12.8 NEAR-SURFACE INTENSIFICATION DURING UNSTEADY TORNADO EVOLUTION

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1. INTRODUCTION

The potential for destructive conditions near the surface in a tornado can change rapidly in time, as evidenced by the striking variability often seen in the damage paths left behind. This variability is echoed on larger scales as well: mesocyclones of a given intensity level may produce violent tornadoes only for a brief portion of their lifetime, or none at all. An essential ingredient in either case is the possibility of intensification of a vortex flow in the region where the core meets the surface (the corner flow) relative to its strength aloft; significant changes in that region can occur more rapidly than a significant evolution of the larger-scale vortex above.

We have argued in previous work that some of the variation seen for different quasi-steady conditions arises due to the sensitivity of the vortex corner flow to the near surface inflow (Lewellen et al., 2000a, referred to as LLX hereafter) and have shown that changes in this near surface inflow can sometimes lead to abrupt and extreme intensification of the corner flow (Lewellen et al., 2000b). Here we consider this latter phenomena, which might be termed "corner flow collapse", more systematically. We utilize results from fully 3D, unsteady, large-eddy simulations, employing a stretched grid to simultaneously allow fine grid resolution in the corner flow region while imposing boundary conditions far from the corner flow. Details of the numerical model used and the simulation procedures employed can be found in LLX.

2. VORTEX CORNER FLOW COLLAPSE

Corner flow behavior can be understood, in large part, by following the flow of low angular momentum fluid (which is approximately conserved) from the near-surface layer, into the corner flow region and then up the central core. Fig. 1 shows angular momentum on a radial-vertical plane at different times during a corner flow collapse. Only part of the simulation domain is represented, and the results have been azimuthally averaged, smoothing out the highly turbulent flow present in the simulation. We have used the angular momentum level in the outer flow, Γ_∞, and minimum upper core radius at the initial time r_i (defined in terms of the maximum swirl velocity, $r = \Gamma_\infty/V$) to non-dimensionalize the results.

In LLX we showed that the corner flow structure depends critically on the flux of low swirl fluid in the surface layer, the "depleted angular momentum flux" Υ. Defining a characteristic swirl ratio for the surface-corner-core flow in terms of this flux and the core radius, r_c, above the corner flow, $S_c \equiv r_c\Gamma_\infty^2/\Upsilon$, we found that the degree of mean near-surface intensification is sharply peaked about a critical "low swirl" value $S_c^* \sim 1.3$.

Initially, in fig. 1a, S_c is below S_c^* because Υ is large; the low-swirl fluid is accelerated radially inward in the near-surface layer by the cyclostrophic imbalance there, but piles up, stagnates and turns upward before reaching a small radius. Any intensification in swirl velocity due to higher angular momentum levels overshooting their equilibrium point to reach smaller radii then lies well above the surface.

The corner flow collapse in fig. 1 is precipitated by shutting off the low-swirl near-surface flow at the outer domain boundary. The low-swirl fluid in the surface layer is then steadily exhausted up the core (fig. 1b), and the flux through the corner, Υ_c, drops in time until S_c approaches S_c^*. Then, for favorable conditions, the corner flow region collapses rapidly to smaller radii (fig. 1c), driven both from above (by the inertia in the upper core flow removing low-swirl fluid from the corner) and from below (by the radial overshoot of near-surface layer flow which, for $S_c \sim S_c^*$, is no longer impeded by a strongly unfavorable radial pressure gradient from stagnating flow). At peak intensification the approach of higher angular momentum fluid to smaller radii forces much higher swirl velocities and lower pressures near the surface than are found aloft; the remaining very low swirl fluid through the corner is forced into a narrow jet off the surface, typically with a vertical velocity larger ($\sim 1.4\times$) than the peak swirl velocity, and capped by a vortex breakdown.

