Mesoanalysis: Some Operational Analysis Techniques Utilized in Tornado Forecasting

Bernard W. Magor

Severe Local Storms Forecast Center, Kansas City, Missouri

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ABSTRACT

The tornado forecast becomes a small-scale problem as the tornado-generating severe-thunderstorm area approaches a particular locality. Consequently, much of this problem can be solved by the best possible analysis of surface synoptic weather data. Various tornado occurrences were investigated and found to be associated with meso-lows. These meso-lows were depicted either by the intersection of two instability lines or by the intersection of a squall line with a northeastern boundary of rain-cooled air. An explanation is given for the formation of tornadoes along this intersection.

1. Introduction

The purpose of this paper is to present a brief for the validity of precise operational analysis which will aid the belabored forecaster in the field. It is hoped that this brief will provide one basis by which the forecaster can detect tornado-producing surface synoptic situations in a formative or very early stage of their life cycle.

2. Subject

Fujita and others [1; 2; 3] have compiled mesoscale studies of tornado situations that are illustrative of the meso-low within which the tornado is formed and which also depict the thunderstorm highs, wave depressions, and pressure-surge lines recognizable on this scale. These studies are classic in their interpretations of convective activity. It becomes immediately obvious, however, that such studies are obtainable only after all available data are utilized and thoroughly studied. Moreover, the time and spatial distribution of observations utilized is much greater than is operationally available.

The subject matter of this presentation is the operational analysis—on a mesoscale—of synoptic data that are received from stations that are separated on a scale no smaller than macro. The operational mesoanalysis is attained by expanding the available data over a time distribution—through utilization of more than one report per station per hour. More concisely, this is to be accomplished through use of special reports, sent on teletype Circuit "A" in the normal scan periods, to supplement *hourly analysis.*

The special reports by their very nature are an elaboration upon specific weather information—*i.e.,* the beginning of precipitation, the strength of strongest gusts, the rapid rising or falling of pressure, *etc.* Also, as will be developed further in this presentation, the voluntary addition of the altimeter setting by the observer who files the special report serves as an invaluable aid to the forecaster who desires to make hourly charts of the pressure tendency.

3. The objective

Since the purpose of this paper is to present some aspects of operational mesoanalysis, it has the objective or, moreover, even the burden of presenting a workable model of the tornado environment as normally seen on a synoptic chart. In pursuing this, the assumption will be made that the air mass has attained or has been forecast to attain a state of convective instability.

The cumulative experience of several seasons of severe-thunderstorm forecasting has brought into the foreground certain meso-low models which are particularly common to the situation wherein, normally, more than one tornado is generated. The cyclonic circulation of the environment surrounding the tornado and identifiable through mesoanalysis is here classified as the meso-low; generally the smallest diameter detectable ranges between 20 and 80 mi. Within this vortex, one can expect to find the micro-low or "tornado low" as defined by Brooks [4].

With the present spacing of synoptic stations in the United States, the chances of intercepting and

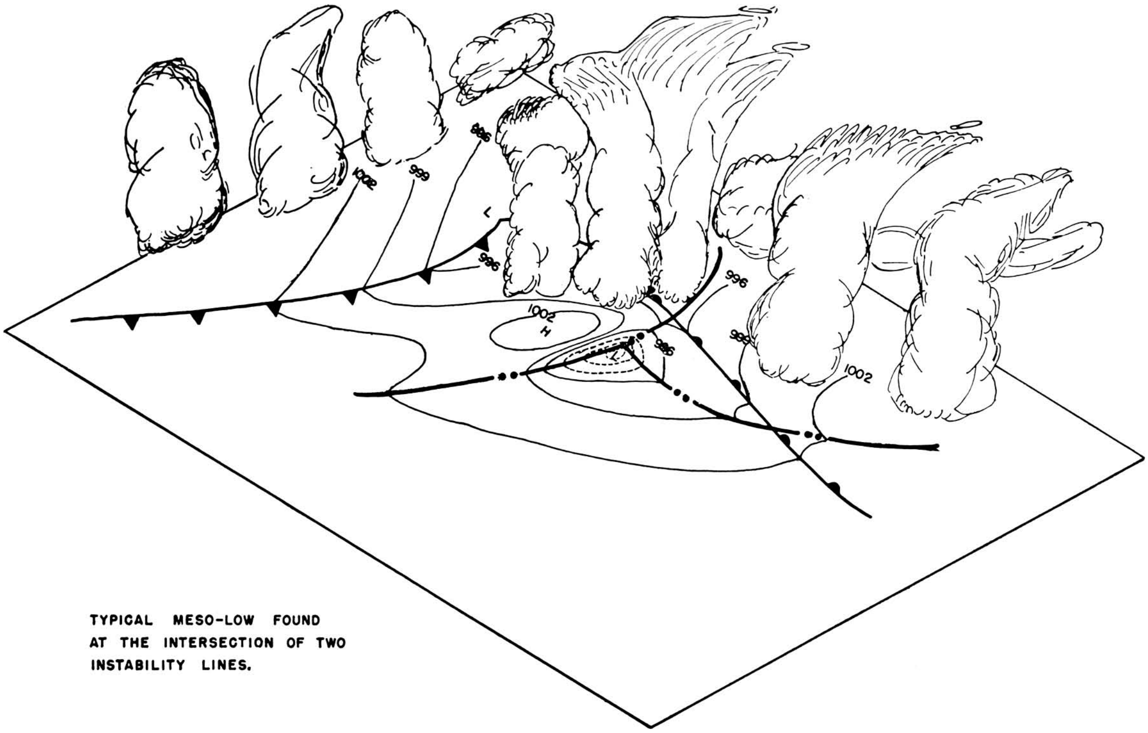

FIG. 1. Typical meso-low found at the intersection of two instability lines.

following this cyclonic circulation on a surface synoptic chart would be extremely small. However, reasoning that this area is characterized by low pressure, it must then occur within a synoptic regime favorable for its generation. We would be inclined to peruse an area which on the surface map would be

(a) within the warm sector of a wave cyclone [5],
(b) along an instability line, especially at an instability line intersection,
(c) within a zone of local converging winds at the gradient level.

Validity for the above lies in the fact that all represent zones of surface convergence helpful to deepening. Moreover, the Beebe and Bates article, "Mechanism for assisting in the release of convective instability" [6], which draws upon the area of intersections of the jet stream with this gradient stream flow, and House's "Mechanics of the instability line" [7] point up how dynamic changes involved in increasing convective instability are also capable of localizing this potential into a small area which will normally be the zone of best convergence.

4. The meso-low model

Fig. 1 is a model of the most commonly observed meso-low detected upon a synoptic chart. It is generally found within the warm sector of a wave cyclone along the intersection of an eastward extending instability line with an advancing instability line usually somewhat more active than the first one. In fact, the instability-line intersection resembles a miniature wave cyclone and has the effect of producing one cyclonic cell within another. The low normally found at this intersection can be drawn with the smallest closed isobar some 20 to 50 mi in diam. It is sufficient to mention in passing that this sized low could often pass undetected for miles through the present day macro network. Accordingly, often the meso-low would be suspect rather than directly observed [8].

