PRESSURE WAVE OBSERVATIONS IN THE CENTRAL MIDWEST, 1952[1]

D. T. WILLIAMS

Tornado and Severe Storm Project, Weather Bureau Regional Office, Kansas City, Mo.

[Manuscript received June 8, 1953; revision received August 3, 1953]

ABSTRACT

Data from the 1952 Tornado and Severe Storm Observational Network indicate that pressure waves (abrupt variations in surface pressure) occur frequently in the Central Midwest. These waves are classified and studied statistically for relationships with certain weather phenomena. Elevation type wave lines are found to coincide with certain synoptic discontinuities (squall lines, cold fronts, etc.). Thunderstorm activity accompanied 78 percent of these lines, and tornadoes occurred with 27 percent. Data on the motion of elevation type wave lines, and on the size, amplitude, and duration of their fields of activity are summarized. A marked tendency for these waves to occur during nocturnal hours is found. Depression type wave lines are found not to coincide with ordinary synoptic discontinuities. A combination type wave is described and some speculation on its significance is made. Examination of the relation of tornadoes to pressure waves shows a tendency for tornadoes to occur in specific portions of the elevation wave field.

INTRODUCTION

For many years meteorologists have recognized that abrupt variations may occur in the surface pressure. Byers and Braham [4] showed how certain such pressure changes may be related to thunderstorms. Williams [15] studied the abrupt pressure rises that occur with a squall line passage. Tepper [9, 10, 11, 14] showed that such pressure rises are actually propagated waves and suggested that they are the cause rather than the result of the squall line. He has given the name "pressure jump" to them from their similarity to hydraulic jumps. In other literature (cf. [1 through 8, and 12]) pressure disturbances of various kinds have been studied, and a variety of names, such as pressure jump, pressure fluctuation, pressure pulsation, propagated pressure wave, elevation type wave, depression type wave, pressure dome, pressure nose, pressure hump, thunder nose, thunderstorm high, and others, have been used to describe appropriate pressure disturbances. The expression *pressure wave*, or simply *wave*, will be used in this paper to denote all such changes in pressure.

Data [2] from the 1952 Tornado and Severe Storm Observational Network indicate that pressure waves occur frequently in the Central Midwest area and that useful relationships exist between such waves and the associated weather. The purpose of this paper is to call attention to several of these relationships that may be of interest to meteorologists. Although occasional speculations are made, most of the information consists of factual and statistical relationships taken from the observational data.

The author made this study at Kansas City, Mo., in his capacity as Field Manager of the Tornado and Severe Storm Observational Network. More complete investigations are being conducted independently by a research group in the Division of Scientific Services, U. S. Weather Bureau, Washington, D. C., and a summary of its findings will be published at a later date.

The area studied includes southern Nebraska, Kansas, and northern Oklahoma. Basic data consist of barograph traces on an expanded time scale of 12 hours per revolution, obtained from 90 cooperative stations which were spaced from 25 to 50 miles apart. The 1952 network of stations was similar to the 1951 network [13], except that stations were less dense and a larger area was covered. Synoptic and hourly reports from stations in the area, and reports of tornado occurrence were also used.

DEFINITIONS AND METHODS OF ANALYSIS

A *pressure wave* is regarded in this study as a considerable change in pressure that occurs during a short interval of time. Pressure waves are recognized as perturbations on the generally steady trace of the 12-hour barogram. For the purpose of this study only those changes in pressure were examined in which there was a clear cut perturbation on the trace of 0.03 inch or more at three or more adjacent stations. Most cases greatly exceeded these limits.

Pressure waves are rarely isolated but occur along continuous lines, which may be identified as *pressure wave lines*. Such a line moves in a continuous manner across an area, and this area may be defined as the *pressure wave field*. No attempt was made to study the few isolated pressure waves that were noted.

[1] Presented at the 119th National Meeting of the American Meteorological Society, December 30, 1952, St. Louis, Mo., under the title "Perturbations in the Surface Pressure, Central Midwest Area, 1952."

[2] Barograms from 90 cooperative stations in Kansas, Oklahoma, and Nebraska; 6 hourly surface synoptic reports from teletype circuits; hourly and special observations from selected First and Second Order Weather Bureau stations in Kansas, Oklahoma, Nebraska, and Missouri; tornado reports from observers and news clipping services. These data were for the period February 1, 1952, through August 31, 1952.

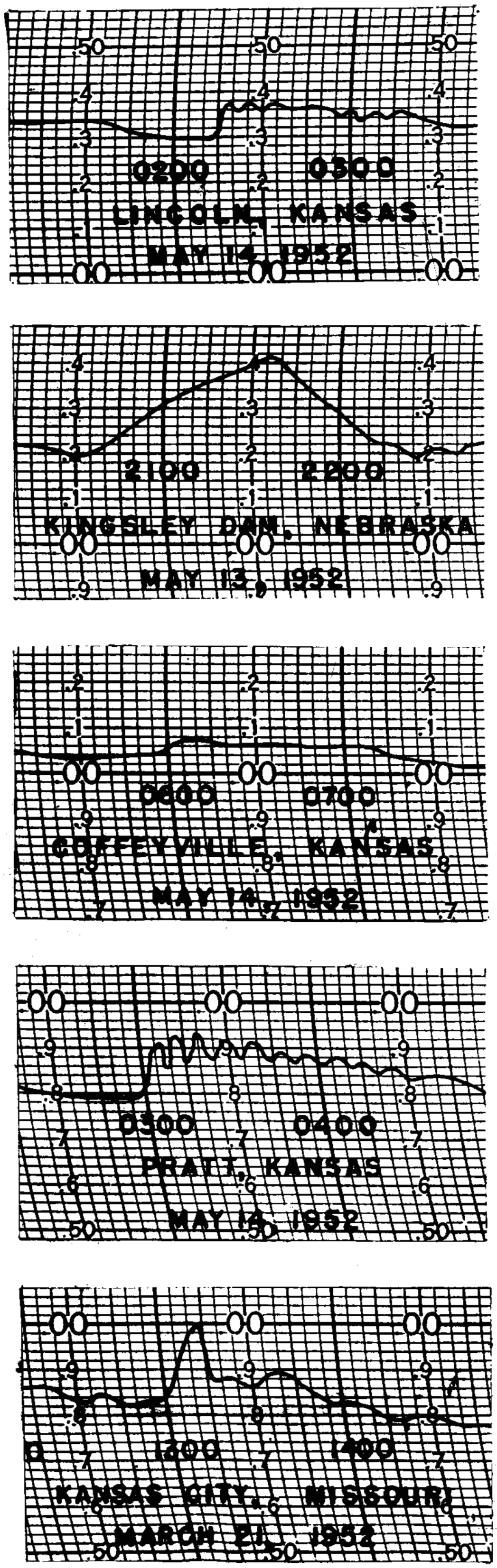

FIGURE 1.—Examples of elevation type pressure waves as recorded by the 12-hour barograph.

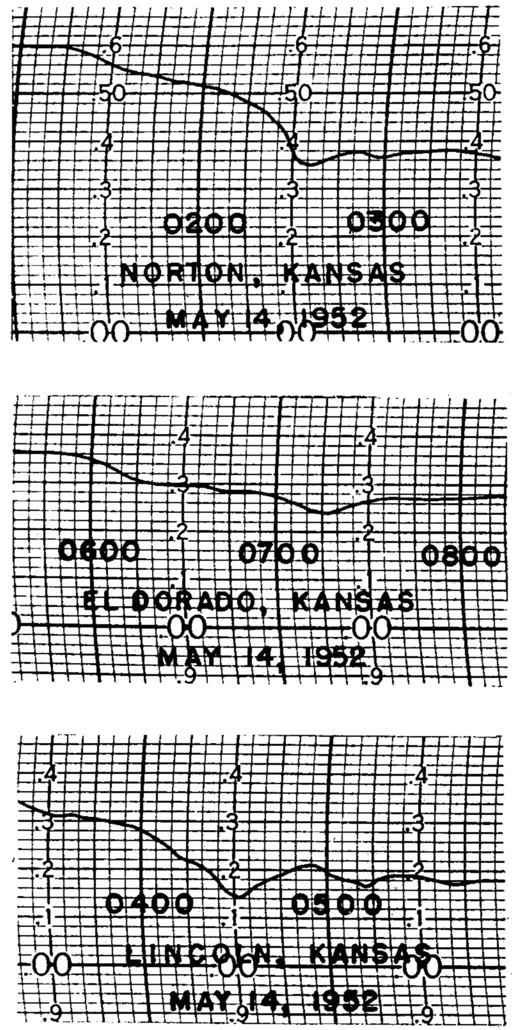

FIGURE 2.—Examples of depression type pressure waves as recorded by the 12-hour barograph.

