13.5 ON THE LIMITS TO NEAR-SURFACE INTENSIFICATION OF TORNADO VORTICES

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1 INTRODUCTION

In a tornadic supercell velocities are intensified within a small region of the storm, within a few tens of meters of the surface where they can do the most damage. How large can near-surface tornado velocities become relative to velocities aloft? Determining the maximum possible tornado intensity near the surface, and what conditions produce them, are longstanding goals of severe storm research. Here we summarize results from two of our recent papers addressing this question (Lewellen and Lewellen, 2006a,b). We use both idealized analytic models and numerical large-eddy simulations to concentrate on one aspect of the problem: the near-surface intensification of a vortex due to purely fluid-dynamic effects. The results reinforce one of the themes from our previous studies: that corner flow structure and near-surface intensification are highly sensitive to properties of the near-surface inflow layer (Lewellen et al., 2000a,b; Lewellen and Lewellen, 2002).

2 IDEALIZED CORNER FLOW MODEL

There is a physical feedback that tends to limit the magnitude of the near-surface intensification of a vortex: higher swirl velocities and pressure drops near the surface relative to conditions aloft imply a vertical pressure gradient that tends to drive a core downdraft, reducing the intensification. There is also a well known purely fluid-dynamic mechanism that can oppose this feedback: balancing the vertical pressure gradient with core updrafts (either central or annular) that decelerate with height, with the enhanced updraft at low levels supported by a radial overshoot in the vortex corner flow produced by cyclostrophic imbalance in the surface layer. A simple analytical model for a steady supercritical end-wall vortex (Barcilon, 1967; Fiedler and Rotunno, 1986) suggests that the level of intensification that can be supported by this mechanism (as measured by the ratio of peak swirl velocities in the corner flow to peak swirl velocities aloft) is limited by the conservation of mass, angular momentum and vertical momentum to a factor ~2, a result supported by many laboratory and numerical studies.

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In Lewellen and Lewellen (2006a) this model is generalized to consider corner flows besides the supercritical end-wall vortex, more general angular momentum distributions and time dependence. The model again uses integrated conservation of mass, vertical momentum, and angular momentum to relate pressure and velocity at a lower level in the corner flow to their values well above the corner flow without any more detailed knowledge required of the flow in between, which is expected to be highly turbulent, strongly dissipative, and possibly including a vortex breakdown. The treatment is analogous to the classic treatment of a hydraulic jump.

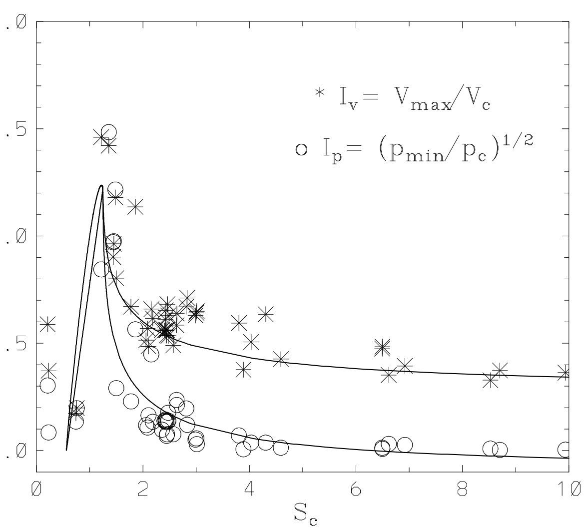

Figure 1: Near-surface intensification of mean swirl velocity and pressure drop relative to conditions aloft versus corner flow swirl ratio. Symbols represent LES results (taken from Lewellen et al. (2000a)); the lines are predictions from the analytic model of Lewellen and Lewellen (2006a).

