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RECORDED PRESSURE DISTRIBUTION IN THE OUTER PORTION OF A TORNADO VORTEX

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ABSTRACT

Records are presented from nine barographs located in a small area close to the path of a tornado. The pressure profile in the range from 720 to 2,300 feet from the path of the tornado center as determined from the barograph records was found to be in good agreement with calculations based on a simple model consisting of a frictionless vortex with in-flow.

INTRODUCTION

On June 8, 1953, a tornado passed through a portion of the Lewis Flight Propulsion Laboratory of the National Advisory Comittee for Aeronautics located at the Cleveland-Hopkins Airport, Cleveland, Ohio. A total of eight barographs were in operation at various locations within the laboratory at the time. These instruments plus one additional barograph at the United States Weather Bureau Station nearby provided records of the pressure changes during the passage of the tornado at distances from the path of the center varying from 720 to 2,300 feet.

The principal purpose of this paper is to present the pressure data and other pertinent information, since it is believed that the observations may be of considerable value in the study of the dynamics of tornadoes. A simple analysis, in which the observed pressure distribution is compared with the theoretical distribution calculated for a vortex with in-flow, is also included.

Appreciation is extended to the United States Weather Bureau for providing a copy of the barogram and other meteorological data from the Weather Bureau Airport Station, Cleveland, Ohio.

GENERAL DESCRIPTION OF STORM

The tornado approached from the west and passed through the southern part of the Lewis Laboratory at about 9:45 p. m. EDT, continuing on an east-northeasterly heading across the Airport. The tornado was associated with a severe thunderstorm with almost continuous cloud-to-cloud lightning. Hailstones up to about an inch in diameter fell in many areas on both sides of the tornado path and one reliable report of hail the size of hen's eggs was received. Hail was not observed at the Airport.

An aerial survey was made the following day to determine the general path of the tornado from areas west of Cleveland to its disappearance over Lake Erie on the east side of Cleveland. It was possible to plot this path from observations of points of destruction such as damaged dwellings and farm buildings and uprooted trees. The plot of the path of the tornado is shown on the map in figure 1. It will be noted from this plot that the tornado maintained almost a straight easterly heading for about 37 miles west of Cleveland Airport and then about at the Airport turned northeasterly to a heading of approximately 55 degrees through the densely populated areas

