PROPOSED MECHANISM OF SUCTION SPOTS ACCOMPANIED BY TORNADOES

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1. INTRODUCTION

Van Tassel (1955) investigated the circular marks left by the North Platte Valley tornado of June 27, 1955. Since then various researchers have studied the unusual appearance of similar marks. Summarized below are the various studies made, the location and date of the storm, and the descriptive name given to these marks.

(1) Van Tassel (1955)
Scottsbluff, Nebr., June 27, 1955
CIRCULAR MARKS in aerial pictures. Marks were assumed to be produced by a single object caught in the tornado funnel. Rotational speed of the object of 484 mph was obtained, but the speed must be divided by the number of objects if more than one existed.

(2) Prosser (1964)
Shelby, Iowa, May 5, 1964
SURFACE MARKS with definite cyclonic curvature. Marks define the axes of most intense destruction. They give impression that an enormous vacuum cleaner had swept the ground clean of vegetation, loose soil, and other movable objects.

(3) Fujita (1966)
Greentown, Ind., April 11, 1965
CYCLOIDAL MARKS. Based on B & W pictures taken from 1000 ft, marks were assumed to be sandy soil loosened by tornado funnel, resulting in high reflectivity.

(4) Fujita (1967)
Greentown, Ind., April 11, 1965
SUCTION SPOTS. Further investigation of telephoto pictures from 500 ft height suggested that cycloidal marks consisted of debris accumulation rather than evacuation. The tornado's vacuum cleaner collected debris but failed to suck it up. The shape of the tornado core was obtained based on radius vectors of suction spots relative to tornado center.

(5) Fujita, Bradbury, Black (1967)
Greentown, Ind., April 11, 1965;
Barrington, Ill., April 21, 1967
CYCLOIDAL SUCTION MARKS. Both aerial and ground survey revealed that suction marks consisted of short pieces of corn stubble deposited on plowed field. Deposit was as high as 8 inches and 5-ft wide.

(6) Waite, Lamoureux (1969)
Charles City, Ia., March 15, 1968
CORN STRIATION. Ground inspection revealed that striation consisted of corn stalk debris mostly deposited but some slightly imbedded in the soil. Assuming that only one deposition area circled around the tornado core, 458 mph speed was computed. The speed must be divided by the number of deposition areas, if more than one area existed.

(7) Fujita, Bradbury, Van Thullenar (1970)
Palm Sunday Tornadoes, April 11, 1965
SUCTION MARKS AND SUCTION SPOTS.
4 to 5 suction spots were confirmed, thus obtaining the translational speed of these spots circling around the tornado center to be 104 to 118 mph.

(8) Fujita (1970)
Lubbock, Tex., May 11, 1970
SUCTION SPOTS AND SUCTION SWATHS.
Severe damage swaths in Lubbock were mapped. 26 out of 28 fatalities occurred within suction swaths covering only a fraction of the area swept by the tornado core. The swath width or suction-spot diameter was up to 40 m while the tornado core diameter, 600 to 1600 m, was 15 to 40 times the diameter of the spots.

(9) Ward (1970)
In NSSL Laboratory, TWIN AND MULTIPLE VORTICES were observed. Honeycomb suction placed above a circular area with direction vanes at its edge for control of inflow angle was used to generate simulated tornado vortex. Multiple vortices circling around the common center were observed when the diameter of the circular area exceeds the height of the suction honeycomb.

(10) Fujita (1971, this paper)
Rantoul, Ill., April 30, 1971
SUCTION VORTICES of a giant dust devil were photographed at 1-sec interval while flying 750 ft above a plowed and seeded corn field. Suction spots are now postulated to be rotating air columns circling around the parent circulation core.

(11) Fujita (to be published)
Marceline, Mo., May 5, 1971. Significant SUCTION SWATHS were photographed just north of the scene of 67 freight cars blown off or derailed by a tornado.

All the researchers more or less agreed that (a) these marks are identifiable from the air but hard to observe from the ground and (b) that they are produced by an intense vacuum cleaning action of several active spots located on or near the edge of a tornado core.

A laboratory model experiment by Ward (1970) succeeded in producing multiple rotating columns around the fringe of a core circulation which was designed to be stationary in nature. His experiment strongly suggested that vacuum cleaner effects appearing in past literature were produced by multiple columns of rotating air.