The model predicts the general structure and intensification of quasi-steady vortex corner flows as a function of corner flow swirl ratio in agreement with simulation results. For example, fig. 1 reproduces fig. 8 from Lewellen et al. (2000a), plotting near-surface in-

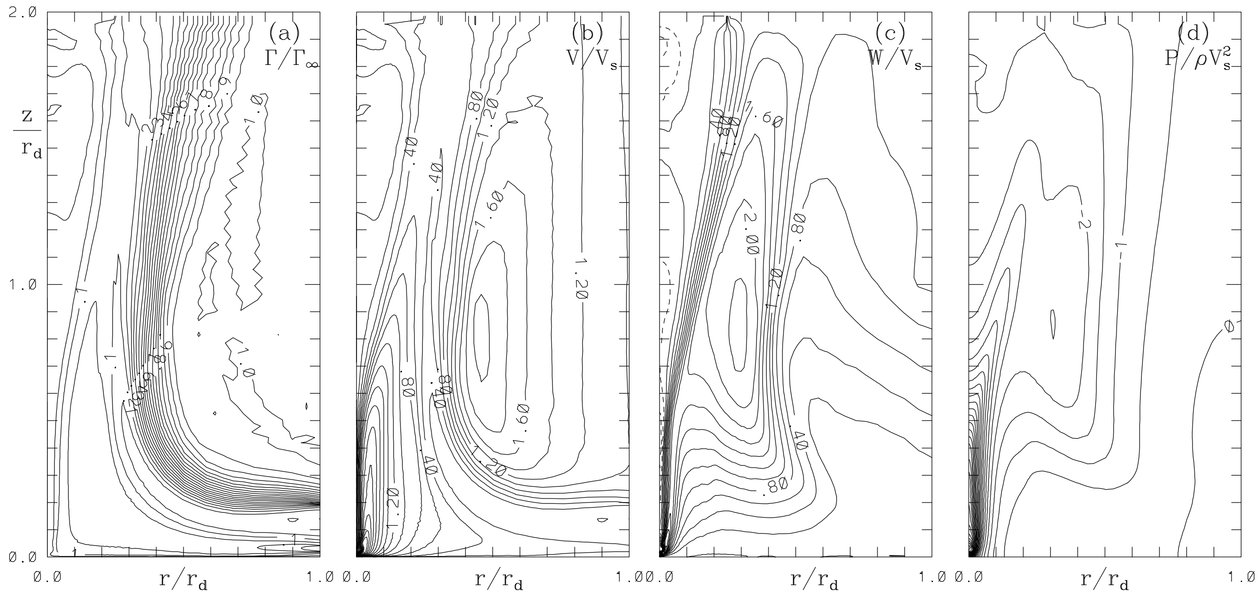

Figure 2: Azimuthal time averages of angular momentum (a), swirl velocity (b), vertical velocity (c) and pressure (d) for a simulation exhibiting nested "inner" and "outer" corner flows on different length scales.

