MICROPHYSICAL AND THERMODYNAMIC STRUCTURE AND EVOLUTION OF THE TRAILING STRATIFORM REGIONS OF MESOSCALE CONVECTIVE SYSTEMS DURING BAMEX

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1. INTRODUCTION

The kinematic and precipitation structure of summertime midlatitude mesoscale convective systems (MCSs) has been documented in many radar studies (e.g., Smull and Houze 1985, Houze et al. 1990). These studies show that MCSs commonly consist of a leading convective line, approximately 10-50 km wide, followed by a more expansive trailing stratiform region (TSR), approximately 50-200 km wide. An enhanced stratiform rain region of intensified radar reflectivity, which is typically oriented parallel to the convective line, often appears within the TSR. A transition zone of mesoscale descent and light precipitation frequently exists between the rear of the convective line and the enhanced stratiform rain region. Two primary flow regimes are usually present within the TSR: a zone of ascending front-to-rear (storm-relative) flow at middle and upper levels, transporting hydrometeors from the convective line rearward to form the enhanced stratiform rain region, and a zone of rear-to-front flow that descends beneath the front to rear flow. This paper focuses on the microphysical structure of the clouds within the TSR and each of the subregions discussed above. The results were compiled from airborne Doppler radar observations, level II WSR-88D radar analyses and aircraft microphysical data from the NOAA P-3 aircraft flown during the Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX) (Davis et al. 2004).

2. CONCEPTUAL FRAMEWORK

McFarquhar et al. (2007, hereafter MF07) provide a detailed description of spiral descent pattern sampling strategy within TSRs behind convective lines. With one exception on 29 June, the locations of microphysical observations were characterized with respect to three trailing stratiform features common to all MCSs examined here: the transition zone/notch region, the enhanced stratiform rain region, and the rear anvil region (Figs. 1 and 2). Data from each spiral descent and horizontal flight leg were classified according to the stage of MCS evolution during which the spiral occurred by tracking each MCS from its initiation to decay using regional composite WSR-88D animations. Twelve of the seventeen spiral descents and numerous horizontal flight legs performed during BAMEX occurred within a typical trailing stratiform MCS. Eleven of the spiral descents and all of the horizontal legs analyzed here were performed at times when a solid band of stratiform rain was readily apparent on plan view tail radar and WSR-88D scans. One spiral, performed on 29 June, was conducted before this time when convective cores were strengthening and beginning to bow. This spiral was conducted within a developing “notch” region of weaker reflectivity (Smull and Houze 1985), which usually intrudes into the back edge of the stratiform precipitation and is often associated with the maximum axis of rear inflow,
indicative of dry air inflow or rear inflow descent. MF07 describe the algorithms used to process the data obtained from the in-situ probes to provide estimates of the total number ($N_t$), total mass content (TMC), observed hydrometeor size distributions, and the calculations of temperature ($T$), relative humidity with respect to ice ($RHi$) and water ($RHw$). The only difference from the analysis presented by MF07 is that a 10 s averaging time was used here instead of 60 s to process the microphysical data in order to determine how short time-scale fluctuations in RH and RIJ speed were correlated with fluctuations in the microphysical data. Details of the data processing will be forthcoming in Smith et al. 2008.

Figure 1: Conceptual radar evolution of a typical summertime midlatitude MCS. Dashed black paths represent the locations and timing of horizontal flight leg tracks while stars represent the locations and timing of microphysical spiral descent patterns flown during BAMEX MCSs. Black shading represents 50 dBZ and above, gray shading represents 35-50 dBZ and the gray outline represents the 0 dBZ echo boundary.
Figure 3: RH (top) and $N_t$ (bottom) as a function of $T$ for spiral descents and horizontal flight legs. For $T < 0^\circ$C, RH$_i$ is plotted, while RH$_w$ is plotted for $T > 0^\circ$C for all panels. A) RH ($N_i$) profile from spiral descent performed in the transition zone on 29 June 2003 (solid black line). Box and whisker plots show RH$_i$ ($N_i$) for two horizontal legs in which the aircraft was in the transition zone. Solid black line inside of box is the median RH ($N_i$) value. The area of the boxes contains the 25th through 75th percentiles. Whiskers extend to 1.5 times the interquartile range. Asterisks represent outliers. B) Median (dashed black line), 25th through 75th percentiles (gray shaded regions) and maximum and minimum values (solid black lines) of RH ($N_i$) for the 9 spiral descents obtained in the enhanced stratiform rain region. Box and whisker plots show RH ($N_i$) values for horizontal flight legs in the enhanced stratiform rain region. Dotted black line is the number of measurements within each temperature bin. C) RH ($N_i$) profiles from two spiral descents (solid lines) and horizontal legs (box and whisker plots) obtained in the rear anvil region.
3. Storm Thermodynamic and Microphysical Structure