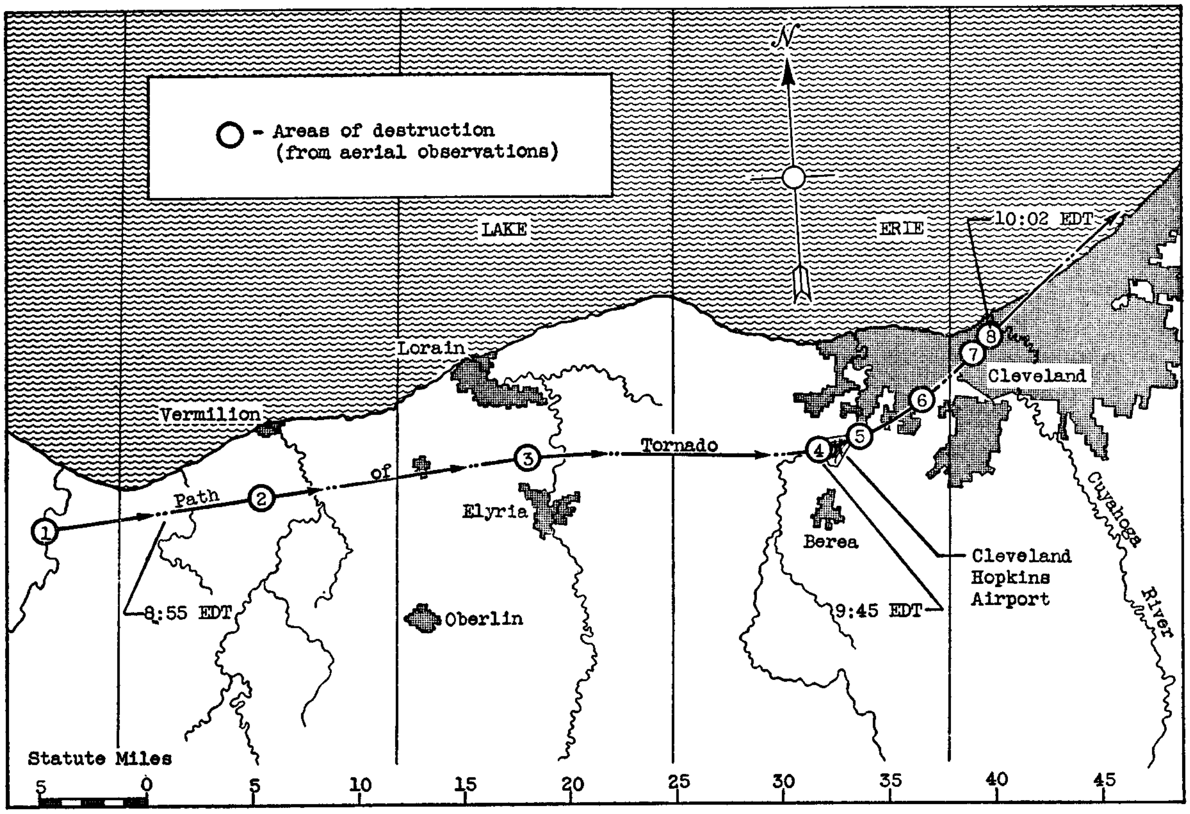

FIGURE 1.—Map of northern Ohio showing path of tornado on June 8, 1953.

of Cleveland. The numbered points along the tornado path indicate all the areas of destruction visible from the air. Other destruction between these points may have occurred. (Ground strikes were difficult to observe over open farming country west of the Airport). However, it was apparent that the center of the tornado skipped over considerable distances along the path.

Because of the large intervals between points of observed damage, the possibility exists that more than one tornado was involved. However, the facts that all the visible areas of damage could be connected by a reasonably smooth curve and that the time of observation at three points (as shown in fig. 1) indicated a nearly uniform speed of about 35 m. p. h. support the hypothesis that only a single tornado occurred. On the other hand, the western extremity of the tornado path may have been farther west than plotted on the map of figure 1. Damage was reported as far west as Bowling Green, Ohio, which is over 90 miles from the Cleveland Airport. Bowling Green is approximately on a straight line extension of the east-west tornado path plotted in figure 1. The aerial survey did not extend beyond the first point on the map.

METEOROLOGICAL DATA

Barograph records.—Barograph traces showing the passage of the tornado were obtained from eight instruments at the Lewis Laboratory located at the points shown on the detailed map in figure 2. The approximate path of the tornado center and the location of points where damage occurred are also shown in figure 2. One additional barogram (from outside the area of fig. 2) was obtained from the Weather Bureau Airport Station located across the Airport about 1.3 miles east of the laboratory.

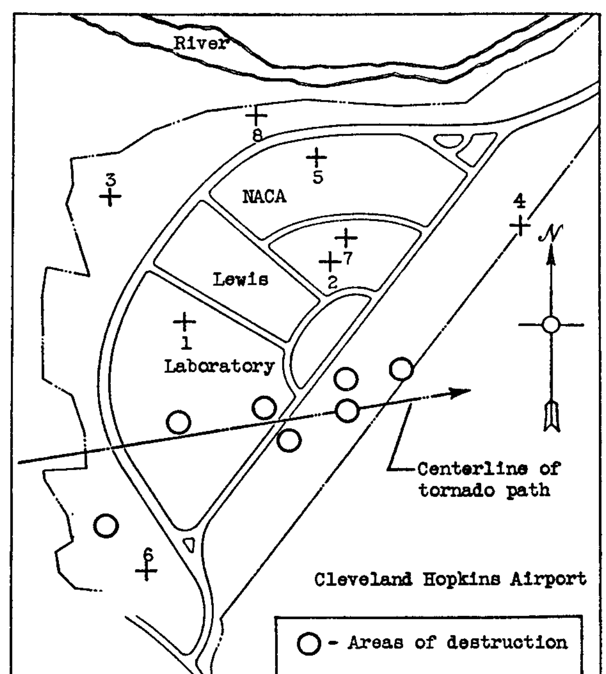

FIGURE 2.—Path of tornado of June 8, 1953, across NACA Lewis Laboratory in relation to areas of destruction and barograph locations.

