Satellite-Observed Cloud-Top Height Changes in Tornadic Thunderstorms

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ABSTRACT

Short-interval geosynchronous infrared satellite data are used to examine 11 cases of tornadic thunderstorms with respect to cloud-top temperature (height) variations relative to tornado touchdown times, and in three cases relative to the initial observation of mesocyclones by Doppler radar. The scale of the updrafts observable with the satellite infrared data is ~10 km. The cases are limited to those with relatively intense tornadoes. In 8 of the 11 cases there is a period of rapid cloud-top ascent 30–45 min prior to tornado touchdown. This upward growth appears to be associated with the formation of the mesocyclone. This ascent is followed by a period of no growth or even a drop in cloud-top height preceding, or at the time of, tornado touchdown. In the three remaining cases cloud-top ascent is evident in the satellite data at tornado touchdown.

1. Introduction

The study of thunderstorm top height changes near the time of tornadoes is important in order to help understand the relation of cloud dynamics to mesocyclogenesis and tornado touchdown. Also, since the storm top is the only portion of the cloud observable with satellite data, it is important to determine what tornado-related characteristics can be inferred from current satellite observations.

Radar observations (e.g., Lemon *et al.*, 1978) indicate that tornado touchdown is often accompanied by a decrease in echo maximum height and a decrease in the height of the Bounded Weak Echo Region (BWER). Both decreases are indicative of a weakening of the updraft. Fujita (1973)[2] proposed that the collapse of overshooting thunderstorm tops is associated with tornado generation and touchdown. Purdom (1971)[3] showed examples of a pause in the rate of anvil expansion (measured from satellite image data) at the times of tornado touchdown. More recently, five tornado bearing clouds on 6 May 1975 were discussed by Adler and Fenn (1979a). An examination of the five clouds elements, having eight tornadoes clearly associated with them, indicated that in seven of the eight cases the first report of the tornado took place during, or just after, a rapid expansion of cloud-top areas defined by equivalent blackbody temperature (T_{BB}) isotherms. This rapid expansion of areas within isotherms implies ascent on a scale of ~30 km, even larger than the scale of an individual infrared (IR) data point (10 km).

In this paper, eleven tornadic storms, including five cases from Adler and Fenn (1979a), are evaluated with respect to cloud top temperature changes relative to tornado touchdown, and in three cases relative to initial reports of Doppler radar observed mesocyclones.

2. Analysis of 11 tornadic thunderstorms

Digital image data from SMS/GOES geosynchronous satellites were analyzed on four case study days (see Table 1) with the aid of an interactive computer/image analysis system called AOIPS (Atmospheric and Oceanographic Information Processing System). Data were from times when the satellite was operated in the short-interval mode, images produced every 3–7.5 min over a swath of limited north–south extent. This high time resolution is necessary to observe rapidly changing convective storms. The digital infrared (IR) data which are the basis of this study have a spatial resolution of ~10 km (depending on location relative to the subsatellite point) and an effective temperature resolution of 1–2 K.

The set of tornadic thunderstorms was limited, for this study, to storms with relatively strong tornadoes. All but one of the storms had tornadoes of intensity F2, or greater [on an intensity scale of F0 through F5 as described by Fujita (1973)]. Kelley

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[2] Fujita, T. T., 1973: Proposed mechanism of tornado formation from rotating thunderstorms. *Preprints 8th Conf. Severe Local Storms*, Denver, Amer. Meteor. Soc., 191–196.

[3] Purdom, J. F. W., 1971: Satellite imagery and severe weather warnings. *Preprints 7th Conf. Severe Local Storms*, Kansas City, Amer. Meteor. Soc., 120–137.

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TABLE 1. Tornadic thunderstorm case study days.

Date	Area	Spacecraft
6 May 1975	Nebraska	SMS-2
24 April 1975	Missouri	SMS-2
20 March 1976	Illinois	GOES-1
20 May 1977	Oklahoma	GOES-1

et al. (1978) have shown from climatology that while only 38% of tornadoes are F2 or above, they account for 98% of tornado fatalities. In a few cases where more than one tornado was produced from a storm, only the data relative to the time of the most intense tornado was examined. One storm with only an F1 tornado was included in the sample because of its long tornado path. This procedure was designed to concentrate the analysis on so-called "supercell" storms (Browning and Foote, 1976), which are the main producers of relatively strong tornadoes (Lemon and Doswell, 1979). It also eliminates the relatively weak tornadoes, for which the time of occurrence is often suspect.

