related to jet axes due to curvature alone.

patterns. (The azimuthal orientation is not significant, since term IV is not considered here.)

b) A jet maximum without curvature. Here, since K and $\Delta K=0$, only term III is significant. Characteristic related divergence patterns are shown in figure 4A.

c) A jet maximum with cyclonic curvature maximum coincident. Terms I, II, and III are significant and divergence patterns are shown in figure 4B.

d) A jet maximum with anticyclonic curvature maximum coincident. Again terms I, II, and III are significant (fig. 4C.)

Many combinations of the foregoing divergence patterns are possible and two optimum patterns of divergence over convergence are shown in figure 5. The foregoing has been treated at length by Riehl et al. [14]. It should be noted that the area dealt with here is in the magnitude range of cyclogenesis, so that similar conditions should apply. There is no inconsistency with other procedures, e. g. the work of Sutcliffe [15].

It may be further noted that term IV contributes to convergence with southerly flow, and vice versa; term V contributes to convergence with warm air advection, and vice versa; and term VI contributes to convergence with positive relative vorticity and vice versa. The proper function of term VI is difficult to state, but it is not unreasonable to consider it of significant magnitude at low levels, permitting considerable convergence with less intense jet structures than those required at higher levels.

A low level southerly jet from a warm, moist source region acts in two ways to create an environment similar to that noted in the majority of tornado occurrences. First, through the advection of moisture at low levels such a jet acts to create convective instability in the region it undercuts. Secondly, it acts to create a means for effecting the release of this convective instability in the following manner. To the left of the axis of this jet,