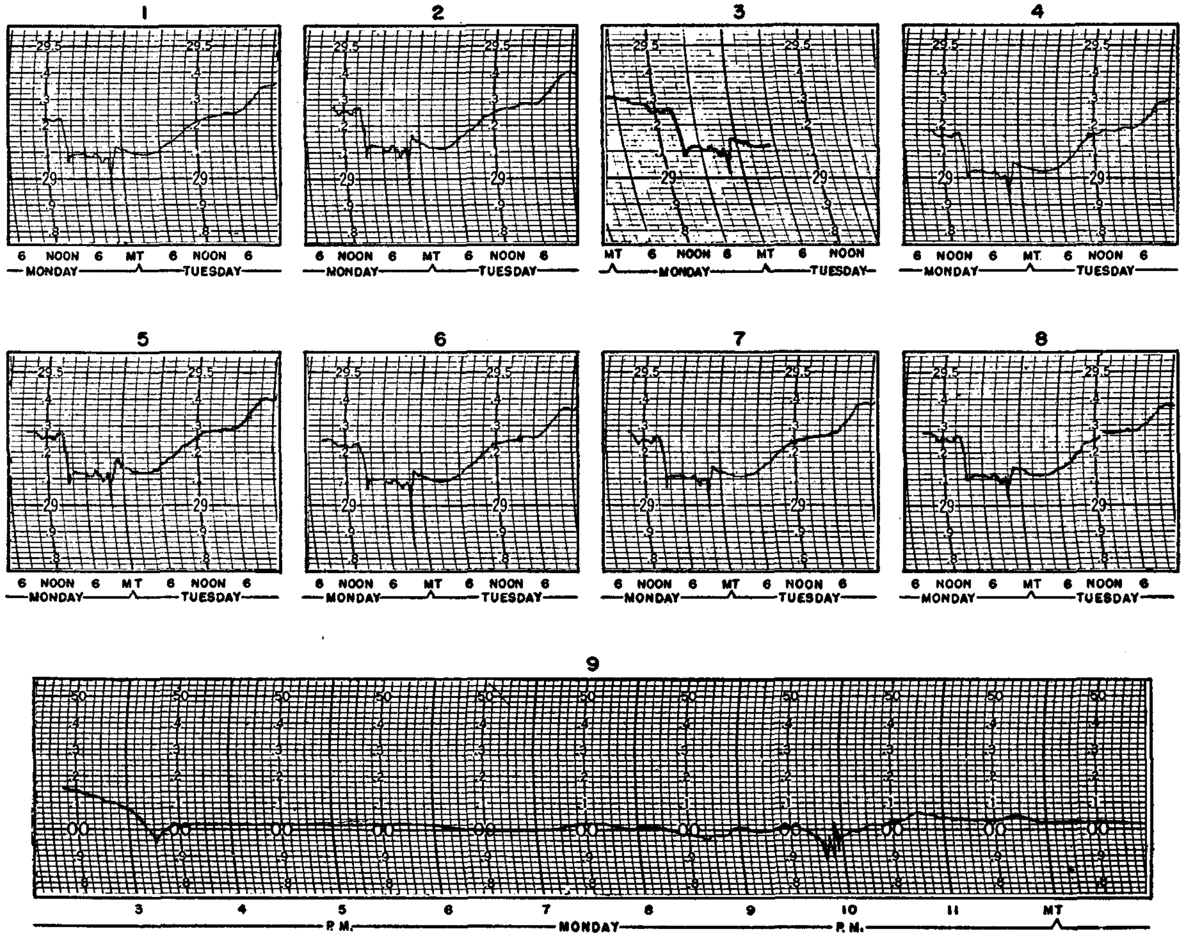

FIGURE 3.—Barograph traces recorded during passage of tornado of June 8, 1953. (Barograms 1–8 at NACA Lewis Laboratory; barogram 9 "fast-run" at Weather Bureau Airport Station.)

The nearest approach of the tornado to the Weather Bureau Station was estimated at about 2,300 feet to the north-northwest. Copies of the barograms are reproduced in figure 3. Station identification numbers from 1 to 8 were assigned to the NACA barograph locations as shown in figure 2, and the Weather Bureau Station barograph was designated as station 9.

As would be expected, the barograms from the eight NACA instruments are nearly identical except for the extent of the pressure drop during the tornado. All the records show a rapid fall in pressure in the early afternoon, amounting to 6 millibars in about an hour. This fall was quickly followed by a slight rise, after which the pressure remained fairly steady until about 7 p. m. EDT. The pressure was unsteady from 7 to 9:30 p. m. followed by a sudden fall as the tornado approached. After the passage of the tornado, the pressure rose steadily for about 45 minutes and then fell slowly to a steady, flat minimum about five hours after the storm.