The results of the 11 storms are shown in Fig. 1. If there is more than one tornado associated with a cloud, only the most intense tornado is considered. Such is the case in Figs. 1a, 1c, 1d and 1f.

Fig. 1 depicts the variation with time of the satellite-observed minimum T_{BB} for each storm relative to the time of the associated tornado. Decreases in T_{BB} imply cloud-top ascent and increases in T_{BB} imply descent. Because of the relatively coarse spatial and temperature resolution in the IR data, small or temporary changes in T_{BB} or in the slope of the T_{BB} curve should be considered suspect and may be artifacts of the data. For example, in Fig. 1i there is a brief stairstep at −40 min, which is probably a data artifact due to the coarse temperature resolution. These stairsteps are common in the data set and usually do not represent pauses in the ascent (or descent), as

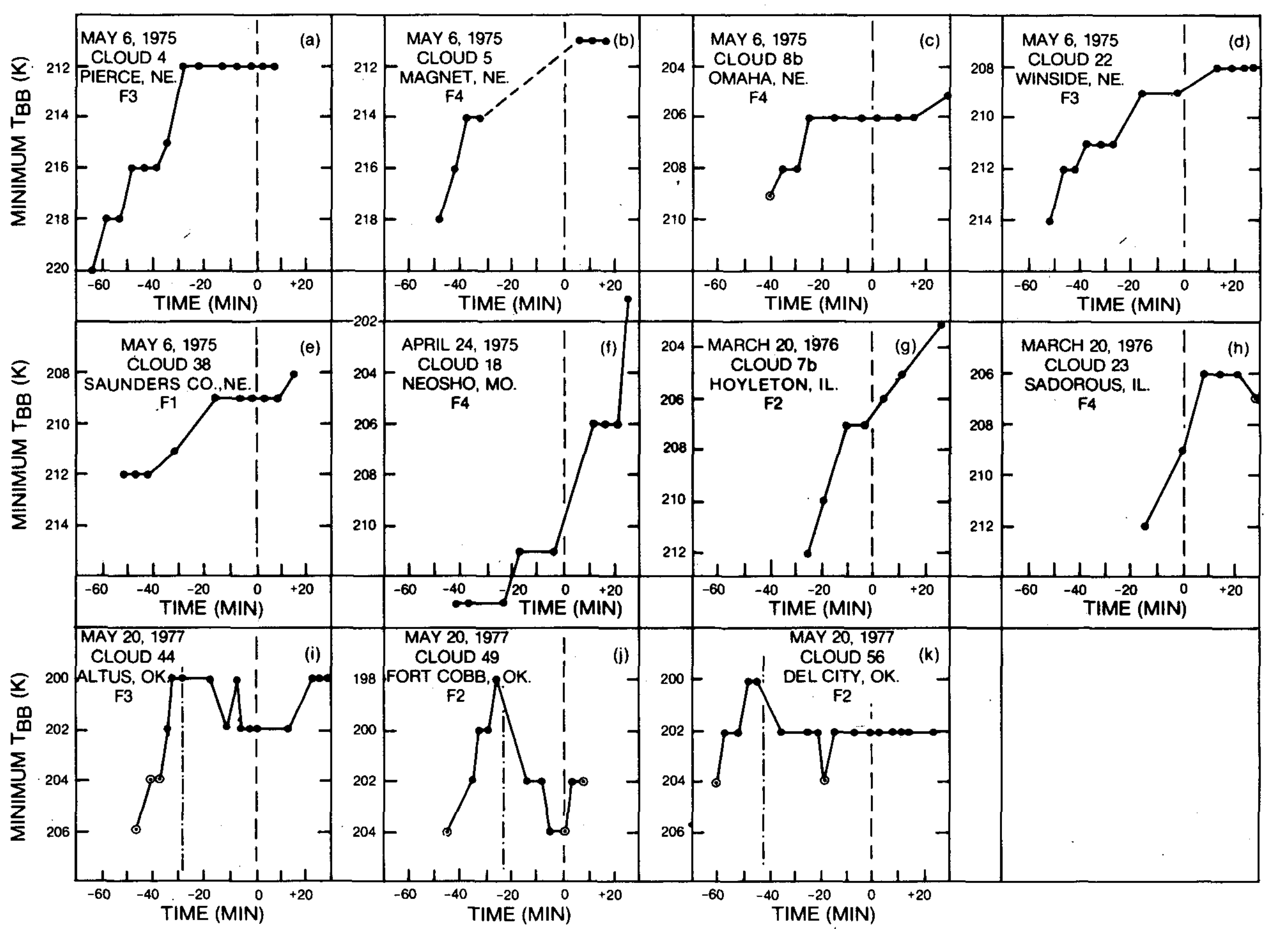

FIG. 1. Minimum cloud-top temperature (T_{BB}) as a function of time relative to the time of tornado touchdown in 11 cases of relatively strong tornadoes. The circled dots indicate the cases of the lowest temperature not being associated with a closed T_{BB} isotherm. The time of the tornado touchdown is noted by the vertical dashed line at the time equal to zero. In three cases (i, j, k) the initial times of mesocyclones observed by Doppler radar of the National Severe Storms Laboratory in Norman, Oklahoma are shown by the vertical dash-dot lines.

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can be seen by the continued expansion of the number of data points within the minimum T_{BB} isotherm during a period of constant minimum T_{BB}. The relation of T_{BB} isotherm expansion near cloud-top center to vertical velocity and divergence has been discussed by Adler and Fenn (1979a).

Another problem is related to the coarse spatial resolution (~10 km) and the position of the satellite IFOV relative to the cloud top. A thunderstorm top will produce a slightly lower observed T_{BB} if the top is centered in an IFOV instead of being split between two adjacent views. Successive satellite views of a constant height storm may occasionally show an observed change in T_{BB}, implying a false height change. An example of this may be the oscillation in panel *i* at −10 min.