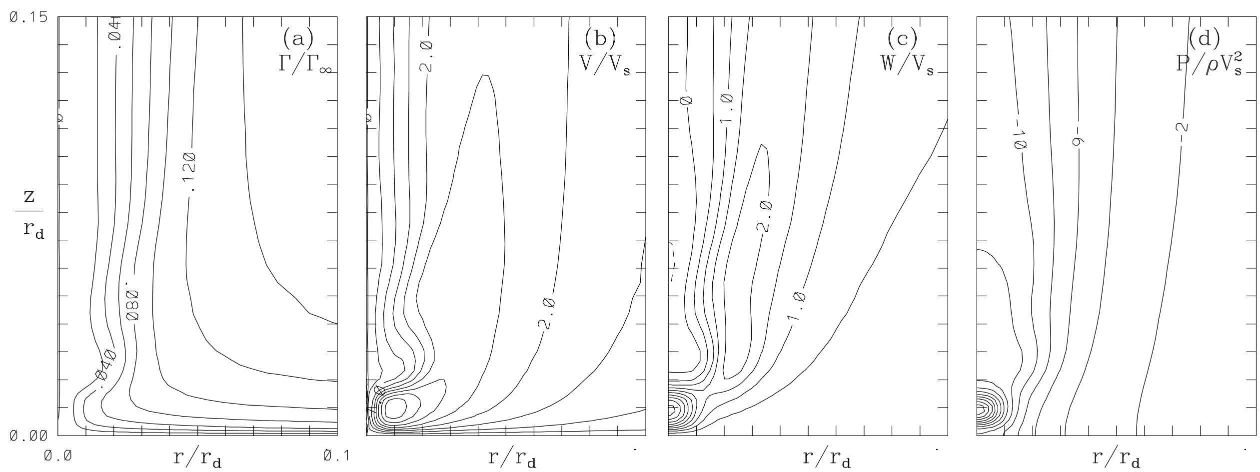

Figure 3: As in figure 2, zoomed in to show the central subdomain.

tensification as a function of S_c for a large set of simulated tornadoes, together with the predicted curve from Lewellen and Lewellen (2006a). The model has some dependence on the assumed swirl distribution in the core; the lines shown are for the simple case of uniform vorticity in the core updraft (corresponding to a Rankine combined vortex for a solid updraft). The model predicts a solid central updraft above the surface for S_c below its value for peak intensification, S_c^*, and an annular updraft for $S_c > S_c^*$, as observed in the simulated corner flows in Lewellen et al. (2000a).

3 CORNER FLOWS WITH ENHANCED INTENSIFICATION

The simplest solutions to the idealized corner flow model support the prevailing view that near-surface intensification is generally greatest, with a value ~ 2, given a supercritical end-wall vortex capped by a vortex breakdown just above the surface; however, the model also suggests ways in which even greater intensification levels can be achieved, e.g., by involving more complex Γ distributions or time evolution. Several such scenarios have been realized with LES in Lewellen and Lewellen (2006a,b); two representative examples are presented below. Note that in presenting results quantities have been nondimensionalized using the angular momentum level in the far field (Γ_∞) and the domain "radius" ($r_d \equiv$ half the lateral domain size) to form length (r_d), time ($t_s \equiv r_d^2/\Gamma_\infty$) and velocity ($V_s \equiv \Gamma_\infty/r_d$) scales.

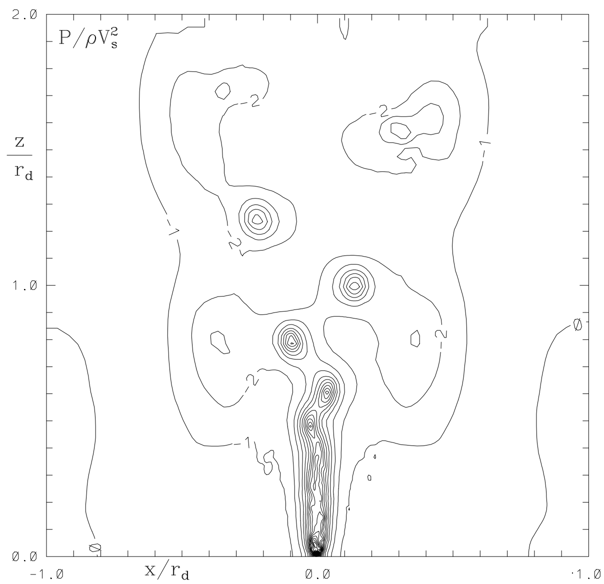

Figure 4: Instantaneous contours of normalized perturbation pressure on a central vertical slice of the nested corner flow simulation showing a large-scale spiral vortex breakdown.

3.1 *A Quasi-steady Nested Corner Flow*

Figures 2 and 3 summarize results from a quasi-steady simulation where enhanced intensification from the boundary layer interaction is produced essentially by realizing "inner" and "outer" corner flows on different spatial scales. To do this, the near-surface inflow at the domain boundary was constructed with varying angular momentum in layers: a thin layer with no swirl just above the surface, a thin layer above it with $\Gamma = \Gamma_\infty/2$, a thick no-swirl layer above them, and finally $\Gamma = \Gamma_\infty$ there-above. The layer thicknesses were adjusted to produce near-critical low-swirl corner flows on both inner (fig 3) and outer (fig 2) corner scales, the former with an abrupt quasi-axisymmetric vortex breakdown, the latter with a spiral-mode vortex breakdown best seen in the instantaneous pressure field (fig 4). Each is accompanied by a significant intensification factor, with the combination producing $I_v \approx$3.2 and $I_p \approx$4.2 as measured in the time and azimuthally averaged flow. This measure underestimates the true intensification because the lateral wander of the inner vortex below the first breakdown is non-negligible in comparison to its small core size. A time average of peak values at each time gives instead, $I_v \approx$5.3 and $I_p \approx$5.2.

