9B.4

# THE ROLE OF THE TRAILING STRATIFORM REGION IN CONVECTIVE MOMENTUM TRANSPORT AND MESOSCALE CONVECTIVE SYSTEM MOTION

Kelly M. Mahoney[+] and Gary M. Lackmann
*North Carolina State University, Raleigh, North Carolina*

## 1. INTRODUCTION

Mesoscale convective systems (MCSs) are commonly characterized by a leading convective line followed by a region of stratiform precipitation. The trailing stratiform region (TSR) is typically 50 – 200 km wide and features two main flow regimes: front-to-rear flow that ascends from middle to upper levels, and rear-to-front flow that descends from middle to low levels. Both airstreams are of dynamical and structural importance to the MCS itself; the ascending front-to-rear flow distributes hydrometeors into the stratiform region from the leading convective region, and the rear-to-front flow (or rear-inflow jet) is heavily influenced by the TSR itself and may directly impact the surface cold pool. The connection between the rear-inflow jet (RIJ) and surface cold pool is one way that the TSR and its associated dynamics may have a marked effect on MCS motion.

Past studies have shown that convective momentum transport (CMT) within an MCS may have implications for operational forecasting through its impact on both MCS motion (e.g., Mahoney et al. 2009) and surface wind gusts (e.g., Geerts 2001). The specific processes most important to both of these phenomena are (i) the vertical advection of the storm perturbation wind, (ii) the vertical advection of the background wind, and (iii) the pressure gradient acceleration associated with the midlevel area of lower pressure. The dynamics, intensity, and spatial extent of the TSR drive the vertical heating profile and buoyancy field there, and thus also largely determine the local vertical motion and perturbation pressure fields. Therefore, it is reasonable to expect that for gust-front-driven MCSs with stratiform regions of varying spatial extent and intensity (or in which different dynamic and thermodynamic processes are emphasized), differences in the low-level momentum field are likely to be realized at the surface. By affecting winds in the leading edge of the surface cold pool, these differences may impact the speed at which the entire system moves as well.

CMT may also be an important mechanism in the generation of extreme thunderstorm wind gusts. While the majority of past studies investigating the causes of severe surface winds have focused on the classic downburst model driven by surface divergence (e.g., Fujita 1985; Wakimoto 2001), some studies have acknowledged the likely influence of the vertical transfer of horizontal momentum (e.g., Brandes 1977; Johns and Doswell 1992; Weisman 1992; Geerts 2001). However, its contribution to wind gusts beneath thunderstorms remains poorly understood.

As Geerts (2001) points out, the literature on strong, convectively-generated surface winds rarely mentions the downward transport of horizontal momentum as a contributing process, despite a number of studies that have found it to be a key driving mechanism (e.g., Eilts and Doviak 1987; Weisman 1992; Orf and Anderson 1999). While some studies of derechoes have mentioned CMT, the summary of windstorm-producing mechanisms in Wakimoto (2001) (in addition to many other summarizing accounts) focuses mainly on thermodynamic and pressure perturbation influences on the downdraft itself. That is, vertical advection terms remain on the left-hand-side of the vertical momentum equation and are thus neglected as potential contributors to horizontal wind gusts, and the horizontal momentum equation is omitted entirely from many of these discussions. It is conceivable that in many cases, strong surface winds may not necessitate an especially intense downdraft itself, provided that strong winds from aloft are brought far enough surface-ward by moderate or even relatively weak downward motions.

Geerts (2001) incorporated CMT of ambient winds into an existing surface wind gust prediction index and found forecast improvements. However, Mahoney et al. (2009) found the transport of ambient momentum to be of secondary significance to the storm-induced perturbation flow; a similar analysis is made by Weisman (1992) as well. Thus, a more complete integration of the CMT physical processes (i.e. pressure gradient acceleration of mid-level winds and the vertical advection of both the ambient and storm-induced winds) into the forecast framework may be beneficial.

This study assesses the degree to which MCS speed and surface wind gusts are altered by varying microphysical processes and environmental humidity in the TSR. An additional goal of this research is to identify environmental signals that may be of utility to operational forecasters with respect to CMT, MCS motion, and surface wind gust prediction.