Lying immediately to a west or northwesterly quadrant of the meso-low, the thunderstorm high cell will generally be found. (This refers to the more common westerly or southwesterly flow patterns; the thunderstorm high could often be found in a northerly to northeasterly quadrant of the meso-low under a northwesterly flow pattern.) It can be readily seen that the gradient of

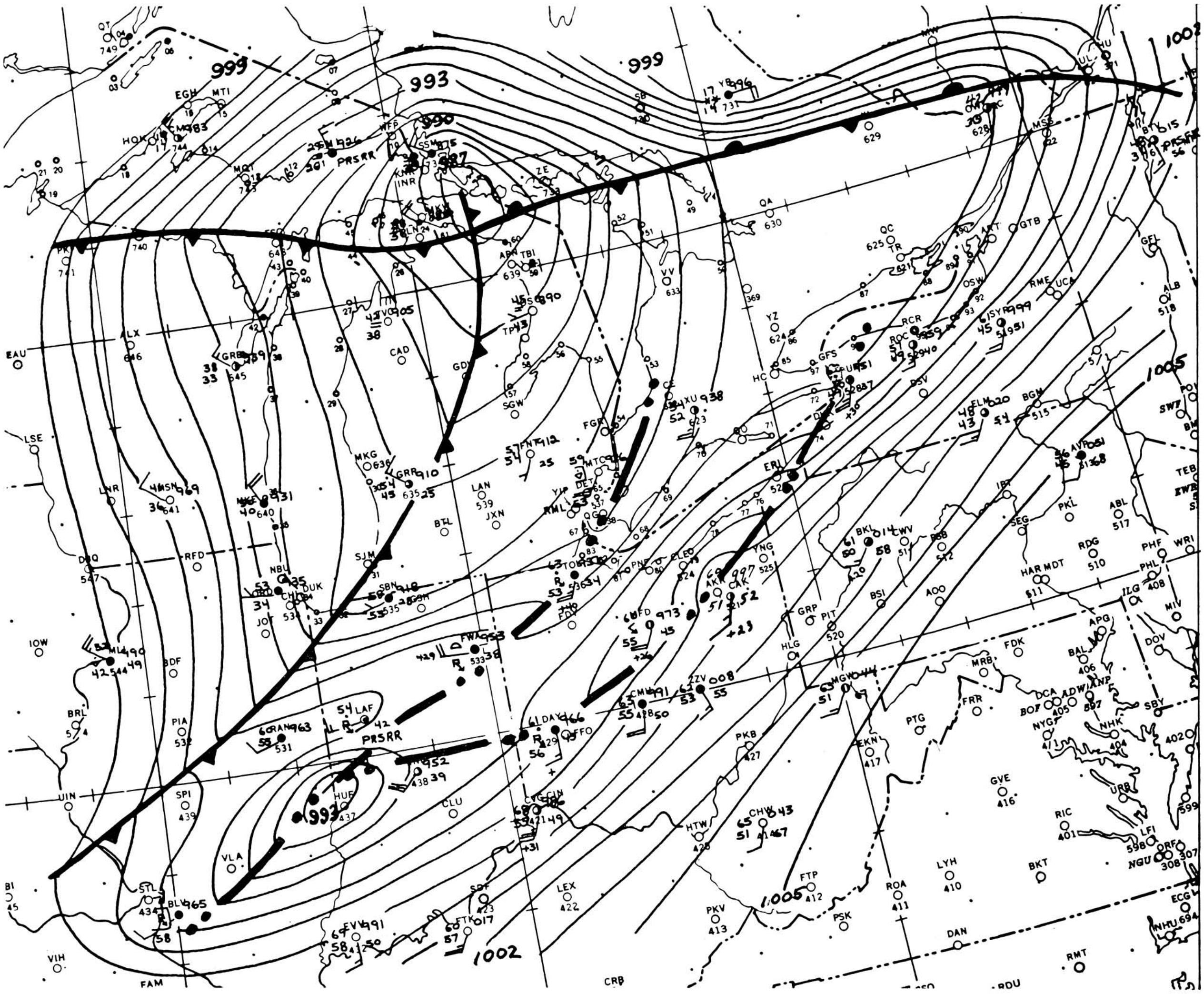

Fig. 2. Surface synoptic section at 0030C 11 March 1955. Station model abbreviated to include only sea-level pressure, temperature, dew point, wind, weather, and significant remarks on activity. In the southeastern quadrant the last two digits (hundredths of an inch) of the altimeter setting are plotted.

pressure between these two pressure cells is quite steep. Assuming the forward movement of the system to be at least 30 kn and often even greater, it is easy to see that an intense meso-low could approach, pass over, and be succeeded by the thunderstorm high over a station within an hour's time.

5. Practical operational examples

The 11 March 1955 Case. A rapidly moving short wave in the jet stream moved out of the Wyoming Rockies during the day of 10 March 1955 and put into motion a frontal system which had been virtually stationary from the western Great Lakes into the central plains. The cooling aloft associated with this short wave was the most obvious element in producing instability activity ahead of the surface front as the momentum of the upper system served to overtake the surface frontal position. The vertical motion associated with this system was also obvious in pulling up moisture from the southwest and converting the airmass in the Ohio Valley into a convectively unstable state [9].

Fig. 2 shows the surface map at 0030C 11 March 1955. Note that the easternmost instability line (here, and in most cases, delineable as the most eastward line of shower activity) extends from Buffalo, New York to Dayton, Ohio and thence westward into a meso-low over Terre