The two vortex breakdowns were diagnosed from the observed behavior – sharp transitions from states with strong upward axial flows to ones with significantly larger core radii, reduced axial velocities and increased turbulence levels. The presence of a second vortex breakdown following a first might seem inconsistent with the interpretation of a vortex breakdown as the transition from a supercritical flow to a subcritical one (Benjamin, 1962). In the present example, however, two different fluid populations are involved: the small-scale central jet flow can transition from super to subcritical in the inner vortex breakdown while the much larger annular updraft accelerates to supercritical above before undergoing its breakdown.

This simulation illustrates two other points stressed in Lewellen et al. (2000a): the inadequacy in some cases of any single parameter (e.g., a swirl ratio) to characterize the interaction of a vortex with the surface, and the extreme sensitivity of the corner flow structure and intensity to the properties of the near-surface inflow. At least three different swirl ratios are relevant in the present case: the domain-scale swirl ratio, and corner flow swirl ratios on inner and outer scales. The sensitivity to the inflow structure has been confirmed by related simulations: the elimination of all the low swirl inflow at the lateral boundaries produces a quasi-steady high-swirl corner flow with multiple secondary vortices, as one would expect from the high domain-scale swirl ratio; eliminating only the lowest thin layer of no-swirl inflow maintains nested corner flows, but now a high-swirl corner inside of a large scale low-swirl corner; most dramatically, eliminating just the thin layer of $\Gamma = \Gamma_\infty/2$ inflow produces a very low swirl corner on the large scale, replacing a strong near-surface intensification with a strong de-intensification.

3.2 *Dynamic Corner Flow Collapse*

Many of the features observed in "nested" corner flows, and significant additional intensification, can be realized naturally without fine tuning in a class of unsteady evolutions we have previously dubbed "corner flow collapse" (Lewellen et al., 2000b; Lewellen and Lewellen, 2002). These scenarios, triggered purely by changes in the far-field, near-surface flow, provide an attractive mechanism for naturally achieving an intense near-surface vortex from a much larger less-intense swirling flow.

The evolution of the peak velocities and pressure drop from an example simulation of corner flow collapse is summarized in fig. 5, and different vertical profiles at the time of peak intensification in figs. 6 and 7. The initial state is from a quasi-steady simulation in which the domain swirl ratio is large but the corner flow swirl