## 2. METHODOLOGY

The WRF model is used in a quasi-idealized framework as detailed by Mahoney et al. (2009). This approach is used to produce a control (CTRL) simulation and four sensitivity simulations as described by Table 1.

| Simulation | |
|---|---|
| CTRL | As in Mahoney et al. (2009), except WSM6 microphysics. |
| DRYM | Mid-levels dried by ~25% following Yang and Houze (1995).<br>Modified sounding shown in Fig. 1b. |
| REVP | Evaporation reduced by 75% in WSM6 microphysics scheme |
| NMLT | Melting removed in WSM6 microphysics scheme |
| NSUB | Sublimation removed in WSM6 microphysics scheme |

Table 1. Sensitivity simulation details

A similar methodology is used by Yang and Houze (1995), in which microphysical processes and environmental humidity are varied in two-dimensional simulations with the goal of determining whether the RIJ is determined more by environmental factors or by physical processes internal to storm. While differences in speed were identified in their simulations, neither this nor surface windspeed magnitude were the focus of the study and were not examined. Here, we implement a similar methodology but use a three-dimensional real-world modeling framework and center our analysis around the role of environmental humidity and microphysical processes in altering MCS motion and surface windspeed, and role of CMT (if any) of doing so.

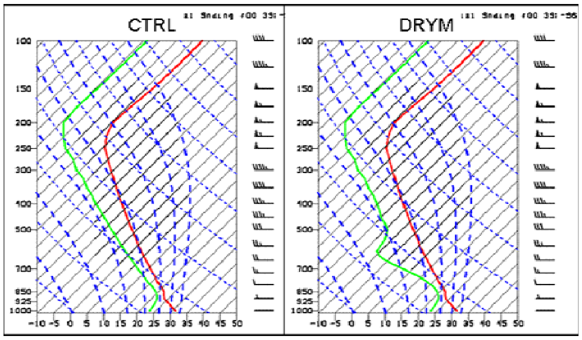

Figure 1. Initial sounding shape (at 39° N, 96°W) used to initialize the CTRL simulation (left) and DRYM simulation (right). Temperature (°C, red line), dewpoint (°C, green line), wind barbs in knots at right.

## 3. RESULTS

Differences in MCS representation and motion between the five simulations can be seen in Fig. 2. The DRYM and REVP simulations show the largest differences relative to the CTRL simulation with respect to overall MCS structure and motion, while differences are evident, but more subtle, in the NMLT and NSUB simulations. The major focus of this manuscript will be on the DRYM simulation.

### *a) DRYM*

#### *i) MCS motion*

The DRYM storm is smaller in size to CTRL but maintains a similar ratio of convective to stratiform area. Marked differences in storm motion are also evident in the more eastward movement of DRYM. In order to understand the cause of these differences in system motion, we ask: *Are the MCS motion changes mainly cold pool intensity-driven, dynamically/CMT-driven, or both?*

To answer this question, the speed at which the system moves is calculated and compared to both the theoretical cold pool speed ($c^1$) and the evolution of the CMT tendency (averaged over a 2-km-deep volume that trails the leading convective line by 120 km) (Fig. 3).

---

[1] $c = \left[ -2g \int_0^H \left(\frac{\theta'}{\theta_0}\right)_{coldpool} \right]^{1/2}$