On April 30, 1971 while returning from a tornado damage survey in Kentucky the author, accompanied by Mr. J. J. Tecson, SMRP meteorologist, spotted columns of dust rising from a seeded corn field about 2 miles southwest of Rantoul, Ill. A quick decision was made to descend from 3000 ft to less than 1000 ft to take pictures of the odd-looking cloud of dust. When Mr. L. A. Schaal, NOAA Climatologist for Indiana, who piloted the Cessna 172, brought the plane to photographic position at 750 ft above the corn field, a strange motion within the dust cloud became apparent. Several dust devils, all rotating anticyclonically, were moving also anticyclonically around a giant dust devil core, just about one order of magnitude larger than individual small ones. Yet these small sized ones appeared to be much stronger than the parent core circulation which was accompanied by a faint cloud of dust around its periphery. Foreseeing the necessity of constant time interval between successive pictures, the author clicked the camera shutter by counting "one-thousand-and-one" between clicks. A series of 12 pictures were taken with Kodacolor X film exposed 1/1000 sec. Research presented in this paper is based on the analysis of those pictures which were enlarged for detailed photogrammetric purposes.

2. ANALYSIS OF THE GIANT DUST DEVIL

After producing a high quality picture sequence of the giant dust devil of April 30, 1971, the site was visited by car on May 9, in an attempt to investigate the local topography and the soil albedo which would have given rise to the strange dust devil.

As shown in Fig. 1, the dust devil was located about 3/4 mile to the west of Interstate Highway 57 running in a north-south direction. Tillage lines extending east-west in the corn field at the measured 3.90 m interval were used to determine y distance and the northward extension of tillage lines in a 10-12" tall field of oats were used for x determination. The dust devil core which was an ellipse, was about 30 x 40 m in size located over a relatively flat surface, 752 ft MSL. Note that approximate contours are drawn for every one foot and that light colored, sandy soil is stippled in the surveyed map.

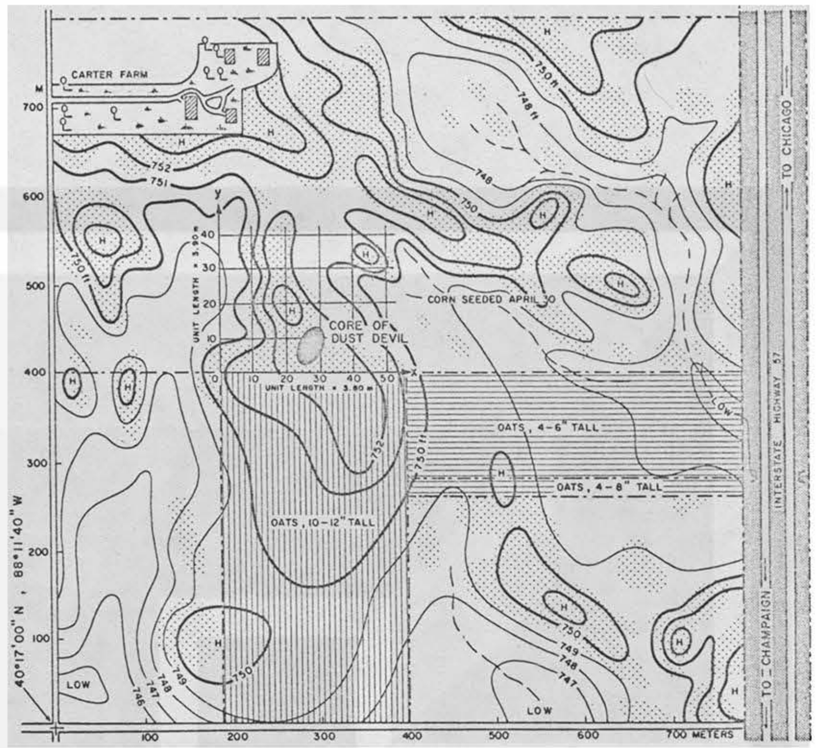

Figure 1. Detailed map of the field 2 miles SW of Rantoul, Ill. where a giant dust devil was photographed at 1558 CST April 30, 1971.