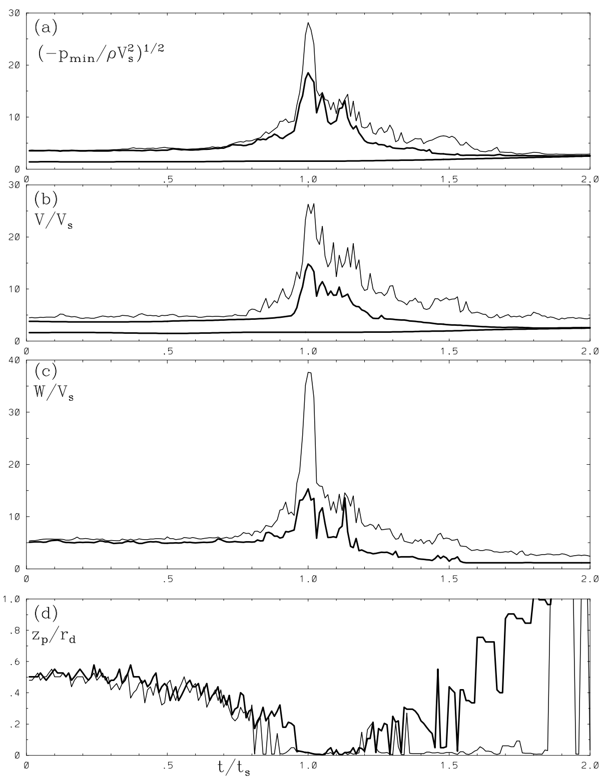

Figure 5: Non-dimensionalized peak pressure drop (a), swirl velocity (b), vertical velocity (c), and height at which the peak pressure drop occurs (d), versus time during a corner flow collapse; peaks taken from the full 3D field (thin lines) or from an azimuthal average (thick lines). The nearly flat lines in (a) and (b) show peak mean values in the upper core near the domain top.

ratio is low, a consequence of a zero-swirl inflow layer above the surface. There is initially a large-scale central updraft, a vortex breakdown at about 2/3 of the domain height, and no large velocities near the surface. The evolution in fig. 5 is triggered by shutting off the near-surface, zero-swirl inflow at the domain boundary. Subsequently the low-swirl fluid in the surface layer is steadily exhausted up the core; its flux through the corner drops in time until S_c approaches S_c^*. At this point the corner flow collapses rapidly to smaller radii, 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 flow for S_c near S_c^*). As a consequence, the peak velocities and pressure drops increase dramatically and drop in height to just above the surface (fig. 5). At the time of peak intensification I_v ≈8.7 and I_p ≈11.9 as measured from the azimuthal averages and I_v ≈15.4 and I_p ≈18.0 taken from the local instantaneous peaks. The analytic model and simulation results suggest that there are three identifiable ingredients in the near-surface intensification produced transiently during corner flow collapse, each contributing (for favorable conditions) approximately a factor of 2 in intensification over conditions aloft: (1) sweeping S_c over S_c^*; (2) nested corner flows on different scales; and (3) a true unsteady contribution with the total momentum flux through the corner decreasing in time.

4 CONCLUDING REMARKS

Given the right conditions in the near-surface inflow layer, purely fluid-dynamic effects can lead – even in quasi-steady state – to much larger near-surface vortex intensification than had previously been thought possible. It should be noted that other physical effects not included here can either augment this intensification (such as buoyancy in the vortex core) or reduce it (such as large debris loading (Gong et al., 2006)).

Lewellen and Lewellen (2006b) includes an analysis of a large set of large-eddy simulations of corner flow collapse designed to determine the basic scaling of the onset, intensification, structure and duration of the phenomenon as a function of the dominant physical parameters involved. Given its robustness and the magnitude of the near-surface intensification achieved, corner flow collapse is an attractive possible mechanism that may sometimes contribute on the tornado scale to tornado variability and on the mesocyclone scale to tornadogensis.