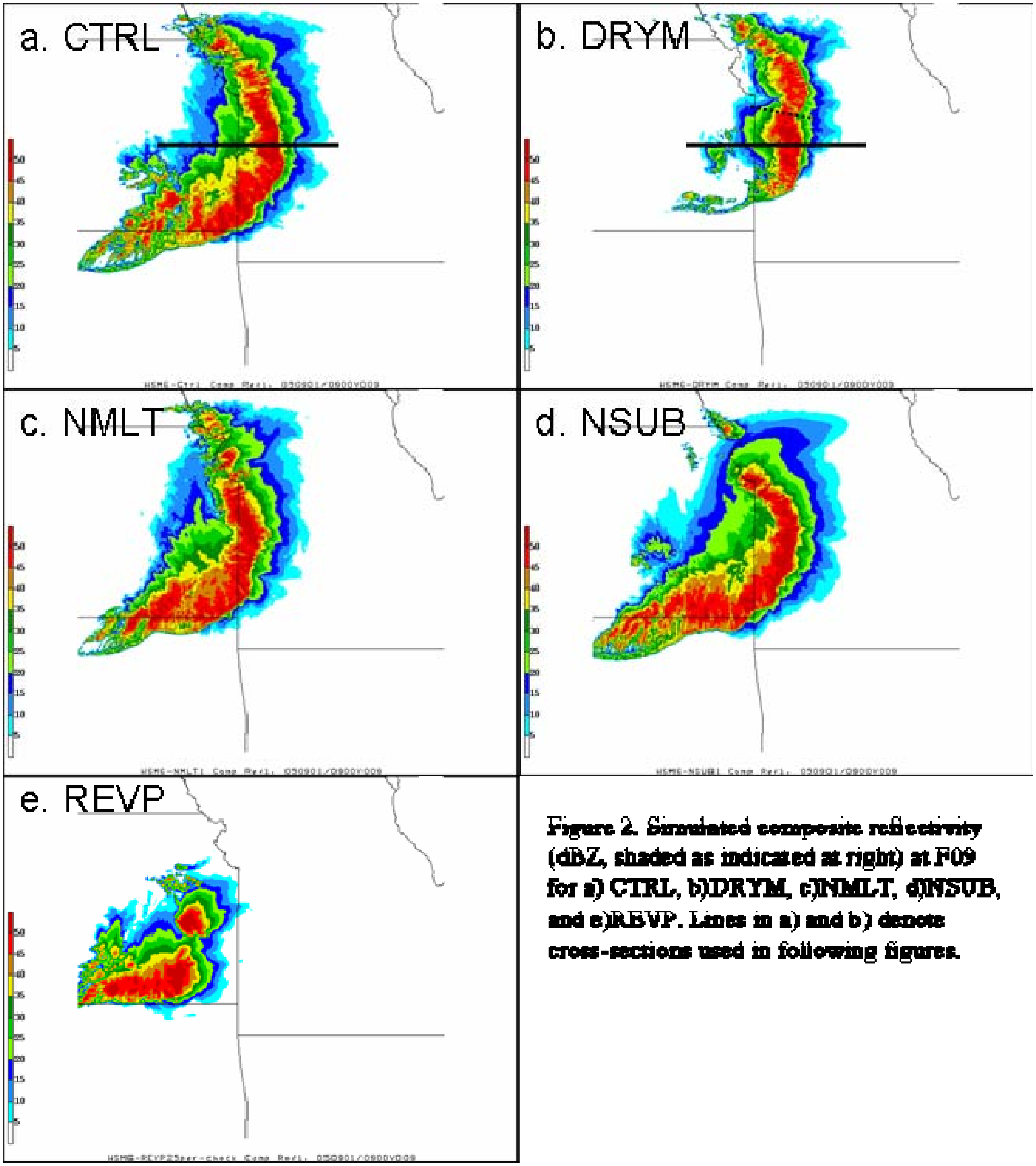

Figure 2. Simulated composite reflectivity (dBZ, shaded as indicated at right) at F09 for a) CTRL, b)DRYM, c)NMLT, d)NSUB, and e)REVP. Lines in a) and b) denote cross-sections used in following figures.

Both the CTRL and DRYM systems accelerate during the simulation, with DRYM moving faster than CTRL at first, but becoming slightly slower by the end of the simulations (Fig. 3a). The theoretical cold pool speed, *c*, is not an especially good predictor of MCS motion for either system, especially in developing/early mature stages (Fig. 3a,b). While it is known that this expression often does not match the true surface speed of the cold pool and MCS, and that the theoretical speed based on density within the cold pool alone may over-estimate the actual cold pool speed by as much as 100% (e.g., Bryan and Rotunno 2008) we use it here establish a general estimate of theoretical cold pool speed, and as a baseline indicator for times of cold-pool-driven acceleration and deceleration.

The CMT tendency remains positive in lower levels just to the rear of the cold pool for both the CTRL and DRYM simulations (Fig. 3c). The tendencies are of comparable magnitude for both CTRL and DRYM, despite CTRL being a stronger system with respect to updraft strength and cold pool intensity.

From these images, as well as earlier findings such as those in Mahoney et al. (2009), CMT is likely important in both simulations, but its significance may be even more marked in early/developing stages in DRYM, when the calculated cold pool speed *c* actually decelerates yet the MCS accelerates. Figure 4 shows the enhanced downward motion in the DRYM simulation that likely leads to enhanced CMT despite a weaker MCS.