In a quasi-steady state vortex, Υ is approximately constant with height up the core, and the flow tends

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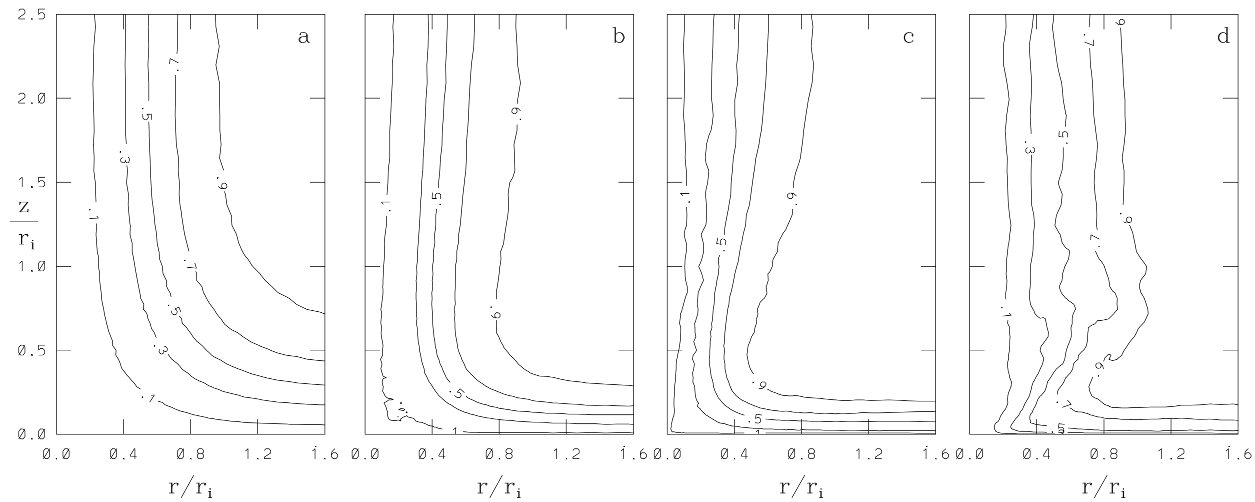

Figure 1: Contours of normalized, azimuthally averaged angular momentum (Γ/Γ_∞) on a radial-vertical plane at different times during a corner flow collapse.

towards cylindrical symmetry; smaller core radii forced by the surface interaction are limited to a small region. For the time varying case leading to corner flow collapse, both Υ and r_c can vary gradually with height, allowing an extended conical structure providing much higher levels of near-surface intensification relative to conditions aloft than can be achieved in steady state.

These intensification levels cannot persist. With the onset of the conical structure a strong vertical pressure gradient develops which first decelerates the axial flow, then drives a narrow central downdraft reaching to the surface, opening the core somewhat to produce a "medium swirl" corner flow configuration with a smaller but still significant degree of near-surface intensification. In the final stages a much wider downdraft descends to the surface opening the core further, eventually leaving a "high swirl" corner flow with little radial overshoot in the surface layer (fig. 1d).

3. DEPENDENCE ON $d\Upsilon/dt$

We can identify three important time scales in this process of corner flow collapse and recovery. First is the time scale, t_e, for exhausting the low-swirl fluid from the corner flow region from above when $S_c \sim S_c^*$. Given a volume $\sim 2\pi r_i^3$, angular momentum level $\sim \Gamma_\infty$, and depleted angular momentum flux $\Upsilon^* \sim r_i\Gamma_\infty^2/S_c^*$ we have $t_e \sim 2\pi r_i^2/\Gamma_\infty$. This is also a characteristic rotation period for the upper core flow. Second is the time, t_s, over which Υ levels into the corner lead to an S_c associated with a significant mean near-surface intensification, which depends on the rate of change of Υ_c. From LLX the favorable range in S_c is narrow and we have $t_s \sim r_i\Gamma_\infty^2/(-d\Upsilon/dt)$. Third is t_d, the time for a large-scale (i.e., a sizable fraction of r_i) downdraft to reach the surface; as discussed below this depends on many factors.

