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SOME ASPECTS OF THE DYNAMICS OF TORNADOES

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ABSTRACT

In this paper an attempt is made to construct a dynamical model for a tornado that may explain some of its known features. The assumption is made that a tornado is dynamically equivalent to a combination of a pure sink and a pure vortex in the hydrodynamic sense. The compressibility of the air is taken into account, but the air is assumed to be dry. Friction is neglected and the motion induced by the disturbance is assumed to be horizontal.

It is found that, because of the compressibility of the air, the flow is separated into three main regions, an outer region in which the flow is subsonic, an innermost region which cannot belong to the outer flow, and a middle region that separates the two, in which the flow is supersonic. Formulas are derived by which the radii of these regions may be computed. The minimum possible pressure and the maximum possible speed are computed. The vertical shape of the funnel is also computed on the assumption that it is parallel to the surface of the critical flow.

CONTENTS

1. INTRODUCTION

Various attempts have been made to construct a dynamic model for a tornado that may be compatible with observational facts. However, most of those attempts have run into some difficulties, either through internal incoherence arising in the theoretical model itself, or through contradiction with some observed facts. Indeed most of those attempts did not go far beyond the stage of mere speculations.

The obvious reason for the difficulty in constructing such a workable theoretical hypothesis is the lack of adequate observational data. Because of the extreme violence of these storms direct quantitative measurements have been next to an impossibility, especially in the core of the storm. This restriction on our knowledge has resulted in the accumulation of a variety of rather descriptive data which are far from the minimum requirements of mathematical treatment.

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Brooks [3] has stated that a major problem in explaining the formation of a tornado is to find the source of the potential energy and the manner in which it is converted into kinetic energy. The present writer wishes to modify this statement in the following manner. "A major problem in explaining the mechanics of tornadoes is to find the source of the kinetic energy and to account for its concentration over a rather small space." The present paper is an attempt to deal with this problem.

The leading thought in the present paper is similar to that expressed by Brunt [4 and 5] whose work was an extension of Rayleigh's [15] work. Brunt postulated that a strong convective vertical current on a rotating disc may be sufficient to initiate a vortex. His work implied that the "eviction" of air, caused by an ascending current, causes the pressure forces to do work on the air particles, and thus produce the kinetic energy required to initiate the disturbance. Because of the convergence of air toward the center of the disturbed area, and as a consequence of the conservation of angular momentum, kinetic energy is created and transported into the central region of the disc, and thus becomes concentrated there manifesting itself in the devastating winds.

Brunt, however, constructed his model on the assumption that the air may be considered as an incompressible fluid. This eliminated the possibility of the creation of kinetic energy by a transformation of internal energy. Moreover, the assumption of incompressibility introduces a singularity at the pole of the coordinate system, and provides no theoretical mechanism by which this singularity may be isolated from the main field of flow.

The present paper is an attempt to extend Brunt's hypothesis to a compressible atmosphere. Indeed the observed wind velocities around the core of a tornado, which are in the proximity of the sonic speed (Flora [8]), leave little doubt that the incompressibility approximation may introduce serious errors into the mathematical model.

2. QUALITATIVE DESCRIPTION OF THE PROPOSED THEORETICAL MODEL

Let it be assumed that, in the undisturbed state, the atmosphere is conditionally unstable, and that it consists of two main layers separated by a surface of inversion, this last condition being an auxiliary but not a necessary requirement. To simplify matters it is further assumed that the air is initially at rest or that it is in uniform horizontal motion. This assumption will be dropped after describing the first stage in the formation of the disturbance.

Because of some additional mechanism a centralized impulse is assumed to act at the inversion which separates the two layers. This impulse is assumed to be strong enough to break the inversion and to release the instability of the lower layer at the place of its action. It is not desirable to speculate, at this stage, on the nature of the mechanism that supplies this impulse, since the dynamic model to be described does not require any particular kind. However, some speculations on this point will be made at the end of this paper.

When the stabilizing inversion is broken at a small spot, the air of the lower layer suddenly becomes unstable and an ascending "current", which pierces the inversion at that spot, results. It is assumed that at a higher level conditions are favorable for the eviction of air, and the maintenance of the ascending jet. Here again no attempt is made to single out one factor that may be responsible for this process, but it may be mentioned that the existence of a swift horizontal jet at a higher level may be enough to do the job.

In order to visualize more clearly what happens when the lower fluid starts ascending at the unstable spot, it may be helpful to think of the process as though it were taking place in the following manner.

Let us assume, for simplicity, that the broken spot in the inversion surface is a perfect circle, and that the air in the cylindrical region below this surface is acted upon by the sudden impulse. The air in that cylinder may be thought of as a "piston" that is being acted upon by a force which pushes it upward parallel to the axis of the cylinder. As the piston moves, a rarefaction "wave" is initiated at the site and spreads radially outward with the local sonic speed, thus conveying the "news" of the strong disturbance to the surrounding air. This air responds by rushing radially inward toward the rarefied region. The creation of a rarefied region results in an unbalanced pressure gradient surrounding that region, which acts on the fluid particles in a radial direction. The particles starting from rest are accelerated in their motion toward the center. In the absence of non-conservative forces, the motion must necessarily be potential. To simplify matters it is sufficient for our present purpose to assume that radial symmetry exists, that the motion in the outer region is strictly horizontal, and that the outer flow at any horizontal plane is the same as that induced by a pure hydrodynamic sink placed at the geometric center of the inner circle.

It is well known that, under the law of a pure sink, an air particle that could reach the center of the sink should attain an infinite speed. But this does not happen. It will be shown, at another place in the present paper, that the inflowing particles can never come nearer to the center of the sink than a certain minimum distance at which their motion must come to a sudden halt. The inner circle surrounding the sink, which is prohibited to the outer flow, is known as the limiting circle, and its radius is called the minimum radius of the sink. The fluid is therefore divided into two separate regimes, an outside region which obeys the sink law and an inside region whose air does not belong to that of the outside region and whose flow does not obey the sink law.

It will be shown later that the velocity of the particles at the limiting circle is not infinite. Explicitly it is equal to the local sonic speed at that circle.

The physical reason for the establishment of the limiting circle is that the acceleration of the inrushing air particles increases as the particles approach the sink. At the limiting circle the acceleration becomes infinite, but the velocity remains finite. Hence in order to push a particle through the limiting circle the outer fluid must exert an infinite force, which is an impossibility.

Before going further in the present discussion, it may be fitting to say a word about the sources of the kinetic energy acquired by the inflowing fluid.

In a dry atmosphere subject to the horizontal flow being postulated, kinetic energy may be imparted to the particles from two main sources. First, the pressure forces that come into play because of the creation of the rarefied region, do work on the particles. This work is converted into kinetic energy. Second, because of the compressibility of the air, the air expands as it approaches the low pressure of the rarefied region and thus a part of its internal energy is converted into kinetic energy which is imparted to the air particles. In a saturated atmosphere, there is also a third source of energy available, namely the latent heat of condensation. As the limiting circle is approached the pressure is reduced, and hence the air particles expand and condensation may start. This source will be neglected in the present work since, although it may introduce some modifications in the magnitude of the quantities to be computed, it is not expected to change the qualitative results to any appreciable degree.