Elevation type waves show a resulting increase in pressure. On a micro-synoptic chart (and occasionally on macro-charts) such a wave is evident as a micro-ridge [15]. The *elevation type wave line* delineates the onset of the ridge. *Depression type waves* show a resulting decrease in pressure. On a micro-synoptic chart (but rarely on macro-charts) such a wave is evident as a micro-trough. *The depression type wave line* is chosen to delineate the bottom of the micro-trough. Examples of elevation and depression type waves are shown in the barograms in figures 1 and 2.

In order to study pressure waves, isochrone charts were constructed. Time of wave line passage and total amount of pressure change were plotted for each station. Isochrones were drawn for 30-minute intervals to show successive positions of the pressure wave lines. Isopleths of each 0.02-inch total change in pressure were also drawn to show the amplitude of the waves. Examples of isochrone charts for elevation and depression type wave lines, which occurred on May 13–14, 1952. are shown in figures 3 and 4.

In addition to isochrone charts, sectional surface synoptic charts of the Central Midwest Area were drawn. In only rare cases were the two charts inconsistent, although frequently the isochrone charts revealed synoptic features that were not apparent on the sectional charts. Exam-

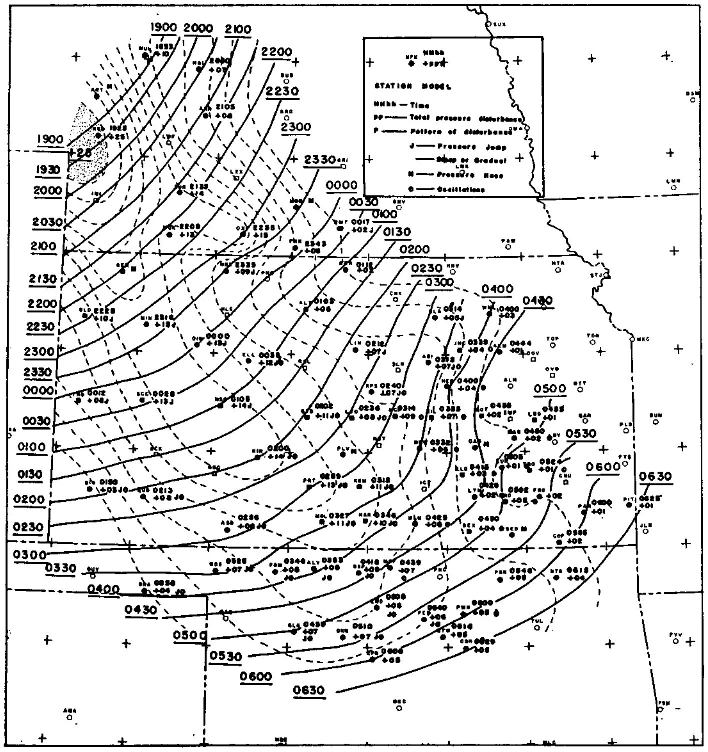

FIGURE 3.—Isochrone chart of an elevation type wave line that occurred with a pre-cold-frontal squall line on May 13–14, 1952. Central Standard Time is used.

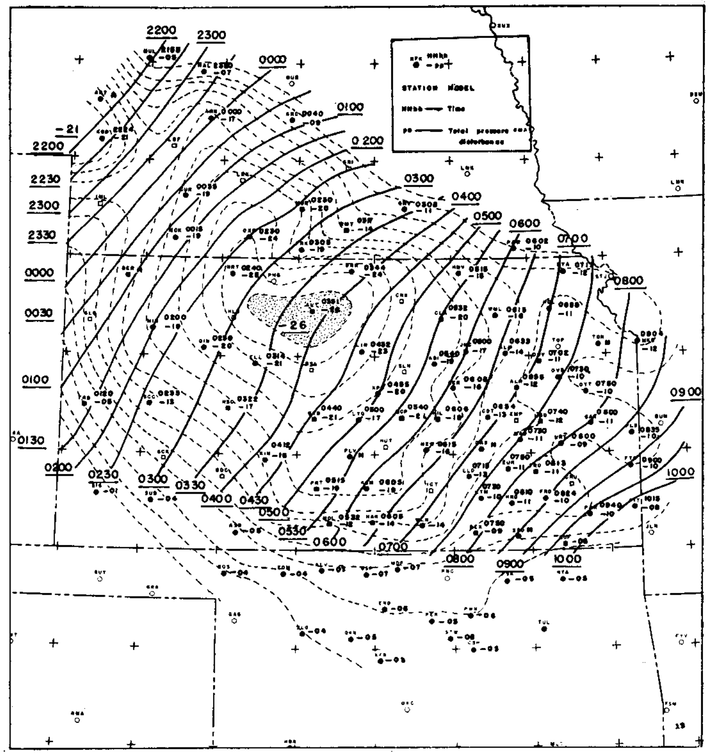

FIGURE 4.—Isochrone chart of a depression type wave line that was associated with the pre-cold-frontal squall line of May 13–14, 1952. Central Standard Time is used.

ples of sectional synoptic charts for the May 13–14, 1952, case are shown in figures 5 and 6.

In some cases series of micro-synoptic charts at 1- or 2-hour intervals were constructed. A series of five such charts, at 2-hour intervals for the May 13–14, 1952, case, is shown in figures 7–11.

ELEVATION TYPE WAVES [3]

WAVE PATTERNS

Elevation type wave patterns on the barograms vary. Generally an elevation type wave is not unique in pattern over all of its field. One or more patterns may occur in the same field with gradual or abrupt transitions from one pattern to another. Following is a listing of several patterns, examples of which are shown in figure 1: pressure jump, steep pressure rise, gradual pressure rise, pressure jump followed by damped harmonic oscillations, and pressure nose.

Pressure jumps have been investigated by Tepper [9, 10, 11, 14], and the reader is referred to his works for a description of them. Steep and gradual pressure rises often appear to be variations of the pressure jump. There is a tendency for an elevation type wave to appear first as a steep pressure rise, after which it may evolve into a pressure jump, thence degenerating into a gradual pressure rise.

The pressure jump followed by a series of damped harmonic oscillations is quite local, seldom occurring over more than 25 percent of the field when it does occur. Oscillations may persist at a station for over an hour with as many as a dozen oscillations occurring during that time. Frequency of oscillation is nearly constant for all cases, and is of the order of 5 to 10 minutes. Amplitude of oscillation may be as great as 0.10 inch for the first oscillation, decreasing uniformly thereafter until completely damped out. Oscillations are discussed by Tepper [14].

Pressure noses are very local and are frequently additive to some other wave, such as a pressure jump. In a few cases it was noted that hail fell at the time of the pressure nose.

There are many variations and combinations of the above patterns. Although recurrent patterns have been listed, the discussion to follow will treat general features of all elevation type waves rather than any special features of individual patterns.

RELATION TO SYNOPTIC DISCONTINUITIES

Of the 243 waves studied, 157 were of the elevation type. These wave lines were coincident [4] with several types of synoptic discontinuities [5] as shown in table 1. Elevation type wave lines were found to coincide with surface cold fronts, cold fronts aloft, pre-cold-frontal

[3] The expression "elevation type wave" is used here in a geometric sense, indicating only that a rise in pressure has occurred. It does not necessarily imply an elevation type wave in the dynamic sense as defined by Tepper [14].

[4] The expression "coincident" must be qualified here. Actually it can only be said that elevation type wave lines apparently coincide with certain synoptic discontinuities. A very critical analysis might reveal that certain such lines are actually distinct and separate from the associated synoptic discontinuities, dependent in part upon a rigorous definition of exactly what constitutes such discontinuities. However, for the purpose of this paper, the lines were in all cases sufficiently close to the associated synoptic discontinuities to be considered as "coincident" in the sense just described.

[5] The analyses of synoptic discontinuities were made by the author and may not necessarily agree with those of other analysts.