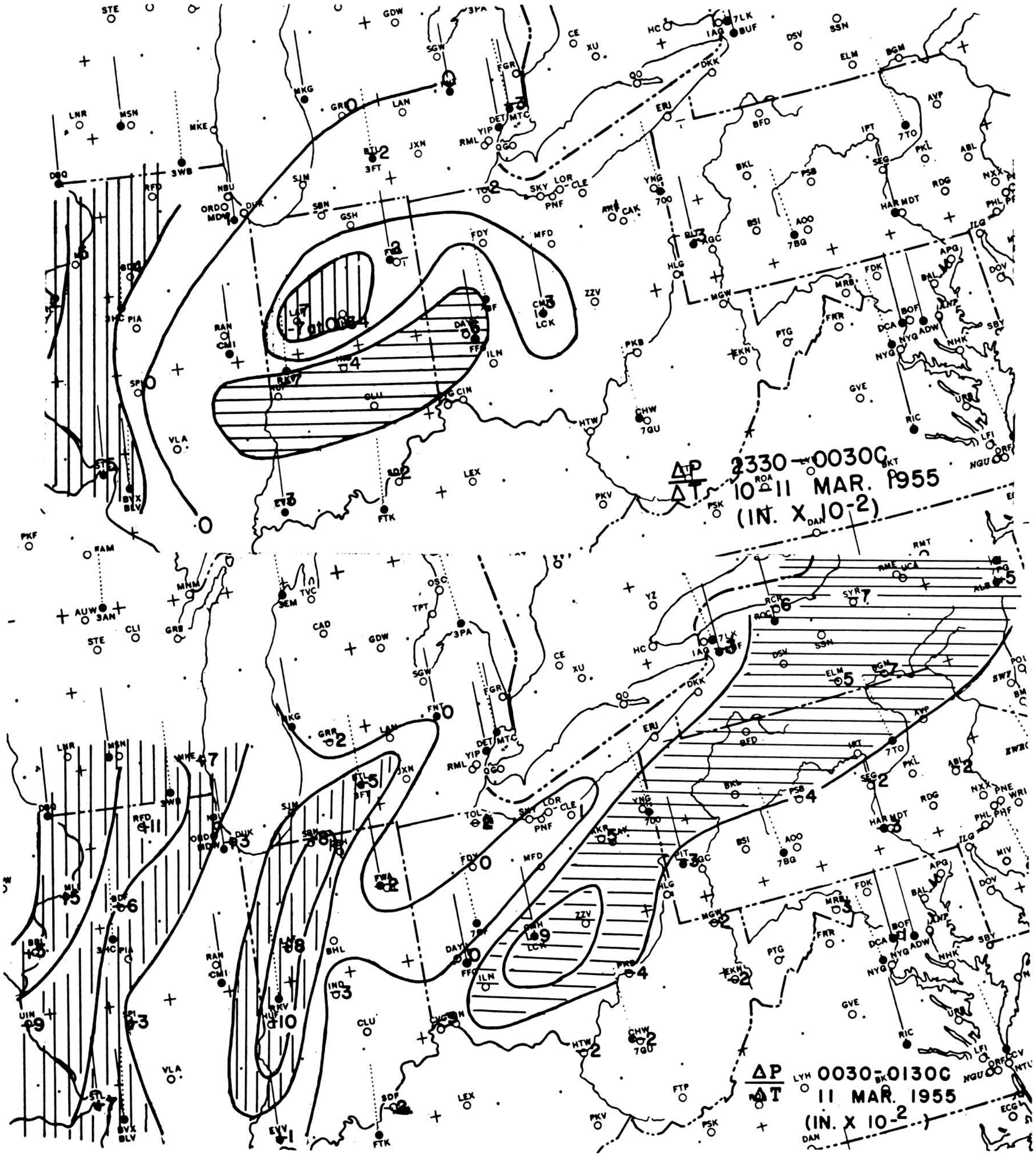

FIG. 3. Hourly pressure change in hundredths of an inch at 0030C and 0130C on 11 March 1955. Changes occurring on specials *within the hour* are plotted in brackets.

Haute, Indiana. Here it makes an intersection with the second and more active instability line extending from Toledo, Ohio southwestward into the meso-low. Indications are already present on this surface chart that the meso-low is moving eastward, for Dayton, Ohio is reporting "pressure falling rapidly," while at Lafayette, Indiana, the pressure is rising rapidly. The station model used in plotting this map is a standard abbreviated model which eliminates the cloud form and visibility but utilizes all reported weather phenomena. In the southeast quadrant, the last two digits (hundredths of an inch) are plotted as reported by the station's altimeter setting.

In fig. 3, the pressure-change chart is composed of the net change in hundredths of an inch of the

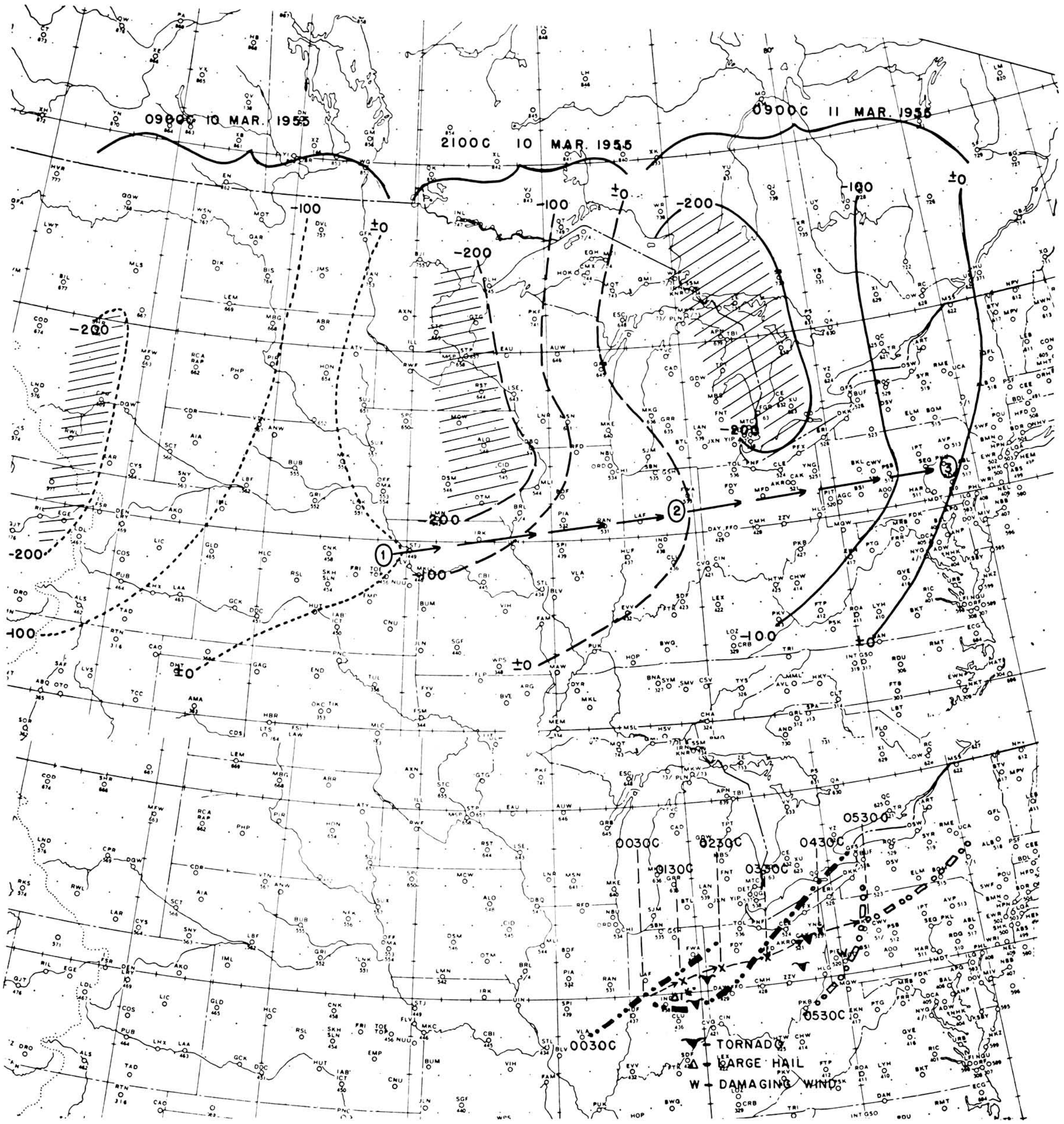

Fig. 4. Top illustration depicts successive positions of the twelve-hour thickness change between 700 and 500 mb for the two radiosonde periods *preceding* and the one radiosonde period *following* the activity that began shortly after midnight 11 March 1955. Bottom illustration gives successive positions of the instability-line intersections from 0030C to 0530C 11 March 1955 along with the indicated locations of recorded severe weather activity.

altimeter settings in an hour. This chart has the particular advantage of enabling the forecaster to take note of the changes that also occur *within the hour* when reported by special weather; such phenomena are plotted in brackets. A particular example of this is the case at Lafayette, Indiana, where we note that the pressure fell 0.07 in. in four minutes after the standard observation was taken at 0030C. This value is equivalent to 2.3 mb and is quite significant on the operational level. In this case, we can fairly well conclude that the "thunderstorm high," or so-called "bubble-high" [10], has just moved over Lafayette. Its apparent speed of motion will be quite important, for the high, being along the leading edge of the squall line, is moving into a sector along the northern periphery of the meso-low where it will serve as not only a trigger for continued thunderstorm ac-