If the flow is strictly horizontal the air particles, drawn from the outer region, which reach the limiting circle, stop in the way of the inflowing particles that are rushing behind them. These latter particles have to slow down and be compressed before reaching the limiting circle. A circular shock wave is formed around the inner region. There is an annular ring of relatively high pressure caused by the compression of the air. The shock wave and its accompanying relatively high pressure move radially outward. The air particles behave as though they were reflected from a "wall" built at the limiting circle. This provides a blocking mechanism in the face of the process. There is now an outward flow superimposed on the original inflow, and the total effect is the same as that of superposition of a source on the original sink. The two would ultimately annul each other.

However, strict horizontal motion may be postulated only in the outer region. In the inner region ascending air exists.

The particles rushing from outside soon acquire a vertical component of motion as they approach the limiting circle. This hinders the formation of shock waves at lower levels and permits the successive particles to move farther toward the limiting circle, and then ascend behind the first particles. The rising air finally stops ascending when it reaches a certain equilibrium level. The "source" is therefore separated from the "sink" and placed at a higher level. The final picture in this process is that of a radial inflow at low levels and a radial outflow at higher levels, with a rarefied "cylindrical' column in the middle of the flow occupied by an ascending jet whose air does not belong to that of the outer region.

In order to keep this process going and to enable it to give birth to a tornado in its final stages, it is required that the vertical motion of the ascending "piston" must be sustained for a sufficiently long time. The energy required for maintaining this upward motion may be caused by the release of the latent instability. This becomes an important factor after the first impulse has stopped acting. This probably is the reason why tornadoes occur in conditionally unstable air with relatively low condensation level (see Fawbush and Miller [6 and 7]).

To sum up what has been mentioned so far about the envisaged process, it may be stated that if an initial state of complete stagnation and homogeneity is assumed, and if a pure sink line is initiated by some mechanism which persists for a sufficiently long time, the result would be the establishment of a rarefied column inside of which there is rising air, and outside of which there is radial flow. At lower levels the radial flow is an inflow, and at upper levels it is an outflow.

3. THE MATURE TORNADO

The discussion presented in the previous section has been based on the assumption that the initial state is that of complete rest or perfect uniformity. This condition is evidently rarely, if ever, realized in nature. There is normally some non-uniformity in the basic flow. Let us assume, therefore, that the basic flow is that of rotation superposed in translation, and consider the flow resulting from an initial sink travelling with the same velocity of translation.

When the air converges toward the rarified region in the manner described previously, its angular velocity increases as it approaches the center, in accordance with the law of conservation of angular momentum. The steady state approached by the disturbed flow is, therefore, that resulting from the superposition of a pure sink over a pure vortex. The air comprising the outer region is a field of radial inflow and rotation. The air particles in the outer region describe spiral paths as they approach the inner region. When they attain a vertical component of motion at the periphery of the inner region, they spiral upward. The inner column with the engulfing air will have the appearance of a "twister".

If there exists a swift narrow jet at a higher level, and if the sink line penetrates at its edge, it may be expected that the horizontal shear across the sink superposes, on the converging air, a stronger rotation. In other words, the "vortex" strength may be expected to increase with height under these conditions.

Because the rotation results from the concentration of a pre-existing field, it may be concluded that the sense of rotation must be cyclonic in a cyclonic flow, and anticyclonic in an anticyclonic flow. This is probably the reason why most of the observed tornadoes have a cyclonic sense of rotation, since tornadoes are more frequent in a cyclonic flow.

When the disturbance attains rotation in the described way, the tornado is in its mature stage. On the rough terrain where friction acts strongly, the ground layer of the tornado column is in the boundary layer of the flow. It is well known that in the boundary later the steady flow is nearly parallel to the pressure gradient (see Goldstein [9]). The flow in this layer is therefore expected to be nearly radially inward. This is probably the reason why some tornadoes are reported to have no rotation. It may be remembeed that the wind direction in a tornado is mostly judged by its effects on the movements of obstructions which exist on the ground.

In anticipation of the results of the mathematical analysis to be presented later, it may be mentioned that when a vortex superposes itself on a sink it acts as a stabilizing factor on it. The minimum radius of the limiting circle is much larger now than its magnitude in the pure sink case. The spiraling air particles may attain much higher velocities. In fact, there will be established an annular ring of supersonic flow, around the limiting circle, in which the velocity of the air particles surpasses the local sonic velocities. The whole field of flow is now divided into three different regimes: an outermost field in which the flow is subsonic, an innermost circular field whose flow does not belong to the outer flow, and an annular ring separating the two regions in which the flow is supersonic. The radius of the innermost region, i. e., of the limiting circle, is the minimum radius. The outer radius of the supercritical region will be called the "critical" radius. The circle surrounding the supercritical region will be called the "critical" circle. The speed of the air particles at the critical circle is equal to the local speed of sound.

If conditions are invariant with height, one may then speak of a limiting cylinder and a critical cylinder in an obvious extension of the two-dimensional picture. If conditions vary with height, as they in general do, then one speaks of a limiting surface and a critical surface. An example of an idealized simple model will be given later. The shapes of the surfaces of that model will be computed.

It may be mentioned here that the supersonic regime cannot live, in nature, for an appreciable period of time. A supersonic flow is highly sensitive to obstructions. Shock waves soon develop, in that regime, which feed on its kinetic energy and eventually destroy it. These shock waves provide the mechanism to disturb the flow in the supersonic regime and allow the air to "leak" into the inner region, a mechanism which must be very effective in the eventual decay of the tornado.

4. MATHEMATICAL ANALYSIS—THE PURE SINK

Let a cylindrical polar system of coordinates be chosen in such a way that the axis points vertically upward and coincides with the center of the initial hydrodynamic sink. For the sake of simplicity friction will be neglected. Moreover, because of the rapidity of process, it is assumed that adiabatic conditions exist. The air is assumed to be dry and no condensation takes place during its horizontal motion.

The equation of motion may be written in the following form.

$$\frac{d\mathbf{q}}{dt}+2\boldsymbol{\omega}\times\mathbf{q}=-\frac{1}{\rho}\nabla p-\mathbf{k}g \tag{1}$$

where $\mathbf{q}$ is the velocity, $\boldsymbol{\omega}$ is the angular velocity of the earth's rotation, ρ is the density, p the pressure, g the acceleration of gravity, and $\mathbf{k}$ is the unit vector in the vertical direction.

Upon multiplying (1) scalarly by $\mathbf{q}$ this equation yields the following:

$$\frac{d}{dt}\left(\frac{1}{2}q^2+\frac{p}{\rho}\right)-p\frac{d}{dt}\left(\frac{1}{\rho}\right)=\frac{1}{\rho}\frac{\partial p}{\partial t}-gw \tag{2}$$

where w is the vertical component of the velocity.

