

PICTURE OF THE MONTH

Spiral Feature Observed at Top of Rotating Thunderstorm

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ABSTRACT

A dark, spiral feature is noted in the geosynchronous satellite visible image of the top of a thunderstorm which also has a Doppler radar-observed mesocyclone. Although the evidence is not conclusive, the feature may represent cyclonic rotation at cloud top associated with the pre-tornado mesocyclone.

1. Introduction

On 20 May 1977 thunderstorms in Oklahoma were observed with Doppler radar and with short interval geosynchronous (SMS/GOES) satellite data. Satellite images were nominally produced every three minutes, thereby providing the time resolution suited for studying rapidly changing clouds. A series of severe thunderstorms developed in southwestern and south-central Oklahoma during the afternoon and early evening, including tornadic storms with mesocyclones observable with the National Severe Storms Laboratory (NSSL) Doppler radar located at Norman, Oklahoma. These storms are being studied to determine the relation of satellite-observed cloud top dynamics to mesocyclogenesis and the occurrence of tornadoes. Some preliminary findings have been discussed by Adler and Fenn (1979). One of the tornadic thunderstorms being studied, the Altus, Oklahoma storm, briefly showed a feature in the visible data which may be indicative of cyclonic rotation at cloud top. Although Fritsch and Maddox (1979) described a case of possible thunderstorm cyclonic outflow observed in a satellite image, the feature discussed in this note is collocated with a mesocyclone report. Fujita *et al.* (1976) show an "apparent swirl pattern" in a satellite image of an intense tornadic storm while the tornado was on the ground.

2. Description of spiral feature

The anvil of the Altus storm is shown in Fig. 1a in the visible image (spatial resolution 1 km) for 2004 GMT (1404 CST). The storm was located on the southern edge of a large, dense cirrus shield produced by earlier thunderstorms. The northern edge of the east-west oriented anvil is nearly indistinguishable from the overall cirrus shield produced by other convection. The active part of the thunderstorm is located near the western edge of the anvil at 34.6°N, 99.4°W. The early afternoon sun angle does not reveal any obvious cluster of overshooting tops, but within the black rectangle in Fig. 1a, a dark, spiral-shaped line is observed. The feature is more pronounced in Fig. 1b where the area within the rectangle has been enhanced by linearly stretching the original digital counts to a large range of gray levels. The dark spiral has its outside end point in the southeastern corner of the rectangular area, and its inner loop near the center of the enhanced area.

Fig. 1c is the corresponding infrared (IR) image (spatial resolution 8 km) with the enhanced portion of the image ranging from an equivalent blackbody temperature T_{BB} of 214 K (black) to 200 K (white). Fig. 2 shows the spatial relationship of the spiral feature in the visible image to the T_{BB} field. The boxed \times in Figs. 1c and 2 denotes the position of the

Doppler radar-observed mesocyclone at low levels extrapolated to cloud-top level (13.5 km), taking into account the parallax produced by the satellite viewing angle. The spiral feature, indicated in Fig. 2 as the dashed line, swirls around the updraft center (cold/high point at 200 K marked with a "C"), with the inner swirl coincident with the mesocyclone location. The exact location of the mesocyclone relative to the satellite observed features is only accurate to about ± 5 km. There is no doubt, however, that the Doppler radar observed mesocyclone is associated with the updraft feature as indicated by the T_{BB} minimum, and is collocated in the vertical with the dark spiral in the visible data.

The IR image (Fig. 1c) and the IR pattern in Fig. 2 (showing selected T_{BB} contours) display a T_{BB} pattern which the authors have often seen accompanying intense thunderstorms. From the point of minimum T_{BB} (point C at 200 K in Fig. 2) two main axes of low T_{BB} spread out downwind to form a U-shaped feature of cirrus debris. Inside the arms of the "U" a distinct warm spot (214 K) is evident ~ 50 km downwind from the updraft. The tropopause temperature is approximately 209 K and the tropopause level (13.0 km) ambient winds are from 244° at 48 m s^{-1} . The IR pattern is indicative of blocking flow around and over the storm updraft. This could produce subsidence centered at the warm spot. An alternate explanation of the warm spot might be the presence of lower stratospheric cirrus being produced by moisture from the overshooting top and trailing downwind. These clouds would take on the warmer temperature of the stratospheric environment and, although not having an emissivity of unity, would be observed as warmer (in terms of T_{BB}) than the cold anvil. However, the first explanation is more likely, at least in this case, because the warm feature developed and remained in place relative to the updraft center which became colder (ascended). The warm feature did not translate downwind as would be expected of cirrus debris.