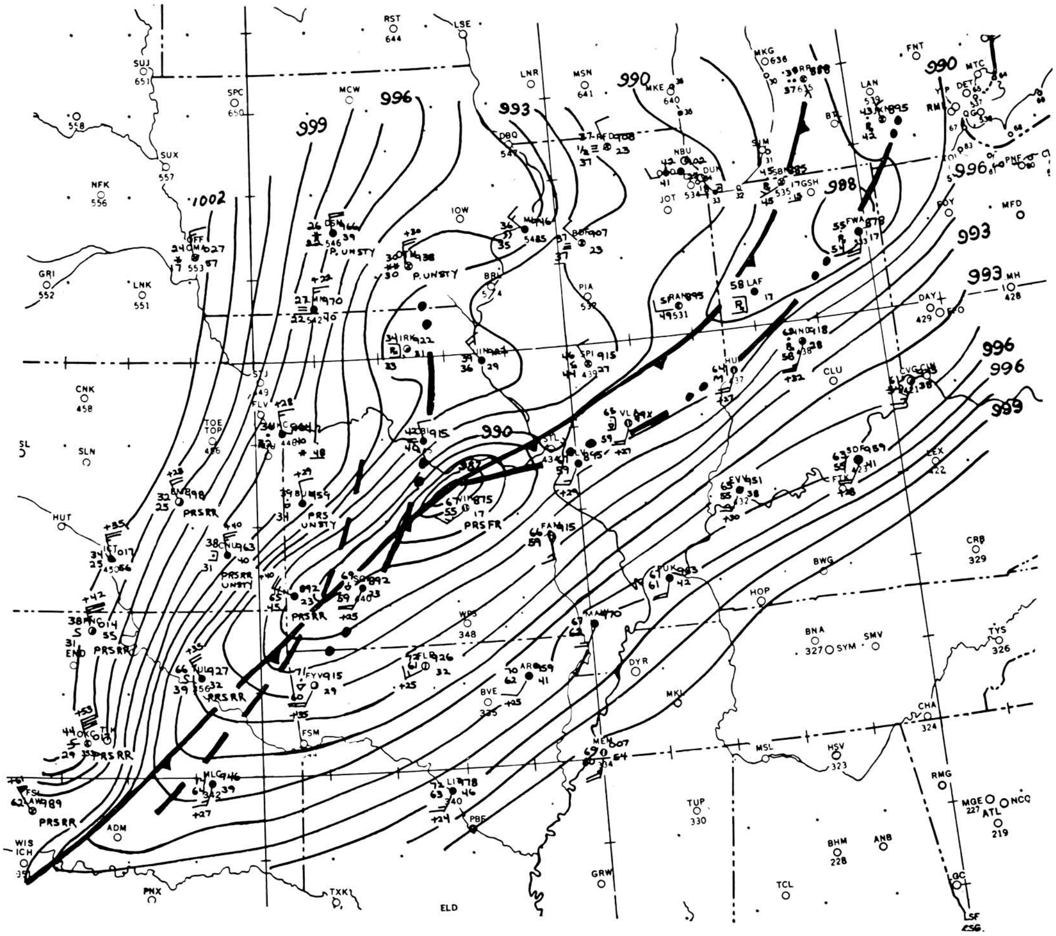

Fig. 5. Surface synoptic section at 2230C 24 February 1956. Station model abbreviated as in fig. 2. Any new altimeter settings sent within the following hour (as at MKC) are plotted and *underlined*.

tivity but also as a mechanical lifting mechanism wherein the southerly flow within the meso-low will be forced aloft, contributing further to the vertical motion already existant.

By 0130C, the meso-low had traveled some sixty nautical miles from being over Terre Haute the hour before to a position just east of Indianapolis. In fig. 3, we note that the 0030C to 0130C change records Lafayette, Indiana as having recovered from the pressure fall experienced *within* the past hour and that the general pressure rise behind the instability line now dominates all of western Indiana. A zone of positive, or at least neutral, pressure tendencies lies along the northern periphery of the leading instability line in Ohio, while the strong falls around Columbus indicate the continued eastward movement of the meso-low.

Fig. 4 is a composite chart comprised of the three successive positions of the twelve-hour thickness change between 700 and 500 mb depicted in the upper portion of the figure while the lower portion illustrates the position of the intersecting instability lines at 0030C and at 0530C with the successive positions of their respective intersections during each elapsed hour in between. Recalling that the major portion of the meso-low extended southward from this intersection, one can compare the positions of the reported severe-weather activity recorded that night through the Ohio Valley and into western Pennsylvania.

It is worthy of note that the zero-change line in the thickness-change pattern arrived over the Ohio Valley ahead of the leading instability line; the second and more active line probably formed as more upward motion took place in the path of increasing cyclonic vorticity advection.

The 24–25 February 1956 case. Fig. 5 illustrates another case which resembles the typical meso-low model with a leading instability line in the warm sector trailing westward to intersect another instability line more normal to it. Again,

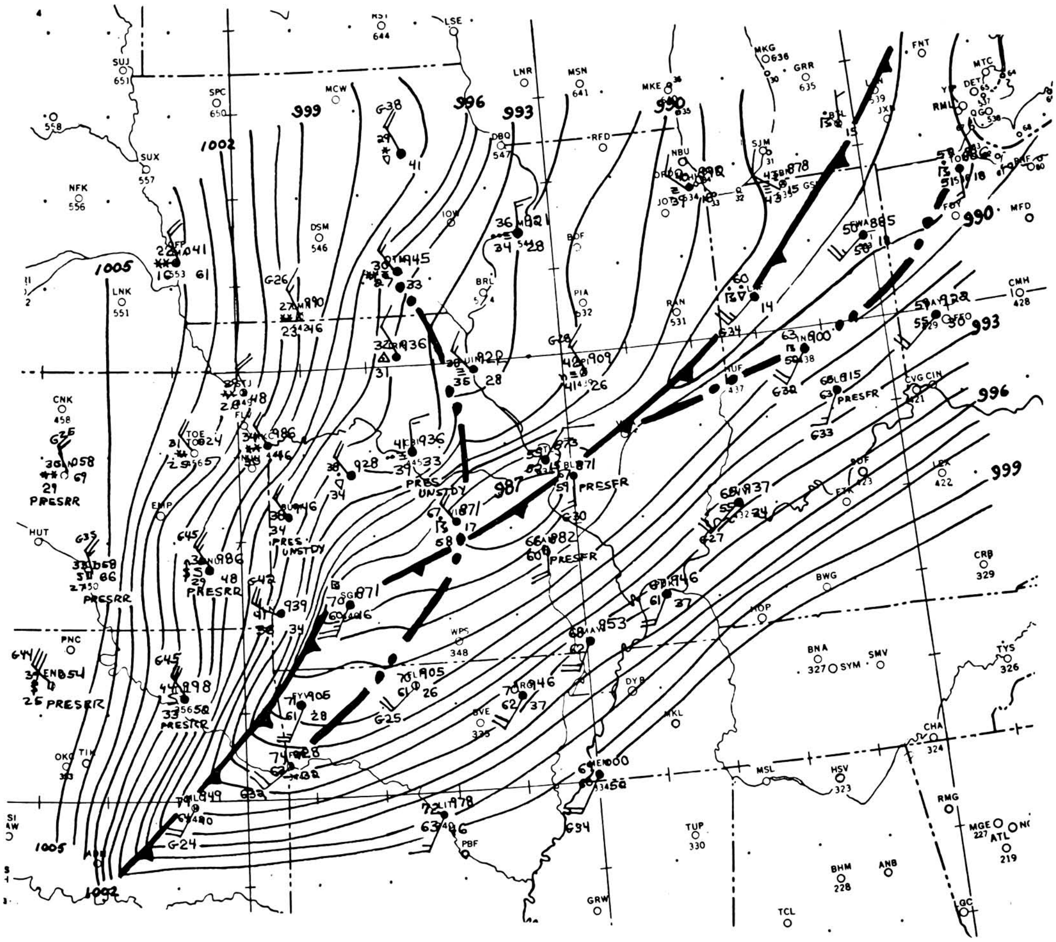

FIG. 6. Surface synoptic section at 2330C 24 February 1956, one hour later than fig. 5. Abbreviated as in preceding illustrations.

