NOTES AND CORRESPONDENCE

Passive Microwave Structure of Severe Tornadic Storms on 16 November 1987

GERALD M. HEYMSFIELD AND RICHARD FULTON* +
Laboratory for Atmospheres, NASA/Goddard Space Flight Center, Greenbelt, Maryland
29 September 1993 and 25 March 1994

ABSTRACT

Passive microwave observations using the Special Sensor Microwave/Imager are presented for severe tornadic storms in the lower midwestern United States on 16 November 1987. These measurements are compared with Geostationary Operational Environmental Satellite infrared (IR) measurements for the same case. The IR observations had a classic "V" cold feature commonly associated with severe Midwest thunderstorms. The minimum microwave brightness temperatures at 86 GHz, which primarily respond to ice scattering by larger ice particles, were located in the convective region and the warm interior region of the anvil top, between the arms of the IR V feature. The interior warm region was the only portion of the entire anvil region that had high 86-GHz polarization difference temperatures. Microphysical implications of these multispectral observations are discussed. The observations suggest that there are large variations of ice microphysical characteristics spatially and vertically in the anvil region. These observations are discussed in the context of previous dynamical and microphysical hypotheses on the IR V feature.

1. Introduction

Severe thunderstorms in the midwestern United States have been studied extensively from the satellite perspective since the inception of the Geostationary Operational Environmental Satellite (GOES). Infrared temperatures of these storms revealed interesting aspects of the growth and mature stages of their development (e.g., Adler and Mack 1986; McCann 1983; Heymsfield et al. 1983a; Heymsfield et al. 1983b; Heymsfield and Blackmer 1988). The GOES data have revealed the frequent occurrence of an 11-μm infrared (IR) "V" associated with Midwest severe thunderstorms—that is, a V- or U-shaped region of low IR equivalent blackbody temperatures T_b with the apex of the V pointed in an upwind direction. A schematic of this feature from Heymsfield and Blackmer (1988) is shown in Fig. 1. It was found by Heymsfield and Blackmer that, often, two distinct embedded warm IR areas occur: the "close-in warm area" immediately downwind of the overshooting cloud tops, and the "distant warm area" farther downwind. The relationship between the IR V and the existence of severe weather has been previously documented (Heymsfield et al. 1983a; Heymsfield and Blackmer 1988; McCann 1983; etc.), and it was suggested to be due to either dynamical (Heymsfield et al. 1983b; Schlesinger 1984; Adler and Mack 1986) and/or cloud-top emissivity differences spatially across the anvil tops (Heymsfield et al. 1983b). The dynamical mechanisms focused on subsidence in the warm region caused either by the negatively buoyant updraft overshooting updraft air, or by environmental air flowing over the convective tops.

Microphysical explanations have also been given for the observed severe storm IR structure such as in Fig. 1. Heymsfield et al. (1983b) suggested based on a simple kinematic model and radiative transfer calculations that the ice water content (IWC) varies spatially across the anvil. The internal warm region was suggested to have lower IWC, thereby contributing to a lower IR emissivity, greater optical depth, and IR brightness temperature characteristic of warmer air temperatures at lower altitudes. More recently, Setvav and Doswell (1991) suggested a relation between Advanced Very High Resolution Radiometer (AVHRR) near-IR channel 3 (3.7 μm) measurements from the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites and storm severity. In the channel 3 data, they found an interesting plume-like feature of high reflectivity in a supercell with an associated IR V feature. This feature was suggested to be due to the

* Other affiliation: Science Systems and Applications, Inc., Lanham, Maryland.
+ Current affiliation: NOAA/NWS Hydrologic Research Laboratory, Silver Spring, Maryland.