Further support for the importance of CMT during developing stages of the MCS is that DRYM possesses a weaker cold pool than CTRL from F05 – F07, yet maintains a faster translational speed during this period.

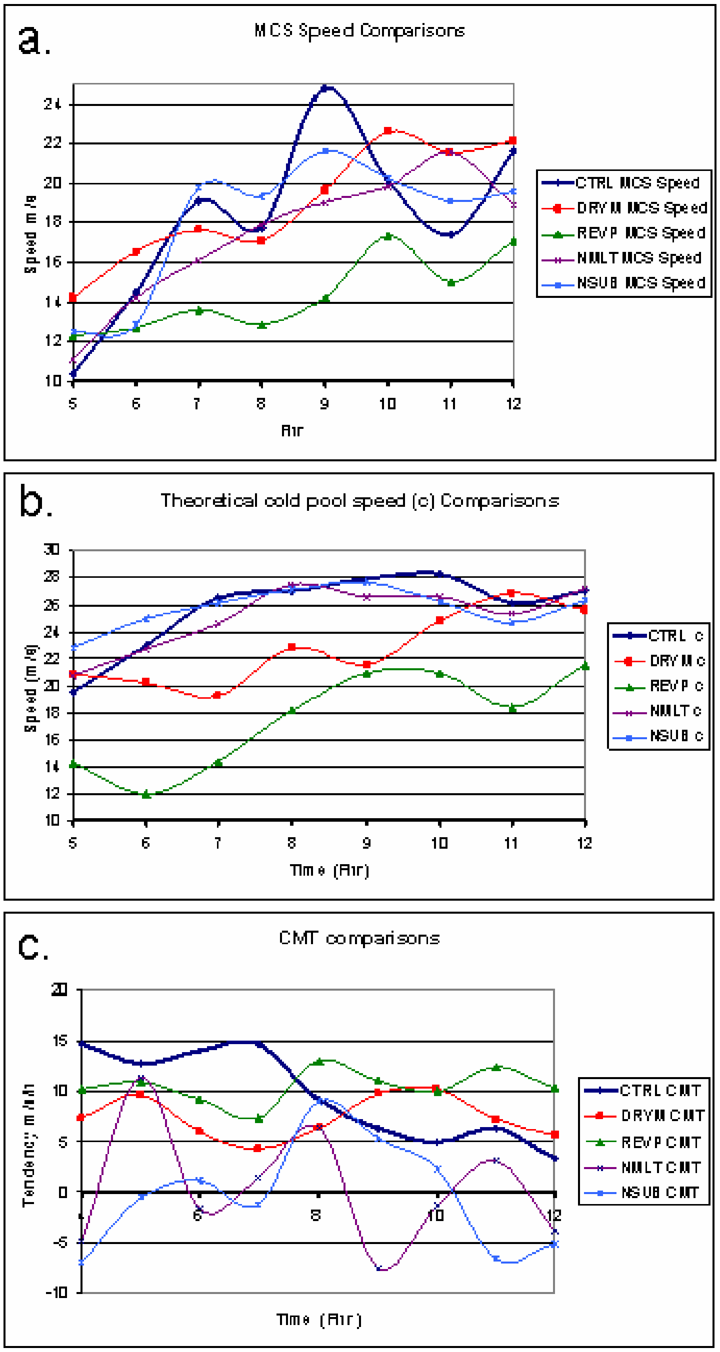

Figure 3. Comparison of all five simulations a) speed of MCS (ms$^{-1}$), b) theoretical cold pool speed c (ms$^{-1}$), and c) CMT tendency (ms$^{-1}$h-1). Note that CMT is shown as a tendency, not to be compared directly with speeds in panels a and b.