In Fig. 2 the IR cold axes are shown by the solid lines. There are clear indications in the IR pattern of an upwind thrust of cloud material west of the updraft center. This interpretation is supported by Doppler radar-observed anvil outflow velocities upwind of the storm. The two main axes imply cyclonic and anticyclonic outflow on the south and north sides of the storm, respectively. This type of blocking flow around the top of the storm is evident in numerical simulations of mature thunderstorms (e.g., Schlesinger, 1978).

The spiral feature is centered on an area of T_{BB} gradient, with low T_{BB} to the west, and relatively high T_{BB} to the east, which implies a downward slope in the cloud surface toward the east. Although the gradient appears quite steep in the enhanced IR

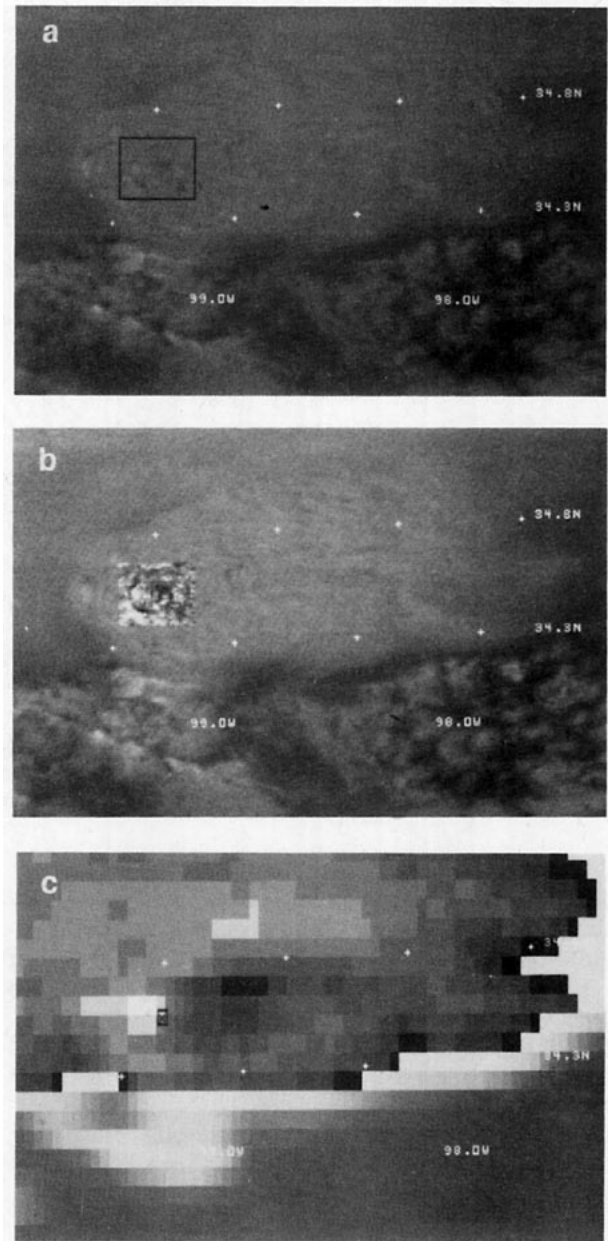


FIG. 1. SMS/GOES image at 2004 GMT 20 May 1977 of thunderstorm over Altus, Oklahoma: (a) visible image with box around spiral feature; (b) visible image with enhanced portion to emphasize spiral feature; and (c) corresponding infrared image with enhanced portion of image ranging from a T_{BB} of 214 K (black) to 200 K (white). Doppler radar observed mesocyclone position indicated by boxed \times .

image (Fig. 1c), the slope is of the order 1:10, based on an approximate radar maximum height of 15.0 km and a tropopause height of 13.0 km (209 K).

At the time of the image in the figures (2004 GMT), the mesocyclone had existed for ~ 15 min. The Altus tornado (intensity, F3) touched down at 2020 GMT, ~ 16 mins after the images in Fig. 1. The T_{BB} of

