3.3 THE RESPONSE OF SIMULATED NOCTURNAL CONVECTIVE SYSTEMS TO A LOW-LEVEL JET

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1. INTRODUCTION

Warm season precipitation has long been observed to exhibit a nocturnal maximum over the central United States, attributed to a preponderance of nighttime thunderstorms and mesoscale convective systems (MCSs) that cross the region (e.g. Wallace 1975; Maddox 1980). Recent work by Parker (2008, hereafter P08) has elucidated some of the dynamical processes at work within these nocturnal systems using idealized numerical simulations. In the interest of isolating these fundamental dynamics, these simulations utilized a simple, 2-D linear wind profile representative of an environment favoring strong MCSs. This, however, neglected a common feature found in nocturnal MCS environments: the nocturnal low-level jet (LLJ, e.g Maddox 1983; Cotton et al. 1989). In light of this, the present work looks to build upon the results of P08 to include the effects of a simulated nocturnal LLJ on elevated convection.

2. BACKGROUND

The LLJ has a long-standing association with warm-season precipitation in the central United States, particularly thunderstorms. It is recognized as a source of unstable air for convective storm development, largely through the advection of warm, moist air from the Gulf of Mexico into regions where storms develop (Maddox 1983; Cotton et al. 1989). These effects can be especially significant for nocturnal convection or storms that form and the cool side of frontal boundaries, as this LLJ-supplied high-θ_e air tends to be elevated. This provides a source of unstable air upon which storms can be sustained despite a stable boundary layer (e.g., Trier et al. 2006).

In addition to helping to prime the convective environment, the LLJ can be a significant forcing mechanism for long-lived convective systems, especially when the jet intersects a frontal boundary (e.g., Augustine and Caracena 1994). As the jet intersects the frontal boundary, convergence and frontogenetic forcing are enhanced, providing a lifting mechanism for storms (Trier and Parsons 1993; Trier et al. 2006; Tuttle and Davis 2006). As a forcing mechanism, the intensity of the jet has as a significant effect on storm intensity, with stronger jets being associated with heavier rainfall (Arritt et al. 1997; Tuttle and Davis 2006).

Missing from this collection of previous work is a discussion about how the development of the nocturnal jet may effect pre-existing convection, i.e. storms that have formed during the afternoon and continue into the overnight hours as the boundary layer stabilizes and the LLJ develops. Possible effects in this realm include changes in the vertical wind shear profile and modulations of the storm-relative inflow. Rotunno et al. (1988) developed a theory for squall line intensity and longevity based on a balance between the low-level shear and cold pool strength. As such, understanding the effect that the LLJ has on vertical shear could be important to better understanding the evolution of nocturnal convective systems. Additionally, Gale et al. (2002) suggested that a key determinant of nocturnal MCS dissipation is the strength of the elevated storm relative inflow (ESRI), with a decrease in this inflow leading to storm dissipation. Given that the LLJ tends to reside in or around the layer of ESRI, it may play a significant role in modulating the strength of this inflow. The present works looks to examine these effects using idealized numerical simulations.

3. METHODS

This work utilized 3D idealized numerical model simulations using version 1.10 of the Bryan cloud model (CM1) described by Bryan and Fritsch (2002). These simulations followed the setup described in P08, and the reader is referred to that publication for the specific details of the model configuration.

In order to study the effects of a low-level jet on nocturnal convective systems, it was of interest to include a low-level stable layer to represent the noc-

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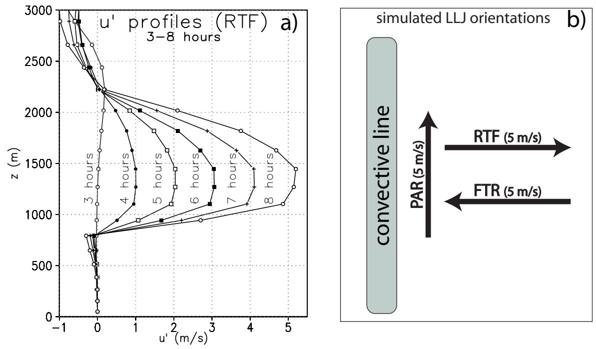

