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The role of the rear inflow current in organizing convective storms

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1. Introduction

The rear inflow current (RIC) is a ubiquitous feature of squall lines (e.g., Smull and Houze 1987), along with the upshear-sloping front-to-rear (FTR) jet, the forward anvil outflow and the subcloud cold pool. It has been clear for some time that the RIC is generated by the convection itself, developing outward as the storm's rising FTR flow organizes and expands (Fovell and Ogura 1988). The current typically traverses the storm's trailing stratiform region as a elevated jet-like feature; its descent in the convective region can bring strong, possibly damaging winds to the surface. The origin and/or organizational role of the RIC has been examined from somewhat different viewpoints in Weisman (1992) and Pandya and Durran (1996), for example. The former extended Rotunno et al.'s (1988; "RKW") theory to incorporate the current's vorticity contribution while the latter interpreted rear inflow formation as a response to convective heating patterns.

RKW theorized that opposing horizontal vorticities associated with the ambient vertical shear and that baroclinically generated at the cold pool gust front combined to determine the slope of the FTR updraft airflow, the updraft canting rearward with height when the pool vorticity is the stronger. Weisman (1992) extended RKW's analysis by including the vorticity contribution associated with the RIC. In this extension, a current that remains elevated as it passes into the convective region helps counteract the cold pool circulation responsible for tilting the storm updraft rearward. A descending current, in contrast, augments the pool vorticity. This analysis is consistent with Fovell and Ogura's (1989; "FO89") results showing that storms having stronger and narrower updrafts also possessed RICs that remained elevated right up to the leading edge but the current descended well to the rear in weaker cases. This analysis cannot address RIC formation and why, where and if it descends. Regarding the former, other research has demonstrated the RIC develops owing to latent heating in the convective region. Nicholls et al (1991; "NPC") showed that the environmental response to a deep tropospheric heat source consists of enhanced horizontal flow directed towards the source in the lower troposphere overlain by source-relative outflow. However, if the heat source is more "top-heavy" the enhanced source-relative inflow may be displaced towards the middle troposphere. Pandya and Durran (1996) used this result to explain the development of the RIC, showing it – as well as other aspects of the storm circulation – could be replicated in a dry model forced by realistic and steady thermal forcing.

It remains to formally demonstrate RIC *descent* is directly due to subcloud evaporative cooling. This is unsurprising: FO89 noted that the RIC and its parcels descended as the cold pool deepened; this strongly implicates the role of evaporating hydrometeors. However, this means that *microphysics* can have a first-order influence on storm strength and orientation. By this argument, how far back behind the leading edge the RIC descends should be a function of the width of the storm's evaporative cooling zone. That width should reflect, in part, how far precipitation particles can travel rearward in the FTR jet. This brings particle fallspeeds, conversion rates, distributional characteristics and drag forces into the equation. There is still a "chicken-and-egg" aspect to this, which we try to address with some experiments using simplified models.

2. Models

Two experiments, employing different model frameworks, are employed to assess the effect of subcloud cooling on the RIC, and the RIC's role in organizing the storm. The ARPS model, initialized as described in Fovell and Tan (1998), was used to investigate the effect of microphysics, albeit in a crude fashion. Rainwater fallspeeds were augmented or discounted

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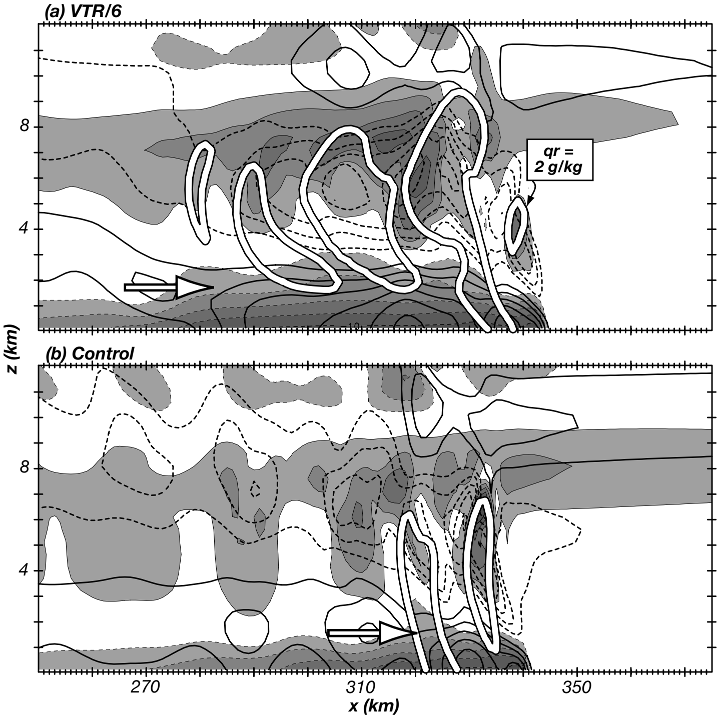

Fig. 1: Fallspeed experiment simulations, showing θ' (shaded/contoured) and u' (contoured) for: (a) run with VTR reduced by factor of 6; (b) Control case. The 2 g kg^{-1} rainwater envelope also shown.

by specified factors in "warm rain" simulations. Reducing the fallspeeds mimics the inclusion of low density ice (Fovell and Ogura 1988). As rainwater fallspeeds decrease, precipitation can travel farther rearward in the FTR airflow. Since slower falling particles are also more likely to evaporate before reaching the surface, an increase in the horizontal extent and strength of the subcloud cold pool is accomplished.