Presented in Fig. 2 are enlargements of 12 dust devil pictures. The pictures were taken at

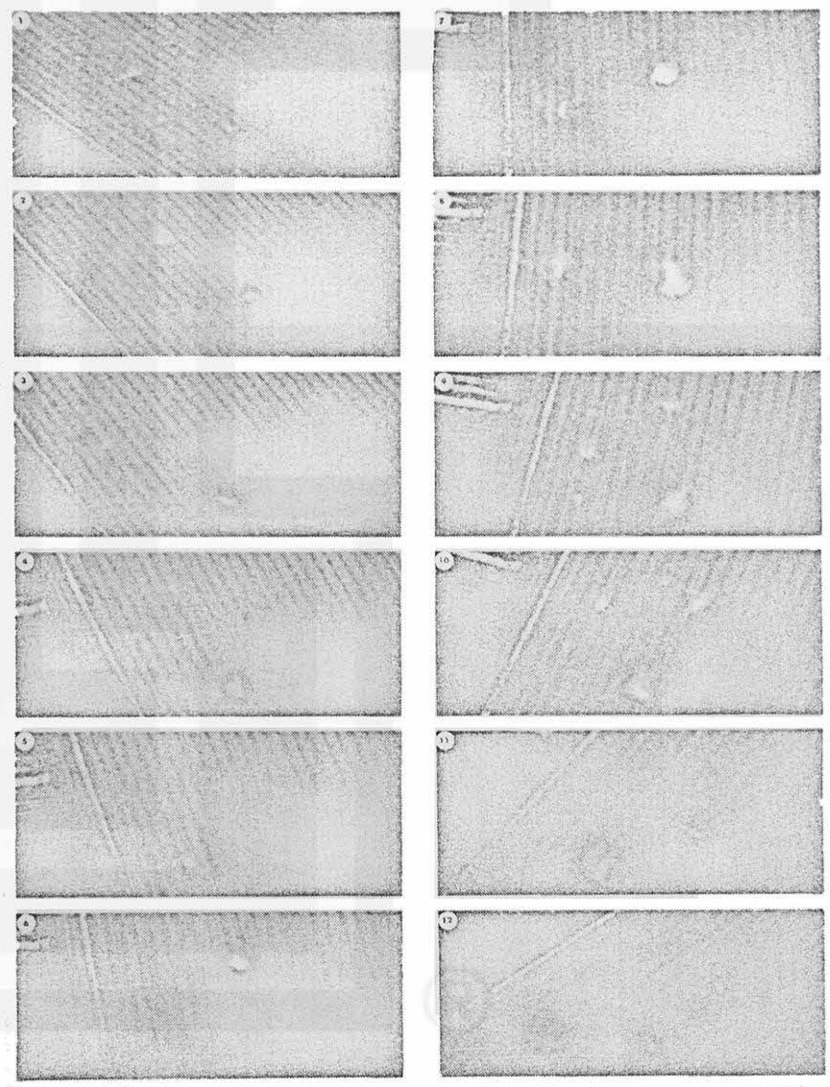

Figure 2. A series of 12 pictures of the dust devil taken at one second intervals.

1558 CST or 2158 GMT under scattered thin cirrus. A comparison of successive pictures clearly indicates that both the individual whirls and the giant core were rotating anticyclonically.

A surface map for 2100 Z (see Fig. 3) shows that the position of the dust devil at 2158 GMT was under the influence of an anticyclone centered just west of the dust-devil position, suggesting that this giant anticyclonic dust devil formed within a much larger scale anticyclone.