---

* Corresponding author address: Dr. Gerald M. Heymsfield, Meso-scale Dynamics and Precipitation Branch, Laboratory for Atmospheres, Code 912, NASA/Goddard Space Flight Center, Greenbelt, MD 20771.
presence of large amounts of very small ice particles (2–4 μm) and/or supercooled water. Because of the high altitude of the severe storm anvils and the lack of in situ measurements, the interpretation of the IR features has been difficult. If part of the explanation is microphysical in nature, it is appropriate to take a multispectral satellite remote sensing approach using wavelengths ranging from the visible to the microwave. Given that no single satellite carries all these frequencies, multiple satellites are necessary in such an analysis. However, the polar-orbiting satellites often pass over the Midwest at different times, and thus, it is not always possible to make satellite comparisons at the same time.

Passive microwave observations have not yet been used to view larger thunderstorms that have mesoscale extent. The Special Sensor Microwave/Imager (SSM/I) aboard a Defense Meteorological Satellite Program (DMSP) polar-orbiting satellite was first launched in 1987 and provides passive microwave measurements at seven frequencies (19H, V; 22H; 37H, V; 86H, V; where H and V denote horizontal and vertical polarization, respectively) (Hollinger et al. 1987). The view angle of the SSM/I conical scan is 37° above the earth’s horizon, and the approximate footprint sizes are about 14 km at 86 GHz, 33 km at 37 GHz, and 56 km at 19 GHz. The F8 satellite used in this study made two overpasses per day at about 0700 and 1900 local time (1200 and 0000 UTC, respectively) over the United States.

The upwelling microwave radiances viewed from space vary considerably with frequency and depend primarily on scattering from ice particles and emission from rain, cloud water, and the surface background. In precipitation, the microwave brightness temperatures are related in a complex fashion to the vertical microphysical structure of the ice and liquid hydrometeors (particle habits, size distributions, etc.). Scattering processes tend to dominate for higher SSM/I frequencies, while at the lower SSM/I frequencies, thermal emission is dominant from liquid water below the freezing level (e.g., Wilheit et al. 1977; Spencer et al. 1989; Hakkarinen and Adler 1988; Heymsfield and Fulton 1988; Smith and Mugnai 1988; Adler et al. 1990). The lack of temperature contrast between a land background with a high emissivity, and precipitation, makes it difficult to detect rain emission over land at the 19- and 37-GHz SSM/I channels. However, the polarization difference temperature (i.e., vertical minus horizontal polarized brightness temperature) over land at the lower SSM/I frequencies is often useful in separating wet soil or water backgrounds with low emissivities from dry land backgrounds (e.g., Spencer et al. 1989). Retrievals aimed at rain estimates and gross characterization of the vertical microphysical structure have been developed using the SSM/I and TRMM (Tropical Rainfall Measuring Mission) frequencies (Kummerow and Giglio 1994; Smith et al. 1992). These retrievals basically employ a radiative transfer model along with an assortment of models of the vertical structure of the rain system. Because of the nonuniformity of land backgrounds, these retrievals provide limited information on the vertical structure because they rely mostly on the scattering signal over land.

The passive microwave and IR structures of mesoscale convective systems (MCS) have recently been studied by Heymsfield and Fulton (1994). They found that stratiform and convective regions for midlatitude and tropical cases over land and ocean backgrounds could be distinguished in the microwave polarization measurements. Convective regions typically had low differences between the vertical and horizontal brightness temperatures at 86 GHz, while the stratiform regions had larger polarization temperature differences at this frequency. Heymsfield and Fulton suggested the presence of more oblate or planar ice crystals in the stratiform region and irregularly shaped and/or tumbling ice particles in the convective region as an explanation for the microwave observations.

In this paper, severe storm cloud tops that have been extensively studied with GOES observations in the previous literature will be examined using SSM/I microwave observations. The MCS case presented here occurred on 16 November 1987 along the Gulf coast and contained severe storms that produced two separate tornadoes at the time of an SSM/I overpass. Since the DMSP at present does not provide digitized visible and IR data, the GOES half-hourly IR data are used for comparison with the SSM/I data. Detailed intercomparisons are performed between the SSM/I microwave and the GOES IR measurements to determine interrelations between them. An interesting polarization fea-
ture is found to correlate well with the IR warm region. The significance of these observations are then discussed in light of previous results and the implications on the structure of severe storm tops.