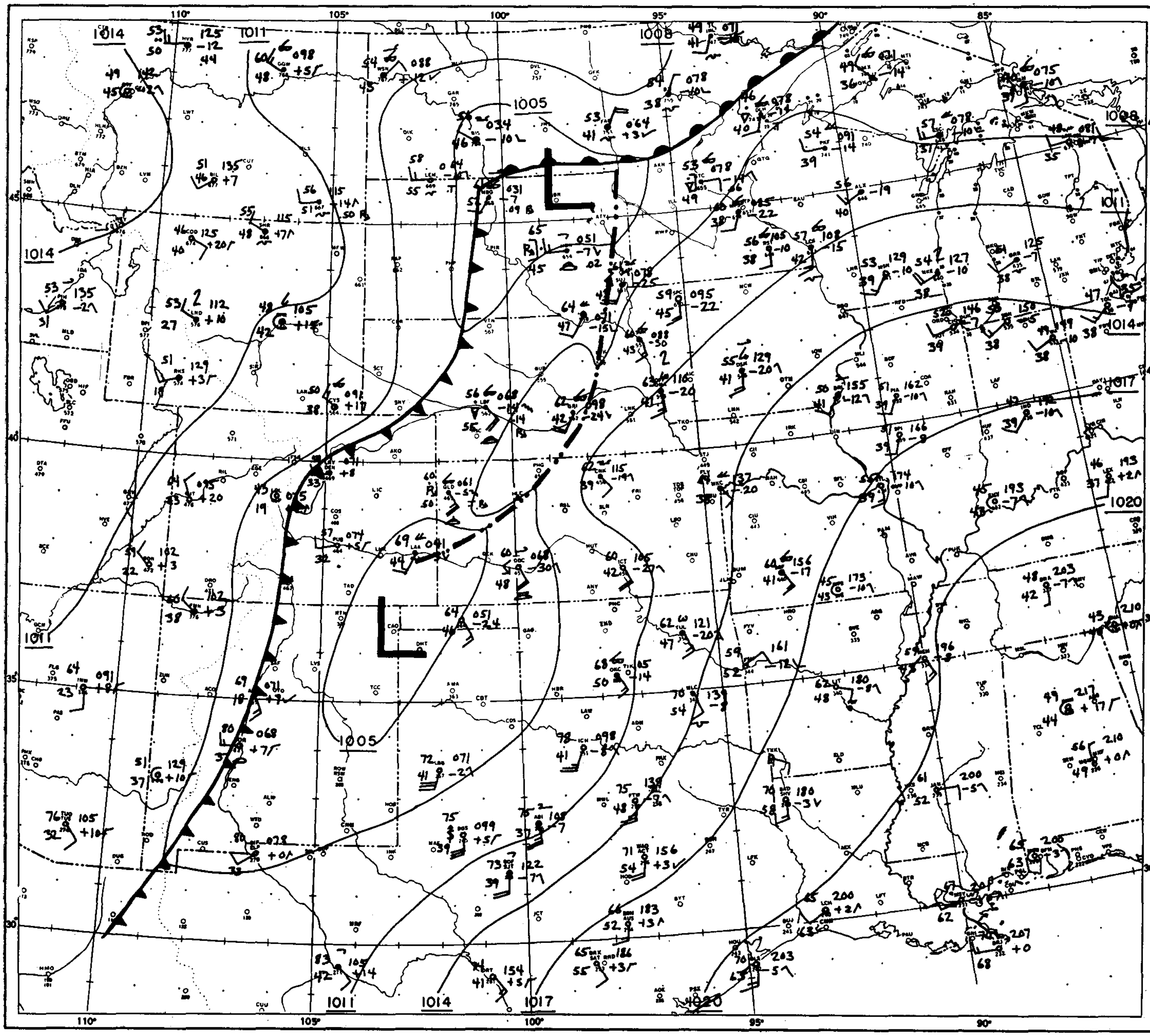

Figure 5.—Sectional synoptic chart of the Central Midwest Area, 0030 CST, May 14, 1952.

squall lines, and isolated squall lines. In addition they also coincided with certain isolated discontinuities which were not obvious at all on the synoptic chart. Elevation type wave lines were never coincident with surface warm fronts.

Most of the wave lines which coincided with isolated discontinuities were small in length and of short duration. Although many of these lines occurred in the vicinity of fronts or squall lines, their orientation was such that they could not properly be classed as fronts or squall lines in the usual sense. Certain possibilities exist relative to these lines: (1) They may represent the movement of so-called "isolated, air mass" thunderstorms; (2) a more refined method of analysis might reveal some of them actually to be fronts or squall lines (Brunk [3] apparently includes similar isolated discontinuities as squall lines); (3) they may represent discontinuities of a unique type which are different from ordinary fronts and squall lines.

The May 13–14, 1952, example, shown in figures 3 and 5–11 is an elevation type wave line which is coincident with a pre-cold-frontal squall line.

Although it is indicated that elevation type wave lines may coincide with certain synoptic discontinuities, it does not follow that such discontinuities always have pressure wave lines in coincidence with them. Furthermore, in many cases, elevation type waves may occur along only limited segments of the discontinuity, rather than along all of it.

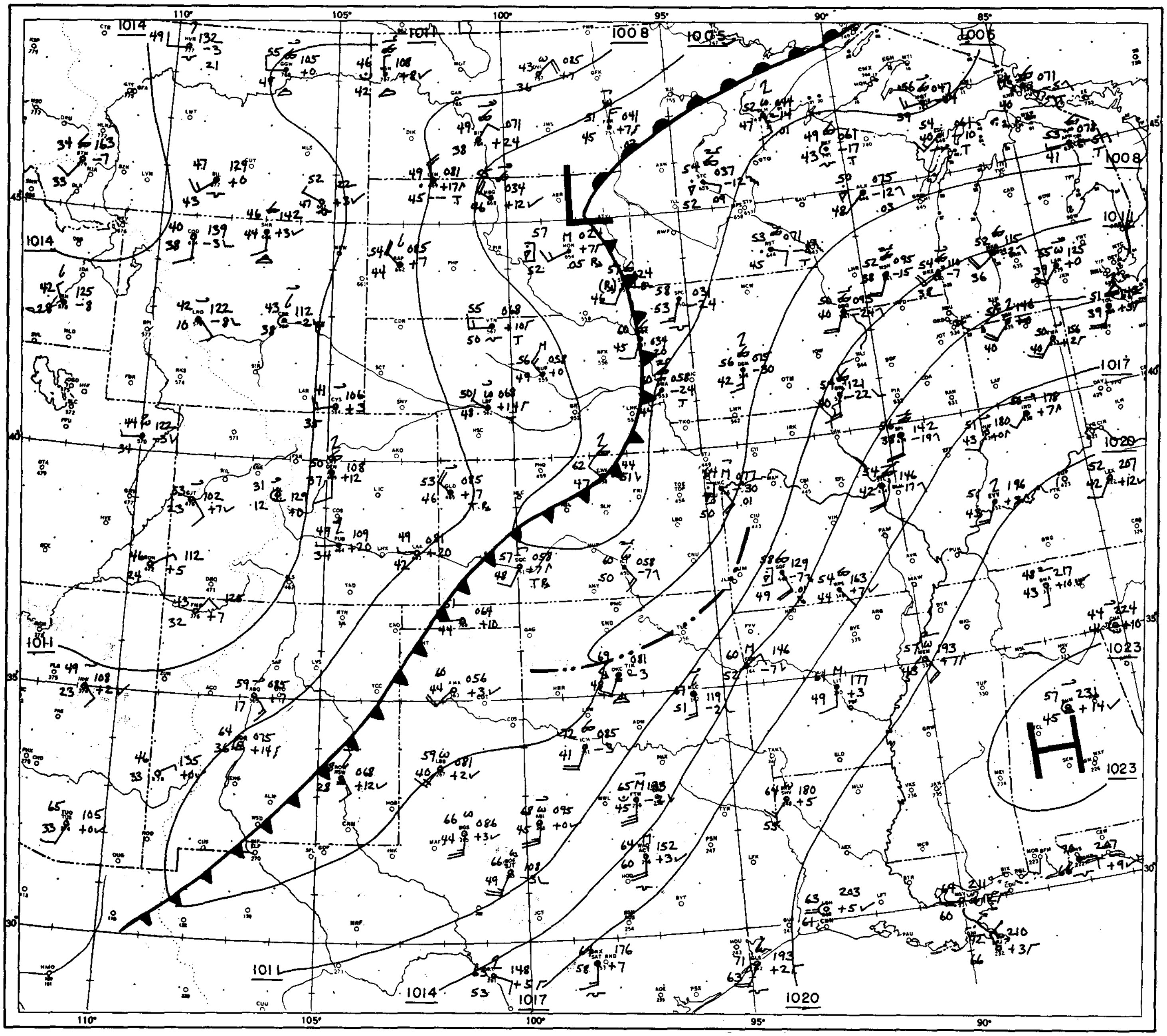

FIGURE 6.—Sectional synoptic chart of the Central Midwest Area, 0630 CST, May 14, 1952.