If it is assumed that nearly all of the pressure change associated directly with the tornado passage occurred within a mile of the center, the pressure fall and recovery took place in less than 4 minutes, since the speed of the tornado was about 35 miles an hour. The time scale of the NACA barographs is approximately 1/16 inch per hour; hence, the chart movement during the tornado passage was less than 0.005 inch. The traces indicating the fall and rise due to the tornado, therefore, should be practically coincident on the barograms. An examination of the traces reveals, however, that the passage of the tornado was recorded not by a single vertical line but rather by a narrow Y-shaped curve. The interval between the time when the pressure began to fall and when it had returned to the original value was about ½ hour, indicating that the tornado vortex was located within a small-scale trough or low-pressure area about 15 to 20 miles across. Other cases of the occurrence of local low-pressure areas around tornadoes have been reported by Brooks [1].

The barogram from the Weather Bureau Airport Station (No. 9, fig. 3), which was obtained with a much higher chart speed, also shows a period of reduced pressure lasting about half an hour. Instead of a single pressure minimum, this trace shows three distinct minima (about 4 minutes apart) one of which was probably due to the tornado, the others being associated with the thunderstorm. The exact time at which the tornado passed the Weather Bureau Station is in doubt because the station clocks had been stopped by power failure a few minutes earlier; hence, it is difficult to determine which of the three pressure minima occurred with the tornado passage. The anemometer record indicates that the maximum wind speed occurred between 9:56 and 9:57 p. m. EDT, about midway between the time of the second and third minima on the barogram. Since there may have been a discrepancy of 2 or 3 minutes between the barogram and the wind record, the tornado may have occurred either with the second or third pressure minimum.

General weather observation.—A summary of the surface weather observations at the Weather Bureau Airport Station is given in table 1. These observations indicate that the air was warm and unusually moist both before and after the tornado, with a maximum dew point of 70° F. just before the tornado. The prevailing wind was from the south from 3:30 p. m. EDT until after midnight except for about 30 minutes of highly variable winds under the influence of the thunderstorm and tornado. A detailed record of the wind for this period was obtained from the record of the triple register and is presented in table 2. (The triple register records the wind direction to eight points at 1-minute intervals and records each mile of wind movement.) The highest wind speed for 1 mile was 60 m. p. h., recorded between 9:56 and 9:57 as the wind direction shifted from south to west, indicating that the direction of the circulation was counterclockwise.

TABLE 1.—*Partial record of surface weather observations at U. S. Weather Bureau, Cleveland Airport Station, June 8, 1953*

Time (p. m. EDT)	Temperature (° F.)	Dew Point (° F.)	Winds		Weather and remarks
			Direction	Speed (m. p. h.)	
12:26	81	65	SSW	13	
1:27	82	64	SSW	17	
2:26	79	65	WSW	10	
3:27	78	66	S	22	Gusts to 27.
4:28	83	69	S	20	
5:27	85	68	S	11	
6:25	85	67	S	17	
7:27	82	67	SSW	12	
8:23	80	69	S	15	Light rain shower.
8:50			S	15	Thunderstorm.
9:04			SSE	10	Thunder and moderate rain shower.
9:24*	78	70	S	10	Thunder and moderate rain shower.
9:37*			NE	10	Thunder and heavy rain shower.
9:53*			E	30	Gusts to 65 tornado N end of field 2050 EST moved ENE.
10:02*			S	4	Thunderstorm.
10:25*	78	69	SSW	13	Thunderstorm.
11:27*	75	67	S	5	

*Observation time uncertain due to failure of station clock.

ANALYSIS

Calculation of pressure distribution in model tornado flow field.—The records of minimum pressure from the various barograph locations may be used to define a portion of the pressure profile of the tornado. It is of interest to compare this observed pressure profile with a theoretical pressure-distance relationship calculated for a simple model of a flow pattern having some of the characteristics of a tornado. The winds at ground level in a tornado have been observed to consist of both in-flow and circulation [2, 3]. The wind follows a spiral path in approaching the center, with rapidly increasing speed.