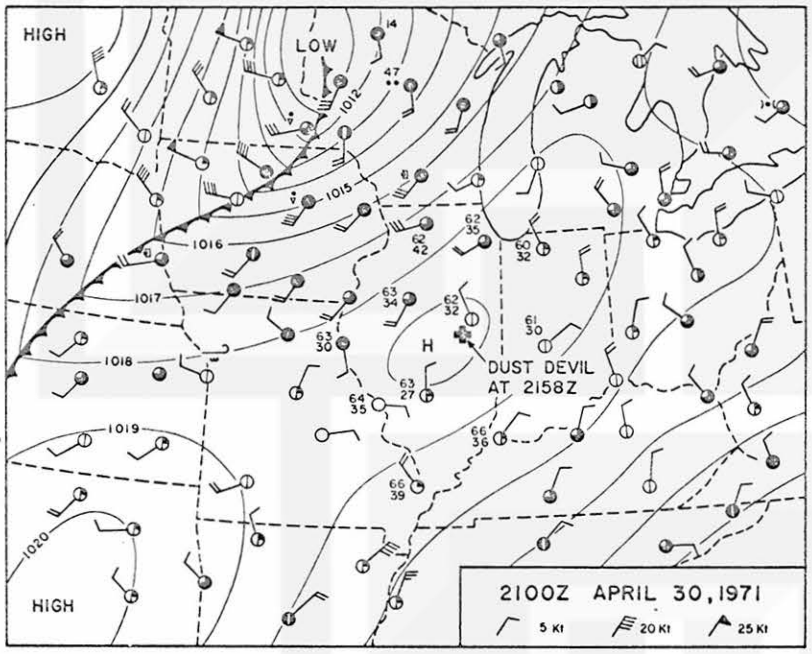

Figure 3. Synoptic chart for 2100 GCT, April 30, 1971.

3. LIFE CYCLE OF SUCTION VORTICES

Since it appears that the behavior of the rotating column around the dust devil core resembles that of a tornado suction spot, the term "Suction Vortex" was introduced to designate the suction spot appearing in the author's past literature.

As expected, a suction vortex becomes whiter as its spinning wind speed increases to kick up more dust. In order to accomplish a crude characterization of these vortices, the appearance of suction vortices were classified into the following five scales of whiteness:

Whiteness Scale	Appearance of dust cloud
0	Hardly visible against the background
1	Diffused smoke-like dust
2	Slightly diffused dust cloud
3	Well-defined white cloud of dust
4	Very bright cloud of dust

These scales were used to identify the degree of whiteness of suction vortices, A through H, appearing in the 12 pictures with ID numbers 1 through 12 in Figure 2.

In order to observe the whiteness changes as a suction vortex moves around the giant core center, the behavior of suction vortex B is presented in Figure 4. The vortex was very dark and weak until it brightened up in picture 6 when it was travelling to the northwest of the core center. An attempt to explain such an explosive intensification of suction vortex B is made later in this paper.

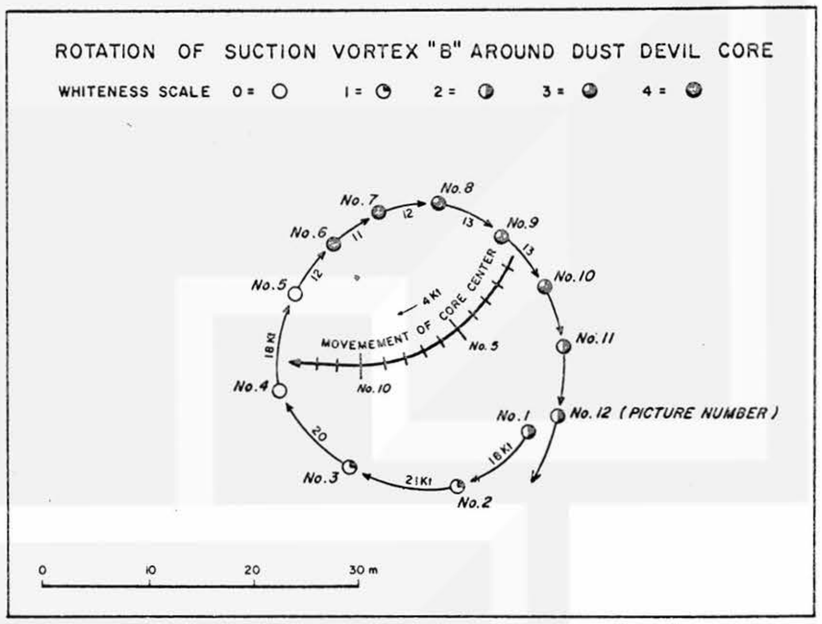

Figure 4. Change in whiteness of suction vortex "B".