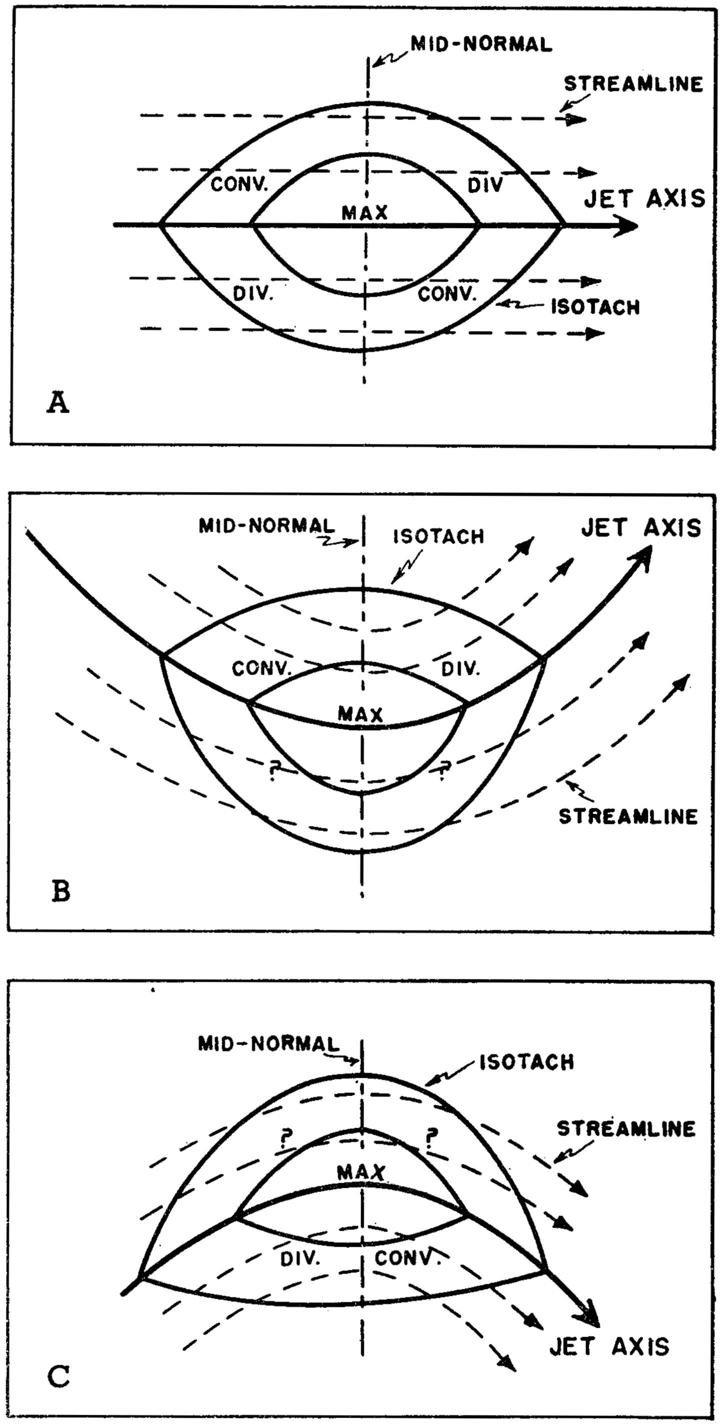

FIGURE 4.—Horizontal divergence patterns related to a jet maximum. (A) Without curvature due to inertial terms only. (B) At maximum cyclonic curvature point due to inertial terms only. (C) At maximum anticyclonic curvature point due to inertial terms only.

terms IV, V, and VI of (10) contribute to convergence, while to the right of the axis, term VI opposes the other terms and the region is indeterminate for qualitative evaluation. Thus, a region of convergence is delineated to the left of the axis (to the west and strongest in the northern end where warm advection is greatest). The deformation of the mean isotherms through the layer in

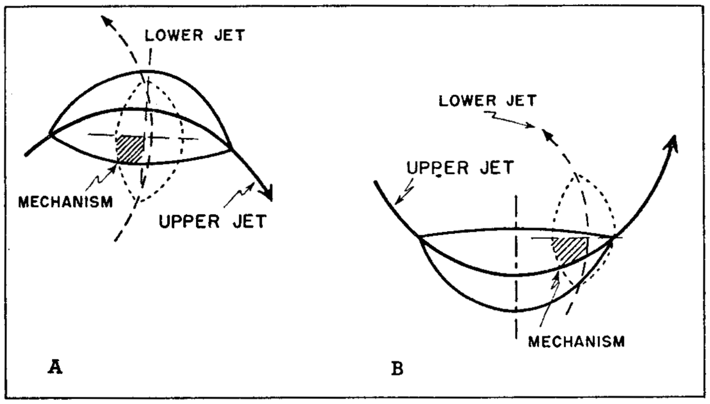

FIGURE 5.—Typical optimum jet configurations.

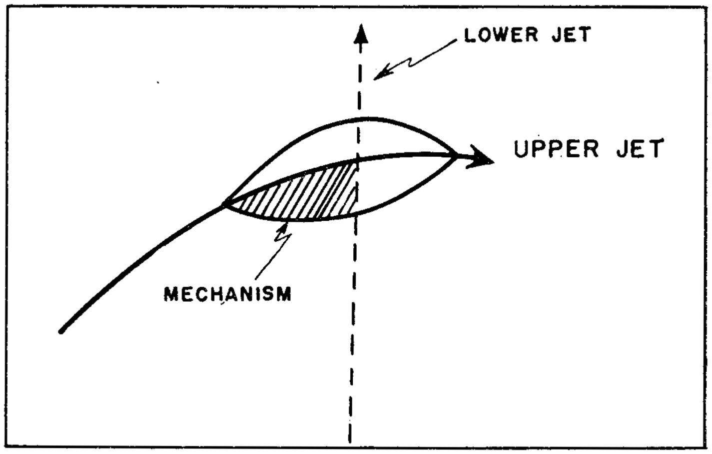

FIGURE 6.—Jet mechanism established through the action of a low level jet from a warm source.

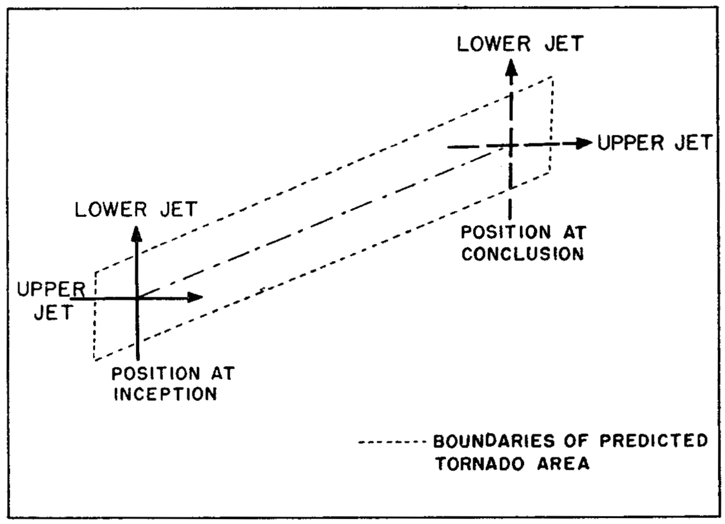

FIGURE 7.—Tornado forecast area delineated by a jet intersection. No curvature and angle of intersection $>45°$.