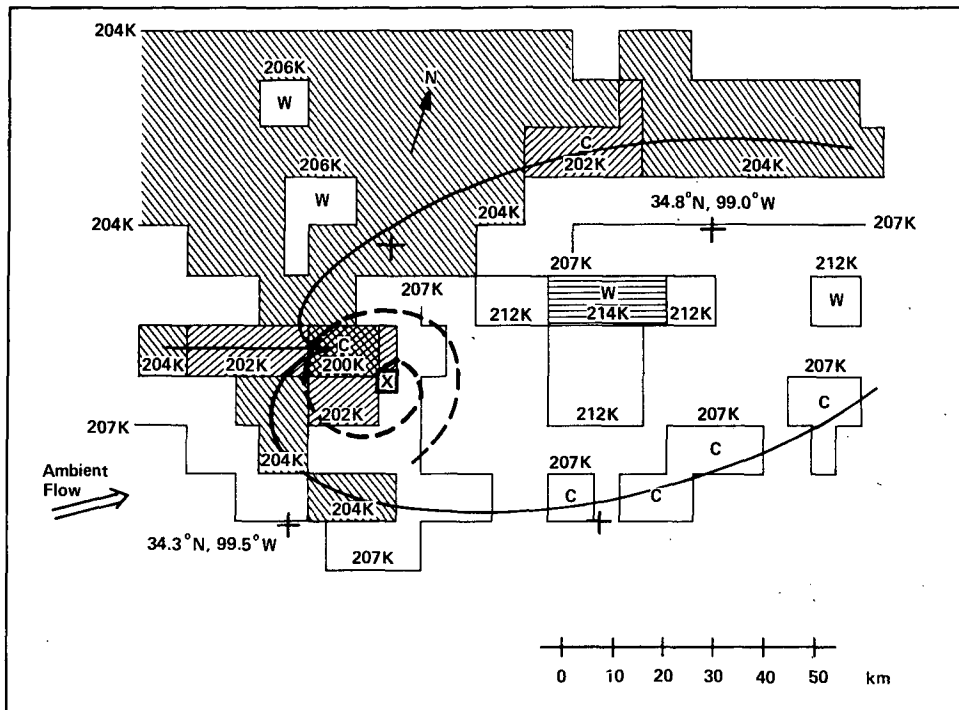


FIG. 2. Relation of spiral feature (from visible image) to infrared features at 2004 GMT 20 May 1977. Doppler radar observed mesocyclone position indicated by boxed \times . Solid curved lines indicate axes of thunderstorm outflow (cold cloud). Relative maxima and minima of T_{BB} are marked by a w and c, respectively.

200 K was the coldest (highest) point achieved by the satellite-observed cloud top. As described by Adler and Fenn (1979) the cloud top had a period of rapid ascent to a T_{BB} of 200 K from 1930 GMT to 1950 GMT just prior to the first report of the mesocyclone at 1952 GMT. Marble size hail was reported at 2000 GMT. The cloud top remained at its highest (coldest) point for 15 min until 2004 GMT, underwent a slight down-up oscillation, and then descended (warmed) to 202 K at about the time of tornado touchdown. Therefore, the spiral feature; seen only at 2004 GMT, occurred during the mature phase of the tornadic thunderstorm approximately midway between mesocyclone formation and tornado touchdown, just prior to an apparent cloud top descent.

3. Possible explanations

Unfortunately, the information is not sufficient to draw firm conclusions as to what the spiral represents in terms of cloud-top circulation. Previous Doppler radar studies of tornadic thunderstorms have not indicated that the mesocyclone vortex extends to cloud top, although the observations usually concentrate on middle to low levels. Recently, however, Wood *et al.* (1979) have noted a mesocyclonic circulation briefly extending to at least

10 km in the Del City, Oklahoma storm on the same day as the present case.

Because the feature was not visible in other images, even those closest in time (12 min before, 6 min after), it is possible (but improbable) that the spiral was briefly formed from a coincidental juxtaposition of shadows from two or more independent features.

The dark spiral of course, is shadow. There is evidence that the shadow is a result of a channel or trench in the cloud top rather than shadow cast by higher cloud. For example, the western part of the feature curves around the west side of the updraft center (see Fig. 2), such that the shadow is in an area where the cloud surface slopes upward away from the sun, according to the IR temperatures. Unless there is a trench or channel in the cloud deck, this alignment should not result in a shadow at this location. Although the relatively coarse spatial resolution of the IR makes the interpretation of the actual slope difficult, the fact that the spiral completes more than a 360 degree revolution, makes it difficult to perceive the feature as a long shadow, on relatively flat anvil cloud, produced by overshooting convective towers. The idea that the shadow represents a channel in the cloud deck is, therefore, reinforced.

Although the spiral is shaped such that move-

ment along the feature from outside to inside results in cyclonic motion, it could also possibly be interpreted as strongly anticyclonic outflow. This would mean that the center of the updraft should be located at the inner loop of the spiral, whereas the IR data indicates that it is not. Also, the available Doppler radar data show no indication of a tight anticyclonic circulation in the vicinity of the spiral.