TABLE 2.—*Wind records from triple register at U. S. Weather Bureau, Cleveland Airport Station, Cleveland, Ohio, during passage of tornado of June 8, 1953*

Time (p. m. EDT)	Wind direction (8 points)	Approximate average wind speed (m. p. h.)
9:35–9:38	SE	6
9:39–9:50	NE	14
9:51	NE	
9:52	NE	25
9:53	NE	
9:54	E	
9:55	SW	
9:56	S	
9:57	W	60 (fastest mile)
9:58	NW	50 (fastest 5 minutes)
9:59	NW	
10:00	NW	
10:01–10:05	SW	25

A simple model having these characteristics may be constructed by combining the flow fields due to a sink and a vortex. It is assumed that the flow is horizontal and two-dimensional, the density constant, and the viscosity zero. A small circle of radius δ is assumed, containing a symmetrical distribution of vorticity giving a total vortex strength of Γ, and containing also a symmetrical distribution of convergence giving a sink of strength $-Q$. Outside this circle, the flow is steady, irrotational, and nondivergent. The flow field is described with respect to a coordinate system attached to the vortex center, and the air at a great distance is assumed to be at rest in this system. A schematic diagram of the model tornado flow field is shown in figure 4. The velocity is given by

$$V_t=\Gamma/2\pi r \qquad (r>\delta) \qquad (1)$$

$$V_r=-Q/2\pi r \qquad (r>\delta) \qquad (2)$$

where V_t and V_r are the tangential and radial velocity components and r is the distance from the center. The magnitude of the resultant velocity V is given by

$$V=\frac{\sqrt{\Gamma^2+Q^2}}{2\pi r} \qquad (r>\delta) \qquad (3)$$

Equation (3) shows that the product of the wind speed and the radius is a constant when r is greater than δ; thus,

$$Vr=C=\frac{1}{2\pi}\sqrt{\Gamma^2+Q^2} \qquad (r>\delta) \qquad (4)$$

where the constant C is proportional to the resultant strength of the sink and vortex. Using the subscripts 1 and 2 to represent conditions at two arbitrarily chosen points for which $r>\delta$, the application of Bernoulli's equation gives:

$$\frac{1}{2}\rho V_1^2+p_1=\frac{1}{2}\rho V_2^2+p_2 \qquad (r>\delta) \qquad (5)$$

where p is the pressure and ρ the density. From equations (4) and (5) is obtained

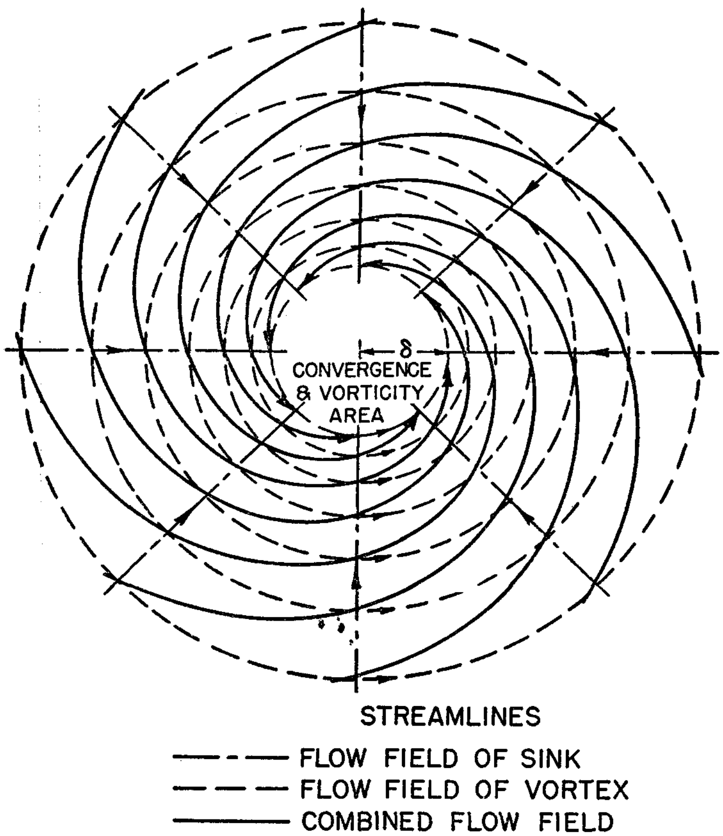

FIGURE 4.—Schematic diagram of model-tornado flow field.

$$\frac{1}{2}\rho\left(\frac{C^2}{r_1^{\,2}}-\frac{C^2}{r_2^{\,2}}\right)=p_2-p_1$$

and solving for C,

$$C=\sqrt{\frac{2(p_2-p_1)}{\rho\left(\frac{1}{r_1^{\,2}}-\frac{1}{r_2^{\,2}}\right)}}\qquad (r>\delta)\qquad (6)$$

Equation (6) shows that the model flow field is characterized by a linear relation between p and $1/r^2$ and that the constant $C=Vr$ may be evaluated from the slope of the line representing p as a function of $1/r^2$.