the pressure is falling rapidly in the path of the meso-low. Between this map and fig. 6 there existed an excellent example of the help that can be rendered by a conscientious observer. At Vichy, Missouri, the pressure fell an additional 0.06 in (two millibars) in the nineteen minutes following the observation, then regained the same amount prior to the succeeding observation. Fig. 6 shows that Vichy's wind has shifted from its original southwesterly direction to the current northwesterly direction and that a thunderstorm is in progress. A casual observation from one map to the other would indicate that a front had passed the station (with no change in the pressure). However, due to adept reporting of specials at Vichy, plus the addition of altimeter setting, one is able to ascertain that not only did a front pass but that a small wave existed upon it.

Fig. 7 shows the change occurring during the hour. Note here that the "bubble" lies to the northwest of the meso-low (over Columbia, Missouri) with the depression wave showing up from Springfield, Missouri to Butler, Missouri. The pressure has fallen 0.07 in (2.3 mb) at Belleville, Illinois while a small zone of zero tendencies in air 20 deg colder from 70 mi east-northeast of Belleville, Illinois to north of Quincy, Illinois outlines a zone of probable mechanical lift when met by the southerlies of the meso-low.

Fig. 8 is another comparison of activity with the translation of the upper-air thickness pattern. Again it is seen that the zero change in thickness moves through the area prior to the beginning of activity and that the lead instability line is quite parallel to it.

6. An indication of the gradient within a meso-low

Fig. 9 depicts a meso-low approaching the Macon, Georgia area. Note that the pressure is

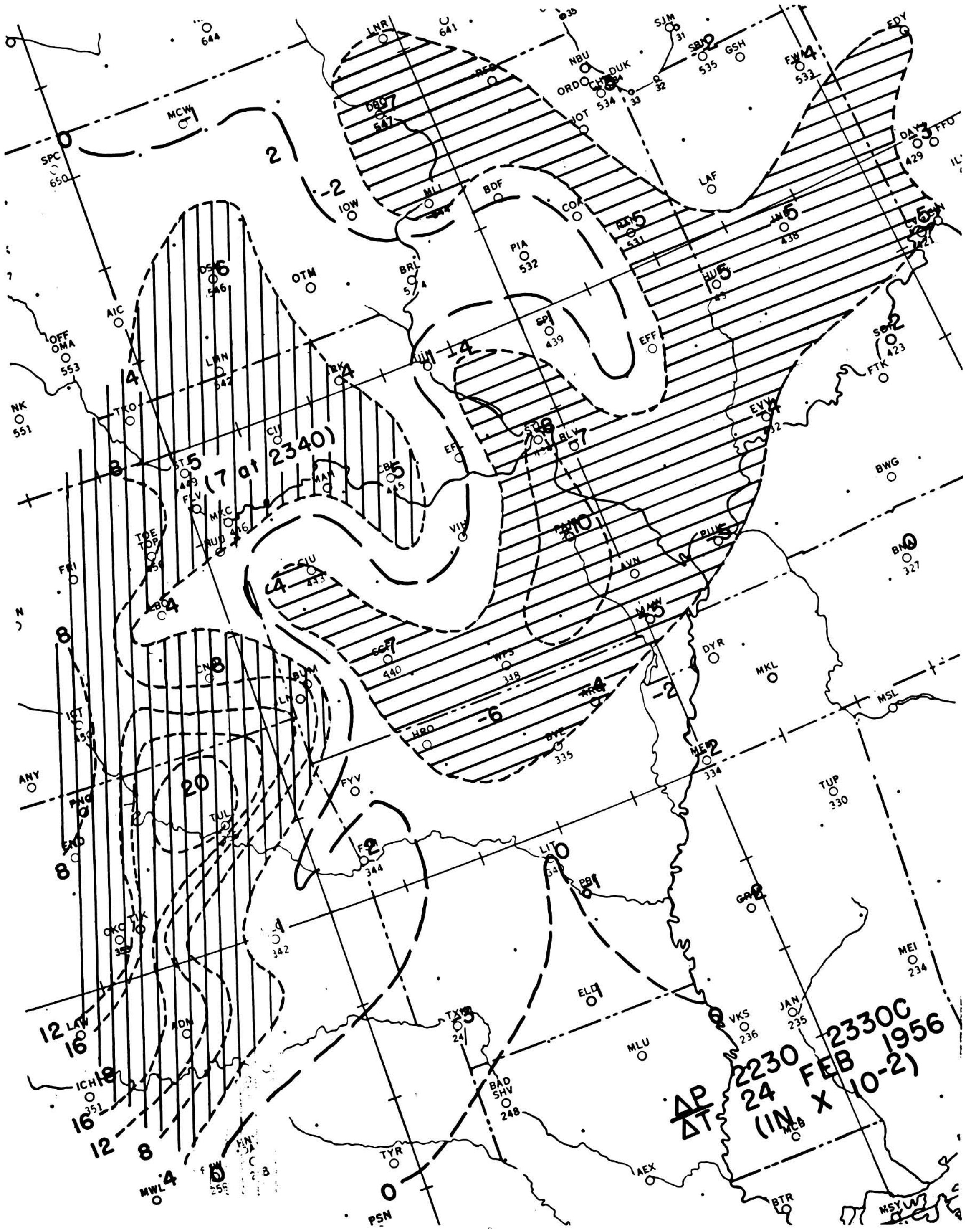

FIG. 7. Hourly pressure change in hundredths of an inch at 2330C 24 February 1956. Changes occurring on specials *within the hour* are plotted in brackets.