Although vortex B showed an explosive intensification, all the other suction vortices showed a tendency to become brighter while passing to the northwest of the core center which moved more or less toward the southwest. To determine the mean conditions of the whiteness values, mean whiteness of all dust clouds was computed by grouping them into their azimuths at 30-degree intervals. The mean whiteness, thus obtained, is shown in Fig. 5. The

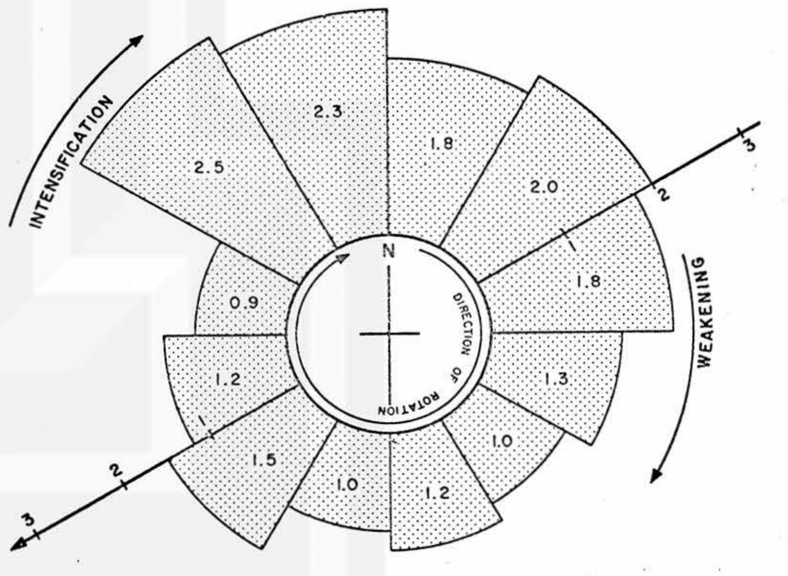

Figure 5. Mean whiteness of 8 suction vortices in a series of 12 pictures. Whiteness within each 30 azimuth was averaged.

figure clearly indicates the tendency for suction vortices to increase their whiteness by stirring up more dust while passing to the northwest of the core center. This means that an intensification takes place in this region. A rather gradual weakening is apparent as the vortex travels around the core through its northeast, southeast to southwest quadrants.

A θ-t diagram (see Fig. 6) indicates the rotation of A through H suction vortices around the core center. Note that the steady changes of vortex

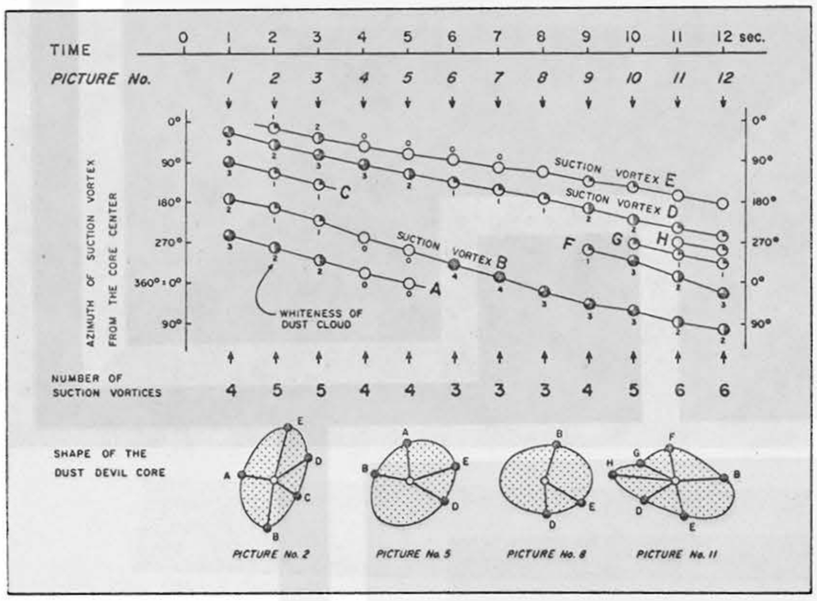

Figure 6. Rotation of suction vortices around the dust devil core.

azimuths reveals the steady rotation of these vortices around the core center. The total number of suction vortices in each picture varies from 3 to 6 in these 12 pictures while the mean number of vortices turns out to be 4.3. It is of interest to repeat the statement that the suction spot number within one of the Palm Sunday tornadoes varied between 4 and 5, according to Fujita, Bradbury and Van Thullenar (1970). This amazing similarity becomes more convincing when the shapes of the dust devil core shown in Fig. 6 is compared with the estimated shapes of the tornado core in Fig. 88 of the above reference.

4. MODEL OF TORNADO WITH MULTIPLE SUCTION VORTICES

Based on observational evidences and their analysis, a model of a giant dust devil with multiple suction vortices was constructed (see Fig. 7). The flow field is expressed by stream lines relative to the center of the dust devil core travelling from right to left. Of these four suction vortices in the figure, A is the oldest and D, the youngest, is undergoing an explosive development in the northwest sector of the giant core. This sector is characterized by a significant convergence in stream lines, bringing the fresh air into the developing suction vortex D.