Equations similar to equation (6) have been used by Williams [4] to describe the pressure distribution in dust whirls and by Deppermann [5] in a discussion of typhoons. A similarity is also noted between the model flow field shown in figure 4 and the pattern of trajectories relative to the moving center of a tropical cyclone as determined by Hughes [6] from flight observations of the wind at 1,000 feet altitude.

Comparison of observed and calculated pressure distribution.—In order to compare the observed pressures with the pressure distribution calculated for the model flow field, it is necessary to refer the observed pressure minima to a common base, because of differences in elevation and instrument settings. Since the tornado occurred during the passage of a thunderstorm, the unsteady pressure occurring just before or after the passage of the tornado does not provide a suitable reference. An examination of the barograms indicated that the flat pressure minimum which occurred about 5 hours after the tornado would provide a suitable reference pressure. The uncorrected values of reference pressure and minimum pressure recorded during the tornado at all stations are listed in columns (1) and (2) of table 3. Because of the uncertainty regarding which of the pressure minima at station 9 (WBAS) was associated with the tornado, both the second and third minima (designated b and c, respectively, in table 3 and fig. 5) were measured.

The measured values of minimum pressure were corrected for differences in elevation and instrument settings by assigning to the reference pressure a standard value of 985 millibars (the approximate average of the observed readings). The differences between the measured values of reference pressure and minimum pressure were converted from inches to millibars and subtracted from 985 to obtain the corrected values of minimum pressure listed in column (3) of table 3. The accuracy of measurement of the barograph traces (using an optical comparator) was about ±0.002 inch, and the maximum possible error due to ignoring air density differences in the reduction to a standard reference pressure was less than 0.001 inch; hence, the overall accuracy of the minimum pressure values is about ±0.1 millibar if errors due to incomplete response of the instrument and buildings are neglected.

TABLE 3.—*Data on minimum pressure and distance from tornado path for 9 barograph stations*

Station no.	(1) Uncorrected reference pressure (in. Hg.)	(2) Uncorrected minimum pressure (in. Hg.)	(3) Corrected minimum pressure (mb.)	(4) Distance from path center, r (m.)	(5) $1/r^2 \times 10^6$ (m.$^{-2}$)
1	29.090	28.860	977.2	233	18.4
2	29.116	28.939	979.0	280	12.7
3	29.115	29.020	981.8	485	4.2
4	29.025	28.833	978.45	271	13.6
5	29.121	29.022	981.65	471	4.5
6	29.092	28.838	976.4	−218	21.0
7	29.104	28.979	980.75	320	9.9
8	29.116	29.030	982.1	580	3.0
9 (b)	29.008	28.903	981.95	−*750	2.0
9 (c)	----------	28.932	982.45	----------	----------

*Estimated.
(b) Second minimum.
(c) Third minimum.

In addition to the pressure data the distance from each station to the center line of the tornado path is required. The direction of the path at the laboratory was determined by constructing an arc of a circle through points 4, 5, and 6 on the map of figure 1. A trial line having the direction of the tangent to the arc at point 4 (the Lewis Laboratory) was drawn on a detailed map of the laboratory, passing about half way between barograph stations 1 and 6, and the perpendicular distance from each station to this line was measured. The final position of the line defining the path (fig. 2) was established by shifting the trial line