Under dry adiabatic conditions the first law of thermodynamics is the following:

$$0=c_v\frac{dT}{dt}+p\frac{d}{dt}\left(\frac{1}{\rho}\right) \tag{3}$$

where c_v is the specific heat for constant volume, and T is the absolute temperature.

The equation of state for dry air is the following:

$$p=(c_p-c_v)\rho T \tag{4}$$

where c_p is the specific heat under constant pressure.

Upon combining (2), (3), and (4) and assuming steady case, integrating along a streamline, Bernoulli's equation is derived in the following form (see Haurwitz [10]):

$$\frac{1}{2}q^2+\frac{\gamma}{\gamma-1}\frac{p}{\rho}+g\Delta h=\frac{\gamma}{\gamma-1}\frac{p_0}{\rho_0}+\frac{1}{2}q_0^2 \tag{5'}$$

where Δh is the vertical distance that an air particle has moved between its initial and final positions; p_0, ρ_0, q_0 refer to the values at infinity and $\gamma=c_p/c_v$.

Let us now assume that we are interested only in the motion of the outside field where it is mainly horizontal, and let the fluid at infinity be at rest with respect to the system of coordinates. Equation (5′) then simplifies to the following form:

$$\frac{1}{2}q^2+\frac{\gamma}{\gamma-1}\frac{p}{\rho}=\frac{\gamma}{\gamma-1}\frac{p_0}{\rho_0} \tag{5}$$

The adiabatic law of expansion is the following:

$$p=\epsilon\rho^\gamma \tag{6}$$

where ϵ is a constant.

The local speed of sound is given by the following relation:

$$c^2=\frac{dp}{d\rho}. \tag{7}$$

Upon combining (6), (7), and (5), Bernoulli's equation takes the following form:

$$\frac{1}{2}q^2+\frac{c^2}{\gamma-1}=\frac{c_0^2}{\gamma-1}=\frac{\gamma}{\gamma-1}\frac{p_0}{\rho_0} \tag{8}$$

where c_0 is the sonic speed at infinity.

Define the Mach number μ by the following relation:

$$\mu\equiv\frac{q}{c} \tag{9}$$

Upon introducing this number in (8), Bernoulli's equation takes the following form (see Milne-Thomson [13]):

$$1+\frac{1}{2}(\gamma-1)\mu^2=\frac{c_0^2}{c^2}=\left(\frac{p_0}{p}\right)^{\frac{\gamma-1}{\gamma}} \tag{10}$$

Now assume that a pure sink is placed at the pole of the coordinates, and consider the flow at any horizontal layer of unit thickness. Let the input of mass into the "two-dimensional" sink be $2\pi m$ per unit time, and let v be the radial speed at a distance r from the sink. The equation of continuity gives the following relation:

$$rv=\frac{m}{\rho} \tag{11}$$

Let it first be assumed that the pure sink is at rest with respect to the flow, and that the field of motion is purely radial, and no tangential velocity exists. In other words, $v=q$ in this case.

From (11) and (10) the following relation is obtained (see Milne-Thomson [13]):

$$r=\frac{m}{c_0\rho_0\mu}\left(1+\frac{\gamma-1}{2}\mu^2\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{12}$$

This relation gives the radial distance of a particle in the field as a function of the dimensionless number μ. If a ring of particles surrounding the sink is considered, then r represents the radius of that ring.

By differentiation of (12) with respect to μ, it is easily verified that r has a minimum value at the point $\mu=1$ (see Milne-Thomson [13]). The minimum radius that a ring may attain, while it is being contracted during its convergence, is therefore given by the following equation:

$$r_{sm}=\frac{m}{c_0\rho_0}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{13}$$

The sink, therefore, can induce inward motion only outside a circle whose radius is r_{sm} as given by equation (13). This circle is the "limiting" circle. The motion inside it cannot obey the same law as that outside it. Since at the limiting circle $\mu=1$, relation (9) shows that the speed of the air particles at this circle is equal to the local speed of sound. In the outer flow, since the air at infinity is at rest, the velocity is less than that of sound. Hence subsonic flow exists everywhere except right at the limiting circle where sonic speed is approached.

In the steady case the acceleration of a particle in the outer flow is given by the following relation:

$$\alpha=v\frac{dv}{dr}. \tag{14}$$

This may be written as follows:

$$\alpha=v\frac{dv/d\mu}{dr/d\mu} \tag{14'}$$

At the limiting circle we have, by definition

$$\frac{dr}{d\mu}=0.$$

Hence, at the limiting circle $\alpha=\infty$ (see Howarth [11]). This shows that in order that a particle may reach the limiting circle, an infinite force has to act on it, which is an impossibility. This result was anticipated in the discussion given in the previous section.

For air $\gamma=7/5$. Upon using the value in equation (13), the latter becomes as follows:

$$r_{sm}=\frac{m}{c_0\rho_0}\left(\frac{6}{5}\right)^3=\frac{1.728m}{c_0\rho_0} \tag{15}$$

Because

$$c=\sqrt{\gamma R^*T} \tag{16}$$

where R^* is the gas constant, it is seen from equation (15) that the radius of the limiting circle is directly proportional to the sink strength measured in volume (m/ρ_0) and inversely proportional to the square root of the temperature of the undisturbed air at infinity.

For a first orientation on the order of magnitude of the minimum radius in the case of a pure sink let us consider the following values. Let $c_0=330$ m./sec., $\rho_0=10^{-3}$ gm. cm.$^{-3}$, and let the sink have such a strength that it induces a radial velocity of 1 cm./sec. at a point 40 km. away from its center.

From (11), it follows that $m=4\times10^3$ c.g.s.u. This is a rather weak sink which may be caused by rising air over a circular area of radius 200 meters, with a vertical velocity of 10 m./sec., if the air for the rising column is drawn over a height of 1 km.

With these values, equation (15) gives the radius of the limiting circle to be 2.1 meters.

The pressure at the limiting circle may be computed from equation (10) after giving μ the value 1. That equation becomes as follows, with $\gamma=7/5$,

$$\frac{p_0}{p}=\left(\frac{6}{5}\right)^{7/2}=1.893. \tag{17}$$

If the pressure at infinity is assumed to be 1000 mb., the pressure at the limiting circle is found to be 530 mb. This value may be taken to represent the pressure at the center of the disturbance since it cannot be far from it. It may be seen that the computed pressure is too low compared with some observations on tornadoes which estimate that pressure to be about 800 mb. (Brooks [3]). This difference may be due to two reasons. First no actual observation is known to have been taken right at the center of the tornado, since most observations have been taken in the neighborhood of the column. Second, in the computed value, it has been assumed that the particles actually reach the limiting circle; but from the physical reasoning given before, it has been shown that this circle may be approached but never reached. Hence the computed value may be considered as the minimum value that may be approached under the conditions described above.

The velocity of the inrushing air at the limiting circle may be computed from equation (10), since at that circle $v_{max}=c$. That equation yields the following relation:

$$v_{max}^2=\frac{5}{6}c_0^2 \tag{10a}$$

Upon substituting the assumed value for c_0, it is found that the velocity $v_{max}=301$ m./sec. Here again the computed value may be somewhat higher than the value estimated on the basis of observation, and it must be considered as a maximum limit for the wind velocity.