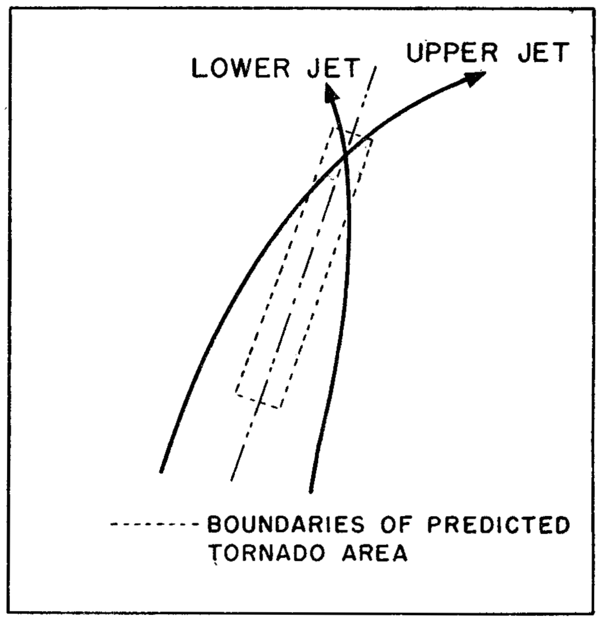

FIGURE 8.—Tornado forecast area delineated by a jet intersection. Anticyclonically curved upper jet axis and angle of intersection $\leq 45°$.

which the low level jet is embedded is such as to create, or accentuate, a thermal ridge coincident with this jet axis and with a maximum thermal gradient along this axis near its difluent region. The resultant wind structure at some level aloft should be similar to the "upper jet" shown in figure 6. The quadrant of the jet maximum aloft noted is favorable for divergence due to terms I, II, and III of equation (10). At this level the contributions of terms IV, V, and VI should usually be negligible in comparison. The resulting divergence over convergence thus acts to modify the environment in the region indicated as "mechanism" in figure 6.

4. APPLICATION

The use of this model 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 appropriate thickness fields. The low level jet is also closely related to surface developments and displacements so that variations in intensity must be weighted accordingly.

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 jet 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. 10 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 motion field.

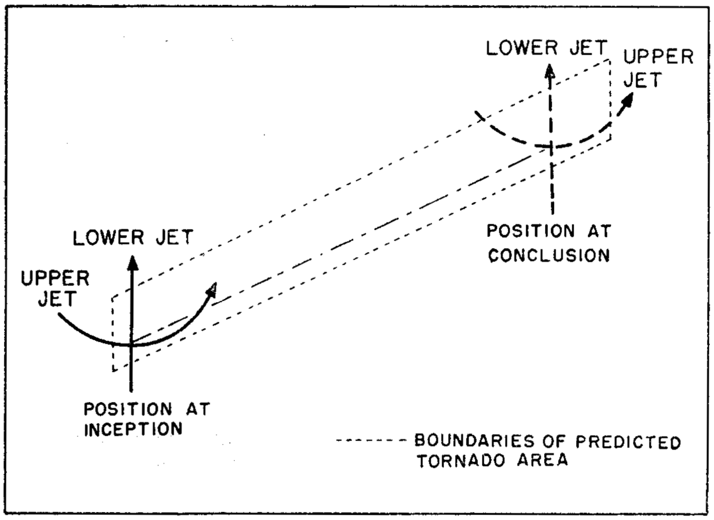

FIGURE 9.—Tornado forecast area delineated by a jet intersection. Anticyclonically curved upper jet axis and angle of intersection >45°.