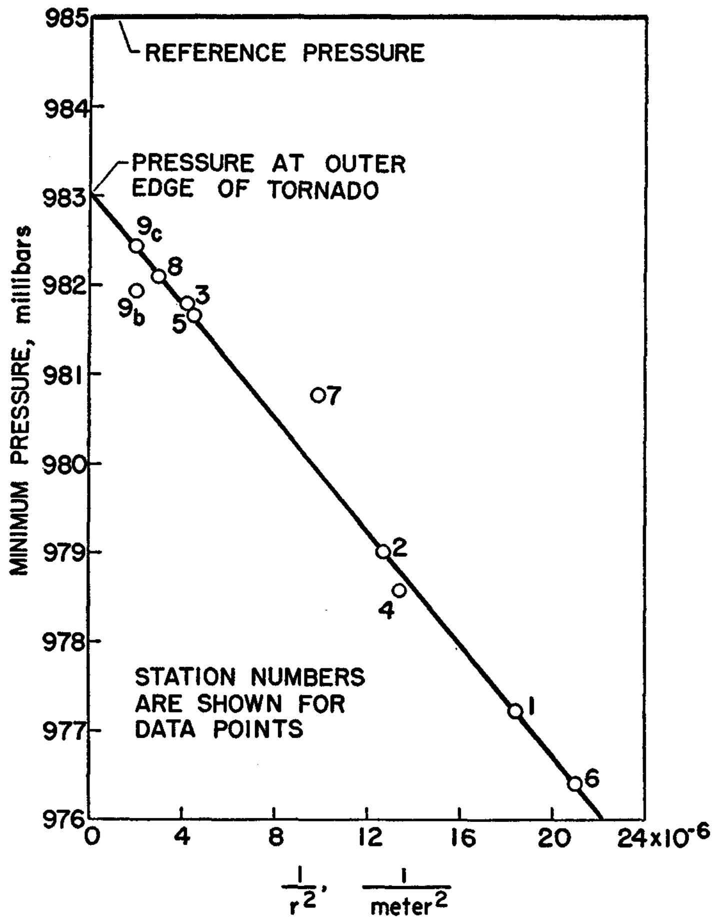

FIGURE 5.—Minimum pressure during tornado passage as a function of the reciprocal of the square of the distance from the path of the center, $1/r^2$ where r is distance from tornado path.

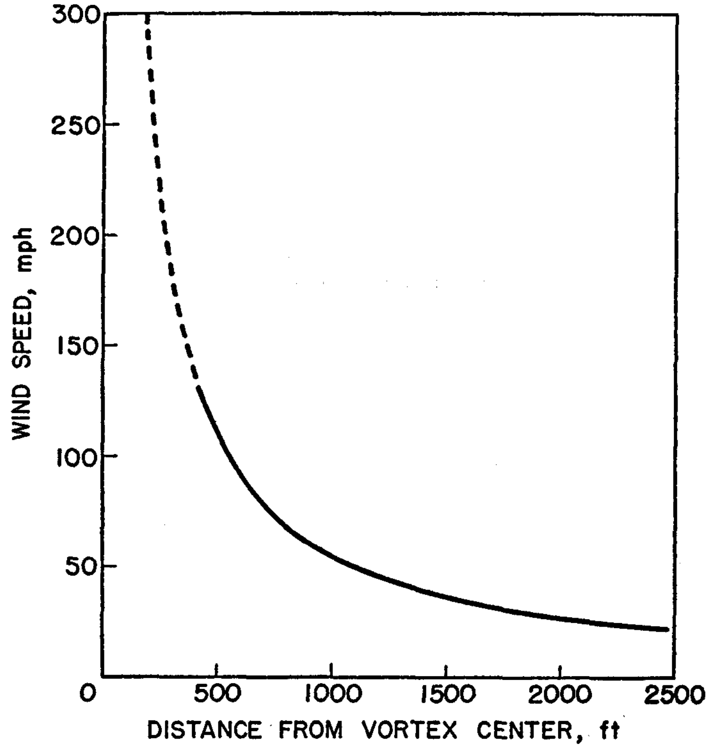

FIGURE 6.—Wind speed in tornado model as a function of the distance from the center.

without changing its direction until a position was obtained such that the point representing barograph station 6 (the only station southeast of the path) on a plot of minimum pressure as a function of $1/r^2$ fell on the line determined by the other stations. As shown in figure 2, the storm path located in this way passes close to the areas where damage occurred. It should be noted that the locations of damage are determined by the locations of structures susceptible to wind damage as well as by the storm path.

Values of distance r from the path and $1/r^2$ are listed in columns (4) and (5) of table 3. The relation between minimum pressure and $1/r^2$ is shown in figure 5. The close grouping of the data points about a straight line indicates that the observed pressure distribution is in good agreement with the calculated distribution over the range of distance covered by the observations. It should be noted that the point representing station 6 was "forced" to fall upon the line because of the method used to locate the path of the center.

A measure of the intensity of the tornado, represented by the constant $C=Vr$, was calculated from equation (6) using the slope of the curve of figure 5, and taking the air density as 0.0114 decigram per cubic centimeter.

$$Vr=7.5\times10^3 \text{ m}^2/\text{sec} \qquad (7)$$

If the speed is expressed in miles per hour and the radius in feet, the constant is 5.5×10^4 m. p. h.-ft. The velocity distribution corresponding to this value of Vr is shown in figure 6.

