PROPOSED MECHANISM OF TORNADO FORMATION FROM ROTATING THUNDERSTORM

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1. INTRODUCTION

The most destructive tornado in the U.S. is known to be the Tri-state tornado of March 18, 1925. The storm travelled through a distance of 219 miles in 3hr 18min, killing 689 persons and injuring 1,980 others. Refer to Flora (1958).

Pearson's (1971) statistics of the 1960-1970 tornadoes revealed that there were 9 tornadoes with path length in excess of 100 miles, of which one was over 200-mile long. Wilson and Morgan (1971) defined "Long Track" (LT) tornadoes and "Very Long Track" (VLT) tornadoes, being 100-149 mi and 150mi or longer path lengths, respectively. Their numbers during 1916-1969 period were tabulated to be 51 LT and 28 VLT tornadoes, while all tornadoes were 16,303. Based on detailed study of these exceptionally long tornadoes, they concluded that such tornadoes must occur with traveling "supercells".

In spite of continuous damage paths reported in historical tornado data, aerial photographic mapping of a number of tornado areas revealed definite variations in storms' intensity and width along their paths. The author obtained a large number of aerial photos covering damage areas of

- Fargo tornadoes; June 20, 1957
- Palm Sunday tornadoes; Apr. 11, 1965
- Lubbock tornadoes of May 11, 1970
- Mississippi Delta tornadoes; Feb. 21, 1971
- Kentucky tornadoes; Apr. 27, 1971
- Missouri tornadoes; May 5, 1971
- Joliet tornadoes; Apr. 17, 1972
- Rio Grande tornado; May 12, 1972
- Iowa and Illinois tornadoes; Sep. 28, 1972
- Georgia - South Carolina tornadoes; Mar. 31, 1973
- Pearsall tornado; Apr. 15, 1973
- Kansas - Missouri storm; May 11, 1973
- Arkansas - Alabama tornadoes; May 27, 1973

Aerial pictures of these tornado areas are being analyzed to obtain the variation of intensity and width as functions of the mileage.

As shown in Fig. 1, the tornado intensity and width vary significantly along the path. Since no eye-witness accounts can be expected throughout the entire track, it would be necessary to define tornadoes based on damage patterns.

A family tornado is defined as being more than one tornado spawned from a thunderstorm cell or Wilson and Morgan's (1971) "traveling supercell". Formation of these tornadoes in a family takes place in succession, so to speak, often spawning a new tornado prior to the dissipation of the old one.

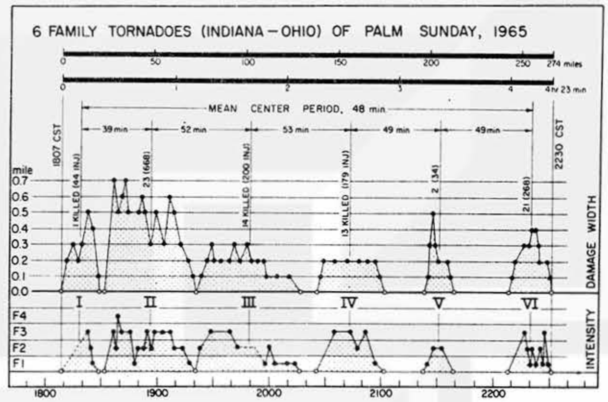

Fig. 1. Variation of damage width and F-scale intensity along the path of Bi-State tornadoes on Palm Sunday, 1965. From Fujita (1971).

Fujita (1963) listed a number of family tornadoes to find their periodic formations. A 45-min period was obtained based on six tornadoes with 15 to 34 mph traveling speed of the parent cells. An addition of the Bi-State tornadoes of Palm Sunday in Fig. 1, with 48-min period and 62 mph traveling speed, does imply the constancy of the period independent of the cell's traveling speed.