2. Observations

Severe thunderstorms occurred in the early evening of 16 November 1987 in northeast Texas, Louisiana, and Arkansas. The images in Fig. 2 are composited from GOES IR, SSM/I $T_b$’s and 86-GHz $\Delta T_{V-H}$ (= $T_{HV}$ - $T_{HH}$), and radar reflectivity data. The GOES IR image at 0052 UTC was within a few minutes of the SSM/I overpass. The nearest overpass times of the NOAA polar-orbiting satellite was almost 3 h after the DMSP overpass, and thus, AVHRR near-IR channel 3 data were not examined. The GOES and SSM/I data were mapped to a common Mercator coordinate system, and it was corrected for satellite viewing angle to a cloud height of 12 km. No corrections for the SSM/I viewing angle have been made to the data, because the shift would be less than the width of one footprint for the deepest clouds, even at 86 GHz. Plan position indicator (PPI) photos of reflectivity from the Longview, Texas, (GGG) WSR-57 radar were used because digital data were not available. At the time of the images in Fig. 2, there were two F-3 tornadoes on the ground, one in northeast Texas near Marietta (total pathlength/duration of about 25 km/20 min) and the other in northwest Louisiana near Shreveport (80 km/65 min; NOAA 1987). The open diamonds in the GOES IR image (Fig. 2a) mark the location of each of these tornadoes, which has an associated cold IR V pattern at cloud top with coldest IR $T_b$ of 200 K. For both storms, the warm interior region of the V is located downshear of the coldest IR $T_b$ associated with the storm’s overshooting cloud top. The coldest IR brightness temperature is 6 K colder than the coldest temperature in the sounding from Longview (GGG) about 1 h earlier (Fig. 3a), indicative of overshooting tops. The storm-relative shear vector near cloud top (13 km) (Fig. 3b) is directed toward the northeast, which approximately bisects the V in the downshear direction of the interior warm region as expected (Heymsfield and Blackmer 1988). The convective available potential energy (CAPE) and the bulk Richardson number (Ri) calculated from this sounding were 1263 m$^2$ s$^{-2}$ and 11, respectively. According to Weisman and Klemp (1986), these CAPE and Ri values are indicative of supercell storms with strong updrafts. Indeed, hail, tornadoes, and severe winds were reported in a number of the storms on this day.

The nearly coincident WSR-57 radar reflectivity PPI from Longview, as contoured from radar photos, is shown in Fig. 2b. Both IR V’s are associated with very strong radar cells along two parallel squall lines with a maximum DVIP (digital video integrator and processor) level 5 (50–57 dBZ) at low levels. Radar reflectivity hooks, indicative of mesocyclones, were reported earlier with both of these storms. The reflectivity core of the Shreveport storm lies very near and somewhat downshear of the vertex of the cold IR V as also observed by Heymsfield and Blackmer (1988).

Figures 2c, 2e, and 2f show the 86H, 37H, and 19H SSM/I $T_b$ at nearly the same time. The cold 86H SSM/I features match well with the highest radar reflectivity cells, where the area of 86-GHz $T_b$ ≤ 260 K [shaded region in panel (c)] roughly corresponds to the area of DVIP level 1 and greater (greater than about 20 dBZ) for this case. Midlevel radar echoes have been found to correlate well with the 86-GHz brightness temperature depressions in aircraft and SSM/I observations (e.g., Hakkarainen and Adler 1988; Heymsfield and Fulton 1988) since this scattering-based channel responds to the large volume ice scattering associated with the convective cores. The minimum $T_b$ at 86H, 37H, and 19H are 77, 176, and 245 K, respectively, over the Shreveport tornadic storm. These are the coldest temperatures the authors have observed in the SSM/I imagery for many different thunderstorm and MCS cases. Even the 19-GHz frequency with a 56-km footprint, which is typically a very poor rainfall detector over land because of lack of contrast between the surface background and precipitation emission, shows a cold minimum $T_b$ of 245 K over the Shreveport storm. It is noted that high-resolution aircraft measurements with pixel resolutions of about a kilometer (Adler et al. 1990; Vivekanandan et al. 1993) have shown lower 19-GHz temperatures (200 K) for intense thunderstorms over a much smaller region than an SSM/I pixel. The low brightness temperatures over the relatively large SSM/I footprint must indicate that the storm updrafts, and hence the ice scattering region, are large spatially. This is in fact often the case with Midwest severe storm updrafts, which often have diameters roughly 10 km.