5. MATHEMATICAL ANALYSIS—THE MATURE TORNADO

In the mature tornado it is postulated that the converging air of the outer region acquires rotation which is superposed on its inward motion. If the motion remains strictly horizontal, and if there is some pre-existing rotation in the undisturbed field, Brunt [5] has shown that a true vortex motion results. The total motion in the outside field is therefore that of a combined sink and vortex. Lewis and Perkins [12] have shown that this theory is in good agreement with some observations.

Let the vortex strength at any horizontal layer be κ, and the tangential component of velocity, induced by the vortex at a point which is at a distance r from the center, be u. The following relation is valid:

$$u=\frac{\kappa}{r} \tag{18}$$

The combined flow of the vortex and the sink at that layer obeys the following law:

$$q=\sqrt{\frac{m^2}{\rho^2}+\kappa^2}\,\frac{1}{r} \tag{19'}$$

This equation may be written in the following form:

$$r^2=\frac{1}{q^2}\left(\frac{m^2}{\rho^2}+\kappa^2\right) \tag{19}$$

Upon combining this and equation (10), the following relation results:

$$r^2=\frac{m^2}{c_0{}^2\rho_0{}^2\mu^2}\left(1+\frac{\gamma-1}{2}\mu^2\right)^{\frac{\gamma+1}{\gamma-1}}+\frac{\kappa^2}{c_0{}^2}\left(\frac{1}{\mu^2}+\frac{\gamma-1}{2}\right) \tag{20}$$

In order to determine the minimum radius of the combined flow, equation (20) may be differentiated with respect to μ, and the result equalized to zero. The stationary values of μ are then found to satisfy the following equation:

$$-\left(1+\frac{\gamma-1}{2}\mu_s^2\right)^{\frac{\gamma+1}{\gamma-1}}+\frac{\mu_s^2}{2}(\gamma+1)\left(1+\frac{\gamma-1}{2}\mu_s^2\right)^{\frac{2}{\gamma-1}}=\frac{\kappa^2\rho_0{}^2}{m^2} \tag{21}$$

where μ_s is the stationary value of μ.

In the case of dry air $\gamma=7/5$. Upon using this value equation (21) takes the following form:

$$-\left(1+\frac{\mu_s^2}{5}\right)^6+6\,\frac{\mu_s^2}{5}\left(1+\frac{\mu_s^2}{5}\right)^5=\lambda^2 \tag{22}$$

where

$$\lambda=\left|\frac{\kappa\rho_0}{m}\right| \tag{23}$$

λ gives the ratio between the vortex strength and the sink strength expressed in units of volume.

Upon putting

$$X=\frac{\mu_s^2}{5} \tag{24}$$

equation (22) takes the following form.

$$5X^6+24X^5+45X^4+40X^3+15X^2-1=\lambda^2 \tag{25}$$

This equation possesses one real root only, hence there is only one minimum point in the $r-\mu$ curve. The first column of table 1 gives the values of this root corresponding to different values of λ.

TABLE 1.—*The first column gives the stationary values of the Mach number μ_s corresponding to the assumed values of the strength parameter λ_s: which is given in column 2. The third column gives the values of the non-dimensional minimum radius R_m; the fourth gives the corresponding non-dimensional critical radius R_c, and the last column gives the non-dimensional width of the supersonic region ΔR.*

μ_s	λ_s	R_m	R_c	ΔR
1	im	im	--------	--------
1	0	1.728	1.728	0
1.225	1.36	2.2	2.29	.09
1.323	1.79	2.43	2.65	.22
1.414	2.32	2.74	3.09	.35
1.5	2.83	3.06	3.57	.51
1.581	3.37	3.37	4.09	.72
2	7.53	5.83	8.45	2.62
2.236	11.31	8.0	11.56	3.56
3.16	46	26.66	50.6	24.0
3.873	119	64	131	67
4.472	223	114.7	245	130
5	428	214.1	471	257
∞	∞	∞	--------	--------

Table 1 shows that μ_s has the value unity when λ_s is zero. This corresponds to the case of a pure sink which was discussed in the previous section. It is also seen from this table that $\mu_s>1$ when $\lambda>0$. This means that in the combined case the flow may become supersonic at the limiting circle. The maximum velocity, namely the velocity of the flow right at the limiting circle tends to increase as the ratio λ increases. When λ becomes infinity, i. e., when the sink strength vanishes and only the vortex is effective, the local Mach number tends to infinity. This may happen if the local sonic speed tends to zero. This case calls for a complete vacuum at the inner core of the vortex, a condition which is rather far from realization in nature, and may be considered as a pure mathematical concept.

It may easily be verified, in a way similar to that outlined in the previous section, that the acceleration approaches infinity as the limiting circle is approached. Hence it may be concluded that the particles belonging to the outer flow never reach that circle but they may approach it asymptotically. Upon the introduction of a vertical component of velocity in the neighborhood of the limiting circle, it follows again that the air particles in that region spiral upward in the manner described before.

Returning to equation (20), and substituting μ_s for μ, the minimum radius that may be attained by a contracting ring may be found. This radius is the same as that of the limiting circle at the horizontal layer under consideration. Before doing so, it may be advantageous to introduce a dimensionless minimum radius R_m defined by the following identity:

$$R_m \equiv \frac{c_0\rho_0}{m} r_{\min}. \tag{26}$$

Equation (20) gives for R_m, after using the proper value of γ, the following:

$$R_m = \left\{\left(\frac{1}{\mu_s^2}+\frac{1}{5}\right)\left[\left(1+\frac{\mu_s^2}{5}\right)^5+\lambda_s^2\right]\right\}^{1/2} \tag{27}$$

The quantity γ_s was used to indicate that the value of γ appropriate for the stationary value μ_s must be used.

The third column in table 1 gives the values of R_m computed from equation (27).

The region inside of which the flow is supersonic is an annular ring surrounding the limiting circle. Its outer radius is the critical radius and is given the symbol r_c. It may be emphasized here that the accelation at this circle is not infinity in this case of the combined flow. Hence the air may cross this circle since it offers no physical barrier. This barrier is now removed inwards to the limiting circle.

Upon putting $\mu=1$ in equation (20), and using the appropriate value for γ, the following value is obtained for r_c:

$$r_c = \frac{m}{c_0\rho_0}\sqrt{\frac{6}{5}}\sqrt{\left(\frac{6}{5}\right)^5+\lambda^2} \tag{28}$$

This may be expressed in terms of a dimensionless critical radius R_c defined by the indentity:

$$R_c \equiv \frac{c_p\rho_0 r_c}{m}. \tag{29}$$

It then takes the following form:

$$R_c = \sqrt{\frac{6}{5}}\sqrt{\left(\frac{6}{5}\right)^5+\lambda^2}. \tag{30}$$

The values of R_c corresponding to the appropriate values of λ are given in the fourth column of table 1. The fifth column of that table gives $\Delta R=R_c-R_m$. This is a measure of the width of the supersonic region.