When suction vortex D travels around the core which is moving toward the left, it would create a suction swath shown in the middle diagram of Fig. 7. If a quick development of suction vortex takes place,

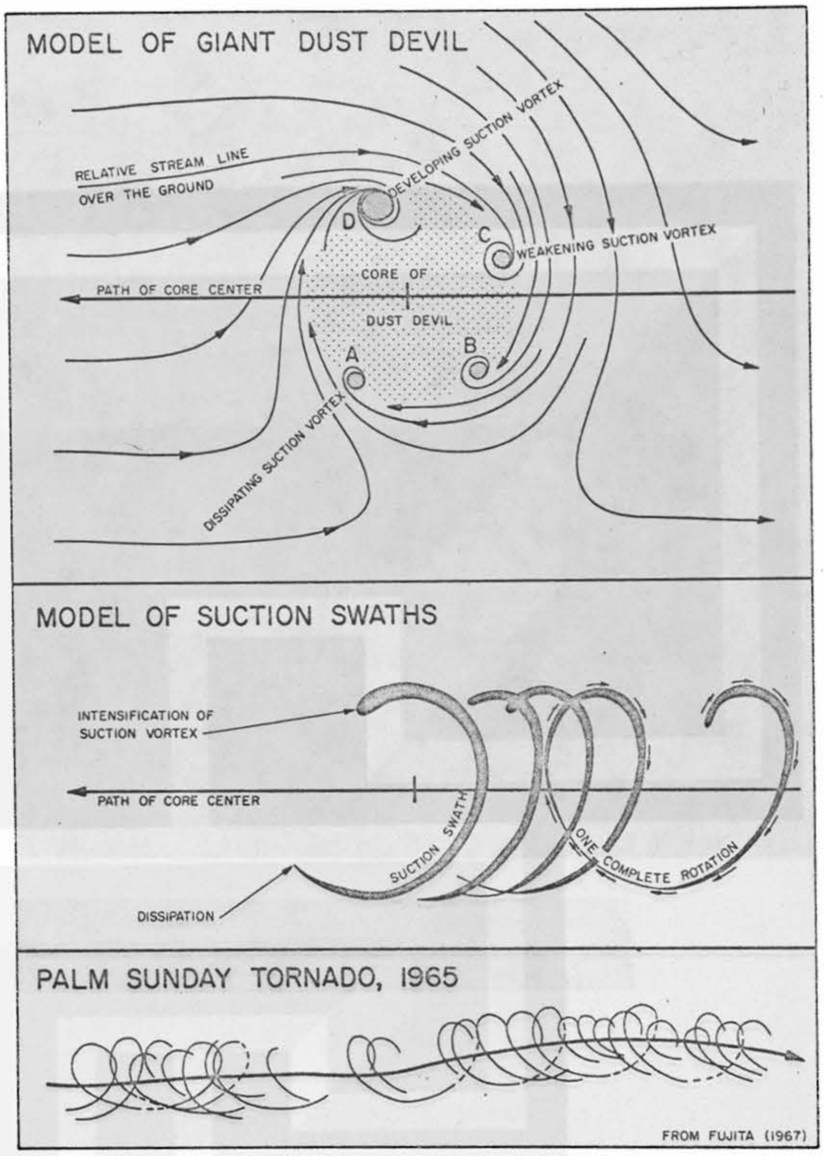

Figure 7. Model of giant dust devil and its suction swaths.

a corresponding suction swath will become pronounced to the northwest of the giant core. A schematic diagram of suction swaths will then show significant asymmetry in such a manner that more debris tends to drift toward the southern envelope of these swaths where weakening suction vortices tend to accumulate more debris.

A striking resemblance is seen between the tornado suction swaths and these model swaths. As shown at the bottom of Fig. 7 the suction swaths of the Palm Sunday tornado (Fujita 1967) is almost identical to the backward view of the suction swaths of a model dust devil rotating anticyclonically. Prosser's (1964) swaths are also very similar to the backward view of the middle diagram suggesting that the intensification of suction vortices took place in the left front quadrant so that a significant amount of debris was deposited in the rear quadrant of his Shelby tornado.