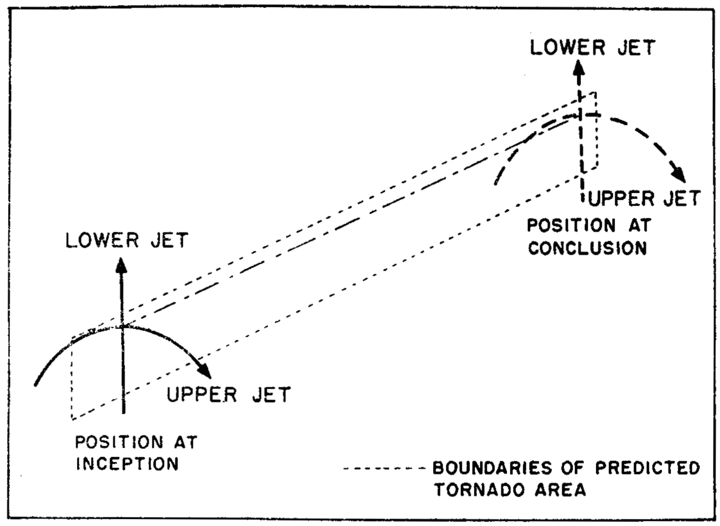

FIGURE 10.—Tornado forecast area delineated by a jet intersection. Cyclonically curved upper jet axis.

A few examples of the use of this technique are illustrated in figures 7 through 10, but the tornado forecasting problem embodies a great deal more than that outlined here. The delineation of a field of critical convective instability upon which the mechanism may act, the problems of frontogenesis and cyclogenesis, the close observation of the progression of related weather, etc., all constitute important—perhaps more important—phases of the total technique.

The first case is that of the normal intersection without curvature. A configuration of jet axes, in an otherwise favorable field, is predicted for a given point as shown in figure 7. This intersection is predicted to move across the field during a time favorable for tornado occurrence. 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.

The second case, figure 8, is that of the anticyclonically curved upper jet axis oriented at an angle of 45° 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 as shown in figure 8. 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 depicted in figure 8 (no movement is shown).

A third case, figure 9, is that of an anticyclonically curved jet axis aloft which intersects the low level jet at an angle of more than 45°. The reasoning and extrapolation of the intersection point is similar to that in the first case. 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 probability of occurrence. The limits of error in positioning the jet axes require inclusion of the intersection point and some area to the north and east. A typical area for tornadoes with such a configuration is shown in figure 9.

A fourth case, figure 10, is that of the intersection of a cyclonically curved jet aloft with a low level jet. This situation is also similar to the first case but weight is given to the area to the north and west of the upper jet, as shown in figure 10. 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. Occurrences with this type of jet structure are usually less intense, rarely attended by more than one or two tornadoes, and frequently associated with "funnel clouds aloft."

5. EXAMPLE

The magnitude of horizontal convergence or divergence is not amenable to either easy or exact calculation. However, a qualitative evaluation of the validity and use of this model may be illustrated through an example of the severe tornado outbreak of March 21–22, 1952.

A rather complete picture of the synoptic situation and thermodynamic properties of this air mass has been given