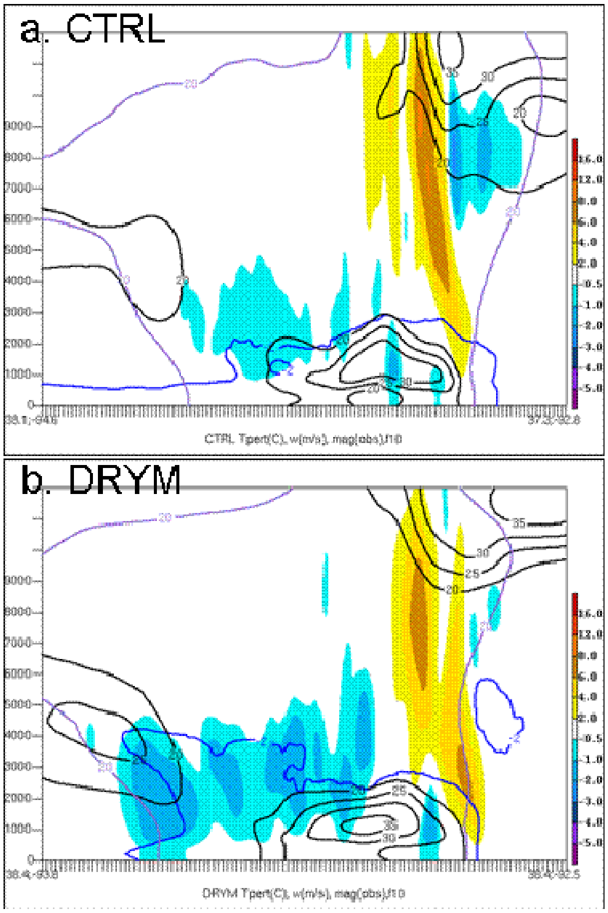

Figure 4. Vertical cross-section shown by solid lines in Fig 2a and 2b respectively of vertical velocity (shaded as indicated at right), and the isotachs (ms$^{-1}$, every 5ms$^{-1}$ beginning at 20ms$^{-1}$, black contours) Enhanced downward motion, u wind in DRYM despite weaker system.

While other processes are clearly at work in altering the actual MCS speed and the theoretical cold pool speed in DRYM (most notably the thermodynamic enhancement of the cold pool via increased cooling from evaporation into the mid-level dry air), the role of CMT likely remains significant throughout both simulations. In fact, the relative importance of CMT in developing stages of the CTRL simulation is still large as well, while cold pool processes appear to better explain MCS motion for each system at later times. This may be due to the time required to establish a mature cold pool thermodynamically, versus more immediate effect of CMT kinematically increasing wind speeds in the leading edge of the surface cold pool.

Despite the significance of the CMT process in determining MCS motion, changes in system speed due to increased CMT in a drier midlevel environment may have relatively limited relevance to the operational forecasting community. While CMT contributes significantly to system speed in both the CTRL and DRYM simulations, it is not immediately clear how to best incorporate the alteration of MCS speed into a forecasting framework; further work will have to be done on a larger set of storm environments to refine its utility. However, a comparison of low-level wind speeds in the two simulations may reveal implications for surface wind gust prediction. This may be of particular interest to operational forecasters and is discussed below.

### *ii) Surface wind speeds*

An estimate of severe surface wind speed incidence is obtained by normalizing the number of severe wind "reports" (i.e., an occurrence of windspeed > 25.7ms$^{-1}$ at any grid point) by storm area (i.e., the number of grid points in which simulated composite reflectivity exceeds 30dBZ). The first two fields in Fig. 5 show that the DRYM simulation produces more than four times the number of severe surface windspeed "reports" than the CTRL simulation.

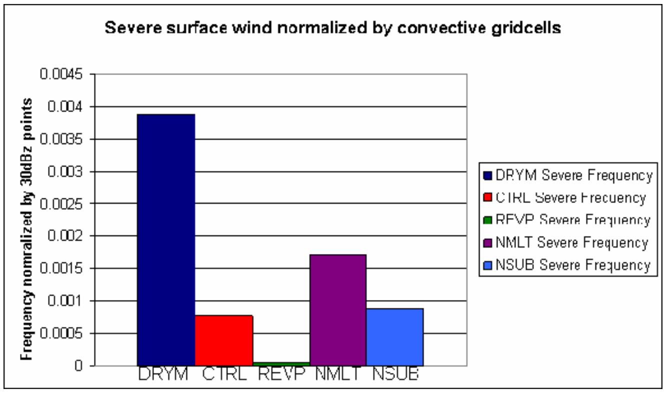

Figure 5. Comparison of the occurrence of severe surface winds (>25.7ms$^{-1}$) normalized by storm area.