In general, because of these data problems, small or short-lived changes in T_{BB} or its slope should be ignored. Changes of 3 K (4 K for the 20 May 1977 storms) can be considered significant, along with smaller variations if they are supported by more than one data point at each end of the change.

Eight of the 11 storms (Figs. 1a, 1b, 1c, 1d, 1e, 1i, 1j and 1k) had an associated rapid decrease of cloud top T_{BB} (as observed from satellite) ~30–45 min before tornado touchdown. This implies a rapid upward movement of the cloud top. These storms also had their period of most rapid area expansion within T_{BB} isotherms prior to the touchdown. On most of these eight storms the rapid decrease in temperature was followed by a reduction in the slope of the temperature-time profile, and in the 20 May cases (Figs. 1i, 1j and 1k) a warming, indicating a cessation in upward growth or a slight drop in maximum cloud height. The Fort Cobb case (Fig. 1g) exhibits a substantial 6 K warming or cloud-top collapse.

The sequence of events at the cloud top can be pictured as being associated with storm evolution in the following way. A period of rapid upward growth at cloud top is associated with or possibly precedes the formation of the mesocyclone at midlevels in the storm. Tornado touchdown is usually associated with a decreasing or near constant maximum cloud top. This sequence of events at cloud top is consistent with radar studies (e.g., Lemon *et al.*, 1978) and with hypotheses proposed by Fujita (1973)[2] which were based on aircraft observations.

Three storms (Figs. 1f, 1g and 1h) showed decreasing cloud top T_{BB} (increasing height) at the time of the tornado touchdown. The tornadoes from all three of these storms were intense with Fujita/Pearson scale ratings (Fujita, 1973) of F4, F2 and F4 for the storms in Figs. 1f, 1g and 1h, respectively.

The Neosho, Missouri storm (Fig. 1) is the most obvious exception to the other eight storms. While the tornado was on the ground, the cloud-top minimum temperature dropped nearly 10 K [over an area of ~100 km^2, one instantaneous field-of-view (IFOV)], indicating strong ascent. It is possible that the strong growth was associated with a new cell, adjacent to the tornadic cell, but this does not seem to be the case from the satellite analysis and examination of available radar data. The cloud top ascended during the first 25 min of the tornado until the time the short-interval data ended.