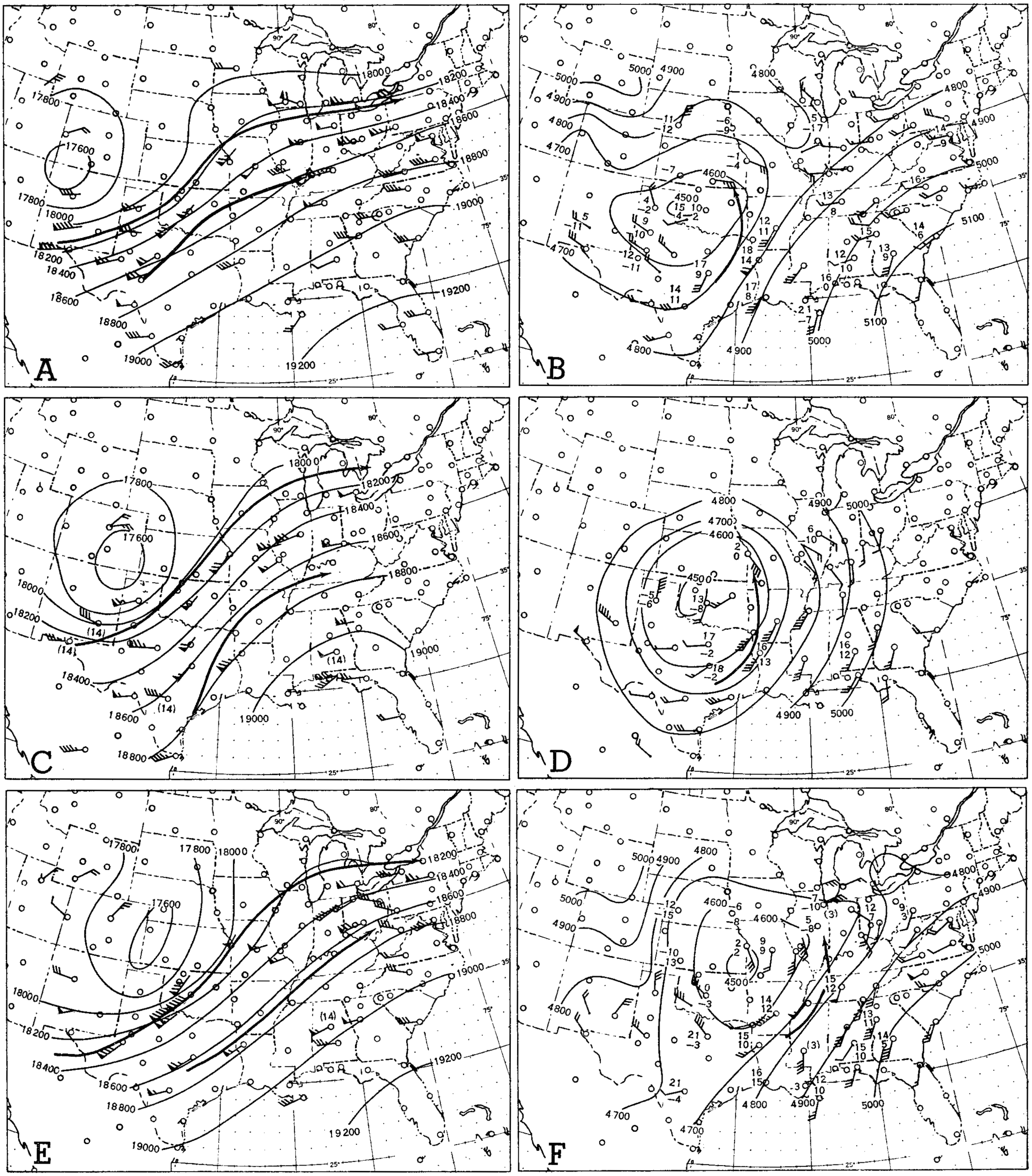

FIGURE 11.—Sectional 500- and 850-mb. charts. Solid lines are contours at 100-ft. intervals. Wind barbs show speed in knots (half barb = 5 knots, full barb = 10 knots, pennant = 50 knots). (A) 500 mb., 1500 GMT, March 21, 1952. (B) 850 mb., 1500 GMT, March 21, 1952. (C) 500 mb., 2100 GMT, March 21, 1952. (D) 850 mb., 2100 GMT, March 21, 1952. (E) 500 mb., 0300 GMT, March 22, 1952. (F) 850 mb., 0300 GMT, March 22, 1952.