Figure 1: a) Time-series of perturbation u-wind profiles illustrating the development of the simulated LLJ. (b) Schematic illustrating the different LLJ orientations. The wind profiles in (a) are from the rear-to-front (RTF) simulation, however the front-to-rear (FTR) orientation has an identical shape, but of opposite sign.

turnal environment. This was handled using the method of P08. A surface-based MCS was initiated using a warm (+ 2 K) line thermal, and allowed to mature through 3 hours. At this point a nocturnal stable layer was gradually introduced to the model by applying a cooling rate to the lowest 1 km of the simulated environment for the duration of the simulation. The resultant evolution simulates the transition from afternoon, surface-based convection to a nocturnal, elevated MCS akin to the "deep-unlim" simulation of P08.

The other necessary component for this study was the gradual addition of a jet structure to the low-levels of our simulation. Based on the results of past climatological studies, we chose to use a jet that was 5 ms^{-1} stronger than the background winds, approximately 1 km deep, with the level of maximum winds located just above the top of the nocturnal stable layer (e.g Bonner 1968; Mitchell et al. 1995; Whiteman et al. 1997). This jet was added to the wind profile in concert with the low-level cooling, gradually increasing to its maximum intensity by 8 hours into the simulation. This too was based on observations, as in nature the LLJ intensifies throughout the evening, reaching its maximum intensity around 0200 local time (e.g. Whiteman et al. 1997). This results in the perturbation wind profile shown in Fig. 1a by 8 hours into the simulation. It should be noted that while several climatologies (e.g. Bonner 1968; Whiteman et al. 1997) place the LLJ maximum winds at approximately 500 m, we chose to center the jet between 1 and 1.5 km as this was just above the simulated nocturnal stable layer, which is where the jet is typically observed.

For the primary battery of simulations presented herein, the strength of the jet is held constant at 5 ms^{-1} stronger than the background winds, however the direction of the jet is varied. Three different jet directions are examined, relative to the simulated MCS: Front-to-rear (FTR), rear-to-front (RTF), and parallel (PAR) (Fig. 1b). The varied configurations allow us to examine the effect that the direction of the jet has on MCS intensity. For comparison, we ran a control simulation (CTL) that did not include the LLJ, which is identical to the "deep-unlim" simulation of P08. The results of sensitivity tests employing varying jet heights and speeds, as well as simulations run without the low-level cooling will be discussed briefly as well.

4. RESULTS

4.1 Overview

An examination of the CTL, FTR, RTF, and PAR simulations demonstrates a fairly similar evolution through 8 hours of simulation. In each case, an initially surface-based MCS develops and evolves into an elevated MCS in a similar fashion to what was observed by P08 (not shown, the reader is referred to P08 for a detailed analysis of this evolution). This uniformity is maintained between the CTL and PAR simulations for the duration of the simulations, but not for the RTF and FTR simulations. This suggests that the LLJ has the most significant effect in the line-perpendicular direction, and a result, we focus our attention on the RTF and FTR simulations for the the remainder of this paper[1]. After 8 hours (once the LLJ has reached its full intensity) the simulated MCSs in the FTR and RTF cases begin to diverge from the CTL. Plan view plots of simulated radar reflectivity illustrate that by the end of the simulation (10 hours) the RTF case weakens considerably compared to the CTL simulation, while the FTR case is maintained at a similar or slightly stronger intensity (Fig. 2). It is also evident from this analysis that the system speeds in the three simulations diverge during this period, with the RTF simulation exhibiting a faster forward motion compared to the CTL, and while the FTR is slower.