a. Thermodynamic profiles

As Fig. 1b shows, only one spiral descent was performed early in the lifetime of a MCS (29 June, first spiral). Two horizontal legs, flown on 2 June, sampled the transition zone in a more mature MCS, and are represented by the flight tracks in Fig. 1b. RH values for all sampling conducted within the transition zone are shown in Figure 3a. As noted by MF07, the 29 June vertical profile exhibited RH values well below 100% throughout the duration of the spiral descent. RH$_i$ averaged 85% for $T<0°C$ and RH$_w$ averaged 57% for $T>0°C$. Such low values throughout the depth of the spiral descent were unique within the BAMEX dataset, and can be attributed to the aircraft’s position within downdrafts in a developing and descending RIJ. The RH$_i$ values for the 2 horizontal legs flown in the transition zone are represented by the box and whisker plots in Fig. 3a. The median RH$_i$ of 90% and 96% are also below saturation, but approximately 8% higher than the mean RH$_i$ value for $T<0°C$ found on 29 June.

The RH$_i$ and RH$_w$ values for flight legs conducted within the enhanced stratiform rain region of TSRs of MCSs are summarized in Figure 3b. Here, RH data from 9 spiral descents performed on the following dates are used to derive the median and percentile values for 0.5°C intervals: 2 June (second spiral), 10 June (first and second spirals), 25 June, 2 July, 4 July (first and second spirals) and 6 July (second and third spirals). The average median RH$_i$ for the spirals for $T < 0°C$ was 102%, with a range of 106% to 96%. The median RH$_i$ decreased downward at a rate of 0.33% °C$^{-1}$. The horizontal flight legs conducted in the enhanced stratiform rain region also exhibited RH$_i$ values higher than those in the transition zone, with an average median of 97%. For $T > 0°C$, the average median RH$_w$ value was 80%, and RH$_w$ values decreased downward more sharply at a rate of 2% °C$^{-1}$. This dichotomy between saturated RH$_i$ values above and subsaturated RH$_w$ values below the melting level occurred in every spiral descent conducted within the enhanced stratiform rain region during BAMEX.

Grim et al. (2008) show that this sharp change in the RH profile develops in response to differential sublimation and evaporation rates due to the rapid increase in hydrometeor fallspeeds from 1 – 2 m s$^{-1}$ for ice to 2 – 11 m s$^{-1}$ for rain. RH values for the rear anvil region are shown in Figure 3c. The 21 June spiral and the first spiral descent on 6 July were conducted within the rear anvil region as the aircraft flew within and eventually underneath the storm rear anvil echo. Five horizontal legs were also conducted within the rear anvil region on 2 June and 10 June.

Consistent with trends observed in the enhanced stratiform rain region, the spiral descent on 21 June shows saturated conditions and on 6 July nearly saturated conditions for most altitudes above the freezing level. However, as the aircraft spiraled down in these cases, it came close to exiting the bottom of the rear anvil echo at $T \sim -1°C$ and RH$_i$ values began a steady and rapid decrease. This contrasts with the RH$_i$ profiles obtained in the enhanced stratiform rain region, as RH$_i$ values there hovered near saturation until reaching the melting level, usually found near + 1.5°C. The average RH$_w$ for $T > 0°C$ for the rear anvil region spirals was 68%, about 13% lower than the value reported from the enhanced stratiform rain region. Median RH$_i$ values in the rear anvil region decreased downward at a rate of about 0.72% °C$^{-1}$ for $T < 0°C$, and median RH$_w$ values decreased downward at 4.7% °C$^{-1}$.
for $T > 0^\circ C$. This rapid decrease in $\text{RH}_{\text{w}}$ below the melting level is approximately 3 times greater than that reported for the enhanced stratiform rain region spirals, suggesting that drier environmental air was eroding the back edge of the system in the rear anvil region. Horizontal leg $\text{RH}_{\text{h}}$ values varied from 48% to 101% in the rear anvil region, with an average median value of 80%. This wide variation occurred because the aircraft exited the rear anvil echo in some cases, but not others. The horizontal legs at $T = -4.5^\circ C$ and $T = -6.0^\circ C$ (median $\text{RH}_{\text{h}}$ of 48% and 64%, respectively) were both conducted between about 20 km and 30 km ahead of the furthest rearward extent of the stratiform anvil echoes but in both instances the aircraft began to sample the echo-free area underneath the anvil. The horizontal legs at $T = -2.5^\circ C$ and $T = -6.5^\circ C$ (median $\text{RH}_{\text{h}}$ of 98% and 89%, respectively) were also performed about 20 km ahead of the furthest rearward extent of the stratiform echo, but the aircraft stayed within the precipitation echo for the duration of these legs. In addition, the leg conducted at -2.5°C was in the presence of the remnants of another linear convective system approximately 20 km behind the aircraft, representing another source of moisture. The fifth horizontal leg performed in the rear anvil region had a median $\text{RH}_{\text{h}}$ value of 101%, but was performed as the aircraft flew underneath of the anvil echo and exited the rear edge of the system completely. It is unclear how such high $\text{RH}_{\text{h}}$ values were maintained in this situation.