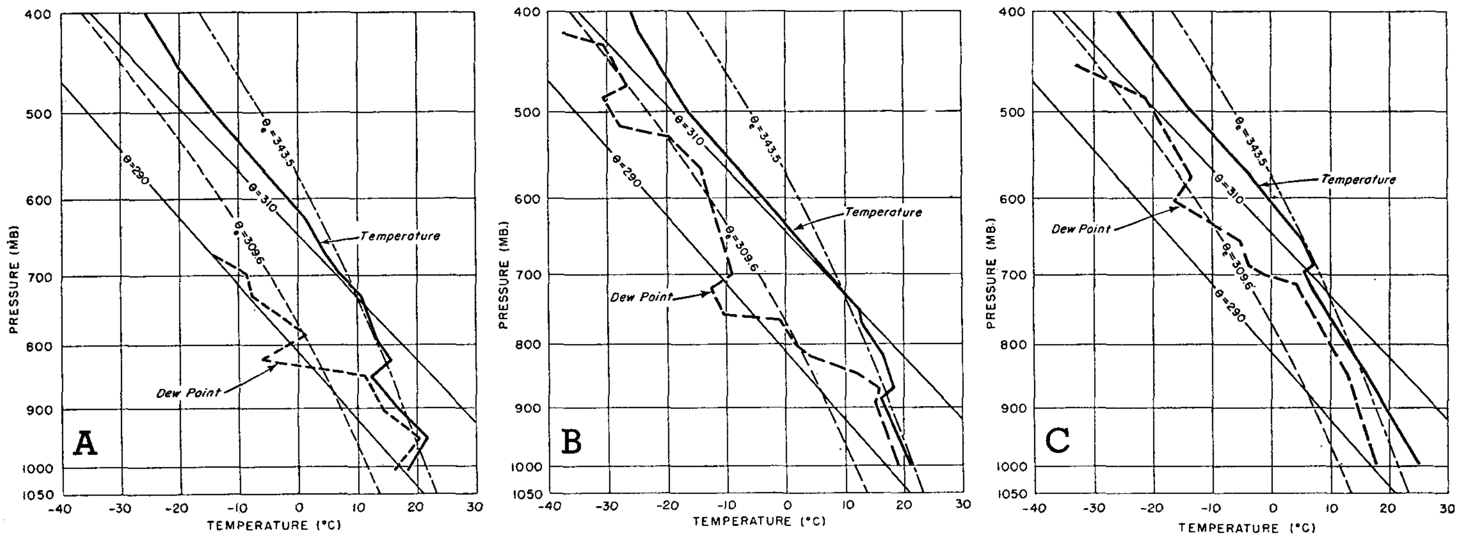

FIGURE 12.—Soundings taken at Barksdale Air Force Base, La., March 21, 1952. (A) 0900 GMT, (B) 1500 GMT, (C) 2100 GMT.

by Carr [16] and will not be dealt with here. Upper air data limitations in both time and space preclude a unique analysis of data at the various constant pressure levels. This is particularly true with regard to the fine structure and so these analyses are presented as being reasonable and not necessarily unique. Charts for 850 and 500 mb. at 1500 GMT and 2100 GMT, March 21 and 0300 GMT March 22 are shown in figure 11.

At 1500 GMT, the mechanism may be delineated over northeastern Texas and southeastern Oklahoma. The jet at 500 mb., figure 11A was not well marked, comprising really only the southeastern limit of a plateau of strong winds associated with the major jet to the northwest. The jet at 850 mb. may be drawn along the Oklahoma-Arkansas border, shown in figure 11B. The action of the mechanism is evident, however, in the ascent of moisture in the area as evidenced by the marked increase in values of dewpoint at 700 mb. over northeastern Texas between the 0300 and 1500 GMT soundings on March 21 (not shown here). These values could not have been advected from the southwest horizontally and environmental lapse rates cast doubt on the possibility of turbulent mixing or other such mechanisms acting to lift the moisture to this level.

A series of three soundings at Barksdale Air Force Base, La., is shown in figure 12. Of particular interest here is the marked change in the air mass structure between the 1500 GMT (fig. 12B) and 2100 GMT (fig. 12C) soundings. Actually, the conversion was not completed as the mechanism described moved to the north of Barksdale and all thunderstorm activity occurred north of this station. The first tornado in this series was reported about 100 miles north of Barksdale.

At 2100 GMT, figures 11C and 11D, the mechanism had moved into southwestern Arkansas and marks rather well the area of the first occurrence, which was nearly synoptic. The two jet patterns were somewhat better delineated at this time. At 0300 GMT, figures 11E and 11F, the mechanism had moved into western Tennessee with attendant tornado activity. Figure 13 shows the location and time of tornadoes with this situation.

Ideally, the example chosen should have included soundings at frequent intervals showing the actual transformation, along with sufficient wind data to illustrate the association or relationship. Unfortunately, data limitations at this time preclude the presentation of such an example. The example shown here is not ideal. Indeed, no ideal synoptic example exists for most postulated models. However, studies in the Severe Local Storms Center show these jet structures to be associated with many tornado occurrences and subsequent adoption of the indicated forecast procedures has yielded excellent results. Even so, caution is advised in the efforts to utilize jet structures in tornado forecasting. The use of only obviously delineated structures based upon reported winds, careless extrapolation, and lack of attention to the total technique will yield discouraging results.