Calculations of total upward mass flux (tmfu) (Fig. 3a) further illustrate the differences in storm intensity, as the FTR simulation features and increase in tmfu over CTL from approximately 4 hours

[1]An additional set of simulations were run utilizing an MCS of finite length rather than the periodic-y configuration shown here. In this case, the line-parallel jet had a more significant impact, intensifying the MCS on the flank upon which the jet was impinging, while weakening the MCS on the opposite flank. These results are discussed in greater detail in a forthcoming publication.

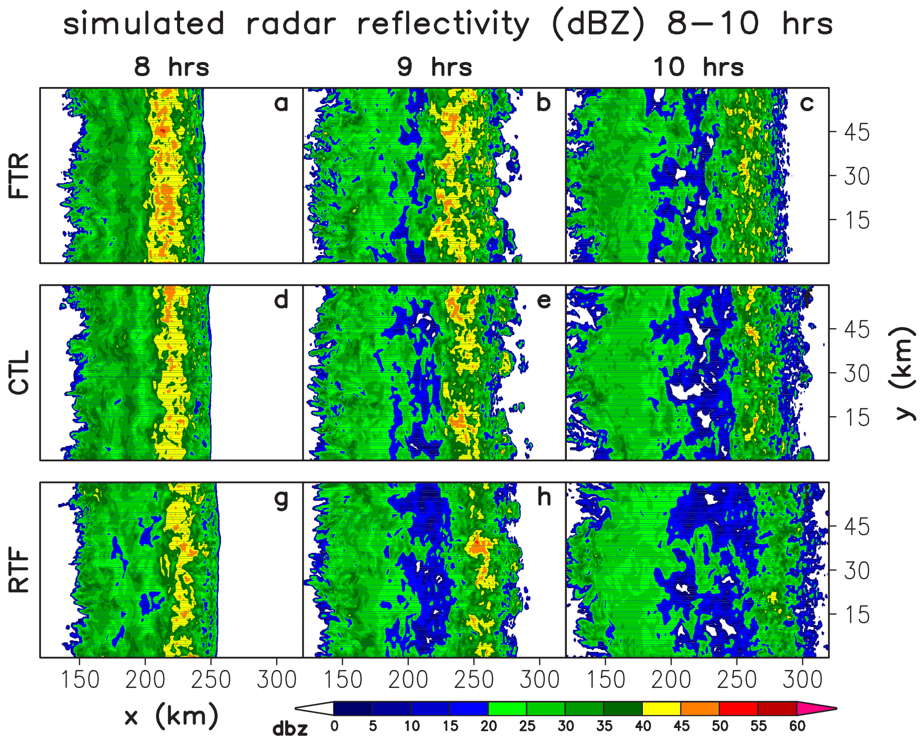

Figure 2: Plan view plots of simulated radar reflectivity (dbz) taken at z = 2 km for the CTL (a,b,c), FTR (d,e,f), and RTF (g,h,i) simulations at 480, 540, and 600 minutes into the simulation.

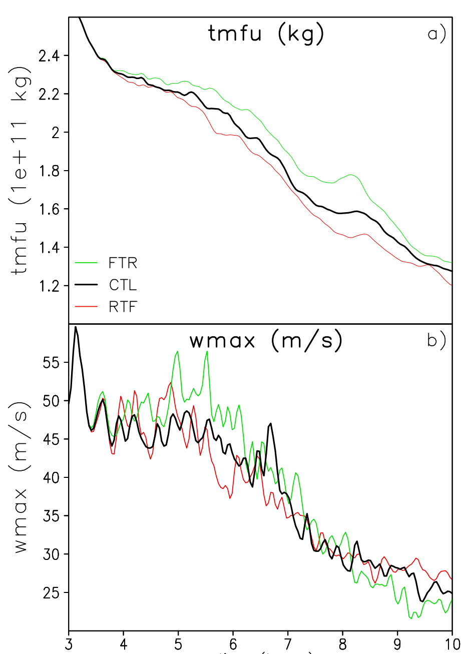

Figure 3: Time series of a) total upward mass flux (tmfu, kg), and b) maximum vertical velocity (wmax, ms^{-1}) from 3-10 hours for the FTR (dashed), CTL (heavy solid) and RTF (thin solid) simulations.