In the hypothetical case of a pure vortex, when there is no sink, R (where $R\equiv c_0\rho_0 r/m$) cannot be taken as a parameter since it attains an infinite value. In this case, however, equation (20) reduces to the following form

$$r = \frac{\kappa}{c_0}\left(\frac{1}{\mu^2}+\frac{\gamma-1}{2}\right)^{1/2} \tag{31}$$

The minimum radius may be obtained from this equation by putting $\mu=\infty$. Upon using the appropriate value for γ, the minimum radius for the vortex case is found to be the following:

$$r_{vm} = \frac{\kappa}{c_0\sqrt{5}} \tag{32}$$

The critical radius for the pure vortex may also be found from (31) by putting $\mu=1$. Thus it is found to have the following value:

$$r_{vc} = \frac{\kappa\sqrt{6}}{c_0\sqrt{5}} \tag{33}$$

The width of the supersonic ring is, in this case,

$$\Delta r = r_{vc}-r_{vm} = \frac{1.45}{\sqrt{5}}\frac{\kappa}{c_0}$$

or

$$\frac{\Delta r}{r_{vm}} = 1.45 \tag{34}$$

This value also gives the maximum fractional width that may be assumed by the supersonic ring.

It may be stated again that the case of a pure vortex, without a sink, is a physical impossibility because it requires a complete vacuum at the inner core, as has already been shown. However, the combined vortex-sink is always possible. The only alternative, according to the present analysis, is a pure sink which calls for initial conditions that are very hard to realize. Table 2 gives the values, in meters, of the minimum radius and the critical radius for a combined vortex-sink flow. The following assumptions are made. The radial velocity is assumed to be 1 cm./sec. at a distance of 40 km. from the center. The sonic speed at infinity is assumed to be

TABLE 2.—*The values, in meters, of the minimum radius r_m, and of the critical radius r_c, and the fractional width of the supersonic flow $\Delta r/r_m$, for a combined vortex-sink flow which has the indicated stationary values of the Mach number μ_s and the corresponding stationary values of the strength parameter λ_s*

μ_s	λ_s	r_m	r_c	Δr	$\Delta r/r_m$
1	0	2.09	2.09	0	0
1.225	1.36	2.67	2.78	.11	.04
1.323	1.79	2.94	3.22	.28	.095
1.414	2.32	3.33	3.75	.42	.127
1.5	2.83	3.71	4.32	.61	.164
1.581	3.37	4.09	4.96	.87	.215
2	7.53	7.1	10.3	3.2	.45
2.236	11.31	9.70	14.0	4.30	.443
3.16	46	32.2	60.3	28.1	.872
3.871	119	77.5	158	80.5	1.03
4.72	223	139	296	157	1.13
5	428	259	570	311	1.20
∞	------	------	------	------	1.45

$m=4\times10^{3}$; $c_0=3.3\times10^4$; $\rho_0=10^{-3}$; $r=1.21\times10^2R$

$c_0=3.3\times10^4$ cm./sec. and the undisturbed density $\rho_0=10^{-3}$ gm./cm^3.

The last two columns of table 2 give the width of the supersonic zone in meters, and its fractional width, respectively. It may be seen from the values given there that the width of this zone increases, in general, with increasing values of λ. The fractional width approaches the value 1.45 as λ approaches ∞, which is the pure vortex case.

In connection with the computed values of the radius of the tornado as outlined above, the following remarks may be made.

First, the observed and reported radius of a tornado is expected to be much greater than the computed values of the critical radius, the reason being that observers estimate the size of a tornado looking at it from outside and at a safe distance away from it. Their estimates are based on dust and other debris that float in the circulation. Obscurities of this nature are usually carried in the region of strong winds which surrounds the critical radius and may have an appreciable extent in the horizontal. The winds reach destructive force long before sonic speed is approached.

As a rough example, assume that the outer fringes of the destructive area have a wind force of a whole gale. The Beaufort scale describes such a wind to be capable of uprooting trees and of causing considerable structural damage. The speed of such a wind is about 100 km. per hour. This is about one tenth of the sonic speed at normal temperature. Since the wind velocity is nearly equal to the undisturbed sonic velocity at the critical circle, it follows that the outer radius of the area of distruction is about ten times greater than the critical radius. Thus in the case of the smallest computed twister given in table 2 where $r_c=2.78$ meters, the "radius of destruction" is about 28 meters.

Second, as has been stated before, the supersonic region is very sensitive to minor obstructions and soon develops shock waves which act to destroy that region. Hence the maximum wind velocity that may occur at the ground level is not expected to exceed that of sound. If supersonic flow is established, it is not expected to last for any appreciable period of time at the ground level. Supersonic speeds may, however, last for a longer period in the free air at higher levels. At those levels sonic speed is normally smaller than its value at the ground because the temperature normally decreases with height.

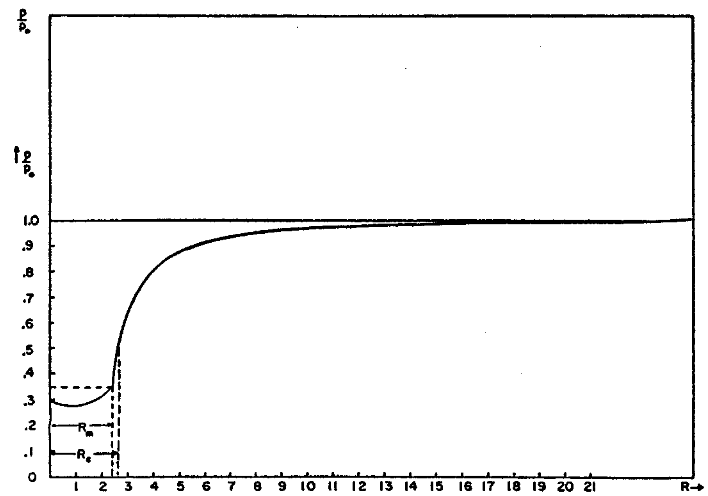

FIGURE 1.—Schematic plot of the variation of pressure with distance from the center of a mature tornado. The abscissa is the dimensionless radius R and the ordinate is p/p_0, where p_0 is the pressure at the undisturbed air. R_c is the dimensionless critical radius, and R_m is the dimensionless minimum radius. The curve was arbitrarily continued inside the limiting circle.

The pressure at the critical circle may be computed from equation (17), and the wind velocity at that circle may be computed from (10a). They will be found to have the same values as computed in the previous sections.

The pressure at the minimum circle, and the sonic speed at that circle may be computed from equation (10), after giving μ the value μ_s. That equation, for air, takes the following form:

$$1+\frac{\mu_s^2}{5}=\frac{c_0^{\,2}}{c^2}=\left(\frac{p_0}{p}\right)^{2/7} \tag{10b}$$

The wind velocity at the limiting circle may be found from (9).