RELATION TO WEATHER

Thunderstorm activity is generally, but not always, associated with the passage of an elevation type wave line, regardless of the type of discontinuity with which it is coincident. In most cases this activity will be evident as a line of thunderstorms more or less coincident with the line. In some cases the activity may be of less than thunderstorm proportions, i. e. rain showers, cumuli congesti, or brief variations in wind direction and velocity. In some cases there is apparently no activity at all. Thunderstorm activity may be extremely variable along the line; some segments of the line may experience little or no activity, while others may have storms of great severity. Table 1 shows those cases of elevation type wave lines which had associated thunderstorms. Verification of thunderstorm activity was assumed if at least one report of thundershowers, thunder, or lightning was made somewhere in the field at the time that or very shortly after, the line passed the station.

In cases where no thunderstorms were reported, these possibilities exist: (1) Thunderstorms may have occurred along segments of the line which did not pass any reporting stations; (2) lesser activity may have occurred; (3) there may have been no activity at all. Tepper [14] shows that (3) does occur. While this is important in substantiating the pressure jump theory, it is not the usual case. Most elevation type wave lines do have associated thunderstorm activity.

In the May 13–14, 1952, case, thunderstorms occurred at 5 of 15 reporting stations, lightning or thunder was observed at 4 others, and variations in wind direction and velocity were reported at 5 others. Only one station showed no evidence of some activity.

Table 1.—*Features of elevation type wave lines according to their coincidence with various synoptic discontinuities*

Features	Type of discontinuity						
	Pre-cold-frontal squall line	Isolated squall line	Surface cold front	Cold front aloft	Isolated discontinuity	No pressure wave field	Total
Number of cases coincident with synoptic discontinuities	28	5	60	14	50		157
Number of combination types	13	2	11	8	10		44
Percent of combination types	46	40	18	57	20		28
Number of cases with damped harmonic oscillations	4	1	16	3	1		25
Percent of cases with damped harmonic oscillations	14	20	27	21	2		16
Number of cases with thunderstorm activity	25	5	42	11	24		107
Percent of cases with thunderstorm activity	89	100	74	79	71		78
Number of cases without thunderstorm activity	3	0	15	3	10		31
Percent of cases without thunderstorm activity	11	0	26	21	29		22
Number of cases, thunderstorm activity undetermined	0	0	4	0	15		19
Number of cases with tornadoes	14	3	11	5	9	13	55
Percent of cases with tornadoes	50	60	18	36	18		27
Number of tornadoes	35	7	36	12	23	30	143

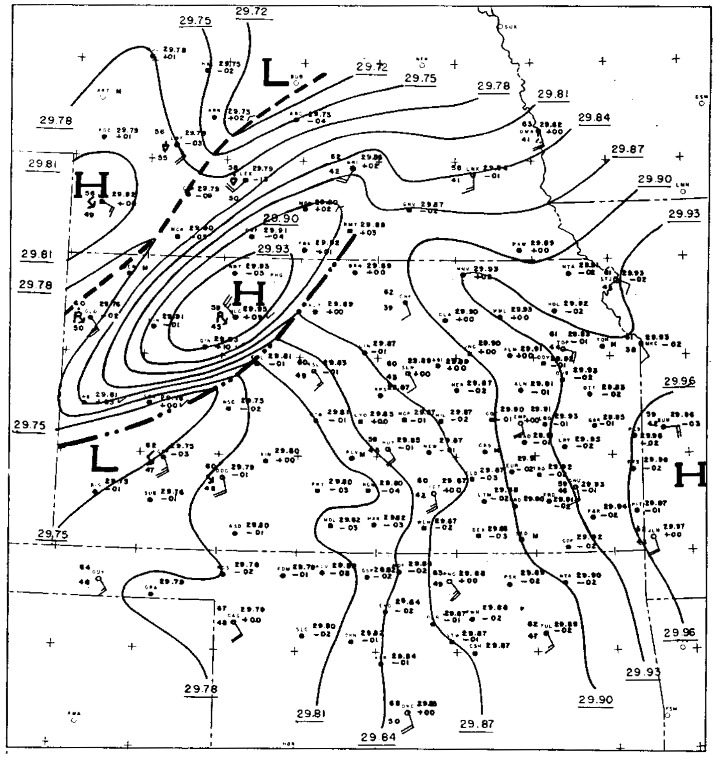

Figure 8.—Micro-synoptic chart, 0030 cst, May 14, 1952. Note that the elevation type wave line (squall line) and depression type wave line have entered the network from the northwest and that they are separated by a small, intense micro-ridge.

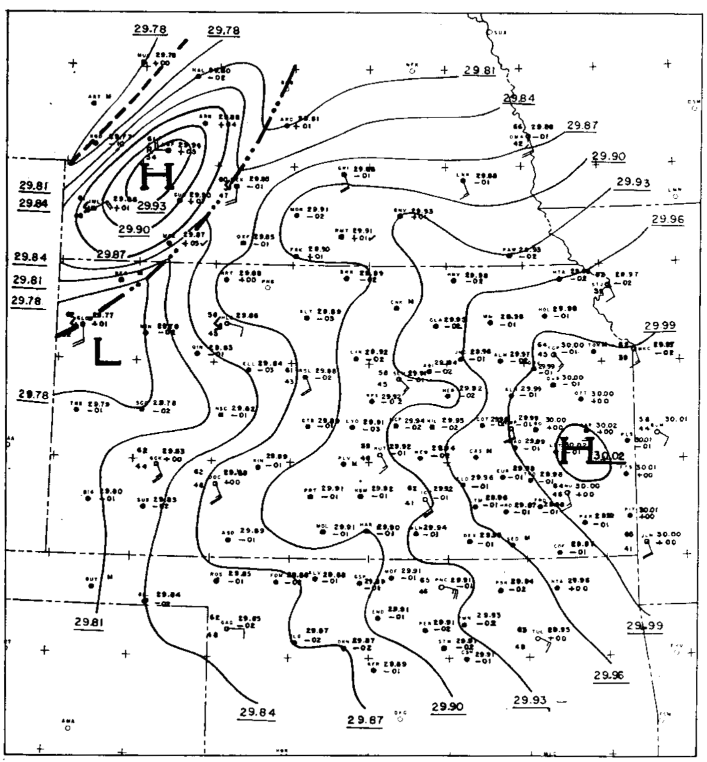

Figure 7.—Micro-synoptic chart, 2230 cst, May 13, 1952. Sea level pressures are plotted in inches and isobars are drawn for each 0.03 inch. Tendencies are plotted in hundredths of inches per 30 minutes. All other data are plotted in the conventional manner.

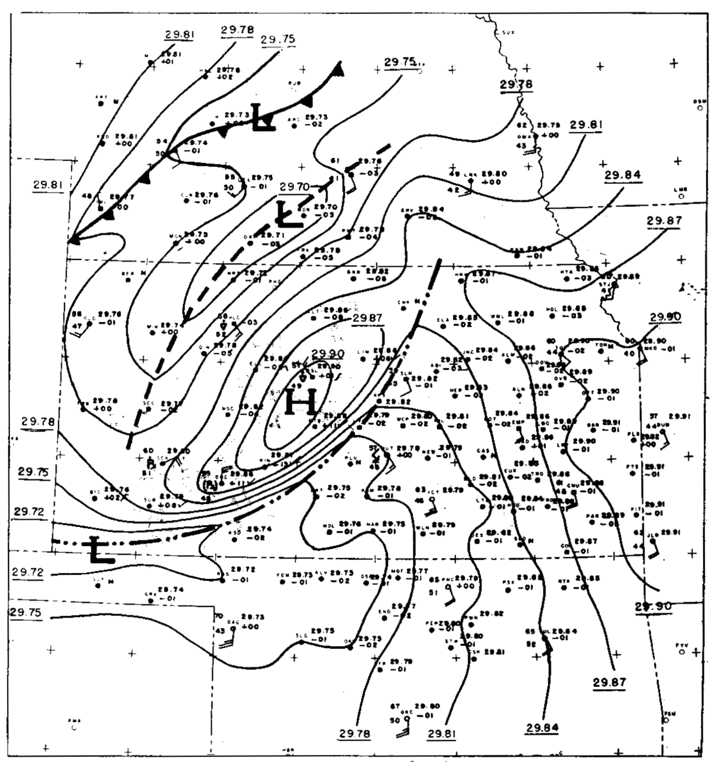

Figure 9.—Micro-synoptic chart, 0230 cst, May 14, 1952. The surface cold front is now entering the network from the northwest. The depression type wave line lies about midway between the cold front and squall line.