b. Microphysical profiles

Vertical and horizontal profiles of $N_t$ and $\lambda$ were examined in the same manner as the RH profiles. Only the $N_t$ values are presented here. See Smith et al. 2008 for other microphysical analyses. Figure 3a (bottom) shows the profile of $N_t$ from the 29 June spiral, along with box and whisker diagrams for two horizontal legs conducted on 2 June within the transition zone. A linear least squares method was used to calculate the average rate at which $\log_{10} N_t$ varied within the layers $T < 0^\circ C$ and $T > 0^\circ C$; fractional rates of decrease of $N_t$ were then determined. The average value of $N_t$ for $T < 0^\circ C$ on 29 June was $1.1 \times 10^{-2}$ cm$^{-3}$, and decreased downward at a rate of 9.4% °C$^{-1}$ in this layer. For $T > 0^\circ C$, $N_t$ averaged $1.41 \times 10^{-3}$ cm$^{-3}$ and decreased downward at a rate of 9.6% °C$^{-1}$. The two horizontal legs had an average median $N_t$ of $3.8 \times 10^{-2}$ cm$^{-3}$. Due to the subsaturated conditions present in this zone above the $0^\circ C$ level, MF07 determined that sublimation and aggregation were causing the decrease in $N_t$ with $T$.

The $N_t$ values for the enhanced stratiform rain region, shown in Fig. 3b (bottom), were significantly higher than those in the transition zone/notch region. The average median value of $N_t$ from spirals in this zone for $T < 0^\circ C$ was $7.3 \times 10^{-2}$ cm$^{-3}$, about seven times higher than that from the transition zone/notch region. The overall rate of decrease of $N_t$ for $T < 0^\circ C$ was 25% °C$^{-1}$, nearly 3 times higher than the rate of decrease reported for the transition zone/notch region spiral. The horizontal legs obtained in the enhanced stratiform rain region had an average median $N_t$ of $5.7 \times 10^{-2}$ cm$^{-3}$ and ranged from $1.1 \times 10^{-3}$ to $1.53 \times 10^{-2}$ cm$^{-3}$. The consistently near-saturated conditions above the melting level in the enhanced stratiform rain region indicate sublimation would not have occurred in this zone. Thus, to the extent that in-cloud heterogeneity did not complicate observed trends, the decreases in $N_t$ found here can be attributed to aggregation (cf., MF07). For $T > 0^\circ C$, the median $N_t$ averaged $2.2 \times 10^{-3}$ cm$^{-3}$ and decreased at a slightly faster rate than $N_t$ in the $T < 0^\circ C$ layer, at 35% °C$^{-1}$. The evaporation occurring in the drier environment below the
melting level is likely the principal cause of this greater rate of decrease in \( N_t \). In the rear anvil region (Fig. 3c, bottom), \( N_t \) values for \( T < 0^\circ C \) averaged \( 5.1 \times 10^2 \) cm\(^{-3}\) during the spiral descents and \( 2.5 \times 10^2 \) cm\(^{-3}\) during the horizontal legs. The rate of decrease of \( N_t \) at \( 24\% \ ^\circ C^{-1} \) was comparable to that reported for \( T < 0^\circ C \) in the enhanced stratiform rain region. For \( T > 0^\circ C \), \( N_t \) averaged \( 4.5 \times 10^{-3} \) cm\(^{-3}\), approximately twice that of the enhanced stratiform rain region spirals for \( T > 0^\circ C \). The rate of decrease of \( N_t \) for \( T > 0^\circ C \) was \( 49\% \ ^\circ C^{-1} \), 13\% higher than the enhanced stratiform rain region spirals, and likely a manifestation of increased evaporation in the drier air.