onward, and the RTF simulation a decrease. This implies that more mass is being ingested by the FTR MCS, accounting for the more intense precipitation associated with this simulation, as seen in Fig. 2. However, an analysis of maximum updraft speed (wmax) shows that after approximately 8 hours (again, once the jet has reached maximum intensity) the RTF simulation features a stronger maximum updraft by approximately 5 ms^{-1} compared to the FTR simulation (Fig. 3b). This presents a slight conundrum in terms of evaluating storm intensity, as typically the strongest updraft would be associated with stronger upward mass flux and more intense precipitation. In order to further evaluate this dichotomy, we next analyze the processes at work in these simulations.

4.2 Changes to low-level wind shear

Rotunno et al. (1988) (hereafter RKW) presented a theory for long-lived squall lines that focuses on a balance between the strength of the horizontal vorticity generated by system's cold pool (c) and by the low-level environmental wind shear (Δu). In the "optimal" case, ($c/\Delta u \sim 1$) the vorticity generated by the cold pool is equal in magnitude and opposite in sign to that generated by the vertical shear. The result is a horizontal vorticity balance that produces a vertically oriented updraft, favoring deep lifting that readily transports parcels to their level of free convection (LFC) and thus sustains the convective system. Since the addition of a low-level jet changes the shear profile above and below the jet, it is of interest to examine how these changes in shear will effect updraft tilt in our simulations. This is accomplished by plotting trajectories for parcels that pass through the MCS.

Trajectories launched through the CTL simulation (Fig. 4a) illustrate a reward tilted updraft, indicating that the negative vorticity generated by the bore driving our elevated MCS (left-hand panel of Fig. 4a) is dominating that produced by the environmental shear. In both the RTF and FTR cases, the vertical shear is enhanced below the level of maximum wind in the jet (left-hand panels of Fig. 4b, c). This owes to the prescribed shape of the jet, featuring a rapid increase in wind below the jet max, with a more gradual decrease above. However, the sign of ω_y is important, as it needs to oppose the negative ω_y generated by the bore (for the optimal case). The RTF case features enhanced ω_y of the appropriate sign (left-hand panel of Fig. 4b,) to create a more RKW-optimal situation and favor the deeper, more erect updraft observed in Fig. 4b. In the FTR case, the below-jet ω_y is of the same sign as that generated by the bore, suggesting sub-optimal conditions, which would explain the more dramatic rearward tilt of the updraft seen in Fig. 4c.

Thus the addition of the LLJ does have a significant effect on storm structure and updraft strength. The RTF jet causes an increase in the shear that opposes the bore, with an associated increasingly vertical orientation of the updraft, as RKW theory would suggest. This accounts for the increased wmax seen in the RTF case. However, it does not explain why the FTR case has the larger precipitation output. To investigate this we analyze how the LLJ effects the storm relative inflow.

4.3 Changes to storm relative inflow

In the case of elevated convection, the key to storm longevity is an elevated source of high-θ_e air that provides the inflow to sustain the storm (the ESRI discussed by Gale et al. 2002). A significant feature of the LLJ is that it tends to be located just above the top of a near-surface stable layer, within this layer of high-θ_e air. This characteristic was recreated in our experimental setup (center panels of Fig. 5a, b). By altering the wind field within this zone of unstable air, the LLJ can have a significant effect on