Fig. 2 shows results from a set of simulations each with the same initial conditions, but with the low-swirl near-surface inflow at the outer boundary of the domain turned off at different rates, allowing Υ_c to vary differently (fig. 2b). In computing the time dependent S_c there is a level of ambiguity not present in the quasi-steady case since both Υ and r_c can vary with height; here we use the flux within the corner, Υ_c, and r_c evaluated at a height equal to r_i. Note that while the corner flow swirl ratio, S_c, varies across a broad range in response to Υ falling, the swirl ratio of the vortex as a whole changes little.

In each case Υ_c drops in time and S_c sweeps from very low swirl conditions to very high swirl, producing a period of significant intensification of the peak azimuthally averaged near-surface swirl velocity, V_{NS} (taken below a height of r_i), relative to the peak averaged swirl near the domain top. There are differences in both magnitude and structure encountered, however, for different ratios of time scales. When t_e/t_s is much larger than 1 (e.g., those cases in fig. 2 with Υ_c dropping fastest), the peak intensification range in S_c is traversed before the corner flow has time to collapse to small radii; the peak intensification is delayed, occurring for S_c well above S_c^*, and its degree is correspondingly reduced. When t_s is increased there is a range for which the corner flow collapse and peak radial overshoot in the surface layer are well coordinated; the intensification is large and the peak occurs for S_c near S_c^*. But if t_s becomes large compared with t_d (as for the case with slowest dropping Υ_c in fig. 2),