Some of the lower-frequency brightness temperature depressions are due to background emission. The 19-GHz $T_b$ is depressed over a rather large area in north-central Texas and Oklahoma to the rear of the southwest–northeast-oriented thunderstorm squall line (Fig. 2f). Although a part of the region of depressed 19- and 37-GHz $T_b$ is due to volume scattering of the microwave radiation by ice within the deep convection (see in particular the Shreveport storm), much of the area of cold $T_b$ results from wetted soil (see Heymsfield and Fulton 1992). This effect is not as pronounced at 37 GHz but there is ambiguity between rain and wet soil background. By using the polarization difference at the lower-frequency channels, wet soil with a high polarization difference can be separated from rain that has a relatively low polarization difference. The soil does not appear to be saturated in the immediate vicinity and below the Shreveport and Marietta storms since the 19-GHz polarization differences (not shown in Fig. 2 but shown in profiles later) were only a few degrees compared to nearly 30-K differences for Oklahoma wet soil
Fig. 2. (a) GOES 0052 UTC IR image (MB enhancement), (b) Longview (GGG) WSR-57 radar reflectivity PPI, (c) 86H-GHz SSM/I image, (d) SSM/I $\Delta T_{\text{MB}}$ image, (e) 37H-GHz SSM/I image, and (f) 19H-GHz SSM/I image at 0055 UTC 16 November 1987. The Shreveport storm is southeast of the Marietta storm; the locations of two F-3 tornadoes associated with these storms at the time of the satellite data are shown as the open diamonds in (a). Contours in (b) start at DVI P 1 and increase in steps of one DVI P level. The vertices of the V feature are located near the open diamonds in (a). Profile positions in Figs. 5 and 6 are shown by lines AB and CD, respectively, in (b) and (f); profile endpoints are also shown in (a) and (c)–(e).
regions found in Heymsfield and Fulton (1992). Microwave rain retrievals (Kummerow and Giglio 1994) use \( \Delta T_{V-H} \) (19 GHz) > 15 K to identify wet soil. Thus, the anvil temperature signatures at 86 GHz discussed later do not appear to be influenced greatly by the surface emission.

The cold SSM/I \( T_B \) at 86 GHz results primarily from the strong scattering of upwelling microwave radiation associated with a deep layer of ice in the thunderstorms. On the other hand, ice scattering typically has a relatively minor effect at the lower SSM/I frequencies (e.g., 19 GHz). The 19-GHz \( T_B \) over rain results primarily from emission by liquid hydrometeors whose blackbody temperature is close to that of the earth’s surface, often making it difficult to detect even the heaviest intensity of rainfall over land surfaces. The 19-GHz \( T_B \)’s shown here are depressed more than typical with SSM/I deep convection in MCSs (e.g., Heymsfield and Fulton 1994). The 37-GHz channel is somewhere in between, as demonstrated by Fig. 2c, with a better sensitivity to precipitating clouds than 19 GHz but less ability to detect low rain rates than 86 GHz.

Figure 4 shows a zoomed view of the Shreveport severe storm presented in Fig. 2 focusing just on the satellite images. The IR image in Fig. 4a is color coded such that blue shades denote relative cold regions and red shades relative warm regions. The interior warm IR region has close-in and distant warm points (bright red regions), defined in Fig. 1, that often occur in severe tornadic storms (Heymsfield and Blackmer 1988). As noted in the hodograph (Fig. 3b), the storm-relative winds veer with height at anvil level (9–13 km). Interestingly, the major axis of the IR V (Fig. 4a) is rotated about 20° clockwise from that of the 86H \( T_B \)’s (see 280-K contour in Fig. 4a). Based on the assumption that the anvil ice particles advect with the storm-relative wind [given by the vector between storm motion (SM) and the hodograph curve in Fig. 3], this is an expected result since the IR senses the near-cloud-top (13 km) upwelling radiation while the 86-GHz microwave channel senses deeper into the storm.