The Hoyleton, Illinois tornado (Fig. 1g) of 20 March 1976 also was on the ground while the satellite-viewed cloud top was ascending. However, the Hoyleton storm did show rapidly increasing height from 40 to 10 min before tornado touchdown, until a brief height plateau was reached at 207 K, just before tornado touchdown. During that constant temperature period, the area within the 207 K T_{BB} isotherm decreased from 200 to 100 km^2, which is equivalent to a change from two IFOV's to one IFOV. This area decrease at constant temperature implies cloud top collapse, or at least constant height. This sequence is similar to an occurrance noted with the Omaha tornado on 6 May 1975 (Fig. 8, Adler and Fenn, 1979a). However, in the Hoyleton case, the storm resumed its upward climb, and continued to ascend during the lifetime of the tornado.

Fig. 1h shows the Sadorous storm with rapid ascent during tornado touchdown, followed by a period of constant height and then descent. The largest area within the 206 K isotherm occurred at the first observation, and then decreased, indicating that maximum storm height happened just after tornado touchdown. Fujita *et al.* (1976) have analyzed this storm and indicate that the tornado reached F4 intensity ~20 min after touchdown. Perhaps, in this case, the cloud-height decrease was associated with the intensification of the tornado vortex and not touchdown itself.

Therefore, a majority of the storms analyzed had rapid ascent of cloud tops 30–45 min before tornado touchdown, persumably during formation of the mesocyclone (documented in three cases). A minority of the storms, however, had ascending cloud tops (at the scale of the satellite observation) at the time of tornado touchdown.

The indicated characteristic cloud-top evolution of the majority of tornadic storms means that we have a first link between satellite observations and tornadic activity. It does not mean, however, that we now have a way to discriminate between tornadic and non-tornadic thunderstorms with satellite data. Intense, non-tornadic storms examined also have a period of rapid growth above the tropopause, followed by relatively steady heights.

The magnitude of the vertical velocities are reasonable when the horizontal scale (10 km) on which they are applicable is considered. A typical rate of temperature (T_{BB}) decrease in Fig. 1 is 0.4 K min^{-1}. Using an appropriate lapse rate, the temperature

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change rate can be converted to an equivalent vertical velocity or cloud-top ascent rate. Hasler and Adler (1980)[4] have compared satellite observed height (from satellite stereo analysis) and IR temperatures for thunderstorm tops. For overshooting tops (above the tropopause) they find a temperature-height relation of 2.5 K km^{-1}, which was approximately midway between ambient and adiabatic for the particular case. However, the horizontal scale of the two observations are different, with 10 km for the IR temperature and 1–3 km for the stereo-determined height, depending on the size and definition of the feature in the visible data. If the two measurements were made at the same scale, the calculated lapse rate would shift toward adiabatic. Therefore, using the 2.5 K km^{-1} lapse rate in Eq. (1)

$$w = -\left(-\frac{\partial T}{\partial z}\right)^{-1} \frac{dT_{BB}}{dt} \quad (1)$$

produces a vertical velocity w appropriate on a horizontal scale of 1–3 km, roughly equivalent to radar resolution at thunderstorm top. Using a 2.5 K km^{-1} value for the lapse rate gives an equivalent vertical velocity of 2.7 m s^{-1}. This is nearly equal in magnitude to the echo top rise rate above the tropopause indicated for the Union City Storm (Burgess and Lemon, 1976[5], Fig. 5.6; Lemon *et al.*, 1978, Fig. 13). However, larger cloud top ascent rates (up to 8 m s^{-1}) have been calculated from satellite IR data for intense convection penetrating through the upper troposphere (Adler and Fenn, 1979b).