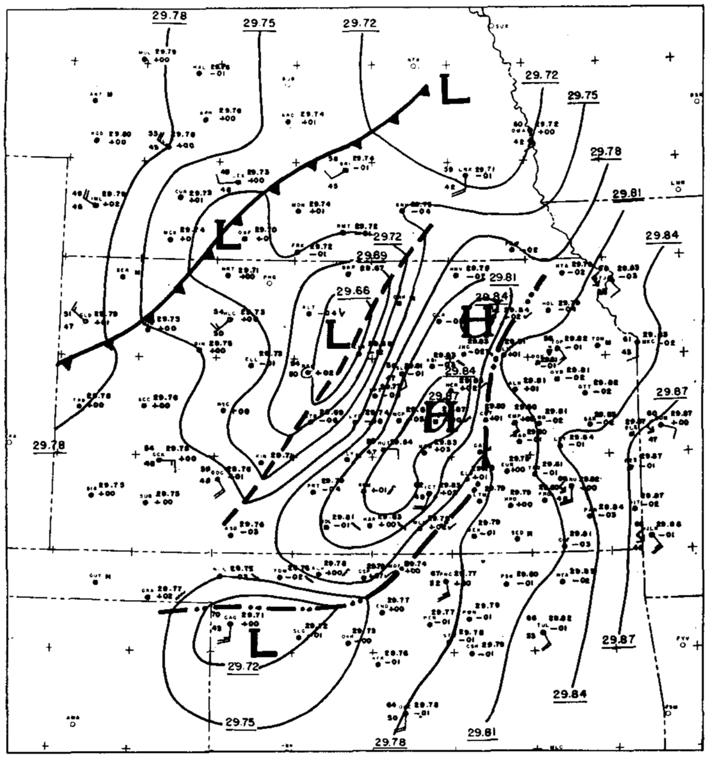

FIGURE 10.—Micro-synoptic chart, 0430 CST, May 14, 1952. The micro-ridge has weakened and elongated. The micro-trough has deepened and its pressure is now lower than the pressure along the surface cold front.

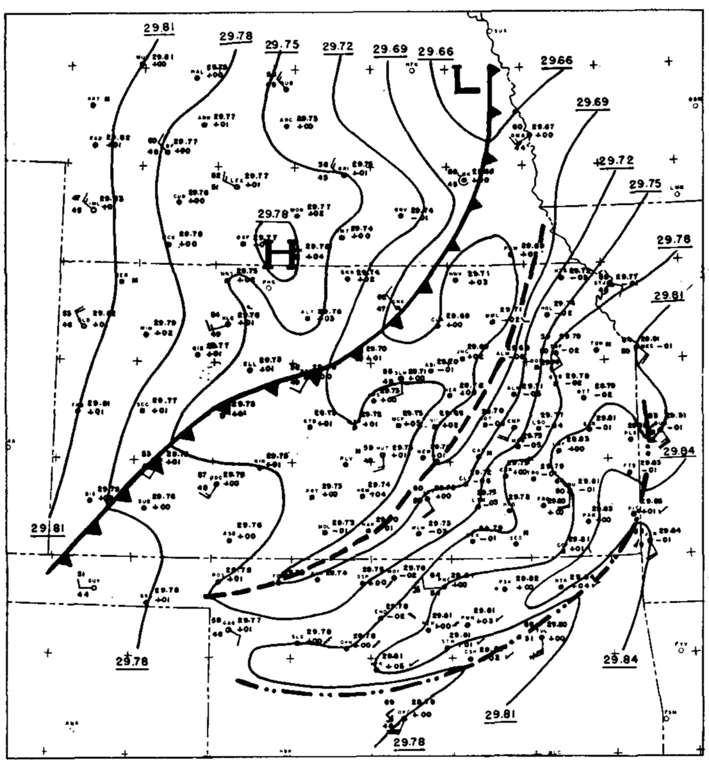

FIGURE 11.—Micro-synoptic chart, 0630 CST, May 14, 1952. The squall line is nearly dissipated. However, a weak micro-ridge and a long narrow micro-trough still remain.

TABLE 2.—*Cases of elevation type wave lines according to directions from which they moved*

Direction in degrees	Number of cases					
	Pre-cold-frontal squall line	Isolated squall line	Surface cold front	Cold front aloft	Isolated discon-tinuity	Total
00–29	-----	-----	2	1	1	4
30–59	-----	-----	-----	-----	-----	-----
60–89	-----	-----	-----	-----	-----	-----
90–119	-----	-----	-----	-----	-----	-----
120–149	-----	-----	-----	-----	1	1
150–179	-----	-----	-----	-----	1	1
180–209	-----	-----	-----	-----	4	4
210–239	2	1	4	-----	7	14
240–269	6	1	6	3	9	25
270–299	6	2	12	6	12	38
300–329	13	1	22	3	8	47
330–359	1	-----	14	1	3	19
Unknown	-----	-----	-----	-----	4	4

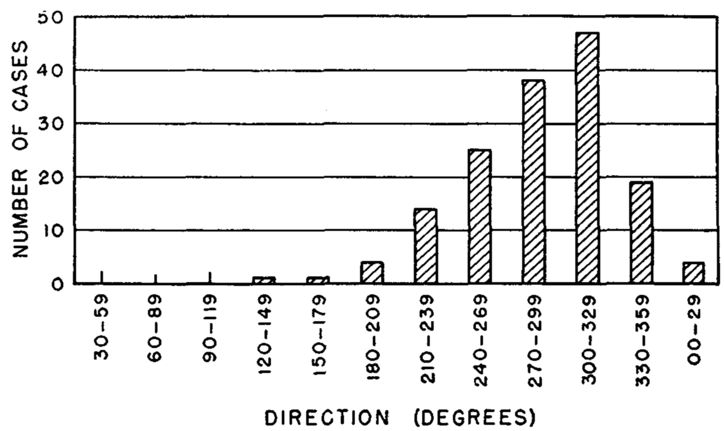

FIGURE 12.—Frequency of directions from which elevation type wave lines moved.

TABLE 3.—*Cases of elevation type wave lines according to speeds at which they moved*

Speed in miles/hour	Number of cases					
	Pre-cold-frontal squall line	Isolated squall line	Surface cold front	Cold front aloft	Isolated discon-tinuity	Total
15–19	3	-----	2	-----	1	6
20–24	1	-----	5	-----	6	12
25–29	5	2	14	2	10	33
30–34	3	1	25	7	7	43
35–39	7	1	8	2	7	25
40–44	5	1	3	3	5	17
45–49	3	-----	2	-----	3	8
50–54	1	-----	-----	-----	4	5
55–59	-----	-----	1	-----	1	2
60 and over	-----	-----	-----	-----	2	2
Unknown	-----	-----	-----	-----	4	4

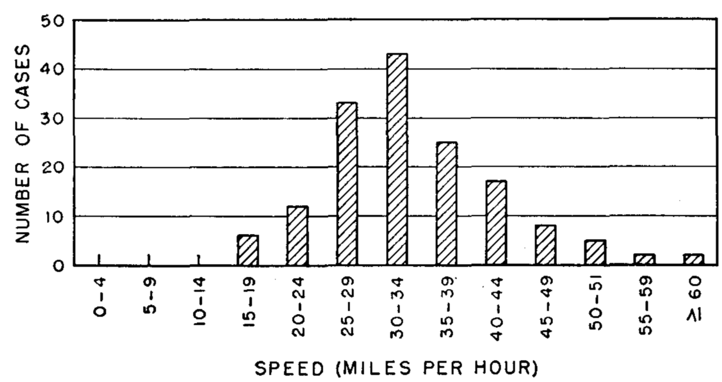

FIGURE 13.—Frequency of speeds at which elevation type wave lines moved.

Although thunderstorms are shown generally to occur along elevation type wave lines, they may also occur without an appreciable pressure wave. Pre-warm-frontal thunderstorms and truly isolated, air mass thunderstorms are in this category. No attempt was made to enumerate those thunderstorms which occurred without coincident pressure wave lines.

MOTION

Motion is assumed to be normal to the elevation type wave line itself, and is usually such that the central portions of the line move in advance of the extremities. Hence, the lines are usually convex toward the direction of motion.

Directions from which the 157 elevation type wave lines moved are summarized in table 2 and the frequency distribution of movement from the various directions is graphed in figure 12. Note that a maximum of lines moved from 300°–329° (northwest), and that none moved from 30°–119° (east and northeast).