Darkow and Roos (1970) and Darkow (1971) gathered 23 cases of family tornadoes between 1955 and 1970 to obtain the median and mean periods of 45 min and 51.5 min, respectively. Very important statistical evidence which was found is the preferable occurrence corresponding to non-dimensional numbers 1, 2, 3, etc., which are the ratio of the tornado interval divided by the shortest interval between families belonging to a specific cell.

These studies strongly suggest an existence of "45-min tornado intervals" applicable to family outbreaks. The standard deviation of the intervals is about 10 min. The variance appears to be caused not by the random spawning but by virtue of the characteristics of the parent thunderstorms.

2. HOOK-ECHO CELLS

It has been known that a parent thunderstorm often takes a shape of a hook at the time of tornado formation. The shape of the hook does not always appear as a genuine fish hook, but it varies significantly.

A schematical variation in the hook shape is presented in Fig. 2. In an early stage of a hook, the

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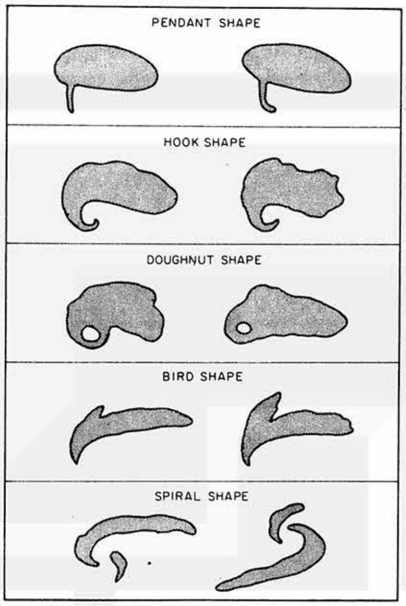

Fig. 2. Typical shape of so-called hook echoes.

parent cloud appears as a large solid echo with a small pendant finger attached (pendant shape). When the pendant changes into a hook, the parent cell deforms, being affected by a circulation field around the hook center (hook shape). Then a hook wraps around to form an eye around the center of the circulation (Doughnut shape). As the circulation intensifies, the parent cell as a whole becomes influenced by a cyclonic flow around the center (Bird shape). Echoes of a parent thunderstorm under the influence of very intense circulation often appear like miniature spirals (Spiral shape). Despite these variations, when a thunderstorm cell on PPI scope displays one of these shapes, the echo is customarily called the "hook echo".

It has been known that a hook-echo cell is a potential tornado producer. Forecasters often upgrade "tornado watch" into "tornado warning" after seeing a hook echo.

There are numerous cases of hook-echo sightings and subsequent studies such as by Huff et al. (1954), Browning (1964), Fujita (1965), and others.

The vertical structure of a hook-echo thunderstorm presented in Fig. 3 reveals a typical pattern of precipitation on the surface. In many cases precipitation is heavy to the north and northwest of the hook center traveling eastward. Areas of hail are found usually in north, northwest, and west quadrants.

The cloud axis often displays a significant tilt from the local vertical, leaning as much as 30 to 45 degrees. The shape of the hook is most significant at about the cloud-base height, necessitating a low-elevation PPI scan in order to confirm the existence of a hook. As the height increases to the middle level, the hook begins to close into a doughnut shape. Both in PPI and RHI presentations, a weak

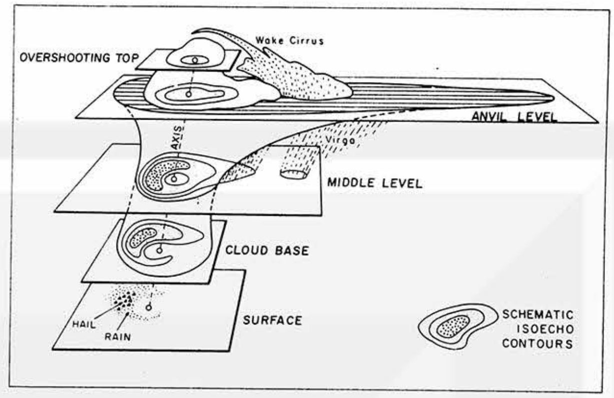

Fig. 3. Three dimensional patterns of radar echo.

echo region is seen around the cloud axis.