Although the giant dust devil failed to produce suction swaths along the loci of its suction vortices, suction vortices inside a tornado are strong enough to capture and accumulate debris and then deposit it along their swaths. For clarification of such a swath refer to Picture 18 from Fujita, Bradbury, and Black (1967) which is a close-up view seen from the ground.

Since it is very difficult to show the curvature of a suction swath in a ground picture, the author took this picture standing on a 6-ft ladder placed on the field. It should be noted that the depth of the corn stubble deposit increases toward the center of the swath, implying that the deposition is most efficient at the center of the suction vortex, where the vertical motion reaches a minimum or becomes negative.

Based on the above evidence, a model of a tornado with multiple suction vortices was constructed.(see Fig. 8). Three schematic suction vortices are collecting and depositing small debris while some pieces are being carried up inside the vortices to be

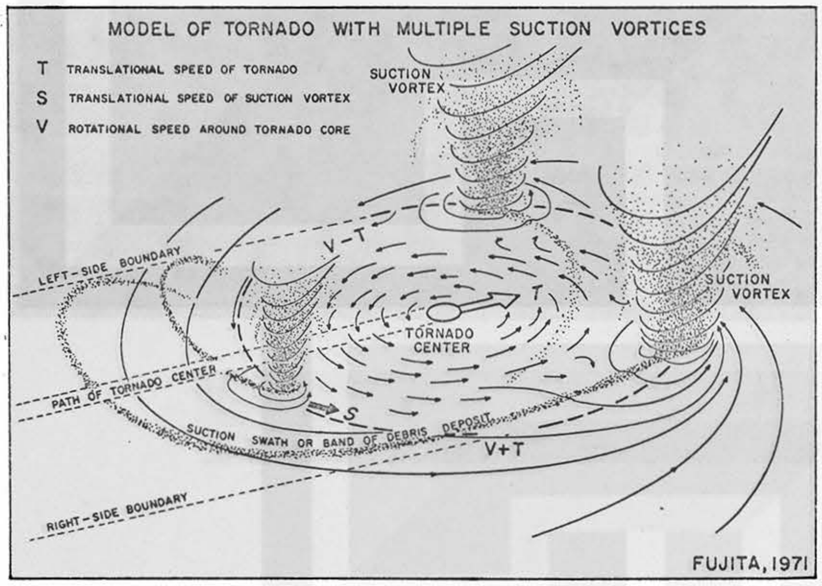

Figure 8. Model of multi-suction tornado.

thrown outward. The translational speed, T, of the tornado center is added to the rotational speed,of the tornado core, V, resulting in V + T, the maximum wind speed by the tornado occurring to the right of the center. On the left side of the storm a minimum speed V - T occurs. The translational speed of a suction vortex, S, may be assumed to be very close to the vector sum of V and T as it moves around the tornado core.

The rotational speed of a tornado with multiple suction vortices does not seem to be extremely high. If we use the number of suction vortices, being 4 on the average, Van Tassel's (1955) speed will be reduced from 484 mph to 121 mph; Waite and Lamoureux, 458 mph to 115 mph, while Fujita, Bradbury, and Van Thullenar's values computed from actual number of suction vortices are between 104 to 118 mph. These speed ranges suggest that the rotational speeds around the cores of multi-suction tornadoes are only about 100 to 120 mph. This is why structures outside suction swaths often escape serious damage when a tornado vortex moves directly over them.

Prosser (1964) stated "there seems to be a sharp transition along the edges of the path (suction swath) from total destruction to little damage". Fujita's (1970) report of differential damage on wooden shack, frame house, and block church in Lubbock is a good example that a shack within a tornado could escape damage if it is located just outside suction swaths.

5. STRUCTURE OF SUCTION VORTICES

The maximum rotational wind speed within a multi-suction tornado is estimated to be only 100 to 120 mph which is not enough to cause severe structural damage. Expressing V, the rotational speed at R, the radius of maximum wind speed, we write the mean vorticity of the solid rotation core of a tornado,

$$Q = 2\frac{V}{R} \tag{1}$$

Applying similar notations, v, the rotational speed, r the radius of maximum wind speed of a suction vortex, the core vorticity, q is given by

$$q = 2\frac{v}{r} \tag{2}$$

Under the simple assumption that a suction vortex with vorticity, q is generated by concentrating Q into a small area while satisfying