Speeds at which the 157 elevation-type wave lines moved are summarized in table 3 and the frequency distribution of the various speeds is graphed in figure 13. A maximum of lines had speeds within the range of 30 to 34 miles per hour.

The above are average values. Since any pressure wave line may accelerate or decelerate either in local segments or along its entire length, there is considerable variation from the averages given.

SIZE, AMPLITUDE, AND DURATION OF PRESSURE WAVE FIELDS

Pressure wave fields varied considerably in size. Some covered virtually the entire network (about 150,000 square miles), and presumably additional areas outside the network were covered in many cases. On the other hand, fields were sometimes as small as a few counties (about 5,000 square miles). It is further possible that some fields were actually smaller than the spacings between stations; hence were not identified. The usual case was one wherein the field covered about half a State (about 40,000 square miles).

Most pressure wave fields had one or two centers of maximum amplitude. In many cases the centers of maximum amplitude coincided with the centers of maximum intensity of the weather elements, such as severe thunderstorms, windstorms, hail, heavy rain, and occasionally tornadoes. Maximum amplitude of pressure wave fields ranged from 0.03 inch to 0.30 inch. The maximum amplitudes as related to coincident synoptic discontinuities are summarized in table 4 and the frequency distribution of all maximum amplitudes is graphed in figure 14.

Duration of pressure wave fields could, unfortunately, be considered only within the network. Although the durations of all fields over the network were computed, the findings do not give a complete picture. However, it was learned that some fields endured for at least 14 hours, while others existed not even 1 hour. Many of the fields were in existence less than 6 hours.

PREFERRED HOURS AND AREAS OF OCCURRENCE

Pressure waves showed a marked tendency to occur during nocturnal hours. Maximum occurrence was between 2100–2259 CST and 2300–0059 CST, with 80 of the 157 waves in occurrence during each of these 2-hour periods. Minimum occurrence was between 1100–1259 CST with only 5 of the 157 waves in occurrence during this 2-hour period. Ratio of maximum to minimum is 16 to 1. The bihourly occurrences according to synoptic discontinuities are summarized in table 5 and the bihourly frequency distribution of all elevation type waves is graphed in figure 15.

Elevation type waves showed some tendency to occur more often in certain portions of the network than in

Table 4.—*Cases of elevation type waves according to their maximum amplitude*

Maximum amplitude (Inches)	Number of cases					
	Pre-cold-frontal squall line	Isolated squall line	Surface cold front	Cold front aloft	Isolated discontinuity	Total
0.01–0.05	3		8		11	22
0.06–0.10	12	3	27	3	21	66
0.11–0.15	6	1	15	3	9	34
0.16–0.20	5	1	8	7	4	25
0.21–0.25	1		1	1	1	4
0.26–0.30	1		1			2
Undetermined					4	4

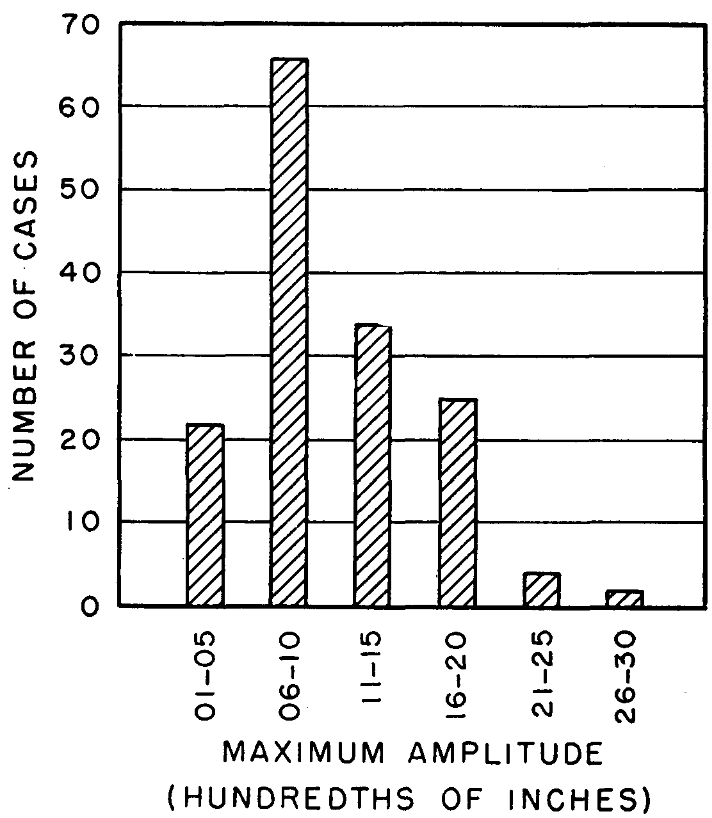

Figure 14.—Frequency of maximum amplitudes of elevation type waves.

TABLE 5.—*Bihourly occurrences of elevation type waves*

Inclusive hours, CST	Number of cases					
	Pre-cold-frontal squall line	Isolated squall line	Surface cold front	Cold front aloft	Isolated discon-tinuity	Total
2300-0059	16	2	37	8	17	80
0100-0259	16	2	35	7	14	74
0300-0459	11	2	34	4	14	65
0500-0659	8	2	26	3	13	52
0700-0859	6	2	17	3	10	38
0900-1059	3	1	9	2	5	20
1100-1259	1	0	1	1	2	5
1300-1459	5	1	1	2	5	14
1500-1659	9	2	14	2	13	40
1700-1859	15	3	20	5	17	60
1900-2059	16	2	29	7	18	72
2100-2259	19	2	34	10	15	80

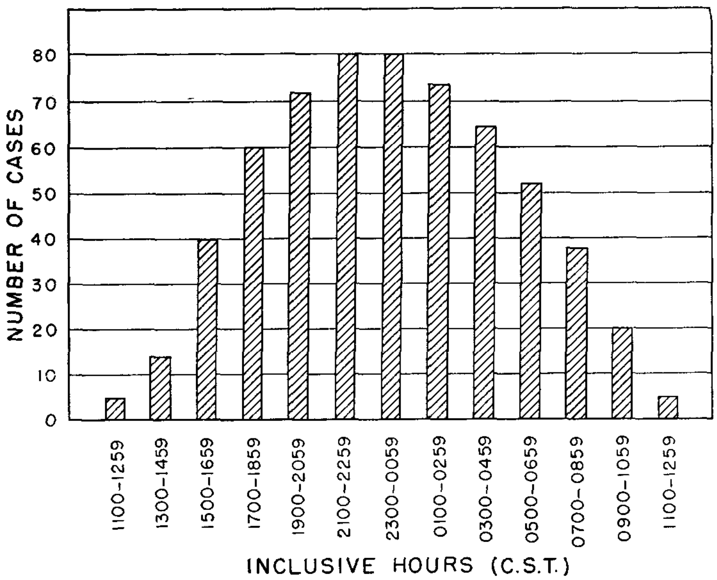

FIGURE 15.—Bi-hourly frequency of elevation type waves.

others. Maximum occurrence was at Ellis, Kans., with 52 of the 157 waves occurring there. However, a line of maxima existed along a general north-south line which is roughly coincident with the 2,000-foot elevation contour. An area of secondary maxima existed farther east where Cottonwood Falls, Kans., had 49 of the 157 waves occurring there. Here again a line of maxima existed in a general north-south line which is roughly coincident with the Flint Hills region of Kansas. The significance of these maxima may be questionable, inasmuch as they occurred near the center of the network; a pressure wave line entering the network at random would have a greater chance of passing the center of the network than any other portion. Subsequent investigations, using data from the larger network of the 1953 project, may either prove or disprove the above findings. Although centers and lines of minimum occurrence did not exist, some portions of the network experienced fewer waves than others. Big Bow in extreme southwestern Kansas experienced only 16 of the 157 waves. The number of occurrences for each station is shown in figure 16.