Between the middle and the anvil levels, the doughnut-shaped area of weak echo reverses into that of strong echo. Browning's (1964) echo-free vault, called "radar vault" in this paper, disappears at this altitude.

The strong-echo area near the anvil level extends upward into lower stratosphere, thus forming overshooting echo turrets on RHI image. When viewed from high-flying aircraft, these turret tops appear as multiple protrusions overshooting beyond the anvil top (see Fig. 4).

Fig. 4. Overshooting tops of May 13, 1973 near San Antonio as viewed from a Learjet flying at 45,000 ft.

Overshooting tops collapse very rapidly and in exchange cirrus clouds jump up from the wake regions of the collapsing tops.

Schematic diagram of three-dimensional air flow within and around a hook-echo cloud, or a "rotating thunderstorm" is shown in Fig. 5. Due mainly to the existence of precipitation-induced downdraft within the rear quadrant of the storm, strong updrafts are often limited to the easterly quadrant and around the cloud axis where no precipitation takes place.

A 70 ft/sec updraft at the 3000 ft base of Fargo tornado cloud was reported by Fujita (1960). The convergence corresponding to these values is

$$\frac{dw}{dz} \cong \frac{70\,\text{ft/sec}}{3000\,\text{ft}} \cong 1.4 \text{ per min.}$$

The vorticity at the cloud base was approximately 2.0 per min.

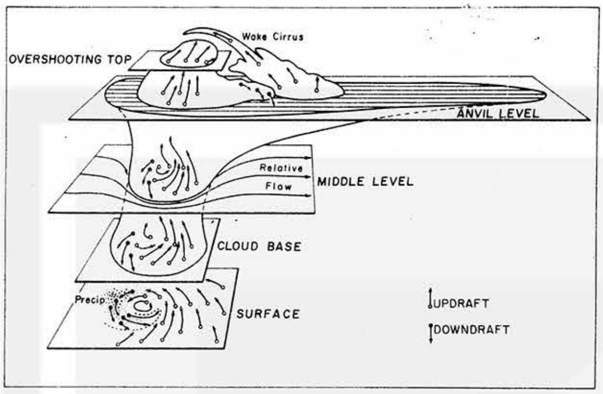

Fig. 5. Schematical diagram of 3-D airflow.

The rate of vorticity increase due to vertical stretching is as large as

$$\frac{dQ}{dt} = -DQ \cong 2.8 \text{ per min}^2$$

Such an extremely large rate of vorticity production is very unlikely to exist all the way into the heart of a rotating cloud. The rotational part of the frictional force,

$$k \cdot \nabla \times F$$

will act against the vorticity concentration. At high levels, the rotating updraft suffers precipitation loading which will reduce the dQ/dt term to zero or even to a negative value. Meanwhile the frictional force will act efficiently to slow down the updraft rotation, resulting in a straight updraft corresponding to each of the overshooting turrets.

The middle level flows, between 700 and 400 mb, go around the rotating updraft. The updraft within this layer often acts as a rotating cylinder which receives the "lift forces" in horizontal directions. For the nature of the lift force refer to Fujita and Grandoso (1968) and Harrold (1966).

Traveling mechanisms of a rotating thunderstorm, thus vary between those of large thunderstorms and small hurricanes. The former, as proposed by Newton (1950), Newton and Katz (1957) have a tendency to move toward the area of low-level convergence created by the cloud itself. Hurricanes and typhoons are often treated as vortices drifting in a steering flow. The translational motion of the low pressure field of a mature-stage storm provides the propagation of the convergence field near the surface.

A thunderstorm of significant rotation may as well be characterized by a cyclonic pressure field at the steering level, extending horizontally as far as 20 to 40 miles in diameter. When such a low-pressure field in the middle level travels under the influence of the steering flow and the lift force, the low-pressure field on the surface will continuously initiate cyclonic convergence field near the ground.