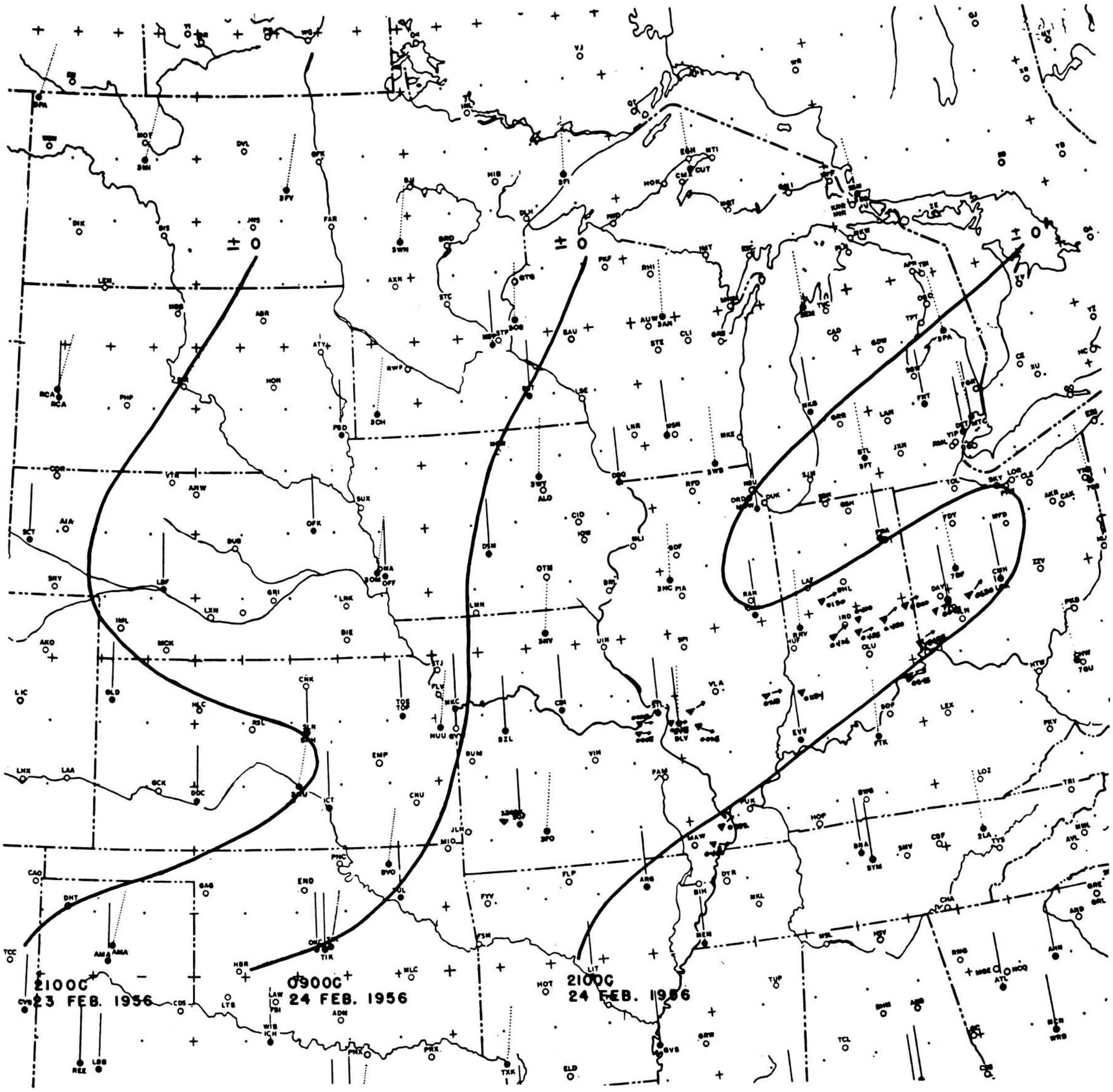

Fig. 8. Successive positions of the twelve-hour thickness change between 700 and 500 mb for the three radiosonde periods of 2100C 23 February 1956 and 0900C and 2100C 24 February 1956.

again reported as "falling rapidly" and that 15 min later the wind shifted to the northwest at 28 kn at WRB (five miles south of MCN). At about this same time, a funnel touched ground briefly over WRB. Also worthy of mention is the fact that, a full hour before this (between 0130C and 0230C), the surface temperature rose five degrees F. During the same time interval, the dew-point temperature rose four degrees at MCN and five degrees at WRB. Another four-degree dew-point rise occurred at MCN the following hour; qualitatively, this represents an approximate increase in *specific* humidity of at least 32 per cent.

It is notable that, at the same approximate time of the funnel occurrence, the suspected tornado low was moving through this area. Fig. 10 shows that at 0130C both stations reported the same pressure but, after the following hour as MCN continued to drop at a fairly steady rate of 0.04 to 0.05 in per hr (3.3 to 3.7 mb), WRB proceeded to drop at twice that rate. At about the same time, both stations (separated by a distance of five nautical miles) reported a difference of 0.02 in (0.7 mb) in pressure with WRB being the lower. This low has a discernible radius of curvature of 35 mi and a pressure gradient

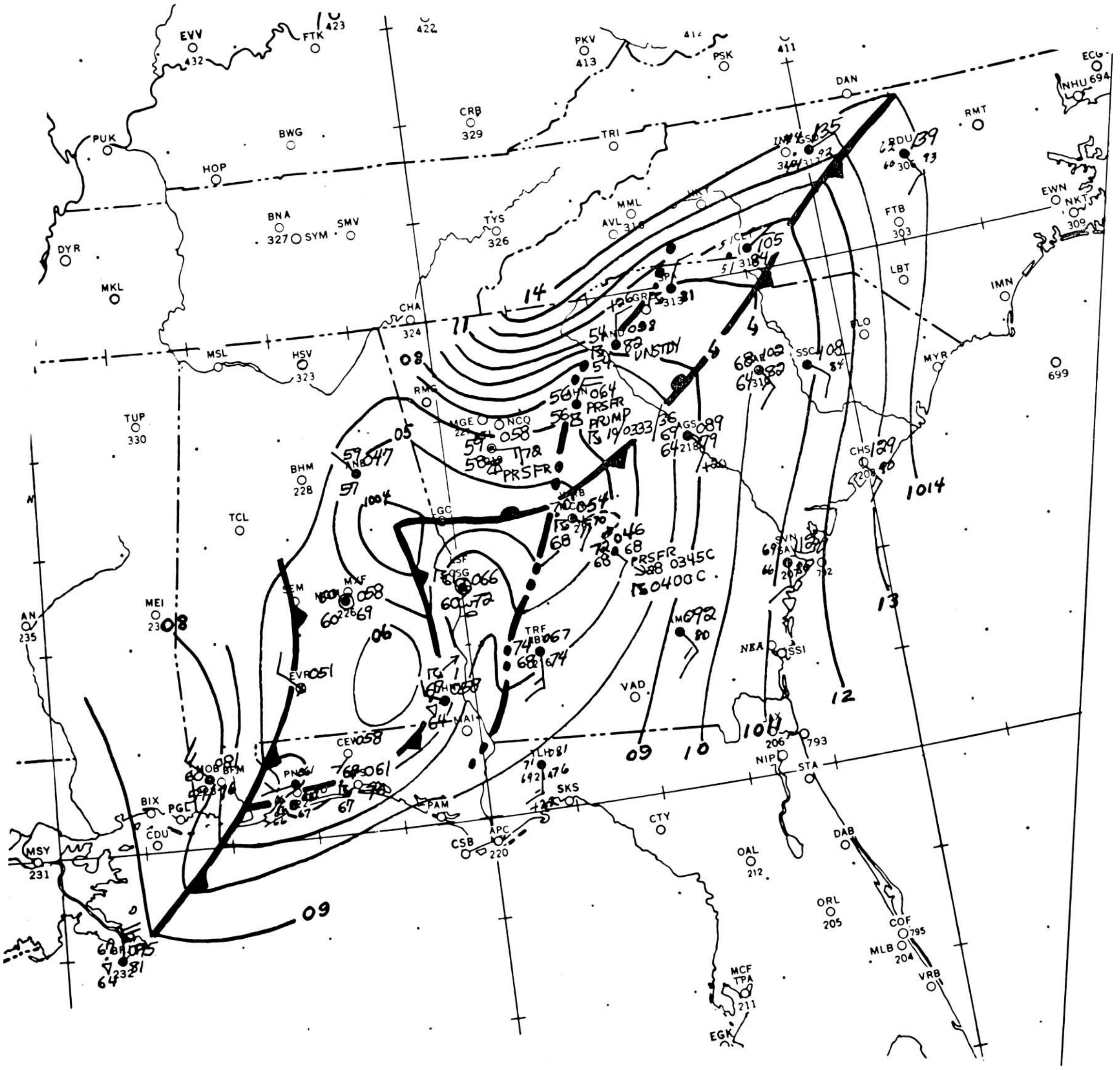

FIG. 9. Surface synoptic section at 0330C 5 April 1957. Abbreviated as in preceding illustrations.