A closer examination of the processes leading to areas of wind speeds in excess of 25.7ms$^{-1}$ reveals that many such areas do not appear to be linked to buoyancy- or thermodynamically driven downdrafts that produce strong horizontal wind speeds via divergence upon surface impact. Instead, many of the spatially-larger areas of severe wind speeds are linked to maxima of downward CMT (Fig. 6). While data of higher temporal resolution is necessary to more completely diagnose the mechanisms and sequence of events that result in the severe surface winds, a linkage as in Fig. 6 indicates a potentially important contribution from CMT in driving enhanced surface wind speeds.

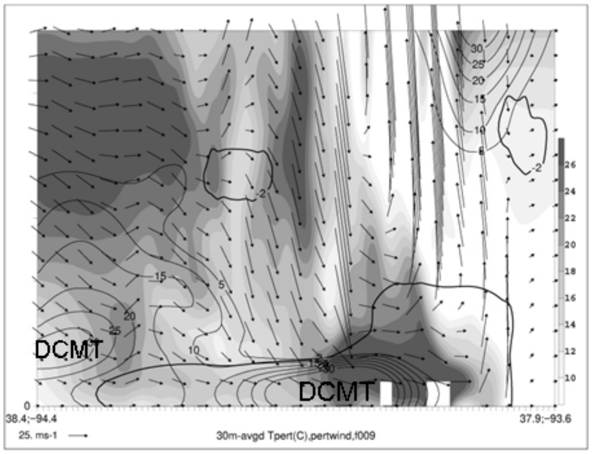

Figure 6. DRYM cross-section at F09 (shown by dashed line in Fig. 2b), magnitude of wind ($ms^{-1}$, shaded), downward-directed CMT ("DCMT"), ($ms^{-1}h^{-1}$, solid contours), cold pool outline T=-2°C (thick black contour), black arrows show ground-relative flow in the x-z plane scaled as shown by reference vector in lower left corner.

*b. REVP, NSUB, NMLT simulations*

Figure 2 also compares the reduced evaporation (REVP), no-sublimation (NSUB), and no-melting (NMLT) simulations at F09 to the CTRL and DRYM simulations. Differences in MCS structure and motion are most marked for REVP, as it is a smaller, weaker, and more southward-moving system.

It is beyond the scope of this particular manuscript to fully analyze the causes of MCS motion changes and severe wind occurrence in these three simulations (REVP, NMLT, NSUB), but preliminary results can be surmised from MCS speed and surface wind speeds (Figs. 3 and 5). MCS speed decreases significantly in response to reducing evaporation, while MCS speed changes are more subtle in the NMLT and NSUB simulation. Across the simulation duration, the NSUB simulation moves at approximately the same speed as CTRL, while NMLT moves an average of ~$1ms^{-1}$ more slowly. These findings suggest that motion changes appear to be linked to decreased CMT for the NSUB and NMLT simulations, while the more dominant effect in REVP is likely the decreased cold pool intensity.

REVP also fails to produce severe surface winds, while the NSUB and NMLT simulations actually produce slightly higher numbers of severe surface winds relative to the CTRL simulation -- but still less than half of those found in DRYM. Early results suggest that the areas of strong surface winds that occur in the NMLT and NSUB developing stages may be driven by more "classic" microburst mechanisms of hydrometeor loading and thermodynamic processes producing strong surface divergence as strong downdrafts intersect the surface. (However, such motions may be the result of unrealistically large concentrations of unmelted/unsublimated, rapidly-descending frozen hydrometeors.) This process is in contrast to the CMT mechanism discussed above for the severe surface winds realized in the DRYM simulation, in which existing stronger horizontal wind speeds are actually brought to the surface instead of forming there due to divergence. The distinction of these processes is a topic of ongoing investigation.