DISCUSSION

The entire model flow field is to be regarded as moving with respect to the ground with the velocity of the center; thus, the velocity distribution shown in figure 6 applies to a moving coordinate system attached to the tornado center. The wind speed with respect to the earth is increased on the right side and reduced on the left side because of the movement of the storm. For example, the wind speed with respect to the moving coordinate system indicated in figure 6 for the Weather Bureau Station at about 2,300 feet from the center is 24 m. p. h. When this value is added to the speed of movement of the storm, which averaged about 35 m. p. h., the result (59 m. p. h.) agrees satisfactorily with the reported maximum wind speed of 65 m. p. h. (table 1). Although no wind measurements are available from the left side of the tornado, an observer, located indoors at station 8, reported that the tornado was visible and clearly audible but no unusually high winds occurred at that time though strong and gusty winds had occurred a short time previously.

Since the velocity of a tornado is generally not the same as that of the surrounding surface air and the model does not provide for relative motion of the tornado in its environment, the moving model represents the actual wind only over a limited area. Although a discussion of the interaction between the tornado and the surrounding wind field is beyond the scope of this paper, a rough estimate of the possible extent of the area in which the model flow field is applicable may be obtained from the barograph records.

As mentioned previously, a consideration of the time required for the passage of the tornado as compared with the duration of the recorded drop in pressure suggests that the tornado was located in a small-scale low-pressure area of the type described by Brooks [1] as a "tornado cyclone". The curve of figure 5 provides a means of separating the pressure drop due to the actual tornado from that due to the tornado cyclone. If the curve is extended to $1/r^2=0$, the corresponding value of p (983 mb.) represents the starting point for the dynamic pressure fall due to the vortex. Thus the pressure drop down to this point is interpreted as being due to the tornado cyclone and the further drop as due to the actual tornado. The flow model discussed herein and the pressure-distance relation defined thereby do not apply outside the limited area within which the corrected minimum pressure was below 983 millibars.

To determine the size of this area, points on the individual barograms corresponding to a corrected-p value of 983 millibars were determined by subtracting 2 millibars (0.06 in.) from the reference pressure. Measurement of the time interval during which the pressure was below this value gave results ranging from 5 to 11 minutes, the average being 8 minutes. Since the speed of the tornado was about 35 m. p. h., a duration of 8 minutes corresponds to the passage of an area slightly less than 5 miles in diameter. It may be concluded, therefore, that the model flow field does not apply at a distance of 2½ miles or more from the center. The data from figure 5 indicate that the model is applicable over the range of the observations, or out to a radius of nearly ½ mile. Thus, the transition zone between the model flow field and its environment apparently occurs somewhere in the range between ½ mile and 2½ miles from the center.

The range of applicability of the model flow field is also limited in the central area of the tornado because the equations are based on the condition that r must be greater than δ. Within the central core of radius δ, the convergence and vorticity are no longer negligible; the product Vr is no longer constant but decreases with decreasing r; and the pressure falls less rapidly than equation (6) would indicate. As shown by equation (4), the radius of the circle of maximum wind speed cannot be greater than δ; hence, the maximum wind speed must be located within the core.

In the case of this particular tornado, the radius of the core was apparently less than the distance to the nearest barograph (720 ft.) since the pressure variation at that distance was in accordance with the irrotational model. It is evident from the pattern of damage (fig. 2) that the radius of the circle of maximum wind speed was much less than 720 feet, probably being of the order of 100 to 200 feet. Therefore, the radius of the core δ, which marks the inner limit of applicability of the model flow field, was probably between 200 and 700 feet.

REFERENCES

1. Edward M. Brooks, "The Tornado Cyclone", *Weatherwise*, vol. 2, No. 2, April 1949, pp. 32–33.
2. Edward M. Brooks, "Tornadoes and Related Phenomena", *Compendium of Meteorology*, American Meteorological Society, Boston, 1951, pp. 673–680.
3. W. J. Humphreys, *Physics of the Air*, Second Edition, McGraw-Hill, New York, 1929.
4. Nelson R. Williams, "Development of Dust Whirls and Similar Small-Scale Vortices," *Bulletin of the American Meteorological Society*, vol. 29, No. 3, March 1948, pp. 106–116.
5. C. E. Deppermann, "Notes on the Origin and Structure of Philippine Typhoons", *Bulletin of the American Meteorological Society*, vol. 28, No. 9, November 1947, pp. 399–404.
6. Lawrence A. Hughes, "On the Low-Level Wind Structure of Tropical Storms", *Journal of Meteorology*, vol. 9, No. 6, December 1952, pp. 422–428.