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THE SENSITIVITY OF SQUALL LINE MOTION TO ENVIRONMENTAL CHANGES IN 3D QUASI-IDEALIZED WRF SIMULATIONS

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

1. INTRODUCTION

The study of mesoscale convective systems (MCSs) is motivated by theoretical questions regarding their formation, movement and dynamics, and also by the high-impact weather that these complex systems often produce. The motion of MCSs in particular is also an important area of study, and one that remains incompletely understood (e.g., Corfidi 2003; Houze 2004). The mechanisms for MCS motion that are most frequently cited in the literature include (i) cold pool dynamics, (ii) gravity waves, and (iii) potential vorticity anomaly propagation (e.g., Raymond and Jiang 1990). However, other processes and influences that are less frequently discussed likely exist as well. For example, the influence of synoptic-scale dynamics is also a significant factor in MCS formation and motion (e.g., Bélair and Zhang 1997; Fritsch and Forbes 2001), but comparatively fewer studies focus on that mechanism with respect to MCS speed specifically. One specific physical process that may also contribute to MCS motion is that of the downward transport of strong zonal momentum aloft toward the surface. While previous studies have examined the process of downward momentum transport for other applications (e.g., derechoes, feedback to the large-scale momentum budget), its explicit contribution to MCS motion seems to be somewhat less frequently discussed. This preliminary study will focus on this mechanism in particular.

Aside from questions concerning the physical processes that drive MCS motion, the forecasting of MCSs by numerical weather prediction (NWP) models is also complex, and has long represented a major challenge to both the research and operational forecasting communities (e.g., Zhang et al. 1994; Wang and Seaman 1997). The movement of these high-impact weather systems is often influenced by both synoptic- and mesoscale processes, and this merging of scales is known to pose a significant challenge to NWP models. Yet despite the importance of the interaction of processes on different temporal and spatial scales, most early modeling investigations of MCSs consider these two scales separately by using 2D idealized models at higher (mesoscale) resolution, or by using 3D full-physics models that looked at larger-scale features. A shortcoming of the former is that the omission of the Coriolis force and thermal stratification of the initial environment precludes a realistically-evolving synoptic environment, and of the latter, that some mesoscale processes are not adequately resolved. The interplay that may occur by combining these two approaches remains comparatively uninvestigated (e.g., Jewett and Wilhelmson 2006).

In this study we seek to blend these approaches into a "pseudo-idealized" framework in order to explore a range of mechanisms for midlatitude MCS motion. Specifically, the following hypotheses are investigated:
(i) Varying synoptic-scale environmental parameters (e.g. mean wind, moisture) may vary the relative importance of the main processes (e.g., cold pools, gravity wave propagation, etc.) responsible for mid-latitude squall lines motion.
(ii) All else being equal, stronger westerly flow aloft will increase MCS and/or cold pool speed via the downward transport of higher-momentum air.

[+] *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

2. METHODOLOGY

In order to examine an MCS that is simplified but also develops in a realistically-evolving surrounding environment, a combination of real-case and idealized modeling techniques are utilized. This combination benefits from the lucidity of idealized simulations by using simplified initial conditions that remove complicating, irrelevant environmental features found in observations, while still accounting for the influence and evolution of a surrounding baroclinic environment (an element largely ignored by many purely-idealized modeling studies of the past). This approach also retains a more realistic treatment of the larger-scale environment characterized by thermal wind balance and accounting for the influence of the Coriolis force; a recent paper by Jewett and Wilhelmson (2006) also discusses the advantages of such a framework.

In order to perform these pseudo-idealized simulations, initial conditions were generated from empirical relationships such that a simple westerly jet stream is present in an environment of convective instability, with a horizontal wind field constrained by thermal wind balance. Figure 1 shows the height and wind fields of the initial state in the x-y plane as well as in a north-south vertical cross-section, and Fig. 2 shows the initial sounding shape. This sounding was produced by adapting the sounding used in Weisman and Klemp (1982) to incorporate characteristics of MCS environments noted in later, observationally-based studies (e.g., Bluestein and Jain 1985; Houze et al. 1990; Parker and Johnson 2004). These modifications include drying upper levels by 10% from their original relative humidity value, and also adding a temperature cap in order to prevent excessive convection in the initially-unstable atmosphere. Vital to maintaining thermal wind balance, the entire sounding is uniformly nudged to be cooler as latitude increases; in this way, the initial conditions more realistically represent the large-scale environment (relative to earlier ideal studies in which a single uniform initial sounding was often used). The convection is triggered by a 2.5°C warm bubble located below the 800-hPa level.