## 4. CONCLUSIONS

This preprint summarizes the results of a series of MCS simulations designed to address the following question: How do MCS motion, CMT, and surface wind speed respond to changes in TSR processes? The following is a summary of preliminary findings:

- When mid-level environmental humidity is reduced, MCS intensity and motion change, but the specific causes of MCS motion differences are subtle. While the direction of motion is different, the magnitude of the ground-speed does not change markedly.
- Despite being a weaker system overall, the DRYM simulation displays comparably large CMT values (relative to the CTRL simulation) due to enhanced downward motion. This appears to at least partially compensate for weaker cold pool forcing during initial storm acceleration. Later in simulation, cold pool forcing is likely the dominant factor in MCS motion, with CMT likely helping to sustain system motion.
- Surface wind speeds are larger in DRYM, and DRYM produces more than twice the number

of severe surface windspeed values per storm area.
- The CMT process brings stronger wind speeds surface-ward, and explains some of the severe surface wind occurrences (i.e., winds in excess of 25.7 ms$^{-1}$) in DRYM, especially during the storm's mature stages.
- MCS speed decreases significantly in response to reducing evaporation, as does system size and intensity. MCS motion changes appear to be largely explained by decreased cold pool intensity. The reduced evaporation simulation also fails to produce severe surface winds.
- MCS speed changes are subtle when melting and sublimation processes are removed. The NSUB simulation moves at approximately the same speed as CTRL, while NMLT moves an average of ~1ms$^{-1}$ more slowly.
- The NSUB and NMLT simulations produce slightly higher frequencies of severe surface winds relative to the CTRL simulation, but still less than half of those found in the DRYM simulation.

CMT appears to have relevance to operational forecasting of MCS motion and severe surface winds. While differences in MCS motion among the simulations presented here may be relatively subtle, the findings may still be of use to forecasters, particularly for storm-term prediction of MCS speed. Future work will aim to integrate knowledge of CMT process into both areas, and explore the potential benefit of incorporating CMT into severe wind forecasting techniques that currently focus on classic thermodynamic and purely downdraft-divergence driven mechanisms.

## 5. ACKNOWLEDGEMENTS

Support for this research was provided by National Science Foundation Grant ATM-0603760, awarded to North Carolina State University. We wish to acknowledge Drs. Matthew Parker, Sandra Yuter, and Anantha Aiyyer for helpful insights and discussions concerning this research. The authors would also like to thank NCAR and the National Science Foundation for the availability of the WRF model.

## 6. REFERENCES

Brandes, E.A., 1977: Gust Front Evolution and Tornado Genesis as Viewed by Doppler Radar. *J. Appl. Meteor.*, **16**, 333–338.

Bryan, G. H., and R. Rotunno, 2008: Gravity currents in a deep anelastic atmosphere. *J. Atmos. Sci.*, **65**, 536–556.

Eilts, M.D., and R.J. Doviak, 1987: Oklahoma Downbursts and Their Asymmetry. *J. Appl. Meteor.*, **26**, 69–78.

Fujita, T. T., 1985: The downburst. SMRP Research Paper 210, University of Chicago, 122 pp. [NTIS PB-148880.]

Geerts, B., 2001: Estimating downburst-related maximum surface wind speeds by means of proximity soundings in New South Wales, Australia. *Wea. Forecasting*, **16**, 261–269.

Johns, R.H., and C.A. Doswell, 1992: Severe Local Storms Forecasting. *Wea. Forecasting*, **7**, 588–612.

Mahoney K. M., Lackmann, G. M., Parker, M. D., 2009: The role of momentum transport in the motion of a quasi-idealized mesoscale convective system. *Mon. Wea. Rev.*, In Press

Orf, L.G., and J.R. Anderson, 1999: A Numerical Study of Traveling Microbursts. *Mon. Wea. Rev.*, **127**, 1244–1258.

Wakimoto, R. M., 2001: Mesoscale convective systems. Severe Convective Storms, Meteor. Monogr., No. 50, Amer. Meteor. Soc., 255–298.

Weisman, M. L., 1992: The role of convectively generated rear-inflow jets in the evolution of long-lived mesoconvective systems. *J. Atmos. Sci.*, **49**, 1826–1847.

Yang, M.H., and R.A. Houze, 1995: Sensitivity of Squall-Line Rear Inflow to Ice Microphysics and Environmental Humidity. *Mon. Wea. Rev.*, **123**, 3175–3193.

---

[+] *Corresponding author address:* Kelly M. Mahoney, North Carolina State University, Dept. of Marine, Earth and Atmospheric Sciences, Raleigh, NC 27695. E-mail: kmmahon2@ncsu.edu