Figure 1 is a plot of p/p_0 against R in the case of $\lambda=1.79$. It can be seen from this figure that the pressure remains almost unaffected until R is 10; then it starts decreasing more and more rapidly as R_c is approached. Between R_c and R_m the slope of p/p_0 becomes almost vertical. The behavior of the pressure inside the limiting circle cannot be predicted from the present theory, and therefore it is shown in the figure as an arbitrary line. The region between R_c and R_m, which is the supersonic region, may be greatly modified in the natural phenomenon, since this marks the unstable region where shock waves are expected to develop. An actual trace may even show a secondary maximum at this region because of the compression of air in the shock region.

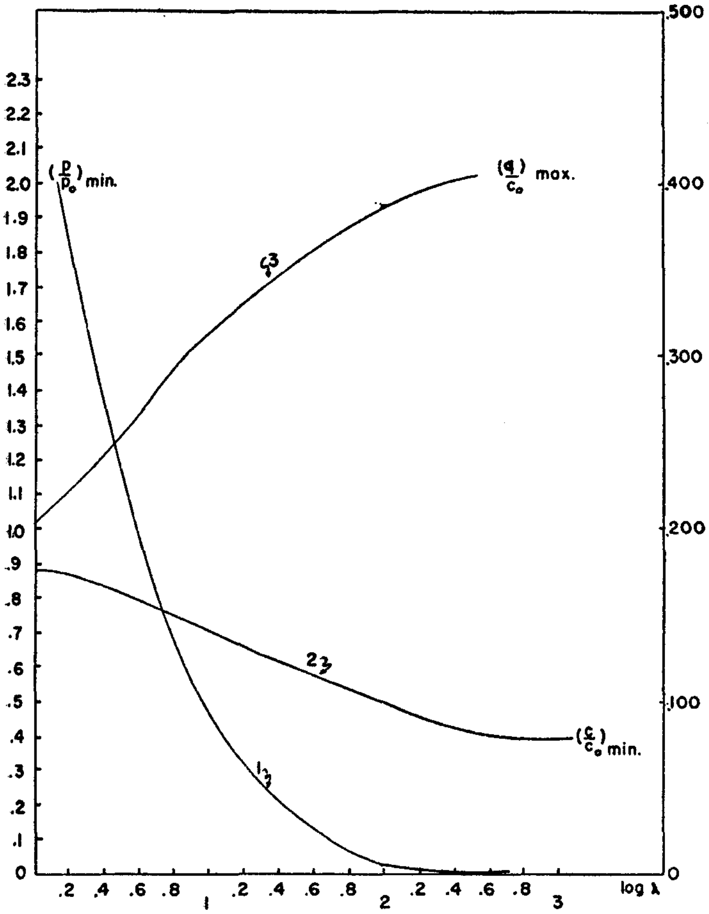

FIGURE 2.—Curve 1 is a plot of $(p/p_0)_{min}$ against log λ. The values of $(p/p_0)_{min}$ must be read on the right hand scale. Curves 2 and 3 are plots of $(q/c_0)_{max}$ and $(c/c_0)_{min}$ against log λ. The values of these variables are to be read on the left hand scale. The values of the three indicated variables are given as functions of the single parameter λ.

Figure 2 is a plot of $(p/p_0)_{min}$, $(q/c_0)_{max}$, and $(c/c_0)_{min}$ against log λ. These are the values at the limiting circle.

6. THE SHAPE OF THE CRITICAL AND LIMITING SURFACES

It has been stated previously that in three dimensions one must speak of a limiting surface and a critical surface. The horizontal cross-sections of these surfaces at any level are the same as their corresponding circles, on the assumption of complete radial symmetry.

The radius of the limiting circle, r_{sm}, may be computed, at any level, from equations (27) and (26). It can be seen from these equations that r_{sm} is a function of the sink strength m, the undisturbed sonic speed c_0, the undisturbed density ρ_0, and the vortex strength κ. In general all of these quantities vary with height, and the exact shape of the limiting surface can be ascertained only after knowing, explicitly, the fundamental relationships between these quantities and height. These functional relationships are expected to change from one individual storm to another. Therefore the surface shape is expected to change accordingly.

Similarly, the critical radius may be computed from equations (29) and (30). It is seen from those equations that the same thing is true in this case also.

In order to obtain a first rough concept of the general shape of these surfaces, the following idealized case will be discussed.

Let m/ρ_0 and κ be independent of height. It then follows from equations (27) and (30) that R_m and R_c are invariants with respect to height. From (26) and (29) it follows that

$$R_i = \frac{c_0 \rho_0}{m} r_i;\ (i=m,c)$$

But

$$c_0 = \sqrt{\gamma R^* T_0} \tag{16'}$$

Therefore

$$r_i = \frac{m}{\rho_0} \frac{1}{\sqrt{\gamma R^* T_0}} R_i \tag{35}$$

Since m/ρ_0 has been assumed to be a constant, it is seen from this equation that r_i is inversely proportional to the square root of the undisturbed temperature.

Let the temperature be given by the following linear relation:

$$T_0 = T_s - \beta z \tag{36}$$

where T_s is the temperature at the ground, and β is a constant lapse rate.

Equation (35) may then be written in the following form:

$$r_i = \frac{m}{\rho_0} \frac{R_i}{\sqrt{\gamma R^*}} \frac{1}{\sqrt{T_s - \beta z}} \tag{37}$$

or

$$A_i \equiv \sqrt{\gamma R^*} \frac{\rho_0}{m} r_i = R_i (T_s - \beta z)^{-1/2} \tag{38}$$

Figure 3 is a plot of A_i against z. In this figure the following values were assumed. $T_s = 280°$K, $\beta = 6°$ per km., $R_m = 2.43$, and $R_c = 2.65$. These last values are the same as those used in figure 2, and they correspond to $\lambda = 1.79$.

It may be seen from this figure that both surfaces are hyperbolic, with an asymptote at $z = 46.4$ km.

Needless to say, the assumptions of constancy that have been made here are crude, and the figure is meant only to give an idea of the general, but not the exact, shape of those surfaces.

7. THE SHAPE OF THE VISIBLE TORNADO COLUMN

The process responsible for the formation of a tornado, envisaged in the present paper, requires an initial line sink established in the atmosphere, probably through the rise of an accelerated vertical jet. It may therefore be surmised that the general shape of the tornado column is that of its "nucleus" sink.

The jet, in general, does not ascend along a vertical straight path, first because it is affected by the horizontal winds at the various levels which it penetrates, and second because, in its ascent, it follows the path of least resistance. This latter restriction is caused by the variation in the degree of stability of the various parts of the air along its path. It therefore may be surmised that a tornado column may assume various shapes, such as the snake shape or the rope shape, so frequently reported. The "branched" tornado column may be explained on the assumption of two rising jets merging together, or one jet splitting into two depending upon the sense of branching.

The horizontal cross section of the tornado column is rather hard to compute analytically. The column becomes visible only because of the opaque obscurities that are suspended in the circulation. At the ground level dust particles and floating solid bodies may be carried, and the shape of the column in those levels may be a function of the wind force and the size of the available particles.