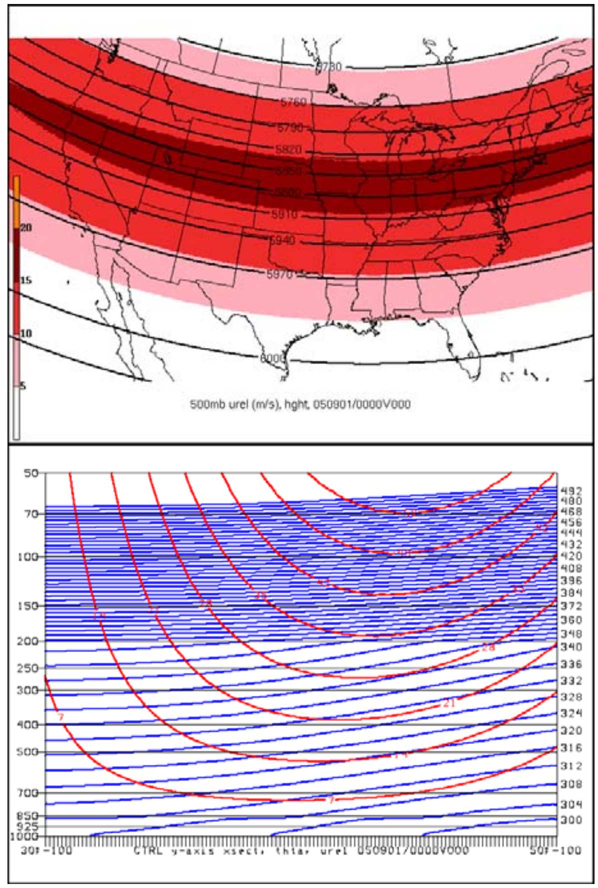

Figure1. Initial background state for idealized MCS simulation. (top) 500-hPa geopotential height (black contours), and u-wind (filled). (bottom) North (right) - South (left) cross-section, isentropes (K, blue contours) and isotachs (knots, red contours)

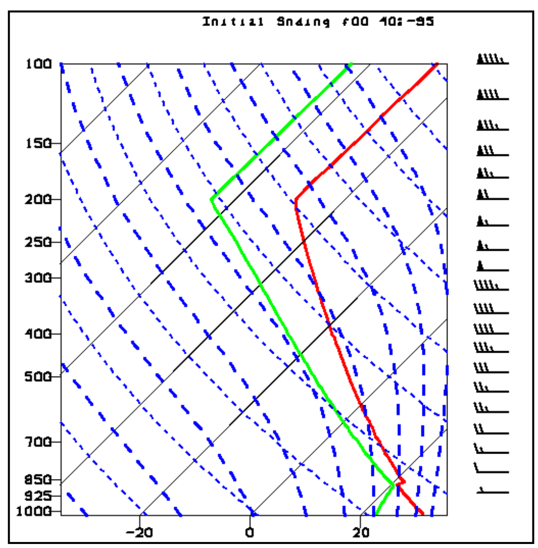

Figure 2. Initial sounding used to initialize the pseudo-idealized MCS simulation. Wind barbs in knots at right.