We found it advantageous to further simplify and manipulate the subcloud cooling more directly. The second experiment used a "no-cloud cloud model" (NCCM) in which supersaturation is removed as is occurs but cloud water is not retained, eliminating both precipitation and water loading. Fovell and Tan's (2000; "FT2000") cooling zone creates and maintains the subcloud cold pool. The width, depth and location of the cooling zone are specified; we have examined the effect of varying the zone's width.

3. Fallspeed experiment

In the fallspeed experiment, rainwater terminal velocities (VTR) were enhanced or reduced by factors ranging between 1 and 6. Figure 1 shows perturbation fields[1] of potential temperature θ' and horizontal velocity u' for the control and VTR/6 runs, along with the 2 g kg^{-1} rainwater envelope. In both cases, the RIC descends as the cold pool deepens. As anticipated, slowing the rate of precipitation fallout facilitated its rearward spread. This encouraged a deeper, wider and also somewhat stronger cold pool, resulting in the RIC descending about 40 km farther behind the storm's leading edge[2].

Augmenting VTR resulted in a still narrower cold pool and a more erect, vigorous updraft (not shown). However, many factors and forcings are convolved in this experiment. Although condensation production is larger, rainwater falls too quickly from the updraft in the most hastened fallspeed cases to collect much condensate, despite the particles' relatively larger sweep-out volumes. Thus, the discounted fallspeed storms generate much more precipitation, leading to substantially larger updraft water loadings.

4. Cooling zone width experiment

The NCCM cooling zone width experiment helps isolate the most direct effects of subcloud cooling on the RIC and storm structure. The simulations shared a favorably unstable sounding with moderate shear below 3 km. For a set 1.5 km depth, cooling zone

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[1] Perturbations are relative to the initial state.

[2] Note the locations of u' maxima.

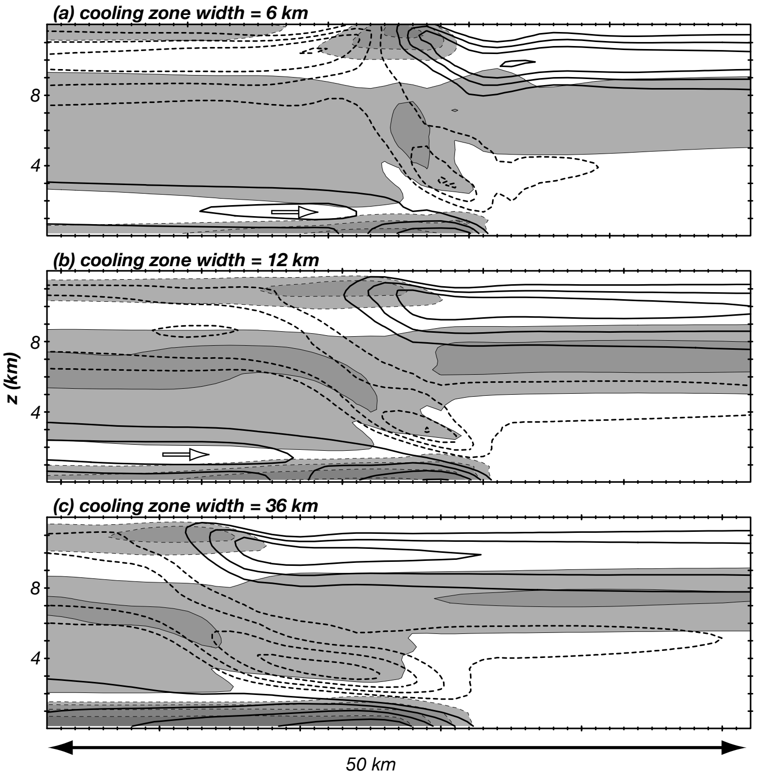

Fig. 2: Time-averaged fields of θ^{-1} (shaded/contoured) and u' (contoured) for cooling width experiment simulations with $x_h = 6$, 12 and 36 km.