In the free atmosphere the column becomes visible because of its associated cloud. It has been shown in the mathematical analysis that the pressure is greatly reduced as the inner core of the column is approached. An air particle moving toward the inner core expands adiabatically, and condensation may take place when its condensation pressure level is reached. This may happen some distance before either the limiting surface or the critical surface is reached. In general it is possible to compute the condensation point, and hence the general shape of the tornado cloud, at the various levels once an ascent in the undisturbed air is known. However, this is not attempted in the present paper, since the assumption of dry air was taken as a starting point. Instead it is assumed that the "cloud surface" may be taken as being parallel to the critical surface. Hence the general shape in figure 3 may also be taken to represent the shape of a vertical tornado column.

8. DISCUSSION AND FURTHER REMARKS

On the basis of the foregoing analysis it may be surmised that an idealized dynamical model, based on the combination of a simple sink and a simple vortex, may serve to explain a number of the observed facts about tornadoes. There are, however, many factors that come into play and must be effective in the actual phenomenon, which have been neglected in this model either for the sake of mathematical simplicity or for lack of adequate quantitative data. The present model, therefore, admits of a number of improvements along which further work may be carried if seen feasible. The following qualitative remarks which are basically speculative in nature are added with the intention of criticizing the theoretical model, and of suggesting some physically possible improvements.

(1) The model assumes the existence of a line sink in the atmosphere that persists for an appreciable period of time which must be long enough to permit the disturbed flow to approach a final state of equilibrium. It has been mentioned that the sink may conceivably be, and most

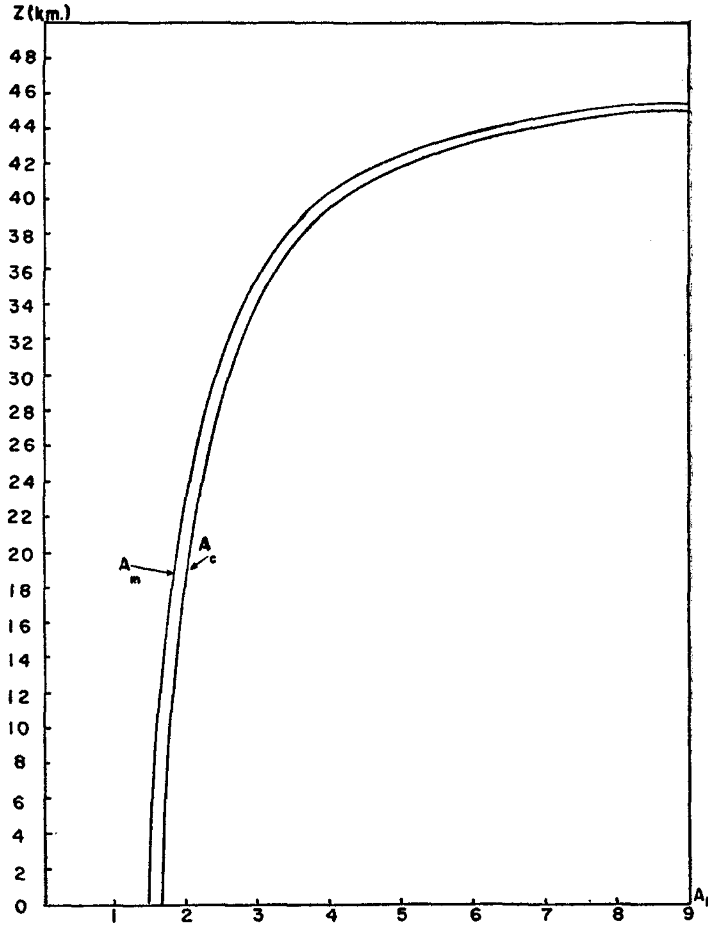

Figure 3.—Schematic representations of the general shapes of the limiting surface and the critical surface in a vertical tornado column. The abscissa A_i is a dimensionless radius and the ordinate z is the height in kilometers. A_m refers to the limiting surface, and A_c to the critical surface.

probably is initiated by a rising current which in turn is caused by the breakdown of stability at a small spot. The idea that the causing impulse must be limited in size to a small region seems to be most adequate for the initiation of a rather strong and well organized "jet" which does not admit internal convective activity that may lead to confused motion.

Such a strong but limited impulse may conceivably be caused by the "falling" down of an overhanging "hump" of cold air, in the way that is thought to happen when "breaking" takes place in the process which leads to the formation of a pressure jump line. This mechanism was first suggested to be responsible for tornado formation by Tepper [17], who in addition suggested that the intersection of two jumps may be more favorable for this process. Newstein [14] has found that tornadoes occur in the area affected by a pressure jump, which result gives further support to this idea.

Another possible mechanism which may supply a localized impulse is the migrating micro-anticyclones called "bubbles" by Fawbush and Miller [7]. It will be shown in a forthcoming publication that these "bubbles" are of the same nature as the well known "solitary waves" which travel at the surface of a canal. In a previous publication the present writer [1] made the remark that solitary waves may exist and be observed in the atmosphere, and he suggested a certain qualitative mechanism for their formation.

The significance of the "atmospheric solitary waves" in this connection is that they are, by their nature, small in extent; but if they break they may yield an appreciable amount of energy at a localized place, a process which is very favorable for the initiation of the required sink if the atmospheric stratification is favorable also.

(2) The two-layer atmosphere postulated in the tornado model is not a necessity as has been stated previously. The model works equally well if a one-layer atmosphere is assumed which is conditionally unstable. The assumption of two distinct layers, however, provides a mechanism for the supply of an impulse through the creation of a squall line or a solitary wave, as speculated in the first remark.

(3) The source of rotation, and hence the vortex circulation, was attributed to the conservation of angular momentum of the converging rings of air. It has been stated that strong wind shear aloft may give a vortex with strong "vortex strength." This suggests that it may be possible that the "vorticity" first appears to start aloft at the jet stream level and then to be conveyed downward by diffusion. This may explain the sometimes observed fact that a tornado appears to start at the cloud level and then build itself downward.

(4) In the computed examples, the sink strength expressed in volume units, namely m/ρ_0, has been assumed to be a constant. It may appear at the first instant that this is a far fetched assumption, and it may be thought that most of the air involved in the rising current is drawn from the lower layers. It is known, however, (see for instance Stommel [16]) that a cumulus cloud entrains a considerable volume of air at various levels. Rough analysis made on the data given in Stommel's paper convinced the writer that the sink strength is well maintained to the top of the cloud. There are, naturally, some variations in the value of the entrained air, but it may safely be said that the sink extends to higher levels with its strength being kept up by the entrained air. In tornado formation entrainment must be expected to be much greater than that in the case of ordinary cumulus clouds, because of the greater vertical accelerations involved.

(5) It has been stated by various observers that destruction in a tornado is caused by the low pressure at the core, as well as by the strong winds of the circulation. It may be seen from figure 2 that the pressure falls considerably only when the critical radius is approached. The pressure gradient at that point must be very great. However, strong and destructive winds extend over a wider area, and may safely be assumed to engulf the area of destructive pressure. In making an estimate of the area of destruction, only wind strength has been taken into account, it being understood that this area includes the area of destructive pressure.