5 ACKNOWLEDGMENTS

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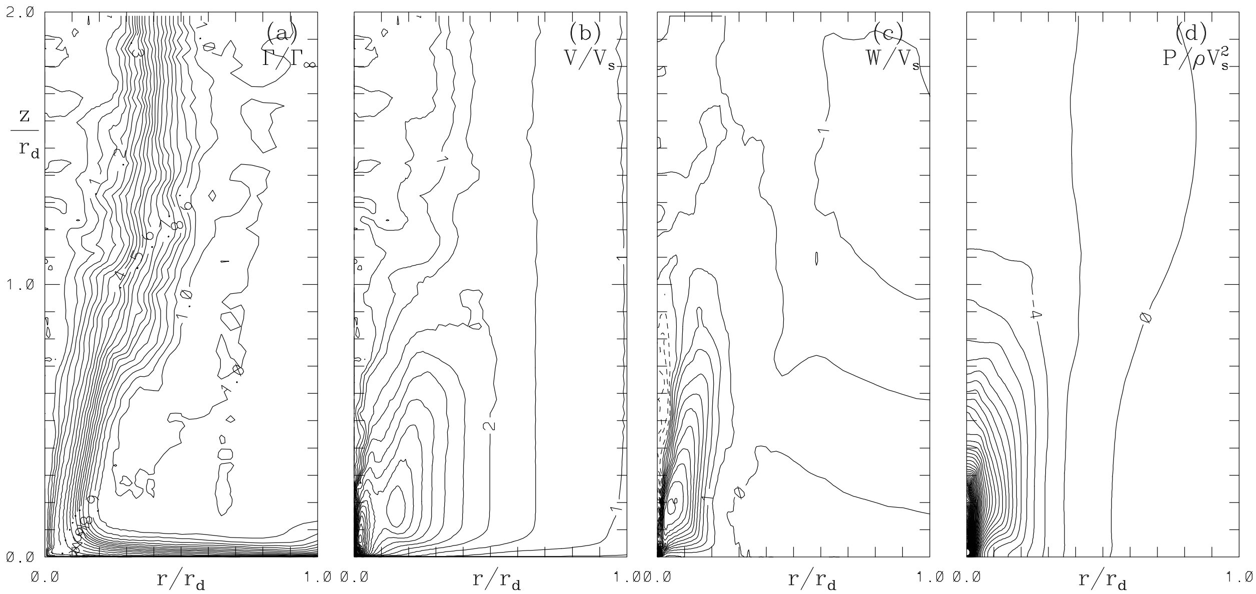

Figure 6: Azimuthal averages of angular momentum, swirl velocity, vertical velocity and pressure shown at the time of peak near-surface intensification for a simulation undergoing a dynamic corner flow collapse.

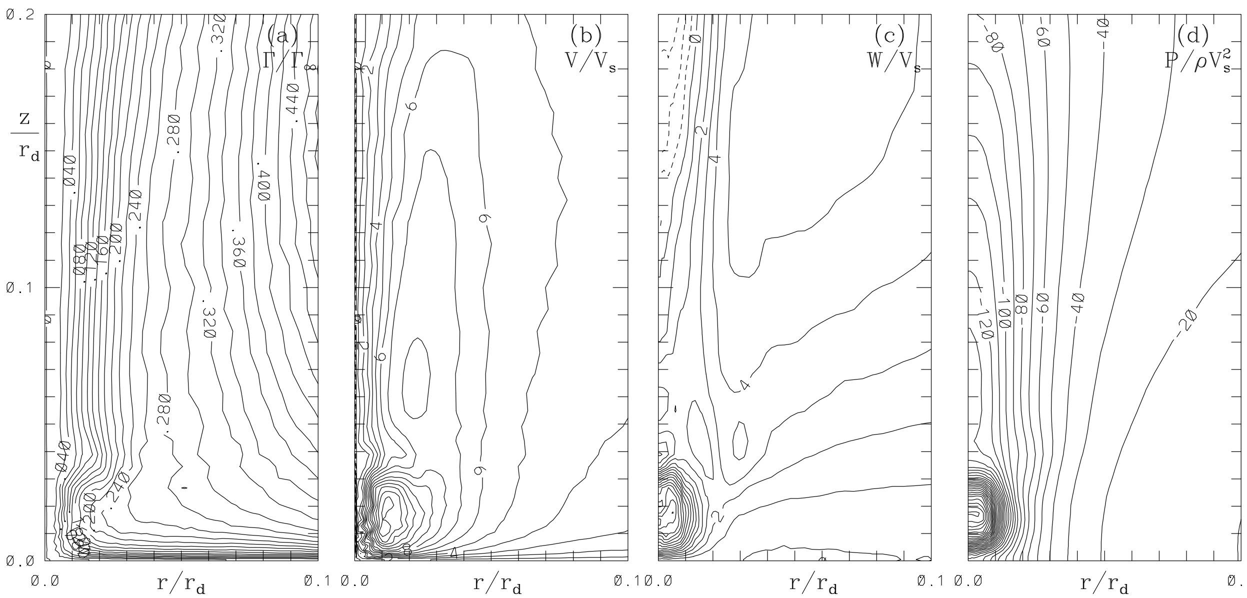

Figure 7: As in figure 6, zoomed in to show the central subdomain.

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