Comparison of the minimum 86H \( T_B \) associated with the Shreveport storm (Fig. 4b) with \( \Delta T_{V-H} \) (86) (Fig. 4c) clearly shows the minimum \( T_B \) corresponding to lower values of \( \Delta T_{V-H} \). This is also illustrated in Figs. 5 and 6, which show corresponding profiles over the Shreveport tornadic storm. Figure 5 is the southwest–northeast cross section along the axis of the anvil IR V as shown in Figs. 2f and 4a by line AB and is oriented approximately along the storm-relative wind vector at cloud top (see the hodograph in Figs. 3b). Figure 6 is the northwest–southwest cross section (see the CD line in Figs. 2f and 4a) normal to the V axis and cutting across the anvil at a distance of 130 km in Fig. 5, which is in the region of highest \( \Delta T_{V-H} \) (86). Figure 5 shows that the coldest SSM/I \( T_B \) [panel (b)] is collocated with the highest near-surface radar reflectivity (Figs. 2b), the tornado position, and it is located between the cold point and close-in warm IR couplet. It is not surprising that a similar relation between radar reflectivity and IR temperatures was found in Heymsfield and Blackmer (1988) since the minimum microwave temperatures are closely tied to the large ice mass region associated with the storm updraft. The \( \Delta T_{V-H} \) is almost zero over the core and then rises sharply to 12 K slightly downshear of this region and then returns to a background anvil value of 4 K at distances greater than about 190 km. In profile CD (Fig. 6), the arms of the IR V have low polarization difference and much higher values of 86-GHz \( T_B \) while the internal warm region has low 86-GHz \( T_B \) and high \( \Delta T_{V-H} \). The
Shreveport storm anvil exhibits similar patterns of 86-GHz polarization temperatures as seen in squall lines in Heymsfield and Fulton (1994)—that is, high $\Delta T_{V-H}(86)$ in the downshear anvil and low $\Delta T_{V-H}(86)$ over the storm core.

The large $\Delta T_{V-H}(86)$ values do not appear to be due to wetted soil since the $\Delta T_{V-H}(19)$ (Figs. 5 and 6) has relatively small values. The Heymsfield and Fulton (1992) paper clearly showed that the 19-GHz channel has a much larger $\Delta T_{V-H}$ than the 86-GHz channel for wetted soil. Also, the resolution of the 19-GHz channel (i.e., 56 km) is adequate to sample the anvil region, which has a width of about 150 km (see transverse profile in Fig. 6). Thus, we believe the polarization differences are due primarily to scattering processes rather than to the semitransparent anvil overlying a wet land background.

The extremely low 86H $T_{b}$ and the near-zero $\Delta T_{V-H}$ in the convective region suggest a significant amount of ice and a low degree of orientation of the ice particles. On the other hand, the downshear half of the IR warm region (distances between 120 and 200 km in Fig. 5) has warmer 86-GHz $T_{b}$ and high 86-GHz polarization difference temperatures, indicative of less ice scattering and strongly oriented particles at upper levels. The abrupt transition illustrates considerable microphysical differences spatially. Since the internal IR warm region partly overlies the coldest 86-GHz $T_{b}$ and low $\Delta T_{V-H}(86)$ as shown in Fig. 5, there is likely to be higher ice mass and relatively disoriented or large
tumbling ice particles in at least the upshear half of this warm region in the vicinity of the storm core. Almost identical features are illustrated in the profiles for the Marietta storm (not shown here).