In Fig. 1 only panels 1i, 1j and 1k show a T_{BB} increase (indicating descent or cloud top collapse) prior to, or at the time of, tornado touchdown. The 6 May cases (Figs. 1a–1c) show a constant temperature with time at the time of the tornado. This difference (between the two days) may be related to the difference in larger scale cloud structure between the two cases and the satellite sensor's response characteristics. The 6 May storms appeared in the satellite images as a narrow line lying along a generally north–south oriented cold front. The east–west extent of the storm's anvils increased with time. As the satellite IR sensor scans from left to right across the scene it moves abruptly from a warm target (ground) to a cold target (thunderstorm top). With a narrow cirrus shield, the sensor may not have enough time to accurately respond to the minimum T_{BB}, especially since it is often located near the left, or upwind side of the anvil. That is, for narrow (in the left-to-right direction) cirrus anvils, the minimum T_{BB} is probably overestimated (i.e., estimated to be warmer than it is). However, as the originally narrow anvil expands with time, the amplitude of the temperature overestimation should decrease as the distance from the left anvil edge to the storm center increases. If, while the anvil is expanding, the actual minimum T_{BB} is warming slightly, this could be obscured by the varying overestimation effect, with the result being a near-constant observed T_{BB} with time. For example, cloud 4 in Fig. 1a has a 35 min period of constant T_{BB} (212 K) while the anvil is expanding. The distance from the left anvil edge (denoted by the 226 K isotherm) to the center of the area of coldest T_{BB} increases from two data points to nine data points over the 35 min time period. Work on a technique to remove this sensor response effect is planned.

On 20 May 1977, the storms (Figs. 1i, 1j and 1k) were imbedded in a very large cirrus shield with a large distance between the left edge and the storms' centers. Thus, the sensor response problem in terms of estimating the minimum T_{BB} should not exist. In these cases, a warming was observed.

3. 20 May 1977 storms

The three intense tornadic storms observed on 20 May 1977 are the best analyzed storms to this date with respect to Doppler radar coverage. A complete analysis of the cases with satellite, Doppler radar reflectivities and velocities, and other data is underway by the authors and others. Preliminary results based primarily on satellite data will be discussed in this section.

a. Altus storm

The Altus, Oklahoma storm was actually a combination of two related thunderstorms which could be identified in both the satellite and radar data. The National Severe Storms Laboratory (NSSL) Doppler radar log indicated only one mesocyclone, but an examination of the positions of the mesocyclone, reflectivity maxima and satellite features showed that two mesocyclones, associated with two storms, were involved. The temperature-height versus time diagram for both cells is shown in Fig. 2. Cloud 37 (the numbering system is from a larger study) was first defined as penetrating the cirrus shield just after 1840 GMT (1140 CST) at 207 K. The background cirrus T_{BB} was 209 K, approximately equal to the tropopause temperature. With dense cirrus shields already existing, such as in this case, the new thunderstorms cannot be detected in the satellite IR data until they significantly penetrate the cloud deck at very cold temperatures.

Cloud 37 peaked at 198 K and remained well defined at 200 K as it traveled north-northeastward. A mesocyclone was first noted at 1932 GMT in the

[4] Hasler, A. F., and R. F. Adler, 1980: Cloud-top structure of a tornadic thunderstorm from 3 min interval stereo satellite images compared with radar and other observations. *Preprints 19th Conf. Radar Meteorology*, Miami, Amer. Meteor. Soc., 405–412.

[5] Burgess, D. W., and L. R. Lemon, 1976: Union City Storm history, the Union City, Oklahoma tornado of 24 May 1973, R. A. Brown, Ed. NOAA Tech. Memo ERL NSSL-80, 35-51.

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Doppler radar observation log, colocated with the satellite feature. The radar-observed circulation, marked as M37 in Fig. 2, perhaps existed earlier, but was not detected because of the relatively long distance (220 km) from the radar to the storm. This mesocyclone remained relatively weak, and was dissipating at the 1952 GMT observation.