Is the spiral feature indicative of cyclonic rotation at cloud top? There is no direct evidence of cyclonic rotation at cloud top. The available Doppler radar observations do not cover the uppermost part of the cloud (above 10 km). An examination of a sequence of satellite images centered on the time of the spiral also shows no obvious cyclonic circulation. However, although the Doppler radar observations for this case clearly do not prove there is cyclonic circulation at cloud top, they also do not negate that idea. The mesocyclone position in the lower half of the cloud as determined by Doppler radar, is located beneath the satellite-observed spiral. The plotted mesocyclone position in Fig. 2 is extrapolated from locations derived from Doppler vertical tilt sequences at 1950–1955 and 2010–2015 GMT. The 1952 GMT Doppler observation was the first indicating circulation associated with the thunderstorm. The mesocyclone at this time does not extend above middle levels, and a clear divergence signature exists at ~ 10 km.

From 1952 GMT to 2012 GMT (the next Doppler radar observation) the mesocyclone in the lower half of the cloud intensifies (shear across the vortex increases). The single Doppler velocity fields for two levels at 2010–2015 GMT are shown in Fig. 3. The original radar elevation angles were corrected downward by 0.8° , following Ray and Weaver (1977). In Fig. 3b the 2 km velocity pattern distinctly indicates the mesocyclone at the position marked with an M. In Fig. 3a the Doppler velocity field at ~ 10 km (at 2014 GMT) is overlain with the outline of the spiral (at 2004 GMT) shifted to take into account the storm movement during the ten minute time difference. A reflectivity contour is also shown in each diagram. The Doppler observation at 10 km (Fig. 3a) shows an ambiguous velocity signature. The points of maximum flow away from the radar (positive values) and maximum flow toward the radar are no longer along the same radar azimuth (indicating pure divergence) as they were in the previous observation (not shown). Instead the points have shifted slightly clockwise to indicate either the presence of positive relative vorticity, or a shift in the axis of divergent outflow. Unfortunately, the correct answer cannot be determined knowing only one component of flow because the angle between the maximum flow points is greater than 45° from the perpendicular to the radar azimuth. However, the speed maxima of this one component

are a possible fit to cyclonic circulation of the size and location indicated by the spiral, especially considering the time difference. It should be noted that at the time of this radar observation, the spiral was no longer in evidence on the satellite image. Thus, although this Doppler radar observation does not positively indicate cyclonic rotation at this height, neither does it preclude its presence. The next higher observation at both times passes above the storm.

Even if both Doppler radar observations bounding the time of the spiral showed no cyclonic vorticity in the top portion of the cloud, this fact would not negate the possibility of cyclonic rotation briefly reaching cloud top. The Doppler radar observations in this case are 20 min apart, with the spiral image time falling about midway between the two radar observations. The idea that the top of the cyclonic circulation could rapidly ascend to near cloud top and then drop back down to intermediate levels is supported by 5 min interval Doppler radar data presented by Wood *et al.* (1979), for the Del City, Oklahoma tornadic storm of the same day. They show the top of the cyclonic circulation jumping upward from 4 km to at least 9 km in 5 min. The highest point observed by the radar was ~ 9 km, although the analysis indicates the mesocyclone extended much higher. Approximately 10 min later the top of the circulation had descended to 7–8 km. Thus the penetration of the Del City mesocyclone to the upper part of the thunderstorm appeared to be very brief, and probably would have been missed by 20 min interval radar data. These observations also may indicate why the spiral feature was only evident for a short time. However, no cloud-top evidence of rotation was evident in the satellite images of the Del City storm.

Multiple Doppler radar studies indicate that in a mature supercell stage the mesocyclone is associated with both the updraft and downdraft, with the circulation center located at, or near, the updraft-downdraft boundary (e.g., Lemon and Doswell, 1979). The intensification of mesocyclones also is associated with collapsing radar tops and the strengthening of the downdraft (Lemon *et al.*, 1978). Therefore, the observed spiral feature could be interpreted as a reflection at cloud top of the intensifying mesocyclone and its associated weakening updraft and intensifying downdraft producing a brief whirlpool effect resulting in a dark channel of subsidence. The spiral is seen as encompassing both the updraft (centered at the IR cold point) and the downdraft (at the inner portion of the spiral). This positioning of the downdraft to the southeast of the updraft is different from that of conceptual models with the main downdraft upwind of the updraft. Therefore, this interpretation would require the updraft-downdraft combination to twist approximately a quarter of a turn with lowering height.