$\frac{\delta P}{\delta n}$ of 3 mb per 22 mi. It should be stressed at this point that these conclusions are drawn as they could be on the operational level; no reference has been made to barographic traces, for this paper is attempting to depict these traces via the clues that *could* present themselves in the current data available at time of activity. The fact of the matter is that the WRB data had to be obtained from that station's logs as the Air Force stations transmit complete reports on pressure only every three hours.

The center of hourly falls associated with this particular meso-low moved northeastward at 40 kn. In slightly over a five-hour period during the early morning, 21 tornadoes were reported within a strip less than 30 mi wide and 240 mi long (fig. 11). The position of each tornado report in time and space was in virtually the same zone wherein the intersection of front and squall line could be analyzed.

Fig. 12 indicates a minus ten hundredths of an inch (3.3 mb) fall center within an hour's time. At Athens, Georgia, the pressure jumped three minutes later to recover all it had lost in pressure the hour before. This occurred as the squall line moved over that station, which was north of the cold front. It is a form of evidence concerning the "bubble high" to the north of the meso-low and increases the conviction that convergence

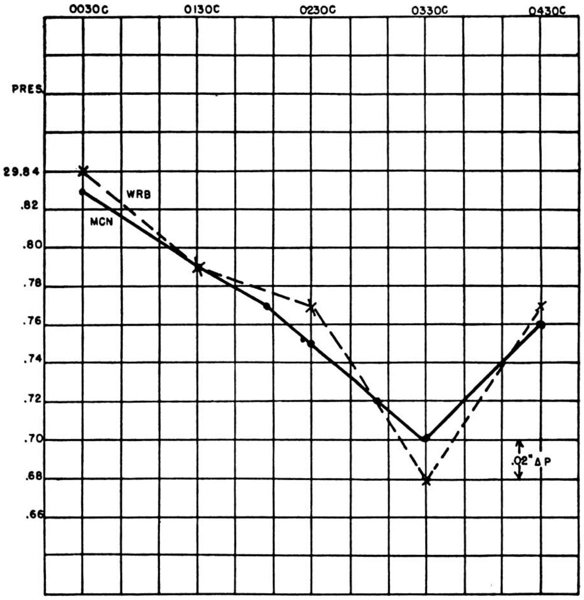

Fig. 10. Assimilated barograph traces at Macon, Georgia and Warner Robbins, Georgia derived from altimeter settings reported on WBAN Form 10A and 10B.

within the meso-low is appreciably increased at this time.

7. Summation

The three cases that have been described were selected because they serve well to illustrate the similarities existing in the application of the idealized meso-low model. In each case, tornadoes were found to occur within an area of low pressure bounded by an intersection of instability lines (in the latter case, one line was actually a frontal surface). The westernmost line generally is the more active and moves along a trajectory virtually normal to the eastern line which preceded it. It can be reasoned that a small-scale area of lower pressure is present at this intersection, for at this point there exists the greatest contrast in densities between air that is being entrained from the surface into a thunderstorm circulation and air that has already descended from a thunderstorm cell. The evidence leaves little doubt that these lows are the mother vortices of a great number of tornado lows.

These cases were selected from a study of eleven occurrences of intersecting instability lines, the southeastern quadrant of which contained either detected or suspected meso-lows. Some eighty-one tornadoes were involved. A significant discovery was that the absolute surface pressure falls (as detected via altimeter settings recorded in the vicinity of the meso-low) would, 50 per cent of the time, be great enough to require an observer to file a "pressure falling rapidly" report within the hour before tornado occurrence. This particular range is in close agreement with the findings of Tepper and Eggert [11].

The meso-low commonly detected by operational type analysis of the most reasonably closed or virtually closed isobar ranged in radius of curvature from ten nautical miles to forty with an average of twenty-six. As indicated in the Warner-Robbins case, there is some reason to suspect that perhaps some of the occasional tornadoes (at least the damaging winds) reported could be generated by the process of occluding the tropical air within a meso-low.

To explore this statement further, the other factors necessary for severe-thunderstorm generation should be recalled. House [7] has shown that, under certain conditions of wind flow, temperature changes due to horizontal advection and vertical motion produce a trend towards the formation within a few hours of a line or narrow band of vertical thermal instability and that this is associated with a marked increase in low-level convergence along the same line or narrow band. This coupling between the gradient-level flow and the wind flow at the level of the jet stream is one mechanism that will create a convectively unstable air mass which, when released, will result in the formation of a line of thunderstorms. The next consideration draws upon the subject matter of this paper—the physical location of the instability line (or lines) in time and space. Forecasting the likely occurrence of the instability line intersection and/or the meso-low is largely a kinematic problem. Since this paper is concerned primarily with analysis, the thickness-change charts were utilized to illustrate rather concisely how the increasing cyclonic vorticity accompanying a short wave aloft in the jet stream could be depicted as decreasing thickness within the troposphere. Since *thickness* lines represent lines of mean virtual temperature, the *thickness-change* lines represent lines of mean temperature change. Therefore, they are indicative of the swath in time and in space of the cooling behind and the warming ahead of a strong wave in the jet stream. As tropospheric cooling initially begins (at the zero-thickness change line), a line of instability could be expected to form. As cooling progressed and intensified, the succeeding instability line (or the final cold front) could be expected to be more intense as long as the wind flow in the gradient