The fact that preferred hours and areas of occurrence

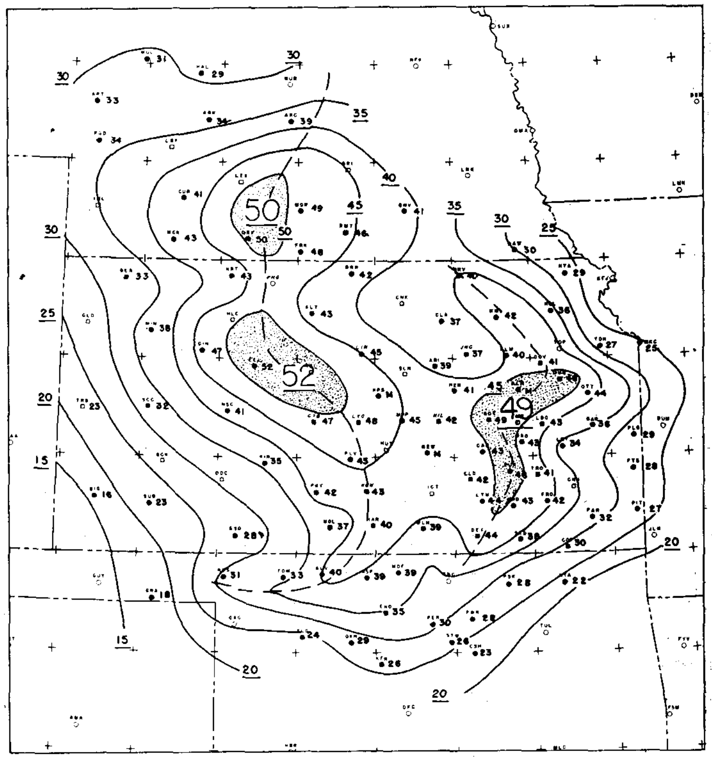

FIGURE 16.—Number of occurrences of elevation type waves per station. Isopleths are drawn for every 5 occurrences

exist for elevation type waves might suggest that synoptic discontinuities generally have such a preference in their occurrence. This is not necessarily true. It is known from these data only that those synoptic discontinuities which coincide with elevation type wave lines have preferred hours and areas of occurrence.

DEPRESSION TYPE WAVES [6]

WAVE PATTERNS

Depression type wave patterns on the barograms vary, and any one field seldom has a unique pattern. A few patterns, examples of which are shown in figure 2 are: Abrupt pressure fall, gradual pressure fall, and V-shaped trough.

RELATION TO SYNOPTIC DISCONTINUITIES

Of the 243 pressure wave lines studied 80 were of the depression type. They are apparently discontinuities of a unique type which do not coincide with ordinary synoptic discontinuities. However, as will be shown later, some of them do have certain associations with various synoptic discontinuities. A depression type wave line, associated with a pre-cold-frontal squall line, is shown in the May 13–14, 1952, case in figures 4 and 7–11.

RELATION TO WEATHER

Whereas elevation type wave lines are characterized by their coincidence with thunderstorm activity, depression type wave lines are characterized by their lack of such

[6] The expression "depression type wave" is used here in a geometric sense, indicating only that a fall in pressure has occurred. It does not necessarily imply a depression type wave in the dynamic sense as defined by Tepper [14].

activity. Although thunderstorms were occasionally present during their passage, such storms were usually in the dissipating stage, having begun with the earlier passage of an elevation type wave line.

OTHER FEATURES

Motion of depression type wave lines; size, amplitude, and duration of the fields; preferred hours and areas of occurrence; etc., were investigated. These features are very similar to the corresponding features of elevation type wave lines, and a discussion of the findings will not be given.

Depression type waves have been recognized by other authors. Brunk [2, 3] refers to them as "pressure pulsations." Tepper [12, 14], uses the expression "depression type wave," which has been adopted by the author.

COMBINATION TYPE WAVES

In frequent cases an elevation type wave was followed by a depression type wave. Time interval between the two waves ranged from less than an hour to several hours. Of the 243 waves studied there were 44 cases (88 waves) of the combination type. An example of a combination type wave is shown in the barogram in figure 17.

Although depression type wave lines never coincide with any synoptic discontinuities, those of the combination type may be considered as associated with certain discontinuities. Table 1 shows various synoptic discontinuities with which combination types occurred. The examples shown in figures 3–11 are combination types.

Thunderstorm activity with a combination type wave is rather sharply defined. It begins abruptly at the onset of the elevation wave and ceases nearly as abruptly at the trough of the depression type wave.

The fields of combination type waves covered about the same areas for their component cases with some exceptions. There was, however, a tendency for the field of one to be offset from the field of the other by as much as 200 miles. Centers of maximum amplitude were offset in the same manner. Direction of the offset was usually north to east for the depression type wave. The offset of fields occasionally produced situations where individual stations in either of the fields experienced one wave but not the other. Small, intense fields were sometimes completely offset from each other.

In the case of a combination type wave associated with a pre-cold-frontal squall line (see figs. 5–11), the presence of the wave lines may lead to erroneous locations of the synoptic discontinuities. Specifically the surface cold front may be placed incorrectly in the trough of the depression type wave line. During squall line formation, this error will indicate an apparent acceleration of the surface cold front. Later, when the squall line (elevation type wave line) and depression type wave line have dissipated, the cold front, being correctly located again, will appear to have decelerated or even to have retrograded.

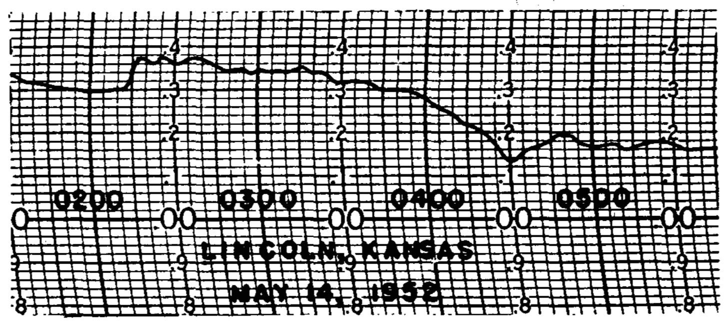

FIGURE 17.—Example of a combination type pressure wave as recorded by the 12-hour barograph.

In attempting to understand the reasons for a combination type wave, the following possibilities are offered: (1) In some cases the depression type wave may represent a return to normal pressure following the passage of the elevation type wave. (2) In a sense the micro-trough of the depression type wave may represent the area from which air was removed to build up the micro-ridge of the elevation type wave. (3) The two waves may represent a unique association which is the result of certain mechanisms.

The question arises concerning those elevation type waves and depression type waves that did not occur in combination. These explanations are offered: (1) Many waves undoubtedly do not exist in combination; the separate waves occur from independent mechanisms. (2) In some cases the apparently missing member of the combination may have existed but may have been obscured by other pressure changes. An extreme offset effect may occasionally make the combination unrecognizable.

Brunk [2, 3] has recognized the combination of waves as related to squall lines. However, there is at present no conclusive evidence to show that the "pressure pulsation" ever develops into a tornado. Neither should this area of low pressure be confused with the "tornado cyclone" [1] or the "micro-low" [15]. These low pressure areas were observed to occur directly along the elevation type wave line. Combination type waves are separated in time and space.

ROTATING STORMS

MICRO-CYCLONES

It was hoped that more could be learned of the micro-low [15] and the tornado cyclone [1]. Although there was frequent evidence of a fall in pressure in advance of the elevation type wave line, no important low centers along the line could be isolated. Either micro-cyclones are exceedingly rare, or else the network was too coarse to indicate them.

TORNADOES

It would be appropriate to present a typical barograph trace of a station experiencing a tornado. However, except for one or two cases where a small tornado occurred within a few miles of a station, no high speed barograph traces of a tornado itself were recorded by the 1952 network. Although it is generally known that a great reduction in pressure occurs within the tornado, the exact relationship of this pressure change to pressure wave lines is not clear enough at this time to indicate a satisfactory idealized trace.

The occurrence of tornadoes was generally (although not always) along elevation type wave lines, i. e., pressure jump lines. This is in agreement with earlier findings of Tepper [9, 11]. A total of 143 tornadoes[7] was reported to have occurred over the network in 1952. These tornadoes occurred under 55 different synoptic situations. Table 1 indicates the occurrence of tornadoes according to their association with elevation type wave lines. From this table it is evident that any synoptic discontinuity that is coincident with an elevation type wave line, can be suspect of tornadoes.

It is indicated that a sizable number of tornadoes occurred without the presence of an elevation type wave field. In this regard certain possibilities exist: (1) A reexamination of the barograms with the knowledge that tornadoes had occurred, might reveal a weak field. (2) The field may have been too local to have been recorded at any of the barograph stations. (3) There may actually have been no field at all.

It was previously indicated that elevation type waves occur much more frequently during late evening hours. In view of the fact that tornadoes are thought to occur most often in the Central Midwest area during late afternoon hours, it may seem inconsistent that such an association exists. This fact leads us to the finding that the earlier an elevation type wave line enters the network, the more likely will be the occurrence of tornadoes. Beginning time for all elevation type wave lines averaged 2110 CST. Beginning times for those which had associated tornadoes averaged 1730 CST or 3 hours and 40 minutes earlier.