3. PULSATION HYPOTHESIS

Photographic experiment of thunderstorm tops conducted jointly by NASA and the University of Chicago during the Spring of 1972 and 1973 revealed that

A. Tops of a severe thunderstorm consist of numerous protruding tops which are growing or collapsing very rapidly.

B. The overall top averaged over a several mile area rises and falls with much longer period, 10 to 20 min for weak storms and over 30 min for severe ones. Shown in Fig. 6 is an example of such a variation.

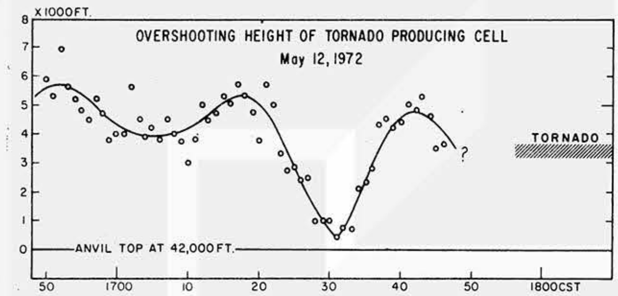

Fig. 6. Variation of the overall top of a severe thunderstorm of May 23, 1972 over southern Texas near Rio Grande. A weak tornado with a 40-mile path length spawned out of this cloud.

C. Relative wind reverses from westerly to easterly few thousand feet above the anvil top. Wake cirrus clouds generated in the wake of the relative westerly move over the overshooting top. Wake vortex-rolls are often seen to the west of a tall overshooting top.

Cross sections of a rotating thunderstorm in its overshooting and collapsing stages in Fig. 7 were constructed based on above observational evidence as well as the past results of radar observations.

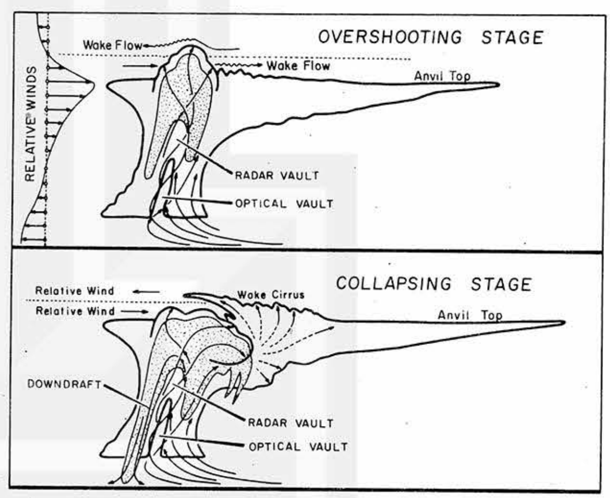

Fig. 7. Radar echo and air flow within a rotating thunderstorm in overshooting and collapsing stages.

In the early overshooting stage, there is no wake cirrus because the anvil cirrus generated near the tropopause simply drifts away from the source regions, forming a flat surface somewhat like that of a "calm ocean". Within a few minutes after a significant overshooting, anvil tops in the wake of the relative westerly wind become fuzzy.

When the overshooting top collapses, the fuzzy cirrus in the wake region jumps up rapidly into the altitude of the relative easterly winds. The western edge of the wake cirrus moves westward relative to the tops, while the tops collapse beneath the advancing cirrus. Since overshooting tops keep collapsing while the wake cirrus advance westward relative to the tops, a time-lapse movie gives an impression that a magic touch of an advancing wake cirrus triggers the collapsing of the protrusions.

Schematic vertical cross sections of radar echo in these two stages are also shown in Fig. 7. In overshooting stage, precipitation particles gradually overload the top portion of the overshooting updraft Local concentration of particles results in a differential overloading, the reflection of which is visible as a number of small protrusions as shown in Fig. 4.