The vertical and horizontal thermodynamic and microphysical profiles provide insight about the structure and microphysical processes occurring in the three zones of MCSs. In general, the results can be summarized as follows: conditions in the transition zone/notch region were subsaturated, especially early in the life cycle as observed during the 29 June spiral. As an MCS matures, the developing stratiform environment is likely moistened from the top by sublimation of particles falling through initially dry air, similar to the moistening described by WH89. Ice saturation is eventually achieved above the melting level within the enhanced stratiform rain regions of well-developed MCSs. Once particles begin to melt, their fallspeeds increase, thereby decreasing observed number concentrations, as noted above. Evaporation rates from more rapidly falling hydrometeors were apparently insufficient to maintain saturation below the melting level. This hypothesis is tested and verified by Grim et al (2008) in a series of model simulations. The effect of more rapidly falling raindrops may be compounded by potentially drier air arriving within an established rear-to-front flow region. In the presentation, we will examine this possibility using thermodynamic and microphysical data analyzed with respect to the front-to-rear and rear-to-front flow regimes.

3. Summary

This study used airborne and ground based radar, and optical array probe data from the NOAA P-3 aircraft, to characterize microphysical and thermodynamic variations in evolving BAMEX MCSs. The findings of MF07 were extended by analyzing the data within the context of key MCS structural features and their evolution. This study represents the first time such analyses have been made across multiple regions of many midlatitude MCSs at varying stages of evolution. Microphysical and thermodynamic data from twelve spiral descents and five horizontal flight legs were categorized according to where they occurred in one of three radar-defined trailing stratiform precipitation zones: the transition zone or notch, the enhanced stratiform rain region and the rear anvil region. These data were also analyzed with respect to whether they were collected within front-to-rear or rear-to-front flow. The main findings of this work are as follows:

1. The 29 June spiral descent was performed before a continuous enhanced stratiform rain region appeared on radar, and exhibited subsaturated conditions both above and below the melting level. \( N_t \) values decreased slowly throughout the depth of the spiral and were roughly an order of magnitude lower for this spiral than those performed in other zones. \( \lambda \) remained nearly constant, suggesting that sublimation was occurring in conjunction with aggregation.

2. In all spiral descents performed within the enhanced stratiform rain region, conditions were saturated with respect to ice above the melting level and subsaturated below the melting level. \( N_t \)
and $\lambda$ values decreased steadily from the top of the spirals to the melting level, suggesting that aggregation was the dominant growth mode of ice and that sublimation in this region was insignificant.

3. Spirals conducted within the rear anvil region showed saturation with respect to ice above the base of the anvil (approximately the -1°C level in the cases analyzed), while conditions along some horizontal legs in this zone showed significant subsaturation. Conditions below the melting level were 13% more subsaturated than those for the same layer in the enhanced stratiform rain region. $N_t$ decreased more quickly here than in the enhanced stratiform rain region, suggesting that sublimation was occurring in addition to aggregation.

4. Relative humidity was strongly correlated to storm motion parallel winds ($r = 0.79$) in spirals performed within the enhanced stratiform rain region, especially to the magnitude of front-to-rear flow ($r = 0.87$). Relative humidity was less strongly correlated to the magnitude of the rear-to-front flow ($r = 0.31$), likely a manifestation of compounding factors of drier air below the melting level, downdrafts, and differences in the relative humidity of the surrounding environmental air being transported into the system by the rear inflow jet.

5. Within two single spiral descents in the enhanced trailing stratiform region, minima in storm motion parallel winds (front-to-rear flow) occurred at the same altitudes as maxima in $T$, $T_d$, $N_t$ and $\lambda$ while maxima of rear-to-front flow were observed at the same altitudes as minima of $T$, $T_d$, $N_t$ and $\lambda$.

Taken together, these findings help to quantify the microphysical and thermodynamic structure of the TSRs of midlatitude MCSs. As the convection merges into a line and broadens, the front-to-rear flow carries hydrometeors rearward where they begin to fall and sublimate in initially dry surroundings. As more hydrometeors arrive, the post-convective environment is moistened from the top down by sublimation. The developing rear-inflow begins to erode the back edge of the system, leading to a notch-like return on radar (see 29 June). As more hydrometeors are carried rearward aloft, the stratiform region expands and saturates with respect to ice downward toward the melting level. Upon reaching the melting level, hydrometeor fallspeeds increase sharply, thereby reducing number concentrations and phase change rates. Thus, saturation is difficult to attain below the melting level. The rear-to-front flow transports potentially drier environmental air toward the convective line, accounting for the subsaturated conditions present above the melting level in the rear anvil region and enhancing sublimation and evaporation.

Acknowledgements. This material is based upon work supported by the National Science Foundation under Award No. NSF-ATM-0413824.

References