At about 1940 (all times GMT unless indicated otherwise), evidence of a second storm (Cloud 44) was observed in the satellite data approximately 30 km to the southeast of cloud 37 and colocated with a second radar reflectivity maximum. Cloud 44 ascended rapidly to 200 K (~4 km above the tropopause) by 1950. An associated mesocyclone was first observed at 1952 by the Doppler radar. Thus, the initiation of the cyclonic rotation appears associated with rapid cloud top ascent and, therefore, a strong updraft. After a relatively stable 15 min period the cloud top temperature oscillated and then warmed. The oscillation around 2010 may not reflect an actual cloud height fluctuation, but an effect of sensor resolution and the location of the satellite data point relative the highest part of the cloud top. However, between 2005 and 2020 there was a slight storm top decrease, just preceding the reported tornado touchdown. The storm top ascended again just after tornado dissipation, a feature also seen in the following two cases.

b. Fort Cobb storm

The Fort Cobb, Oklahoma storm developed to the southeast of the Altus storm and also had two associated cold features in the satellite IR data. One of the features, identified as cloud 49, was first defined at 2045 and reached a temperature of 202 K, then weakened and became difficult to define in the IR field until 2210. At that time (see Fig. 3), the time sequence of IR images showed a sharp cloud top ascent from 204 to 198 K in 18 min. A mesocyclone (mesocyclone A) was initially observed at the time of maximum height. The next observation of the storm was 12 min later and the storm top has warmed 4 K, or ~2 km, based on a lapse rate halfway between ambient and adiabatic. After 2240 the cold

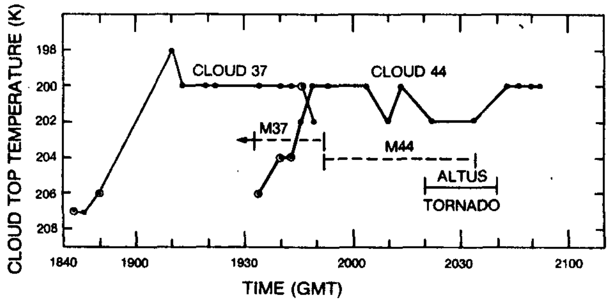

FIG. 2. Minimum cloud top temperature as a function of time for cloud elements associated with the Altus, Oklahoma tornado of 20 May 1977.

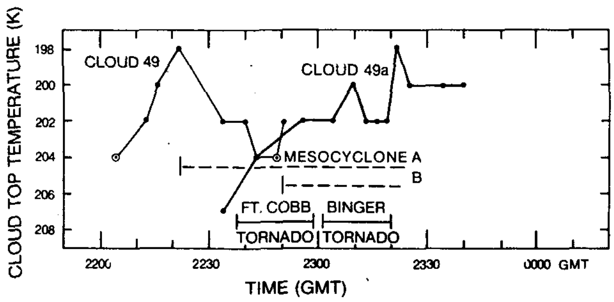

FIG. 3. Minimum cloud top temperature as a function of time for cloud elements associated with Fort Cobb, Oklahoma storm of 20 May 1977.

feature in the IR data became more difficult to follow and may have been just a piece of outflow debris. The times of the associated tornadoes are shown in Fig. 3 based on analysis presented by Johnson *et al.* (1980).[6] The touchdown of the Fort Cobb tornado occurred at the end of a period of sharp decrease in the satellite-observed height with a temperature change from 198 to 204 K.

As the first IR feature (cloud 49) became indistinct and disassociated from the main radar echo (and mesocyclone A) at approximately 2230, another T_{BB} minimum (cloud 49a) was defined 30–40 km to the southwest of the mesocyclone position. This new feature in the IR field had an associated radar reflectivity maximum. Between 2230 and 2300, the satellite data indicated cloud-top ascent as this new updraft center (as defined in the T_{BB} field) raced toward the northeast at 30 m s^{-1}, finally catching up to the location of the original reflectivity maximum at approximately 2250. The new IR feature, labeled 49a, became dominant and was located near both mesocyclones (which are approximately 8 km apart), although it was probably related to the updraft associated with mesocyclone B. A detailed study of the complex evolution of radar and satellite-observed features during this period is underway.

The top of cloud 49a continued to ascent until 2310. The apparent flattening of the curve between 2255 and 2305 is an artifact of the poor vertical (temperature) resolution (2 K) in the satellite data. Although the minimum temperature remained constant at 202 K the number of IR data points at that temperature increased from two to ten, indicating continued ascent. The second tornado, associated with mesocyclone B and an updraft along the gust front (Ray *et al.*, 1981), touched down during this period of apparent cloud-top ascent. Again, as in the Altus case, the cloud top rose after tornado dissipation.