The term "vault" by Browning (1964) is an important radar characteristic of a rotating updraft. Marwitz (1972) called the counterpart portion of the echo in Grover, Colo. storm "weak echo region" (WER). Although the preferable choice of the terms "vault" or "WER" is debatable when applied to hook-echo cells of various shapes, it is likely that the magnitude of convergence and vorticity within a specific cloud will hold a key to the selection of a proper term. Since weak echo or no echo in Browning (1964) and Marwitz (1972) cases are the characteristic features of newly condensed small droplets, large convergence within a significant depth is definitely required in both cases.

The magnitude of the in-cloud vorticity or the rotational rate of a hook-echo thunderstorm is important. When the rotational rate is slow, updraft

TABLE 1. Expected shape of echo and cloud around the rotation axis

Rotational rate	Echo	Cloud
slow	WER	Thick
moderate	Radar Vault	Thick or Thin
fast	Radar Vault	Optical Vault
very fast	None	Eye

trajectories do not display significant curvature, thus allowing the low-level air to converge into a relatively large area to produce an extensive overhang of echo. Beneath a storm of moderate rotation, the inflow air loses its angular momentum while spiraling toward the rotation center. If the friction is effective enough to produce a uniform updraft around the cloud axis, a Browning-type radar vault packed with thick cloud of small droplets will form.

In case the friction is not sufficient to act as a killing agent of a fast-rotating inflow, the immediate vicinity of the rotation axis becomes a restricted area for the inflow. Thus, a cloud-free "optical vault" will form. Since rotating updraft spirals around the optical vault, a radar vault is to be found above and outside the optical vault (see Fig. 7). A rotating supercell which produced a 150 mph wind at Tecumsa, Mich. on Palm Sunday, 1965 belongs to such category. Refer to Fujita et al. (1970).

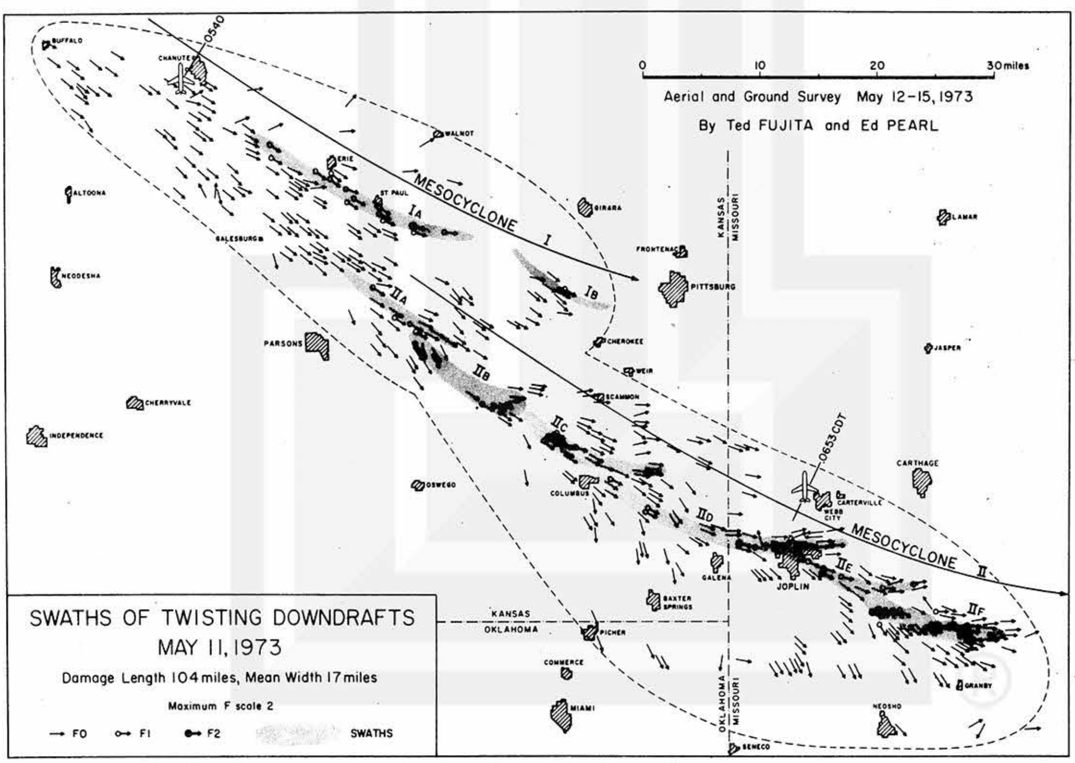

Fig. 8. Swaths of twisting downdraft on May 11, 1973. A wide spread damage by up to F 2 wind caused over 25 million dollar damage. 5000 trees were uprooted in Joplin.