These initial conditions were then simplified further to remove terrain and landuse variation; thus, the entire model domain is flat and consists of "savanna" landuse (one of the predominant landuse categories found in the east-central US). These input files were then used by the 3D "real" WRF model to generate an MCS that possesses many of the features observed to be important in observed cases. The details of the WRF model setup for the control run (CTRL, hereafter) presented here are:

- 00 UTC initialization; run out 12 hours; output every 5 minutes
- 4-km grid spacing
- 450x450 gridpoint domain
- 31 vertical levels
- Explicit convection (no CP scheme)
- Lin microphysics
- YSU planetary boundary layer (PBL) scheme
- Dudhia shortwave radiation and RRTM longwave radiation
- Noah land surface model
- Initial conditions on World Meteorological Organization (WMO) 218 grid, with 12-km grid spacing

In order to examine the changes that result due to changing the large-scale environmental parameters, another simulation was produced in which the background wind speeds were increased (by approximately 50%). This simulation will be referred to as "FAST".

3. QUASI-IDEALIZED SIMULATION COMPARISON: CTRL VS. FAST

Figure 3 illustrates the simulated radar reflectivity field of CTRL and FAST at hour 09 (F09). Both systems evolve into a quasi-linear MCS structure exhibiting a leading intense convective line, with a small region of lighter, trailing precipitation, reflecting the archetypal "leading convective-trailing stratiform" MCS structure (e.g., Newton 1950; Houze et al. 1990). The FAST simulation is spatially larger, and moves faster (~17 m/s vs. 30m/s for CTRL and FAST, respectively.)

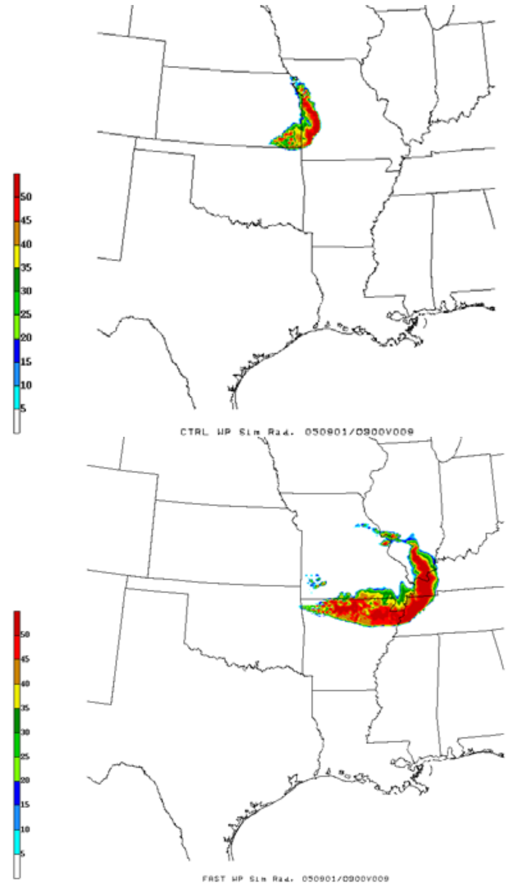

Figure 3. Simulated base reflectivity for CTRL pseudo-idealized simulation at F09.

Near-surface temperature perturbation quantities are shown in Fig. 4, in order to illustrate changes in the surface cold pool; the cold pool in the FAST simulation is deeper and colder relative to the CTRL simulation, consistent with the findings of studies such as Rotunno et al. 1988.

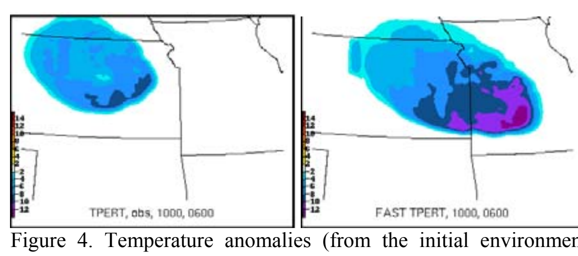

Figure 4. Temperature anomalies (from the initial environment) at 1000hPa, F06 for (a) CTRL and (b) FAST

Cross-sections through the MCSs at F09 are shown in Fig. 5. The positive u' field outlined in solid purple contours shows the area of the largest perturbation *u*-winds, and the vectors illustrate the flow in the *x*-*p* plane, in a storm-relative sense. From this depiction, the rear inflow jet (RIJ) signature is apparent in both simulations as descending flow from the rear of the system, into the cold pool, and the expected front-to-rear flow is also apparent as storm-relative winds extending east-to-west from above 500 hPa in the convective region. Strong convergence is also found at the leading edge of the cold pool. This, in addition to the pressure perturbation field (not shown) is consistent with the hydrostatic response to a convective heating maximum overlying a surface cold-pool, and the associated acceleration of the rear-to-front and front-to-rear flow matches the findings of many past studies, such as Lemone (1983), Zhang et al. (1989), and Yang and Houze (1996).