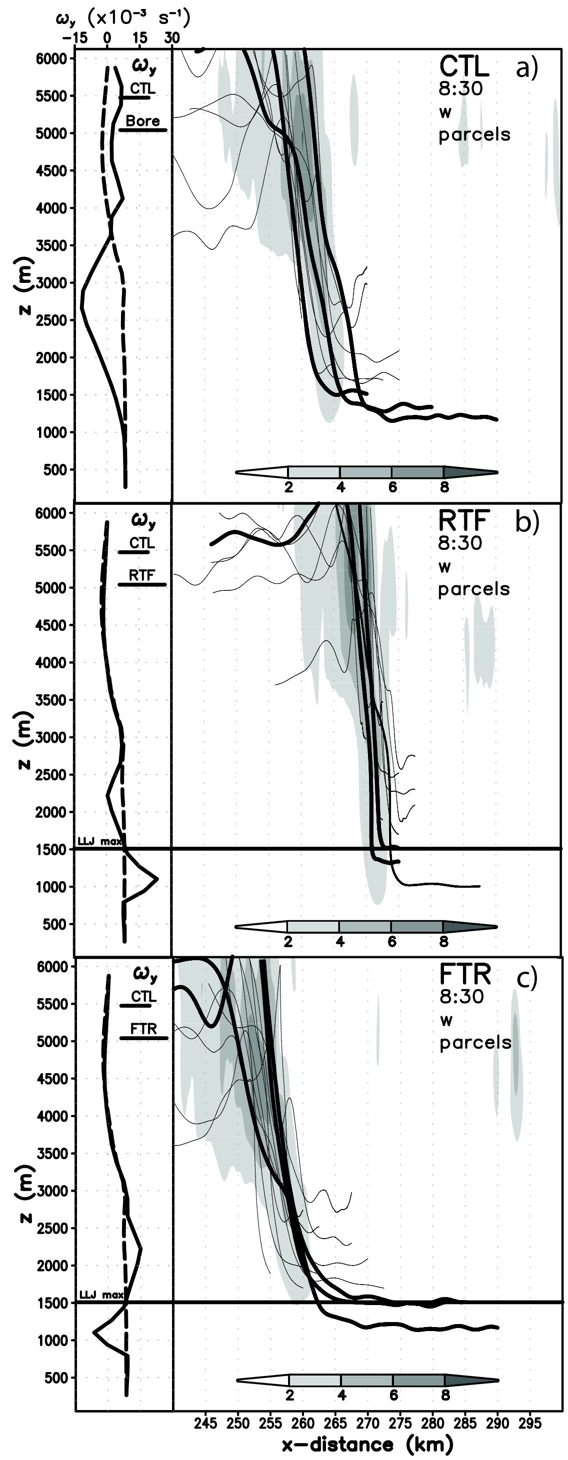

Figure 4: Vertical cross section of along-line averaged vertical velocity (w, shaded as shown) and parcel trajectories, and horizontal vorticity (ω_y s^{-1} left-hand panel) for a) CTL, b) RTF and c) FTR simulations at t= 8 hours, 30 minutes. In a) the solid line in the ω_y plot represents horizontal vorticity generated by the bore, whereas in b) and c) it denotes that generated by the LLJ. The varying trajectory thicknesses denote the parcel starting heights, with medium contours originating below 1000 m, heavy contours originating between 1000 and 1500 m and thin contours originating above 1500 m. The trajectories are taken over the course of 1 hour, centered at 8 hours, 30 minutes. The solid horizontal line in each plot denotes the level of maximum winds in the LLJ.