Further increase in the rotational rate will result in the inflow-restricted cylinder extending all the way to the cloud top, resulting in an open top or an eye.

During the collapsing stage of protrusions, precipitation particles try to descend toward the region of the rotating updraft to find their way down toward the back side. The updraft will be suppressed to a point of little or no overshooting but the rotation is maintained. During this stage, heavy precipitation takes place in the northwestern sector of the cloud.

In the lower to the lowest levels, falling raindrops tend to move cyclonically around the rotation center. When viewed on PPI scope a hook echo embraces, in part or totally, the core of the updraft which has been weakened. A rotating cloud in this stage is likely to be characterized by a hook echo. The downdrafts in the rear sectors are very strong, descending in a "twisting" manner rather than "straight".

A "twisting downdraft" will produce an arc of high wind swath on the ground. Destruction within a swath is comparable to that by F 2 or weaker tornadoes. An example of significant swaths of twisting downdraft is shown in Fig. 8.

4. PROPOSED MECHANISM OF TORNADO FORMATION

A formation mechanism of tornadoes proposed in this paper is limited to those spawned from rotating thunderstorms. Damaging tornadoes with long tracks, such as discussed by Pearson (1971) and Wilson and Morgan (1971) are likely to be in this category.

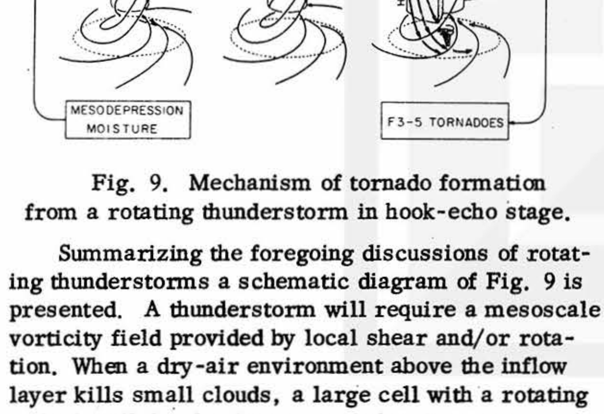

Fig. 9. Mechanism of tornado formation from a rotating thunderstorm in hook-echo stage.

Summarizing the foregoing discussions of rotating thunderstorms a schematic diagram of Fig. 9 is presented. A thunderstorm will require a mesoscale vorticity field provided by local shear and/or rotation. When a dry-air environment above the inflow layer kills small clouds, a large cell with a rotating updraft will develop into an overshooting storm.

The vorticity of Fargo tornado cloud at its base was in the order of $10^{-2}sec^{-1}$. Doppler radar measurements of June 2, 1971 storm by Brown et al. (1971) obtained the vorticity of a hook echo circulation of the order of $10^{-2}sec^{-1}$. It is likely that this magnitude of vorticity is a characteristic of rotating updrafts at low levels.

Overloading of precipitation particles will result in a collapsing of protrusions, inducing a twisting downdraft inside the west to south sectors of a rotating storm.

The magnitude of the vorticity on the ground beneath such rotating clouds is at least one order of magnitude smaller than $10^{-2}sec^{-1}$. As shown in Fig. 10, the area indicated with + symbols is exceptional because a combination of the horizontal shear and the cyclonic curvature of twisting downdraft enhances the cyclonic vorticity. A 10^{-2} or larger vorticity can often be found there.