[6] Johnson, B. C., K. W. Johnson, P. S. Ray, J. S. Bradberry, J. J. Stephens and W. C. Bumgarner, 1980: The morphology of some tornadic storms. *Preprints 19th Conf. Radar Meteorology*, Miami, Amer. Meteor. Soc., 311–316.

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c. Del City storm

The Del City storm also involved two thunderstorms, identified in the satellite data as clouds 53 and 56 (see Fig. 4). Cloud 53, which had a period of rapid growth at 2240 to a minimum temperature of 200 K is referred to as the "hailstorm" in the study by Ray *et al.* (1981). As cloud 53 collapsed another storm (cloud 56) appeared to the south, grew, moved northward, and caught up and merged with the hailstorm. Cloud 56, the main feature, reached a temporary height maximum at 202 K at 2305–2325, then descended slightly to 204 K. A new surge in the updraft was noted between 2335 and 2355 as the storm top reached 200 K. This period of cloud top ascent was coincident with the formation of the mesocyclone.

The cloud-top temperature fell back to 202 K, then remained nearly constant for one hour as the storm moved in a northeast direction. Although this period was marked by constant temperature, the position of the cold feature was twice redefined slightly southeastward in a non-continuous manner. This redefinition is probably related to the effect of the IR cold area beginning to represent debris from the updraft and moving off from the storm core and radar echo until a new surge in the vertical velocity reestablishes the IR cold point over the updraft itself.

No cloud-top collapse was noted in association with tornado touchdown in this case. Although there is a 30 min absence of data centered at 0015 GMT, there is evidence supporting cloud top rise after tornado dissipation. This was also evident in the Altus and Fort Cobb cases, and may represent reintensification of the storm through a new updraft on the storm flank, or revitalization of the original updraft.

4. Mechanisms for rotation generation and intensification

The mechanisms by which certain thunderstorms produce the initial storm-scale rotation, or mesocyclone, and the mechanisms by which this rotation is concentrated to produce a tornado are not completely understood. However, recent research using observations from Doppler radars (e.g., Heymsfield, 1978) and results of three-dimensional numerical models (e.g., Schlesinger, 1980) have indicated that the two dominant terms in the vorticity equation related to vorticity changes following a fluid parcel are the concentration or stretching term, and the tilting term, shown in Eq. (2) as the two terms to the right side of the equal sign:

$$\frac{d\zeta}{dt} = -\zeta(\nabla_H \cdot \mathbf{V}) + \left(\frac{\partial w}{\partial y}\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\frac{\partial v}{\partial z}\right). \quad (2)$$

The vertical component of relative vorticity is given by ζ, while u, v and w are the components of the vector velocity $\mathbf{V}$. This formulation neglects the solenoidal term, the frictional torque term, and terms involving the earth's vorticity. Although the stretching and tilting terms are the most important, Lemon and Doswell (1979) suggest that the solenoidal term may also be a significant, but secondary, contributor.

The satellite observations presented in this paper cannot, by themselves, answer the vorticity mechanism question, but do complement the studies based on radar observations and other data. A majority (8/11) of the satellite cases indicate that during the development of the mesocyclone the thunderstorm top is rapidly ascending, implying intensification of the storm updraft. This relation confirms radar case study observations (e.g., Lemon *et al.*, 1978) of echo top height increases during mesocyclonesis. Lemon and Doswell (1979), in developing a descriptive model of mesocyclone evolution, indicate that the Bounded Weak Echo Region (BWER), which implies updraft, is colocated with the mesocyclone in its early stages. If the vorticity center is indeed colocated with the updraft at this stage, the implication is that the vorticity increase associated with mesocyclone generation occurs through the vertical stretching of the air column in the rapidly intensifying updraft. However, the tilting term must also be important, at least along the updraft edges, where the gradient of vertical velocity is large. Although numerical model results (e.g., Schlesinger, 1980) in-