$$\frac{dQ}{dt} = -DQ \tag{3}$$

we solve this equation assuming that D, the divergence of the wind field, is independent of time and uniform within the suction area. Thus we have

$$\frac{dQ}{Q} = -D\,dt \tag{4}$$

Then we integrate both sides, keeping in mind that Q increases to q between time, t and $t + \Delta t$ Equations (1) and (2) are put into Eq. (4) after its integration, th

$$\ell n\, q - \ell n\, Q = D\Delta t$$

$$n\left(\frac{v}{V}\cdot\frac{R}{r}\right) = D\Delta t$$

$$-D = \frac{1}{\Delta t}\,\ell n\left(\frac{v}{V}\cdot\frac{R}{r}\right) \tag{5}$$

Because of the fact that R is 10 to 30 times larger than r, we may assume that

$$R \cong 20r \tag{6}$$

There is no way of knowing the ratio of rotational speeds of a suction vortex and its parent tornado. For the dust devil described in this paper, however, V and S measured from dust motion were approximately 15 kt which represents a speed just strong enough to stir up dust around the giant core. The rotational speed of the suction vortex is estimated to be at least 30 kt which would generate a dense mass of dust inside the vortex. If we accept these values as being realistic we may express

$$v \cong 2V \tag{7}$$

This relationship is expressed in Fig. 9 showing the

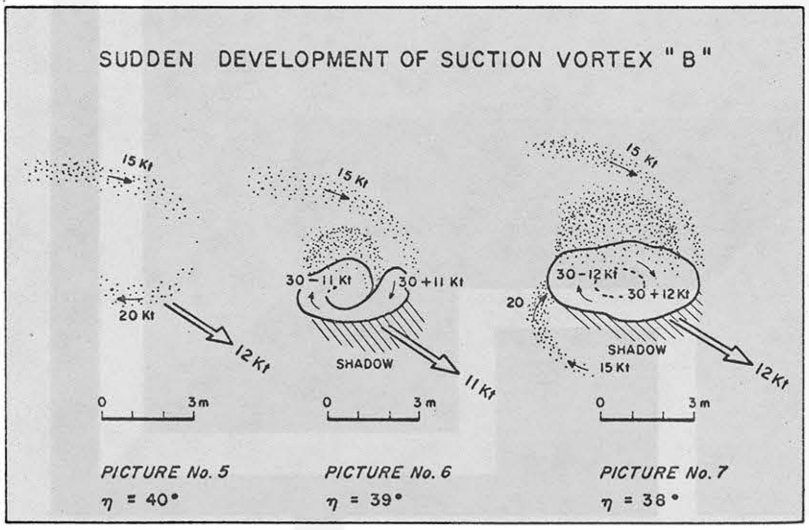

Figure 9. Sudden development of suction vortex "B".

stages of an explosive development of suction vortex B at one-second intervals. It is amazing to see that the development of the dust whirl "B" took place only within one second, necessitating a tremendous concentration of vorticity. The convergence required for this explosive development can be computed from Eq. (5), (6), and (7). Assuming that $\Delta t \cong 1$ sec, we have

$$-D = \frac{1}{1} \ln(2 \times 20) = \ln 40 \cong 3.7\,\text{sec}^{-1}$$

This magnitude of convergence required to create a suction whirl in picture 6 (see Fig. 9) can be applied to tornadoes because the computation involves the ratios in velocities v and V, and radii r and R. The vertical velocity W_h at height h above the surface turns out to be

$$W_h \cong -Dh \cong 3.7h \text{ m/sec} \tag{8}$$

which gives 3.7 m/sec at 1-m height and 10 m/sec at 2.7-m height above the surface.

When the suction vortex reaches a steady state the flow around the vortex center tends to achieve a cyclostrophic balance, thus not requiring a rapid inflow to compensate for such a large value of $-D$. When Δt increases to 5 or 10 sec due to small crossing angles of inflow stream lines the vertical motion will become insignificant reaching up to about 1 m/sec at 1-m height. A suction vortex then acts as a debris collector but the collected debris cannot be carried away due to a reduced vertical motion field inside the suction vortex.

6. FURTHER RESEARCH

As an extension of this research, the multi-suction tornado model is now being expanded into that of single-suction tornadoes. An additional progress report on the future work will be distributed at the time of the Kansas City meeting in October.

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