In seeking a further relationship between elevation type wave lines and tornadoes, it became apparent that tornadoes did not occur at random in the pressure wave field. It was possible to classify tornadoes into three general categories relative to the portions of the field in which they occurred, as follows: (1) At or near the inception of the field. (2) At or near the southern boundary of the field. (3) At or near the center of maximum amplitude. Table 6 summarizes the number of occurrences relative to these categories. An idealized isochrone chart showing these areas of occurrence is given in figure 18.

In seeking an answer as to why tornadoes occurred in certain portions of the field and not in others, this fact was noted: In most cases where tornadoes occurred, there was a marked difference in amplitude of the pressure wave

TABLE 6.—*Number of tornadoes located in various parts of the pressure wave field*

Location relative to pressure wave field:	Number of tornadoes
At or near inception of field	23
At or near center of maximum amplitude	47
At or near southern boundary of field	23
No unique portion of field	11
Undetermined	9
No apparent pressure wave field	30
Total	143

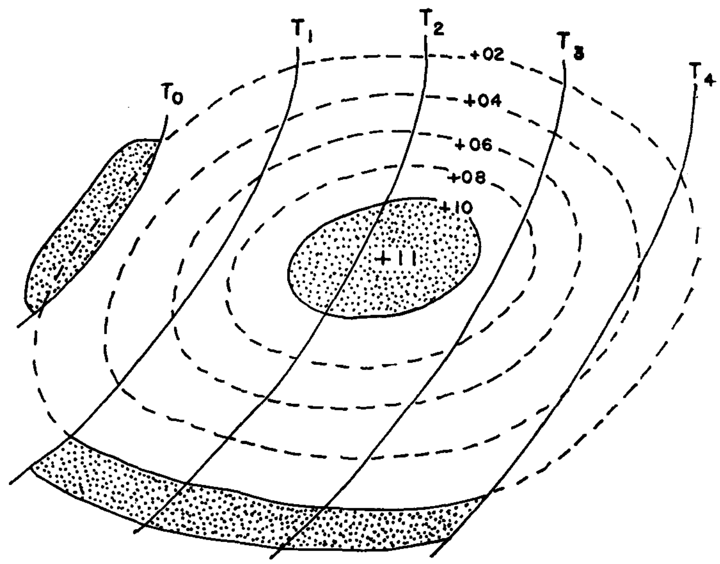

FIGURE 18.—Idealized isochrone chart showing preferred areas of tornado occurrence. Tornado areas are shaded.

from one side of the tornado zone to the other. Change was always from little or no wave to an intense wave. Such changes frequently occurred within a distance no greater than the spacing between stations (25 to 50 miles), and very likely within much smaller distances (possibly less than a mile). Direction of change was either normal to the wave line and in the direction of its motion, or northward along the line. A study of the forces prevailing to cause such variations in the pressure wave might reveal how tornadoes are generated. Specifically a very large wind shear value might be obtained, and the resulting vorticity could be sufficient (other conditions favorable) to generate a tornado.

DUST DEVILS

On three occasions dust devils, or whirlwinds, occurred very close to the station at Big Bow, Kans. On two of these occasions there were no clouds in the sky. Although the dust devils did not occur along pressure wave lines, it is interesting to note that changes in pressure did occur locally. Pressure change on the Big Bow barograph for the best case was a nearly symmetrical V-shaped trough of about 1 minute width and 0.04 inch depth.

CONCLUSIONS

1. The frequent occurrence of pressure wave lines and associated weather indicates that such weather is very

[7] Reports of tornadoes were screened from all available sources, including observer reports and news clippings. Not all tornadoes were confirmed. Although the accuracy of these reports leaves much to be desired, the information is probably as reliable as it has been in previous years.

common. Much of the thunderstorm activity, severe and otherwise, in the Central Midwest area, is related to pressure wave lines.

2. Elevation type wave lines may coincide with certain synoptic discontinuities; namely, pre-cold-frontal squall lines, isolated squall lines, surface cold fronts, and cold fronts aloft. They may also be isolated. They do not coincide with surface warm fronts. Elevation type wave lines are characterized by thunderstorm activity, which may be severe.

3. General features of elevation type wave lines are amazingly similar, even though such lines may coincide with a variety of synoptic discontinuities.

4. Depression type wave lines are discontinuities of a unique type, which do not coincide with ordinary synoptic discontinuities. They are characterized by a lack of or cessation of thunderstorm activity.

5. The continuity of pressure wave lines and their continuous movement indicates that there is nothing random about the occurrence and movement of severe storms. Although truly isolated air mass thunderstorms occur, many storms thus labeled actually coincide with isolated pressure waves that move in a regular manner.

6. Many elevation and depression type waves occur in combination.

7. The existence of preferred hours and areas of occurrence suggests that diurnal and topographic forces are dominant in the genesis of pressure waves, this being true even though the pressure wave line may be immediately related to some synoptic discontinuity. The occurrence of pressure waves in the Central Midwest area is believed to be intimately related to the presence of the Rocky Mountains.

8. The occurrence of most tornadoes along elevation type wave lines (or pressure jump lines) substantiates Tepper's findings. Tornadoes occur in enough cases (27 percent for the 1952 season) to make this assocation significant. The further tendency for tornadoes to occur in certain portions of the pressure wave field is of interest and may indicate some of the forces that generate tornadoes.

9. Pressure waves may be of very short duration and may cover a very small area. This localizing of the forces involves leaves a most difficult forecast problem. A knowledge of typical features of pressure wave lines will help to minimize this problem.

ACKNOWLEDGMENTS

The author is indebted to the following: Mr. C. F. Van Thullenar and Mr. D. C. House, who gave frequent suggestions and encouragement; Mr. Harry A. Gordon, Jr., who performed much of the routine computations; and Dr. Harry Wexler and Dr. Morris Tepper, whose interest and guidance made the preparation of the paper possible.

REFERENCES

1. E. M. Brooks, "The Tornado Cyclone" *Weatherwise*, vol. 2, No. 2, Apr. 1949, pp. 32–33.
2. Ivan W. Brunk, "The Pressure Pulsation of 11 April 1944" *Journal of Meteorology*, vol. 6, No. 3, June 1949, pp. 181–187.
3. Ivan W. Brunk, "Squall Lines," *Bulletin of the American Meteorological Society*, vol. 34, No. 1, Jan. 1953, pp. 1–9.
4. H. R. Byers and R. R. Braham, *The Thunderstorm*, U. S. Weather Bureau, Washington, D. C., 1949. (See pp. 66–71.)
5. John C. Freeman, Jr. "Map Analysis in the Vicinity of a Pressure Jump," *Bulletin of the American Meteorological Society*, vol. 31, No. 9, Nov. 1950, pp. 324–325.
6. John C. Freeman, Jr., "The Solution of Nonlinear Meteorological Problems by the Method of Characteristics," *Compendium of Meteorology*, American Meteorological Society, Boston 1951, pp. 421–433.
7. T. Fujita, "Micro-Analytical Study of Thunder Nose," *Geophysical Magazine*, vol 22, 1951, pp. 71–88.
8. T. Nanekawa, "Study of Minor Fluctuations of Atmospheric Pressure, Part I", *Memoirs of the College of Science*, Kyoto University, Series A, vol. 17, No. 6, 1934.
9. M. Tepper, "A Proposed Mechanism of Squall Lines: The Pressure Jump Line," *Journal of Meteorology*, vol. 7, No. 1, Feb. 1950, pp. 21–29.
10. M. Tepper, "Radar and Synoptic Analysis of a Tornado Situation," *Monthly Weather Review*, vol. 78, No. 9, Sept. 1950, pp. 170–176.
11. M. Tepper, "On the Origin of Tornadoes," *Bulletin of the American Meteorological Society*, vol. 31, No. 9, Nov. 1950, pp. 311–314.
12. M. Tepper, "On the Dessication of a Cloud Bank by a Propagated Pressure Wave," *Monthly Weather Review*, vol. 79, No. 4, Apr. 1951, pp. 61–70.
13. M. Tepper, "The Tornado and Severe Storm Project," *Weatherwise*, vol. 4, No. 3, June 1951, pp. 51–53.
14. M. Tepper, "The Application of the Hydraulic Analogy to Certain Atmospheric Flow Problems," *Research Paper No. 35*, U. S. Weather Bureau, Washington, D. C., 1952.
15. D. T. Williams, "A Surface Micro-Study of Squall-Line Thunderstorms," *Monthly Weather Review*, vol. 76, No. 11, Nov. 1948, pp. 239–246.