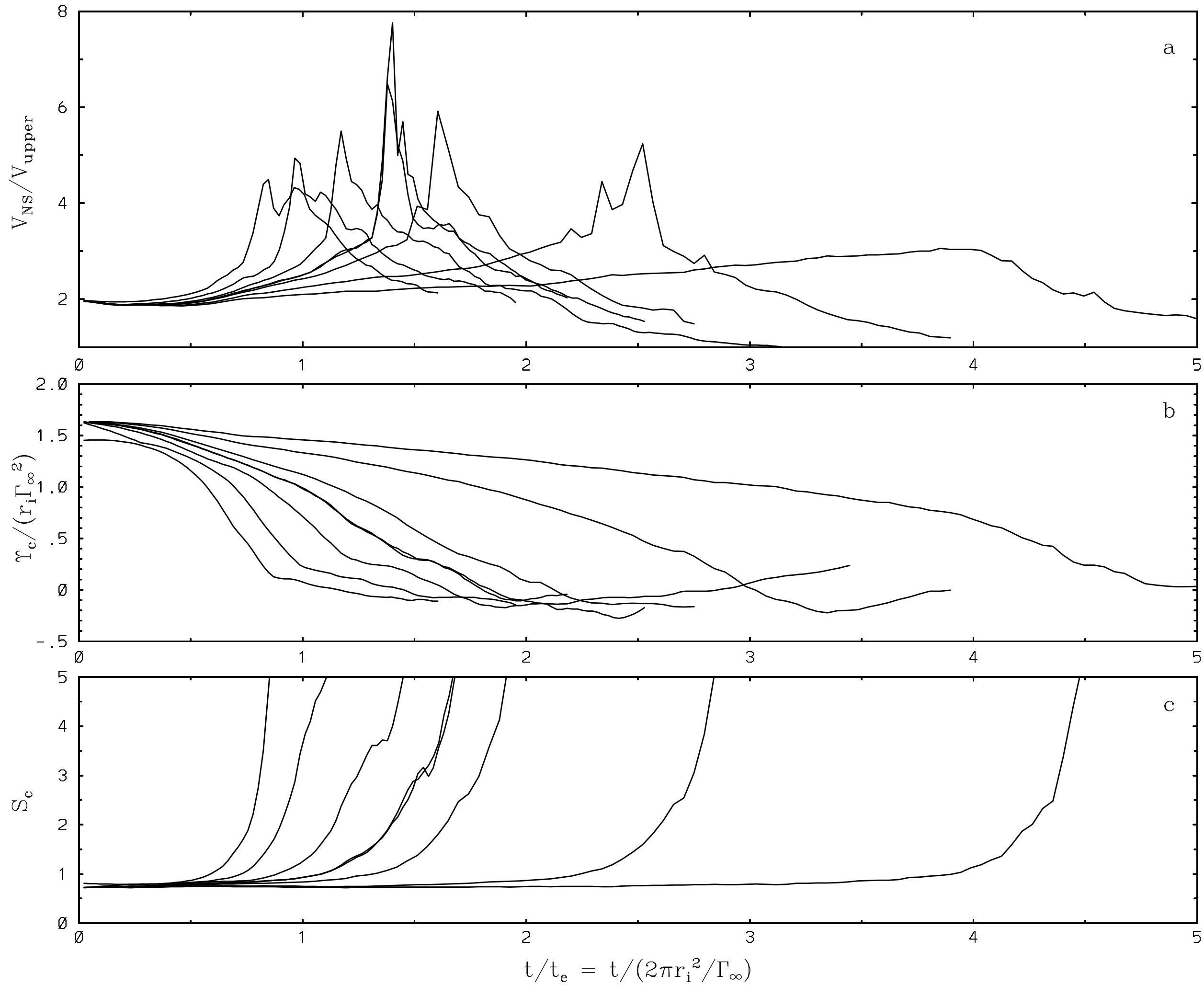

Figure 2: Near surface intensification of swirl velocity (a), non-dimensionalized depleted angular momentum flux through the corner flow (b), and corner flow swirl ratio (c) vs. time for a series of simulations.

then a significant central downdraft reaches the surface before the corner collapses maximally or S_c reaches S_c^*, preventing a larger peak intensification from being reached. Examination of the developing 3d flow structure in these cases confirms this basic picture.

This qualitative picture holds across a large range of conditions, though quantitative comparison becomes more challenging. Figures 3 and 4 show summary results at the peak intensification point from a large set of simulations varying the initial vortex conditions (e.g., core size, convergence, initial S_c, breakdown structure,angular momentum gradients, etc.), domain sizes, upper boundary conditions, numerical parameters, and nature of the surface layer change leading to the corner flow collapse (e.g., total shutoff of the low-swirl near-surface flow, partial shutoff, introduction of high swirl flow replacing low swirl, abrupt or gradual shutoff, or imposition at different radii).

The non-dimensionalized $d\Upsilon/dt$ on the x axis is equal to our estimate for t_e/t_s. High values (i.e., a rapid drop in Υ) lead consistently to peak conditions with medium or high swirl structure and reduced intensification levels; the greatest mean intensification occurs for t_e/t_s of order 1 and occur when S_c is near S_c^*. In order to compare intensification levels for different initial conditions the initial intensification level (generally occurring well off the surface) was divided out. This factor can reach ∼2.5 when a strong vortex breakdown appears in the upper core, and the overall intensification level is raised from that in fig. 4 accordingly.

Fig. 4 is complicated for small t_e/t_s by the variation in t_d for different conditions. The point at which further increase of t_s leads to a drop rather than in-

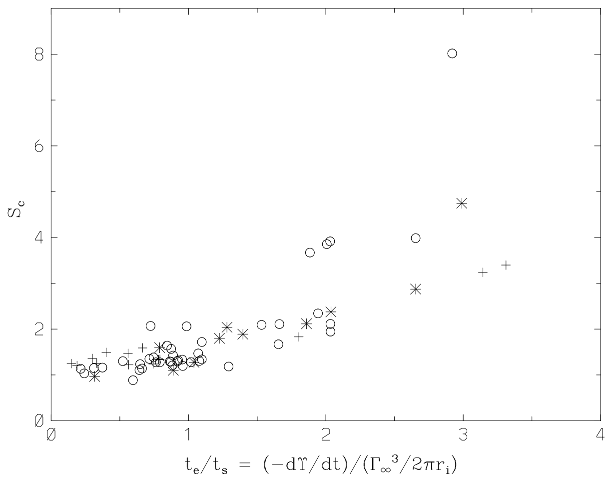

Figure 3: Corner flow swirl ratio at time of peak swirl velocity intensification vs. normalized rate of change of depleted angular momentum flux.