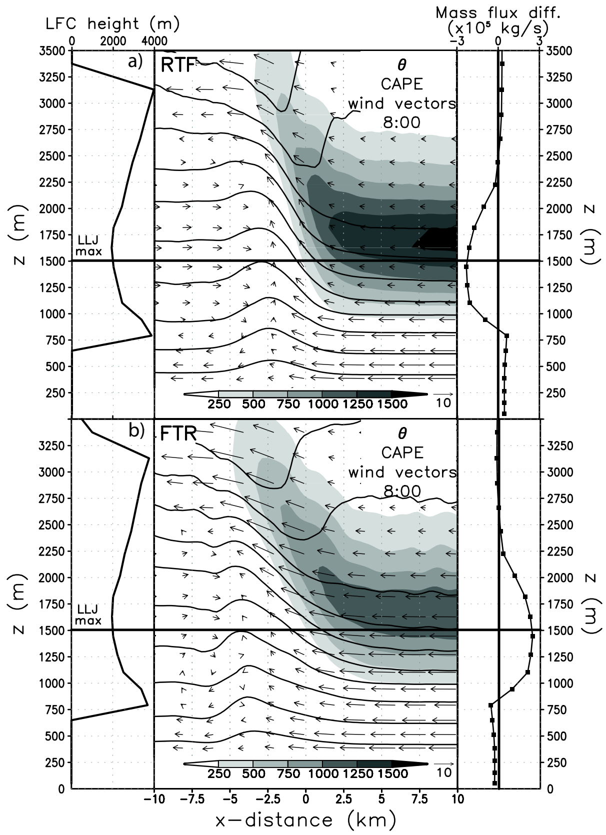

Figure 5: Vertical cross section of along-line averaged potential temperature (θ , contours), wind vectors (ms^{-1}, scale vector in lower right corner) and CAPE (j kg^{-1} shaded as shown) flanked by vertical profiles of LFC height (m, left-hand panel) and storm-relative horizontal mass flux difference (jet simulation-CTL) in the pre-line region ($x10^5$kg s^{-1}, right-hand panel) for a) RTF and b) FTR simulation at t= 8 hours. The solid horizontal line in each plot denotes the level of maximum winds in the LLJ.

the ESRI that sustains an MCS (Gale et al. 2002). This was very evident in the case at hand, as the simulations including the RTF jet experienced a decrease in ESRI, owing to the jet being directed away from the MCS (represented by the decreased storm relative mass flux in Fig. 5 a), while the simulations with the FTR jet featured an increase (Fig. 5b).

These variations in ESRI ultimately correspond to differences in precipitation output. As warm, moist air parcels are fluxed into the storm they ascend through the the updraft region. More air being fluxed into the storm results in more parcels being lifted, more condensation taking place per unit time, and greater hydrometeor production. This increase in hydrometeor production ultimately results in an increase in precipitation output, as seen in the FTR simulation (i.e. Fig. 2). The opposite can be observed within the RTF simulation,

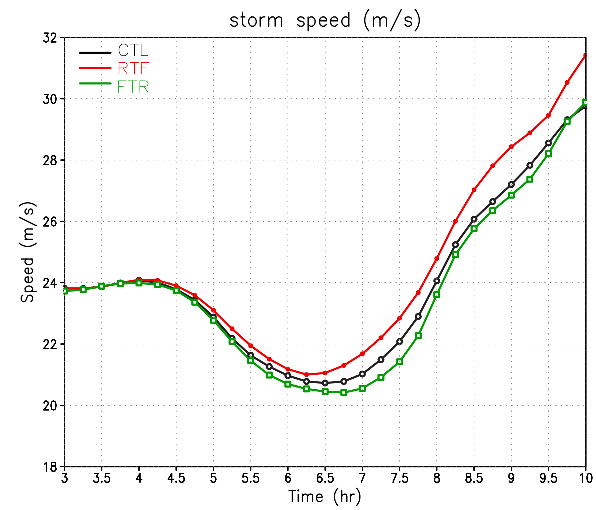

Figure 6: Time series plot of storm speed for CTL (black), RTF (red) and FTR (green) simulations.

wherein decreased mass flux leads to fewer parcels being ingested into the storm and lifted, decreased hydrometeor production, and ultimately a decrease in precipitation. Furthermore, since the difference in storm motion between the FTR and RTF MCSs (another factor that can impact storm-relative inflow) are rather small (< 2 ms^{-1}, Fig. 6), we can attribute these changes in mass flux to the addition of the LLJ.

4.4 Sensitivity tests

In addition to the benchmark CTL, RTF and FTR simulations discussed thus far, a series of sensitivity tests were run to examine the impact of change the jet height and speed, and how the jet impacts MCSs that remain surface-based (i.e. no low-level cooling). While a full discussion of the results of all of these test is beyond the scope of this paper, a brief summary of key points will be included:

- Changes to the speed of the LLJ did not fundamentally change our results. While the shear/inflow modulation effects where amplified, the overall impact on the storm was the same. For example, when the speed of the FTR LLJ was increased, the mass flux into the MCS increased, and a concurrent increase in intensity was observed as well.