While there were no polarization measurements for this case, there is a strong likelihood that large ice and hail were present with these storms based on the storm reports. Radar polarization measurements in convective storms (e.g., Fulton and Heymsfield 1992) have inferred that updraft regions with large centimeter-sized ice particles above the freezing level can be strongly depolarized [i.e., have large linear depolarization ratio (LDR)] because they tumble during descent. Thus, while the near-zero $\Delta T_{\nu-H}$ (86 GHz) can be explained partly by irregularly shaped ice particles, it is plausible that larger tumbling ice particles that are strongly depolarized are present in this case.

3. Discussion

The observations suggest that there are significant microphysical differences across the anvil both spatially and in the vertical. Since the GOES IR senses upwelling radiation near the cloud top and the depressions in the 86-Hz SSM/I $T_b$'s result primarily from ice scattering over a large integrated cloud depth, it is difficult to determine precise mechanisms from this data. However, several inferences are noteworthy. The IR $\nu$ arms at the anvil outer edges are relatively transparent at the SSM/I microwave frequencies, implying weak volume ice scattering due to either thin anvil thickness and/or relatively small ice particles. The interior IR warm region has low microwave $T_b$'s over a large portion, implying considerable ice scattering and larger anvil thickness than the edges. This strong scattering region in the radiometric observations is consistent with previous comparisons of radar observations with GOES IR observations (Heymsfield and Blackmer 1988), where the high radar reflectivity anvil plume extended down the center of the IR anvil between the cold IR $\nu$ arms. The radar observations here (Fig. 2b), which are of poorer quality, also show a similar correlation between the radar plume, the 86-Hz $T_b$'s (Fig. 2c), and the IR $\nu$ (Fig. 2a). The location of the close-in IR warm point downstream of the convective core (W in Fig. 5a) is well correlated with the position of an embedded 86-Hz $\Delta T_{\nu-H}$ maximum (Fig. 5c), the latter of which suggests a high degree of particle orient-

**Fig. 5.** Profiles over the Shreveport tornadic storm along the storm-relative shear vector at cloud top (see AB Fig. 2f) of (a) GOES IR $T_b$, (b) SSM/I $T_m$, and (c) SSM/I $\Delta T_{\nu-H}$. The tropopause temperature from the 0000 UTC 16 November GGG sounding is shown in (a). The C and W denote the cold and close-in warm infrared temperature locations.

**Fig. 6.** Same as Fig. 5 except oriented normal to the shear vector and axis of the GOES IR $\nu$ (see CD Fig. 2f). This profile crosses the profile in Fig. 5 at a distance of 130 km, in the center of the warm region downshear of the cloud summit.
tation. Interestingly, Setvák and Doswell (1991) found higher 3.7-μm AVHRR channel 3 reflectance in the anvil interior. They suggested this was due to large amounts of very small (few micron) ice particles. Particles this size are perhaps more pristine (e.g., plates, needles, etc.), lacking riming, would be more polarized in the microwave, and would have lower IR emissivity. The combined IR–microwave data presented here, along with the previous Setvák and Doswell observations, hint at a large variation of the mean sizes of ice particles spatially and in the vertical. That is, in the interior warm IR region, we surmise that there are very small ice particles at higher altitudes overlying a layer with larger particle sizes detected by radar. Along the anvil edges in the V arms, the particles are larger but too small to be detected by radar and of higher IR emissivity. This structure is consistent with the previous hypothesis in Heymsfield et al. (1983b), which suggests that the IR emissivity varies across the anvil due to variation of the ice content vertically.

The degree to which electrical activity in these storms near cloud top is influencing the cloud microphysics (i.e., particle habits and orientations) is not known. Polarization radar measurements from thunderstorms indicate that changing electric fields associated with lightning activity can have a significant impact on hydrometeor alignment in thunderstorms (e.g., Krehbiel et al. 1991; McCormick and Hendry 1979; Hendry and Antar 1982). Recent balloon soundings of the electric fields in thunderstorms (Marshall and Rust 1993) have shown that there is much more similarity between electric field soundings in MCS stratiform regions than soundings through isolated thunderstorms. The electric fields in their MCS cases showed repeatable charge structures in the MCS stratiform regions. Whether these electric fields can produce widespread alignment of anvil ice particles and subsequently large microwave polarization difference temperatures over areas 100 km or more wide as in this case will require more data than available for this study. This would require a more focused experiment with this objective.