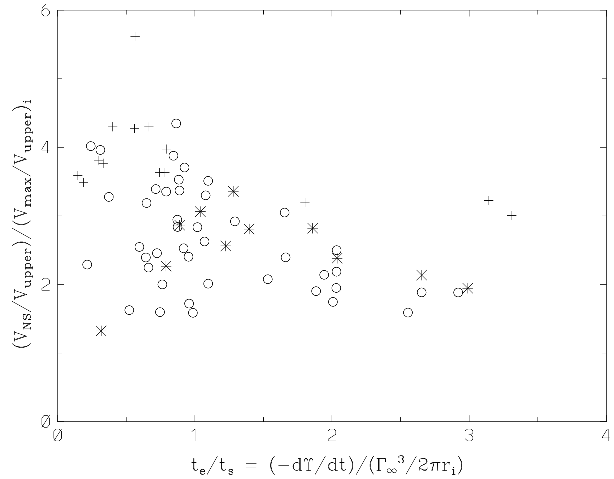

Figure 4: Normalized near-surface swirl velocity intensification vs. normalized rate of change of depleted angular momentum flux.

crease in peak intensification depends on t_d, as can the peak intensification level and duration over which significant intensification occurs. Typically t_d depends on many factors affecting the upper core conditions (initial S_c, Υ history, angular momentum gradients, core pressure, breakdown structure, t_e, etc.). For example the "*" and "+" points in figs. 3 and 4 are each based on a single set of initial vortex conditions. In the "*" set (from which the cases of fig. 2 are taken) a relatively low ($\sim 4r_i$ AGL) vortex breakdown is initially present; a breakdown is there in the "+" set as well, but higher up ($\sim 10r_i$ AGL). During corner flow collapse a large-scale downdraft originates from above the breakdown, reaching the surface more quickly in the former case. Accordingly in the latter case the peak mean intensification level increases for smaller values of t_e/t_s than in the former, allowing greater intensification (and longer duration) for optimal conditions.

4. COMMENTS

A class of vortex conditions has the potential to produce very significant intensification near the surface through a "collapse" of the corner flow, but whether that potential is strongly realized depends, in large part, on the nature of changes in the near surface flow, making its ultimate predictability very challenging. For example, on the mesocyclone scale, corner flow collapse is a possible route by which the rear-flank downdraft could promote tornadogenesis. But in this scenario whether a strong tornado (or any) actually occurs may depend on the state of the mesocyclone when the downdraft reaches the surface, the radius at which the downdraft is located, its strength or extent, how rapidly or completely it wraps around the mesocyclone center, etc., since all these affect the rate of change of the flux of low-swirl fluid into the corner flow region. Similarly, on the tornado scale these results suggest that rapid and significant changes in near-surface intensity and structure can be promoted by fairly modest changes in the low-level flow environment.

ACKNOWLEDGEMENT: This research was supported by NSF grant ATM-9876450.

References

Lewellen, D. C., W. S. Lewellen, and J. Xia, 2000a: The influence of a local swirl ratio on tornado intensification near the surface. *J. Atmos. Sci.*, **57**, 527–544.

Lewellen, D. C., W. S. Lewellen, and J. Xia, 2000b: Nonaxisymmetric, unsteady tornadic corner flows. *Preprints, 20th Conference on Severe Local Storms*, Amer. Meteor. Soc., Orlando, FL, 265-268.