6. FURTHER RESEARCH

At least two avenues for further research are suggested here. The more important is the necessity for further knowledge of the vertical structure of the air mass in the immediate vicinity of tornadoes. Some data from the proximity soundings previously mentioned are presently available for study but it is impossible to positively determine pressure, temperature, or moisture gradients in the vicinity of tornadoes from these data. The dearth of observational information is always a serious handicap in meteorological research but it is particularly acute in the field of severe local storms. The aerological nature of such information is stressed since it has been the experience of severe weather forecasters that surface data alone are too frequently inconclusive, and sometimes

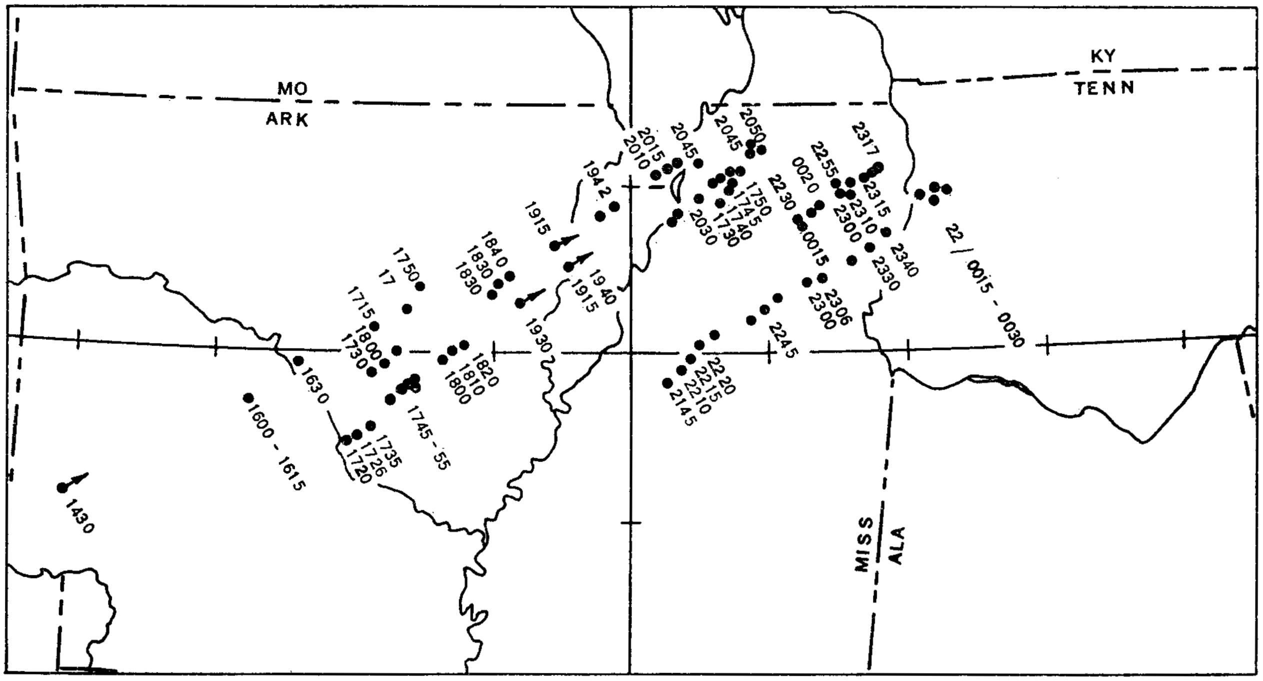

Figure 13.—Plot of tornado occurrences on March 21 through the early morning hours of March 22, 1952. Times shown are in Central Standard Time.

misleading. It will therefore become necessary to procure additional aerological information from a more dense network than is presently available, at least for a limited period for study, before our meteorological knowledge of tornado development can justify forecasts of much smaller areas than those now attempted (10,000–20,000 square miles).

Secondly, further research should take into account the differences in air mass structures, as well as in the synoptic situations which evidently produce them, so that occurrences can be classified into broad types. The study of proximity soundings already points to at least four different types of precedent soundings (soundings within the airmass in which tornadoes occurred, but some 6–12 hours prior to development). Another basis for the classification of tornado types is indicated through the use of related jet configurations, and indices to relative intensity, areal distribution, and probability are inherent in such a classification.

7. CONCLUSIONS

(a) Patterns of divergence over convergence may be delineated on synoptic weather charts by appropriate jet structures which are observable and predictable, within reasonable limits, with the present observational network.

(b) The model of jet structures proposed here acts upon convectively unstable air to create, or help create, limited areas of optimum parcel instability wherein maximum thunderstorm activity and tornadoes occur.

(c) This model constitutes an extension of the physical interpretation of several empirical rules successfully used in tornado forecasting.

(d) This model, when used with other parameters, provides a method which is useful in tornado forecasting.

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