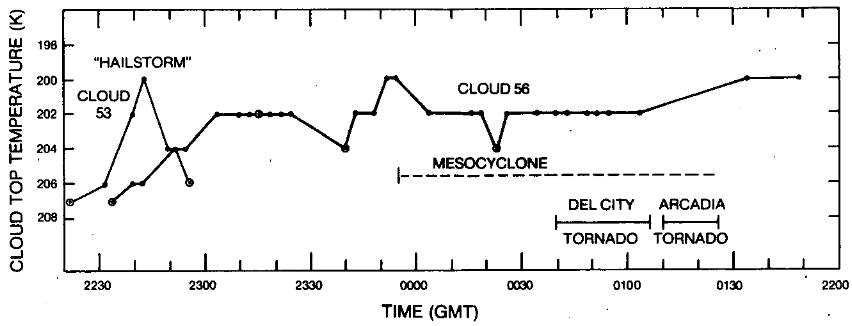

FIG. 4. Minimum cloud top temperature as a function of time for cloud elements associated with the Del City, Oklahoma storm of 20 May 1977.

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dicate dominance by the tilting term in this early stage, this dominance is artificial because the models eliminate stretching at the earliest time by assuming no ambient vorticity (vertical component) in the initial flow field.

Tornado touchdown was associated (in a majority of cases) with satellite-observed constant or decreasing cloud top height. These observations are in agreement with radar echo-top information such as in the Union City tornado case (Lemon *et al.*, 1978). Lemon and Doswell (1979), synthesizing observations from a number of cases, conclude that the vortex intensification and tornadogenesis is associated with updraft weakening, downdraft formation upwind of the updraft and a shift of the vortex center from the updraft center to the updraft-downdraft boundary. This implies that the tilting term may be dominant at this stage, as weakly indicated by observations (Ray *et al.*, 1976; Lemon and Doswell, 1979), and strongly indicated in model results (Schlesinger, 1980). The satellite data merely emphasize that vortex intensification is apparently related to updraft weakening in most cases. Although this observation also fits the "vortex valve" concept of vortex-updraft interaction (Lemon, 1976,[7] Lemon *et al.*, 1978; Brandes, 1978), observations of the intense vortex being situated on an updraft-downdraft boundary (e.g., Brandes, 1978) appear to eliminate this theory.

The majority of storms depicted in Fig. 1, therefore, agree with previous observations of echo top behavior in tornadic storms and the conceptual model of Lemon and Doswell (1979). The three exceptions (Figs. 1f, 1g and 1h) may be just slight variations of the model (this is plausible with Figs. 1g and 1h), or may be radical departures (likely for Fig. 1f). The Neosho term (Fig. 1f) displays rapid cloud-top ascent during and following touchdown of a very intense tornado (F4). This may imply that the stretching term may still be very important at this stage, in this case.

5. Summary

Infrared geosynchronous satellite data have been analyzed to determine thunderstorm top height variations relative to the time of tornado touchdown. In eight of eleven cases of relatively strong tornadoes, there was a period of rapid height increase (temperature decrease) 30–45 min prior to tornado touchdown. A typical value for this temperature decrease above the tropopause is 0.4 K min^{-1}, which is equivalent to a cloud top ascent rate of $\sim$3 m s^{-1}. In three cases where Doppler radar observations were available, this period of rapid cloud top ascent coincided with the development of the mesocyclone. In the same eight cases, the time of tornado touchdown was a period of nearly constant height, or slight height decrease (temperature increase). This sequence of satellite-observed events in the evolution of these tornadic thunderstorms is similar to radar-observed echo top changes noted in other tornadic thunderstorms and is consistent with a conceptual model (Lemon and Doswell, 1979) in which the mesocyclone vorticity is generated primarily through the stretching of the vertical air column in a rapidly intensifying updraft. The intensification and descent of the vortex to form a tornado is related to a weakening of the updraft, formation of a downdraft, and a shift of the vortex to the updraft-downdraft boundary, so that the tilting term becomes dominant in the generation of vorticity.

Acknowledgment. The authors thank the personnel at the National Severe Storms Laboratory for supplying the Doppler radar log and radar data used in this study. Douglas A. Moore, Raymond Wexler, and other colleagues provided numerous insights into the 20 May 1977 case.

[7] Lemon, L. R., 1976: Tornadic storm evolution: Vortex value hypothesis. Appendix G, the Union City, Oklahoma Tornado of 24 May 1973, R. A. Brown, Ed. NOAA Tech. Memo. ERL NSSL-80, 229–234.

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