- The jet-induced shear located near the base of the bore (approximately 1000-1500 m AGL) has the most dramatic impact on updraft intensity. Namely, the strongest vertical motions were observed when the LLJ generated positive ω_y within this layer.

- In simulations run without low-level cooling (i.e. a surface-based MCS), the impacts of the LLJ-generated shear play a larger role in modulating storm intensity. As a result, the RTF MCS ends up becoming more intense than the FTR simulation by the end of the simulation. This is likely because the enhanced shear allows the RTF MCS to lift low-level parcels, which in this case have CAPE, and thus compensate for diminished inflow in the jet layer. The FTR MCS still benefits from enhanced inflow in the jet layer, however the less-optimal shear limits low-level lifting and thus its ability to ingest near-surface parcels.

A more detailed analysis of these results will be presented in a forthcoming publication by the authors.

5. DISCUSSION

Based on the results discussed above, it is evident that the LLJ effects both updraft organization and storm relative inflow in our simulated MCS. It is the latter of these that has the strongest effect on the intensity of the MCS. This makes sense, as at the most basic level it is the supply of high-θ_e air that is of primary importance to storm sustenance. Once this supply is cut off, or reduced as in the RTF case, the storm will weaken and dissipate. If this occurs, the tilt of the updraft becomes academic, as there are few/no parcels to be lifted by the updraft to sustain the storm. Thus the LLJ has the most significant effect on storm precipitation output by modulating the amount of mass that is ingested by the storm and subsequently condensed into precipitation.

This is not to discount the importance of updraft tilt when it comes to lifting parcels to their LFCs, as even the strongest storm-relative inflow will be of little consequence if cannot be sufficiently lifted. However, in the case at hand the depth of the bore lifting is sufficient for parcels to reach their LFCs via isentropic ascent. The LFC for elevated parcels in this case is approximately 2 km, and the bore extends up to 2.5 km (Fig. 5a, b). As a result, in this case, storm precipitation output is governed by the amount of mass being fluxed into the storm by the storm-relative inflow, and the tilt of the updraft is of little importance.

6. CONCLUSIONS

Idealized numerical simulations were used to investigate the effects of a simulated nocturnal low-level jet on an elevated, nocturnal MCS. These simulations demonstrated two primary results. First, the addition of the LLJ has a dramatic effect on the low-level vertical wind shear within the jet layer, with the direction of the jet governing whether the shear is increased or decreased in this layer. This change in shear can in turn have a notable effect on the tilt of the storm's updraft, as discussed by RKW.

Second, the addition of the low-level jet works to modulate the storm relative inflow, again with the direction of the jet governing whether the inflow increases or decreases. This change in storm-relative inflow appeared to have the most significant effect on storm intensity in terms of precipitation output. The FTR (RTF) jet resulted in increased (decreased) storm relative inflow, and an associated increase (decrease) in intensity. Thus the presence of the LLJ appears to play an important role in modulating storm intensity beyond merely priming the environment for convection or providing a forcing mechanism as outlined in prior studies.

These results also suggest that, provided that parcels can readily reach their LFCs, the tilt of the updraft determined by the cold pool/shear balance theory presented by RKW, is of secondary importance to the strength of the storm-relative inflow when it comes to determining storm intensity. This is not to say that the tilt of the updraft is not important in cases wherein parcels need to be displaced to a greater altitude to reach their LFC, but rather that in the case at hand it was of little importance. It is important to note that this finding is likely specific to MCSs that are elevated and feeding off inflow from a layer that is co-located with the LLJ. In experiments run without low-level cooling, increased shear due to the LLJ enhanced low-level lifting, enabling the MCS to ingest CAPE-rich parcels from below the layer wherein the LLJ was limiting the storm-relative inflow. This appeared to effectively compensate for the diminished storm-relative inflow within the jet layer seen in the RTF configuration.

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