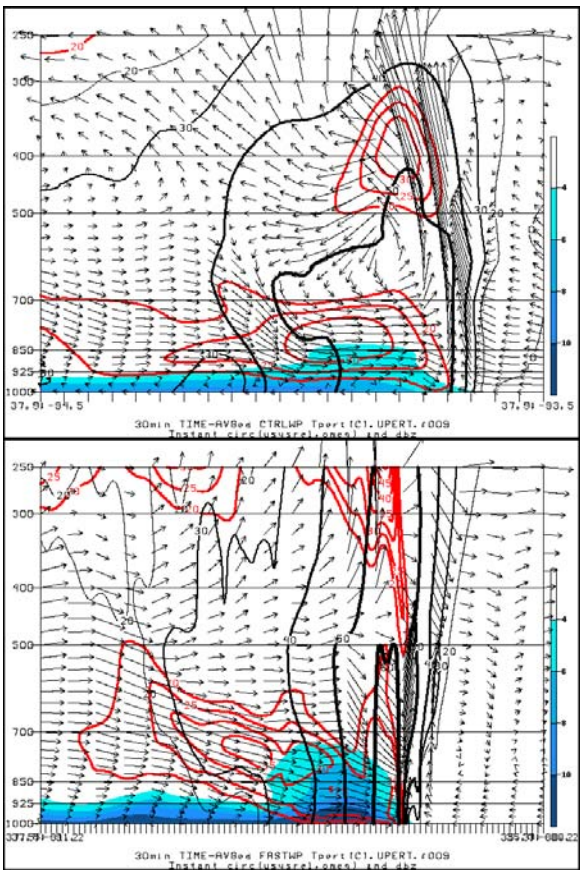

Figure 5. East-west cross-section through the leading edge of the MCS. Cold pool (T' < -4°C filled in blue, as in color bar to right), magnitude of wind perturbation (m/s, contours every 5m/s beginning at 20m/s), and simulated reflectivity (dBz, black solid contours, every 10 dBz beginning at 20 dBz). Black arrows show storm-relative flow along cross-section in the x-z plane. Data have been time-averaged over a 30-minute period.

Figure 5 also illustrates differences in the location of the strongest perturbation westerlies; while the area of enhanced westerlies remains slightly elevated above the cold pool in the CTRL simulation, the FAST simulation reveals stronger values of u′ near the surface (just behind the leading edge of the cold pool), in addition to in the descending RIJ as well (around 700mb). The descending rear-to-front flow vectors also illustrate these differences, as the FAST simulation's circulation vectors show a larger downward component and a more direct feed into the cold pool, relative to the CTRL simulation's rear inflow that remains more elevated above the cold pool.

A momentum budget was computed for both simulations in order to further illustrate these differences, and also toward the ultimate goal of quantifying the effect of vertical momentum transport on MCS motion. The momentum budget is based on the methodology of Mechem et al. 2006, and calculates the following terms from the u-momentum equation:

$$\underbrace{\frac{\partial u}{\partial t}}_{TEN} = \overbrace{\underbrace{-u\frac{\partial u}{\partial x}}_{UHA} \underbrace{- v\frac{\partial u}{\partial y}}_{VHA}}^{HA} \overbrace{\underbrace{- \omega\frac{\partial \bar{u}}{\partial p}}_{VA\bar{U}} \underbrace{- \omega\frac{\partial u'}{\partial p}}_{VAU'}}^{VA} \underbrace{+ fv}_{COR} \underbrace{- \frac{\partial \phi}{\partial x}}_{PGF} \underbrace{+ R}_{RES},$$