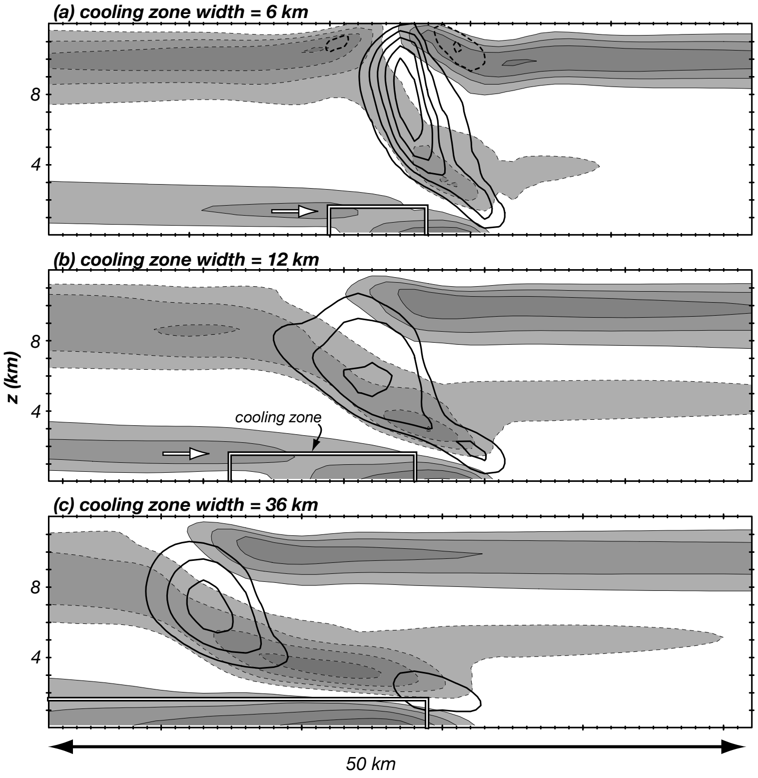

Fig. 3: A in Fig. 3, but showing contoured w atop shaded/contoured u'. Box enclosing location of time-averaged cooling also shown.

widths (x_h) ranging between 3 and 72 km were examined. In each case, air within the cooling zone was nudged towards a θ' value of -10 K over a time scale of 10 min. As in FT2000, the cooling zone's position was kept fixed relative to the gust front.

In all cases, the applied cooling-induced pools initiated deep convection that was quickly organized into the classic FTR/RIC configuration of mature squall lines. Propagation speeds varied from only between 13.5 and 17.3 m s^{-1}, increasing with x_h. For relatively narrow widths, there was a large sensitivity to the specific cooling zone width employed. Expanding the zone beyond 36 km, however, had relatively little incremental effect on any storm aspect.

Figures 2 and 3 present time-averaged θ', u' and vertical velocity (w) fields obtained for zone widths of x_h = 6, 12 and 36 km. All three storms possess rearward-tilting FTR airflows. The wider the cooling zone, however, the more tilted and less concentrated that flow and its time-averaged lifting became. The more tilted storms had RICs that descended farther behind the storm leading edge. As remarked in FO89, it seems like the RIC "props up" the FTR jet from behind and beneath.

Indeed, this result is strongly reminiscent of FO89's Fig. 22, in which the FTR airflow became more tilted and the RIC descended farther to the rear as the low-level shear intensity was reduced. Here, all simulations possess the same initial low-level shear and roughly comparable cold pools. The dramatic variation among cases clearly demonstrates the RIC has a first order effect on storm structure and its location of descent is controlled by the cooling zone width.

Regarding temporal behavior, the storms evolved from weak and significantly multicellular entities to strong and nearly steady unicellularity as the RIC descent location approached the leading edge (Fig. 4). Thus, *from the same sounding, shear, and cold pool depth and intensity, very different storm structures and behaviors may be obtained, controlled by the width of the subcloud cooling zone*. FT2000 revisited the Garner and Thorpe (1992) parameterized moisture (PM) model, which employed a similar subcloud cooling zone, in part to demonstrate the PM framework can support convection that is both long-lived and unsteady. They showed that adding convective instability increased the likelihood of the storm being multicellular. The present experiement shows that multicellularity is also favored by wider cooling zones.

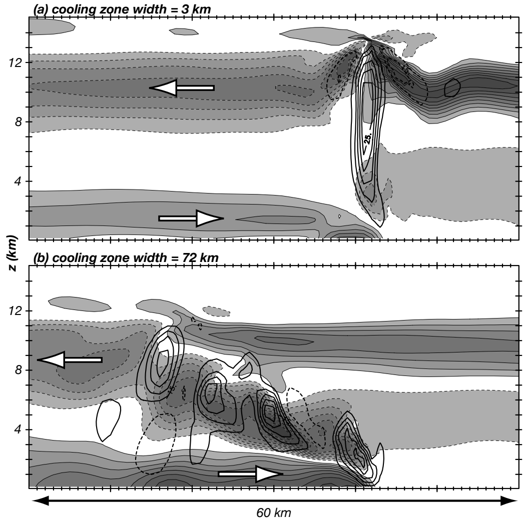

Fig. 4: As in Fig. 3 but instantaneous fields from the x_h = 3 and 72 km cases.

5. References

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Acknowledgments. This work was supported by NSF grant ATM-0139284.