Combined cloud–radiative models (e.g., Adler et al. 1990; Mugnai and Smith 1988) are limited by the complex nature of clouds and the general lack of knowledge of the ice particle characteristics (shapes, sizes, distributions, mass densities, etc.). The sparse measurements of actual ice particle characteristics in convective storms combined with the complex modeling associated with the details of ice scattering have led to the assumption of spherical particles in the microwave models and retrievals. Generally, the models have demonstrated reasonable success in obtaining low 86- and 37-GHz brightness temperatures with ice layers with significant vertical extent, as would be found with deep convection as in the case presented here. But the effect of ice size distributions and/or the presence of large ice (i.e., hail) and/or extremely high concentrations of smaller ice particles is just beginning to be examined.

Thus, it is difficult to apply these models to the present observations that show large polarization signatures at the 86-GHz frequency. Recent radiative transfer modeling (Evans and Vivekanandan 1990) using a discrete dipole approximation for simple ice particle shapes (plates, columns, and needles) has shown that significant 85-GHz polarization brightness temperatures occur for plates and columns, and that modeling with equivalent volume spheres poorly approximates the ice crystal results. High-altitude (>12 km) in situ microphysical measurements in Midwest storms are nonexistent and they are critically needed to address the above observations, as well as to improve the realism of the radiative transfer models.

With the measurements here that respond more to the details of the microphysical structure, it is not possible to determine the role of subsidence to the lee of the storm core as has been suggested in previous papers mentioned in the introduction. Subsidence in this region would cause particles to sublimate and possibly be of smaller size in that region. Additional information on the anvil ice structure may be provided by high-frequency (86–325 GHz) microwave channels that are available in the Millimeter-wave Imaging Radiometer on the National Aeronautics and Space Administration (NASA) ER-2 aircraft package (Racette et al. 1994). Possibly, regions of subsidence could be indirectly determined by using the profiling capability of this instrument.

4. Conclusions

Comparisons between the SSM/I microwave observations and the GOES IR data have been performed for the Shreveport and Marietta severe thunderstorms on 16 November 1987. The IR observations for these storms had the classic V feature in the GOES IR observations. The maximum polarization temperature difference at 86 GHz in the SSM/I observations correlated well with the internal warm region in the IR observations. The observations lend support to the idea that there are large variations of ice microphysical characteristics spatially and vertically in the anvil region. The convective region has a predominance of symmetrical and/or tumbling ice particles that cause relatively low 86-GHz microwave polarization difference, while the anvil interior is dominated by more oriented ice crystals that produce larger polarization differences. In addition to the dynamical hypotheses mentioned in the introduction, the cloud-top microphysical variations are a partial explanation for the IR structure (Fig. 1) observed with many severe storms.

Future measurements may provide better understanding of convective storms and their associated anvils. The recently launched GOES-8 will provide a factor of 2 improvement in IR resolution compared with GOES-7. The TRMM microwave radiometer (Simpson et al. 1988) will provide a factor of 3 resolution
improvement over SSM/I and will sample latitudes lower than about 38°N; the TRMM radar will cover up to about 36°N. This coverage will be sufficient to detect some of the severe storm cases as presented in this paper. Remote sensing instruments on the NASA ER-2 aircraft, which can overfly deep convective storms, can provide multispectral measurements of the upper-level cloud structure. Also, the new nadir-pointing ER-2 Doppler/polarization radar mounted on that plane can provide vertical structure information that may be valuable in deciphering the observations presented in this paper.

Acknowledgments. We appreciate the contribution of Mr. Harold Pierce in data processing and in preparation of some of the images presented. This work was supported by Dr. Ramesh Karak in the Dynamics, Radiation, and Hydrological Processes Division at NASA Headquarters in Washington, D.C.

REFERENCES