where u = the total u-wind, $\bar{u}$ = the background wind field (i.e. u at F00), u' is the perturbation u-wind, defined as $u' = u - \bar{u}$, and ϕ is the geopotential height. The terms in (3.1) can be described as: the local u-wind tendency (*TEN*), the horizontal advection by the u-wind (*UHA*), the horizontal advection by the v-wind (*VHA*), the vertical advection of the background u-wind field $\bar{u}$ ($VA\overline{U}$), the vertical advection of the perturbation u-wind field u' (VAU'), the Coriolis force (*COR*), the pressure gradient force (*PGF*), and the residual (*RES*) [or "subgridscale effects," as termed in Mechem et al. (2006)]. *HA* and *VA* describe the total horizontal and vertical advection fields, respectively.

Figure 6 reveals that the vertical advection (VA) term is qualitatively similar in each simulation, but that there exist some differences in the location of the VA term maxima. In the FAST simulation, the maximum located above and slightly ahead of the cold pool is not as large as in the CTRL run; however, within the trailing stratiform region, where the descending rear-to-front flow branch is observed in Fig. 5b, the VA term is approximately double the magnitude relative to the CTRL simulation. Combined with the differences in the rear-to-front flow branch noted in Fig. 5, this suggests that the effect of vertical momentum transport varies according to the behavior of the RIJ – a factor that may largely be a byproduct of the large-scale environment (e.g., Weisman 1992). These differences will be the focus of ongoing investigation.

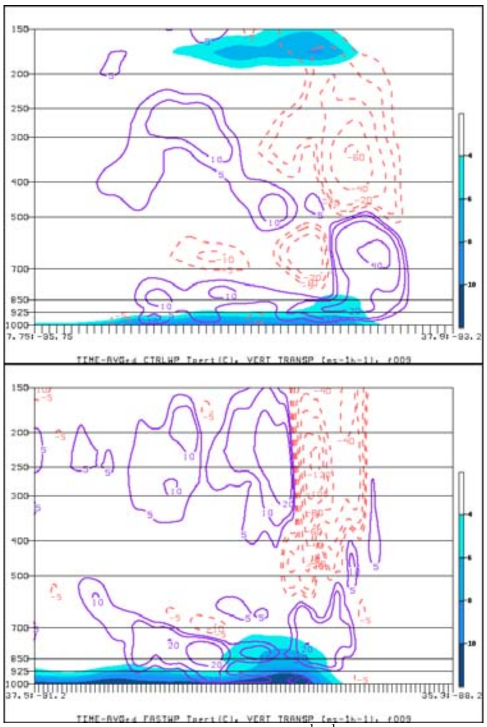

Figure 6. Vertical advection terms (ms^{-1}h^{-1}) for (top) CTRL and (bottom) FAST simulations.

4. PRELIMINARY CONCLUSIONS AND FUTURE WORK

This preprint summarizes the results of an initial investigation into the effect of vertical momentum transport on MCS motion in varying large-scale flow, and the isolation of this effect by utilization of a quasi-idealized WRF model framework. The following is a summary of preliminary findings:

- Vertical momentum transport is a non-negligible process in the determination of the momentum budget of an MCS, and likely contributes to its forward motion.
- The contribution of vertical momentum transport to MCS motion may differ according to the synoptic environment, and whether the RIJ descends to the surface or remains elevated.
- The quasi-idealized model environment is a useful testbed for investigating the hypotheses explored here. The advantages of an easily-defined base-state and elimination of the full detail of observed case simulations, combined with the realism of a background environment in thermal wind balance, provide a framework in which the dynamics and evolution of the MCS and its surrounding environment may be simultaneously examined.

Research is ongoing to explore these preliminary findings in much more detail. One component of this future research will also assess the impact of the neglect of momentum transport in model CP schemes (as many operational CP schemes either neglect the process, or implement an over-simplified parameterization). From these initial results it appears that the omission of this process may lead to a negative bias in the forecasted forward speed of a model MCS if such a scheme is employed. The quasi-idealized modeling approach will allow for methodical hypothesis-testing in this regard.

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