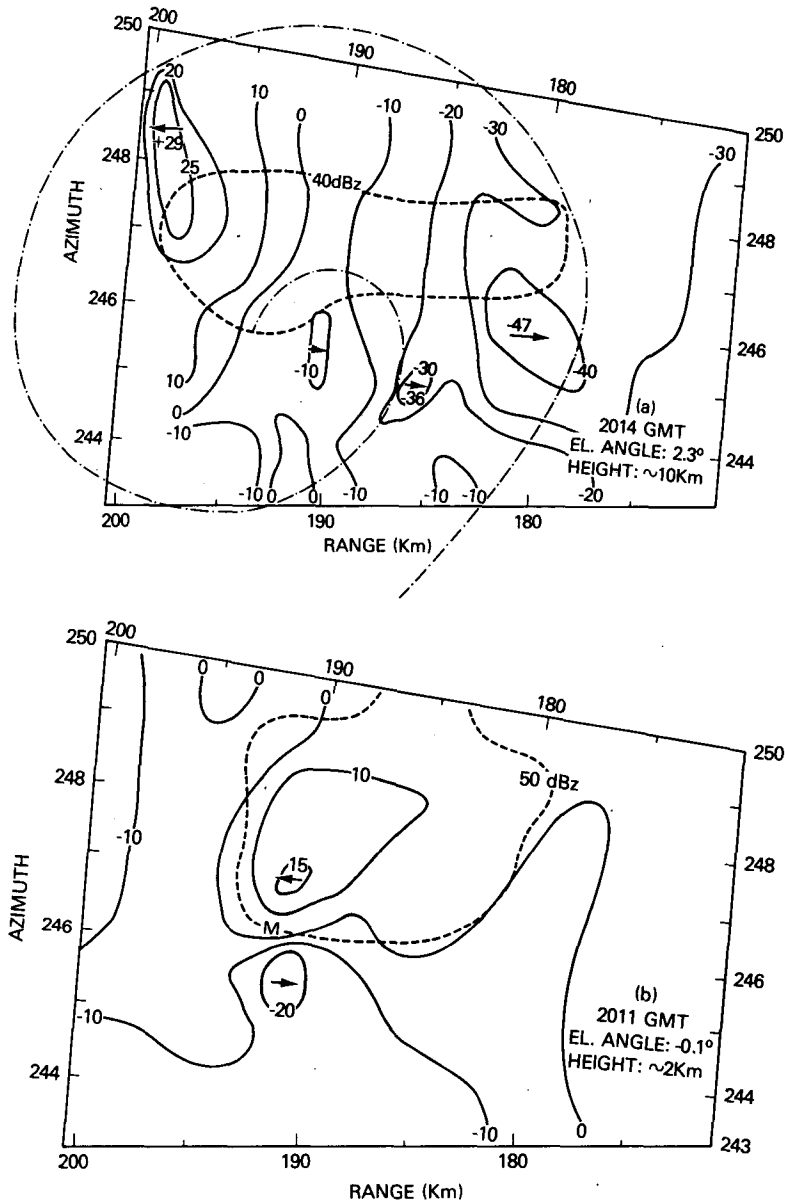


FIG. 3. Single Doppler radar radial velocities observed by National Severe Storms Laboratory radar at Norman, Oklahoma. Solid lines are velocities in meters per second, with positive values indicating flow away from the radar. A mean storm motion of 10 m s^{-1} toward the radar has been subtracted from the original values. The dashed lines are reflectivity contours. (a) Flow pattern at 10 km at 2014 GMT 20 May 1977; dash-dot line is satellite-observed spiral feature at 2004 GMT. (b) Flow pattern at 2 km at 2011 GMT 20 May 1977; M indicates mesocyclone position at that altitude.

4. Conclusion

The briefly observed dark spiral feature at thunderstorm top has been colocated in space and time above a Doppler radar observed mesocyclone which preceded the Altus, Oklahoma tornado of 20 May 1977. Although the evidence is weak, one possible explanation of the feature is that it represents

a short term indication of cyclonic rotation at cloud top associated with the intensification of the mesocyclone and its associated downdraft. If this interpretation is correct, the spiral is the first satellite-observed indication of cloud-top cyclonic rotation colocated with a Doppler radar observation of an intense, tornado producing mesocyclone. Even if this interpretation is correct, it is the only such

feature observed by the authors in their analysis of a dozen intense tornadic storms with short-interval satellite data.

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