(6) A word may be added about the similarity of the dynamical model proposed here for a tornado and that proposed by the author for a hurricane in a previous publication [2]. It seems that the two models are quite similar. The main differences are first, that the compressibility of the air is neglected in the hurricane model because the velocities are always much smaller than that of sound; and second, in the hurricane model a pure vortex motion is possible whereas this is not physically possible for a tornado. The reason that the vortex is possible in a hurricane is the assumption of a two-layer atmosphere. The "vacuum" produced in the lower layer by the vortex motion is filled by air of the upper layer.

(7) The assumption that a tornado circulation is dynamically equivalent to a combination of a sink and a vortex provides the embryo for the decay of the tornado. As explained before, the field of the combination results in the creation of a supersonic region which surrounds the limiting circle. This region develops shock waves which may be responsible for the death of the twister. This is probably the reason why tornadoes do not live for a long time.

(8) In deriving Bernoulli's equation for the outer region vertical velocities, friction, and the latent heat of condensation have been neglected. Because of these factors the model must be considered as a first approximation to a more exact one that may take them into consideration.

(9) It may finally be concluded that the proposed model may be found to give some plausible explanations for some of the observed facts about tornadoes. The model admits of various improvements and various checks. It is hoped that some exact quantitative observations may become available, and it may then be possible to check the results of the model, and to carry on the improvements, in a more intelligible way.

ACKNOWLEDGMENT

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Weather Notes

Editorial Note.—Many years ago the *Monthly Weather Review* published detailed eye-witness accounts of exceptional storms. These accounts both enrich the meteorologist's knowledge of storms and provide him with particular details that cannot be found elsewhere. Because such information bears directly upon questions the meteorologist must attempt to answer about weather phenomena (for example, the identification of storms as tornadoes), and because the information has potential value in both the research and service programs of the Weather Bureau, publication of eye-witness accounts of exceptional storms and other meteorological phenomena is being resumed in this issue. These accounts will appear from time to time under the heading "Weather Notes."

THE STORM AND TORNADOES OF MARCH 3, 1955

On March 3, 1955 thundersqualls developed to the west of Chicago and swept east-southeastward over Chicago, Ill., Gary, Westville, and on beyond Fort Wayne, Ind. At the eastern end of this path the storm struck after dark, but elsewhere the storm itself produced nearly the darkness of night, and even autoists were obliged to turn on headlights. Hail accompanied this storm over much of its path. The stones averaged nearly ¼ inch in diameter and barely covered the ground, but in some places stones were as large as golf balls and covered the ground, and inflicted much damage. Tornadoes were observed in this storm. Damage typical of tornadoes was inflicted at various places along the path of this storm, though at some of these places no one reported seeing a funnel cloud. To be sure the terrifying nature of the storm was such as to send most potential observers to cover in basements, and the darkness may have been a factor in obscuring funnels that may have occurred.

In Chicago the main features were hail and extreme darkness, with the height of the storm at about 1515 to 1530 CST. The storm was preceded by mammatus cloud formation. During the storm strange colored casts were observable, varying from greenish purplish to orange, such as is often associated with the more violent convective storms and tornadoes. Wind was not a serious factor in Chicago. Midway Airport reported a peak gust of 38 mph, while the University of Chicago reported one gust to 42 mph. Some minor wind damages were suffered, and it is likely that at some points in the city, higher speeds were reached. A pressure jump of over 0.12 inch was recorded at Midway Airport. Lesser jumps were observed at the University of Chicago and in the Loop. The pressure profiles during the storm at the three locations were vastly different, indicating the possibility of very small local circulations. The Meteorologist at Argonne National Laboratory in Lemont reported that the pressure change there was suggestive of tornadic activity in the vicinity. A man at 2315 E. 68 St., Chicago, reported that he observed a definite funnel cloud just east of straight south from his location, estimated at 5 to 10 miles away and apparently traveling eastward. This funnel was very dark and easily seen as it was backed by a lighter, yellowish or orange background. The bottom of the funnel was obscured by buildings, so that it could not be determined if it reached the ground, but its diameter at the lowest observable point was about one-tenth only of the diameter at the point where it was attached to the general cloud base. As the location of the funnel, as described, may have been in the Lake Calumet-Wolf Lake area, it might actually have reached the ground without being noted, as there is but little in the area that is subject to damage. It is perhaps more likely that the funnel did not reach the ground. As this funnel was observed by a man who had once experienced a severe tornado and also was seen by his wife, and as they were able to sketch and describe it so well, there is practically no doubt that it existed.

To the south of Chicago, in Park Forest, Ill., and along U. S. 30, hailstones the size of golf balls fell. Automobiles were dented and windows broken.

As the storm swept over Gary, Ind., it hit the eastern part particularly hard, especially in the Miller Beach and Odgen Dunes areas. Hail at Ogden Dunes was measured as large as 1¾ by 1½ inches, with many stones averaging 1¼ inches in diameter. Depth of stones on the ground was measured at 2½ inches, with drifts up to 10 inches deep. The pressure jump at the Duneland Observatory was only about 0.05 inch. Winds, however, were much stronger than recorded at Chicago, and reached a fastest mile averaging 58 mph from the northwest at 1601 CST. The five-minute maximum was 46 mph. Gusts to 60 mph were observed until the observer thought best to take refuge in the cellar. Peak gusts are conservatively estimated to have reached near 75 mph. The wind drove the hail nearly horizontally, so that many windows were broken. One house had 77 panes smashed. Greenhouses suffered serious loss. Much water damage resulted from hail and rain entering through broken windows of homes, and also much damage to roofs resulted from the wind and hail. Damage in the Ogden Dunes area was estimated at $150,000. Many automobiles were badly dented by hail. One woman in Gary was injured when her hand was cut by falling hailstone. As the above dollar loss is for only one 2-square mile area, and as the area of severe damage was 7 miles long and ½ to one mile wide, total damages in the Gary-Ogden Dunes area may be in excess of ¼ million dollars. (Revised figure is over $1,000,000 for Lake and Porter counties alone.)

The next community to be hard hit was the Village of Westville, at the intersection of U. S. 6 and Indiana 2. Here damages of $100,000 were suffered in an area about 5 miles long and about ½ mile wide. Within this area paths of severe damage were on the order of 50 to 100 feet in width, made by tornadoes which were observed by several people. The largest single loss was to a garage and contents at the mentioned intersection called West Point where a $50,000 loss was sustained, including loss of four trucks and four automobiles. Attendants and customers were unhurt, being in the office at the time, the only part of the building remaining intact. Debris from this building could be seen for a great distance, ½ mile or more to the southeast, and heavy metal parts were moved considerable distances. Though the general distribution of the debris did not indicate much rotation, the roof of this building was seen to have made a nearly complete circle after the building "exploded", landing on U. S. 6, only a few hundred feet from the original site. The force of destruction and nature of the damage were definite indications of a tornado, as well as the fact that a straight wind could not have reached this building without damaging other nearby and less substantial buildings. Many trees and one shed were destroyed within two miles to the west of this garage along U. S. 6, though the major area of damage was eastward from this point, in an area about 3 miles to the east.

(Continued on p. 98)