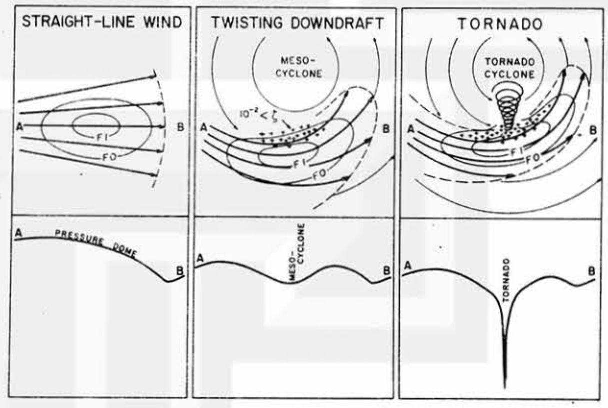

Fig. 10. Swaths of straight and twisting downdrafts.

This location of large vorticity coincides with the location of the hook to the south of an eastward-moving storm. Over 70% of tornadoes in the category under discussion form and stay in this particular location.

Straight-line winds caused by downdrafts of non-rotating thunderstorm is also shown for comparison purposes. Thus the figure will show a transition from straight-line wind to tornado by way of twisting downdraft.

5. TORNADO FORMATION AND MAINTENANCE IN RELATION TO BOUNDARY-LAYER STABILITY

Recent statistics of tornado-occurrence time indicates the formation of strong tornadoes long after the maximum thunderstorm activities. A number of nocturnal tornadoes with damaging intensity were observed this year.

Tecson's (1972) statistics of 1965 tornadoes revealed the occurrence of stronger tornadoes at later hours of the day. Fujita (1972) found a similar tendency in 1971 tornadoes. These results suggest a need for a certain stability to maintain strong tornadoes which will allow the surface air to spiral into the central region of tornadoes. Unstable conditions such as super adiabatic lapse rate just above the surface will stimulate the surface air to ascend prematurely before approaching the center.

TABLE II. Late-hour occurrence of strong tornadoes

F-Scale Intensity	Median Occurrence Time 1965	1971
F 0	5 PM	4 PM
F 1	6 PM	4 PM
F 2	7 PM	5 PM
F 3	7 PM	5 PM
F 4	8 PM	5 PM
F 5	9 PM	8 PM

Lack of tornadoes in the central regions of major metropolitan areas in recent years is likely to be related to a larger instability over giant cities in the evening due to a heat-island effect. In addition, the city roughness plays a role of tornado dissipation.

It is also likely that the downdraft air being mixed with the mesocyclone indraft provides a low-level lapse rate favorable for the surface air to converge into a tornado.

6. CONCLUSIONS

Foregoing discussion and evidence of rotating thunderstorms do present difficult problems in predicting tornadoes spawned from rotating supercell thunderstorms. For better understanding and subsequent short-range prediction of tornadoes, it would be necessary to determine following characteristics.

a. Rotational characteristics

1. Depiction of characteristic hooks by PPI radar
2. Rotation of precipitation particles by Doppler radar
3. Deviation of cloud motion by PPI radar and/or geostationary satellite

b. Pulsation characteristics

1. Echo-top height measurement by radar
2. Vertical motion measurement by Doppler radar
3. Radiation temperature of overshooting tops by geostationary satellite
4. Characteristics of wake cirrus by geostationary satellite

c. Surface stability

1. Determination of surface temperature by geostationary satellite
2. Determination of mesoscale instability by geostationary satellite

To accomplish these measurements, it would be necessary to establish a network of Doppler radars in addition to that of current search radars. The roles of geostationary satellites are of extreme importance. It would be necessary to increase the horizontal resolution of both visible and IR sensors. Forthcoming SMS/GOES will provide us with visible data approaching the requirement. IR resolution must be increased by all means as well as the picture frequency in the order of every few minutes. In order not to waste scan time, sectional scan covering one to several state areas is desirable.

It is highly recommended that cloud truth experiments involving SMS/GOES, Aircraft, Radar, and conventional observations are carried out over the selected regions of tornado-spawn areas to determine predictability of these storms.

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