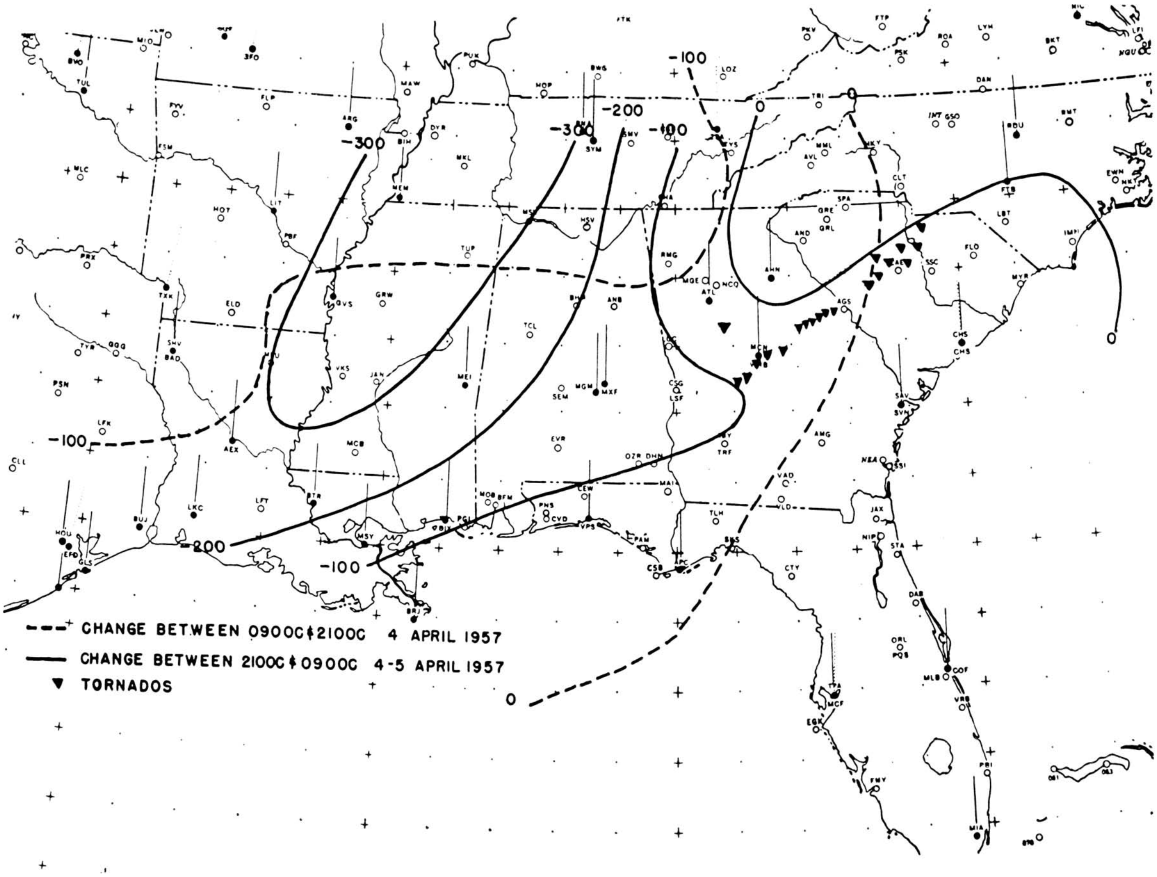

FIG. 11. Successive positions of the twelve-hour thickness change between 850 and 500 mb for the two radiosonde periods of 2100C 4 April 1957 and 0900C 5 April 1957.

level continued to carry unstable air into the trough ahead of this line. Therefore, two or more lines of instability and increasing intensities could be formed within one storm system.

Finally, we arrive at the question "from whence comes the tornado?"

Many valid arguments can be presented at this point, and it is simply suggested here that past forecast experience suggests that tornado occurrence may be directly related to rate of release of convective instability over a small zone in lateral space, confined by thunderstorms and dominated by cyclonic vorticity aloft. Hence, the circumstantial arrangement of individual thunderstorm cells could conceivably present the necessary amount of mechanical "blocking" to a southerly flow of unstable air to produce relatively large amounts of upward motion of the air and thus a rapid rate of release of instability. The stronger the gradient-level convergence in such a case, the greater the severity of the activity. If a meso-low of small proportions can form and maintain itself for a sufficient period of time (and some have been tracked for hundreds of miles), there is the possibility that the winds within the gradient levels could contain velocities normally expected within the jet stream. These velocities in themselves can be damaging without consideration of the addition of the force of the thunderstorm downdraft which might become entrained in the flow or, which is possibly even more important, the accelerations in velocity which could be brought about within the tornado low itself due to conservation of angular momentum.

8. Conclusions

Considering the macroscale of the ordinary synoptic reporting network, it must be realized that operational mesoanalysis must rely upon the *increment of time.* (This, therefore, calls for a particular dedication upon the part of each and every observer to file significant, concise reports—*viz,* rapid changes in pressure and sudden increase in temperature, and adding the altimeter settings to the special weather report even though it is not mandatory [12].)

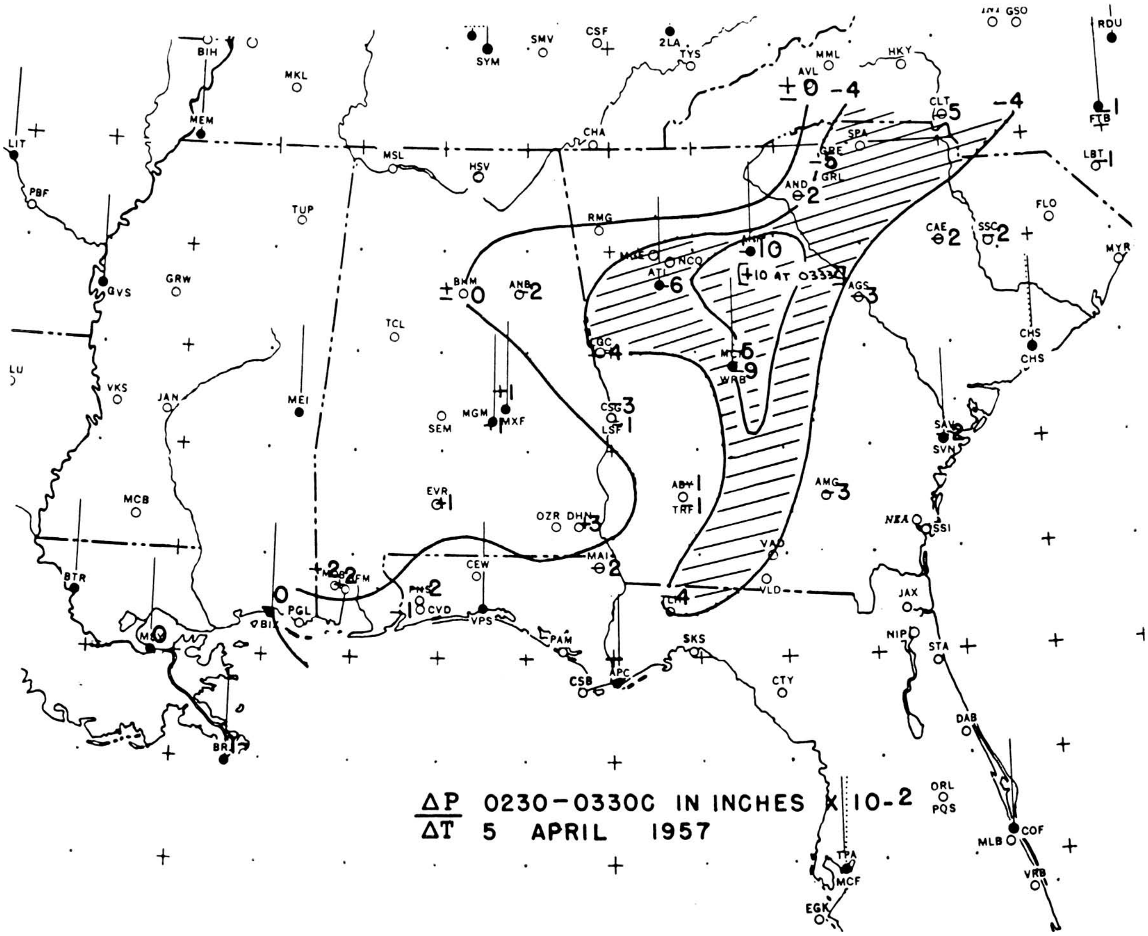

Fig. 12. Hourly pressure change in hundredths of an inch at 0330C 5 April 1956. Changes occurring on specials *within the hour* are plotted in brackets.

Of first-order significance in operational mesoanalysis is the recognition of the convective activity itself. The depression wave in the lee of a thunderstorm "bubble high" can exhibit as abrupt a fall in tendency as can the meso-low which preceded the high. Therefore, radar analysis can also be utilized and integrated into the synoptic activity chart to illustrate more completely the location and rate of movement of the suspected or identified mesosystem, thus ultimately increasing the confidence of the forecaster charged with warning the public of an impending severe storm and who at the same time is cognizant of the many possibilities of overstressing a warning.

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