P10.3 EFFECTS OF FINE-SCALE DEBRIS ON DIFFERENT TORNADO CORNER FLOWS

Baiyun Gong*, D. C. Lewellen, and W. S. Lewellen
West Virginia University, Morgantown, WV.

1 INTRODUCTION

Studying tornado debris clouds is potentially important for several reasons: they represent one of the primary visual signatures of a tornado; large debris loadings can significantly enhance damage potential; differences between air and debris flow can complicate interpretation of Doppler radar measurements of velocity fields. In previous work we showed that, in addition, the presence of small-scale debris (e.g., dirt, sand), can in some cases significantly change tornado wind speeds and structure in the corner flow region (Lewellen et al., 2004). Debris centrifuging, negative buoyancy of debris and angular momentum transport by debris were all found to be important mechanisms through which the debris alters the tornado corner flow.

Here we extend our earlier results by using an extensive set of high-resolution large eddy simulations of the interaction of a debris-ingesting tornado with the surface. Sample summary results of debris cloud properties and debris effects on the flow structure are provided for simulated tornadoes with different sizes, strengths and cornerflow structure, and for different sizes and densities of debris. In addition, we propose a preliminary identification of the most important dimensionless parameters governing debris dynamics in tornadoes for the simple case of a single debris type.

2 NUMERICAL MODEL

The basic numerical model and simulation procedures employed here are as described in Lewellen et al. (2000), and the debris implementation as in Lewellen et al. (2004). The latter employs a two-fluid model (Marble, 1970): air is treated as the primary fluid (incompressible), and the debris is treated as a second continuous fluid, pressureless, of variable density and comprised of mono-sized spherical particles, coupled with the airflow through drag forces. Only the drag and gravitational forces are considered and debris volume fractions are assumed small (though debris mass loading can be high) so that particle-particle interactions can be neglected. Surface fluxes are dependent on the flow structure just above the surface and assumed surface and debris properties. A more detailed description will be provided elsewhere (Lewellen et al., 2006; Gong, 2006).

3 SIMULATION SET

A host of physical variables directly affect debris lofting, debris cloud structure, and changes in air-flow structure due to debris loading. We have conducted an extensive set of simulations to explore the affects of some of the most important of these. In the absence of debris the lowest order effects of many variables on tornado structure can be included through the corner flow swirl ratio, S_c (Lewellen et al., 2000). When debris is included additional parameters of potentially primary importance must be considered including: tornado size and strength (which we roughly classify by upper core radius, r_c, and swirl velocity, V_c, scales); debris diameter (d_p), density (σ) and availability; gravitational acceleration (g) and air viscosity (ν). The effects of these parameters are not all independent; for example increasing tornado size or strength, or decreasing gravity or debris size or density would all lead to an increase in total mass of the debris cloud. To organize the results of these parameter studies we propose an initial guess for the three most critical dimensionless parameters governing the behavior of tornado corner flows with debris (assuming a single debris type):

(1) the corner flow swirl ratio S_c;

(2) the ratio of a characteristic radial acceleration in the flow to gravity $A_a \equiv \frac{V_c^2/r_c}{g}$; and

(3) the ratio of a characteristic flow velocity scale to the terminal velocity of a debris particle in free fall $A_v \equiv \frac{V_c}{w_t}$, where $w_t = \sqrt{\frac{4gd_p\sigma}{3C_D\rho}}$ for particle Reynolds number dependent drag coefficient C_D.

At least roughly, S_c measures tornado structure without debris, A_a the relative importance of debris centrifuging, and A_v the relative ease of debris lofting.

For the principal simulation set we start from quasi-steady, non-translating simulations without debris of low, medium and high swirl tornado cornerflows. The velocity and/or length scales in these simulations

*Corresponding author address: Baiyun Gong, MAE Dept. PO Box 6106, WVU, Morgantown, WV, 26506-6106; e-mail: bgong@mix.wvu.edu.

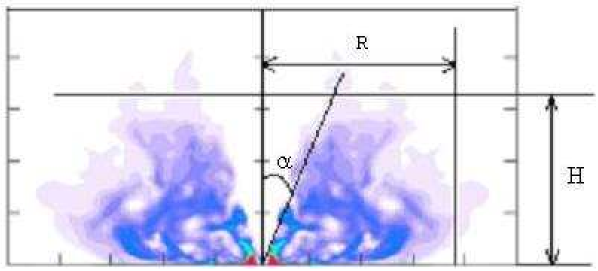

Figure 1: Instantaneous debris loading on a vertical cross section through a sample debris cloud showing schematically definitions of debris cloud height, radius and cone angle.

were then scaled and debris with different properties allowed to be picked up to produce a large set of simulations. In some cases g and ν were also varied. Values were generally chosen to provide independent variations of A_a and A_v, for example by varying d_p (to vary A_v with A_a constant) or scaling V_c together with d_p so that A_a varies with A_v unchanged. Some sets of variations were performed to achieve the same (or nearly the same) values of S_c, A_a, and A_v in different ways (e.g., by simultaneously varying d_p and σ, or g and ν). Generally speaking these simulations give similar values for our summary measures (e.g., the different sets of points in fig. 2 below). This lends support to our choice of principal dimensionless governing parameters.

Ranges in which the parameters varied include: $S_c = 0.8 \sim 12.$, $V_c = 50. \sim 150.$ m/s, $d_p = 0.1 \sim 2.0$ mm, $\sigma/\rho = 800 \sim 8000$ (mostly 2000). The nominal domain size was 2×2×2 km^3, finest vertical resolution 1 m at the surface, finest horizontal resolution 2 m for low swirl cases and 4 m for others. Simulations were run until near quasi-steady conditions were reached and then time and azimuthal averages taken for the results presented below.

4 RESULTS

Sample summary results are presented in the figures. They fall naturally into two categories that we consider in turn: properties of the debris cloud and effects on the airflow.

4.1 *Debris Cloud*

To summarize the debris cloud size and shape we compute nondimensionalized total mass, height, radius and interior cone angle. Figure 1 illustrates the latter three schematically. They have been defined such that 98% of the total debris mass falls within the the cloud limited by the given measure (e.g., below height H).

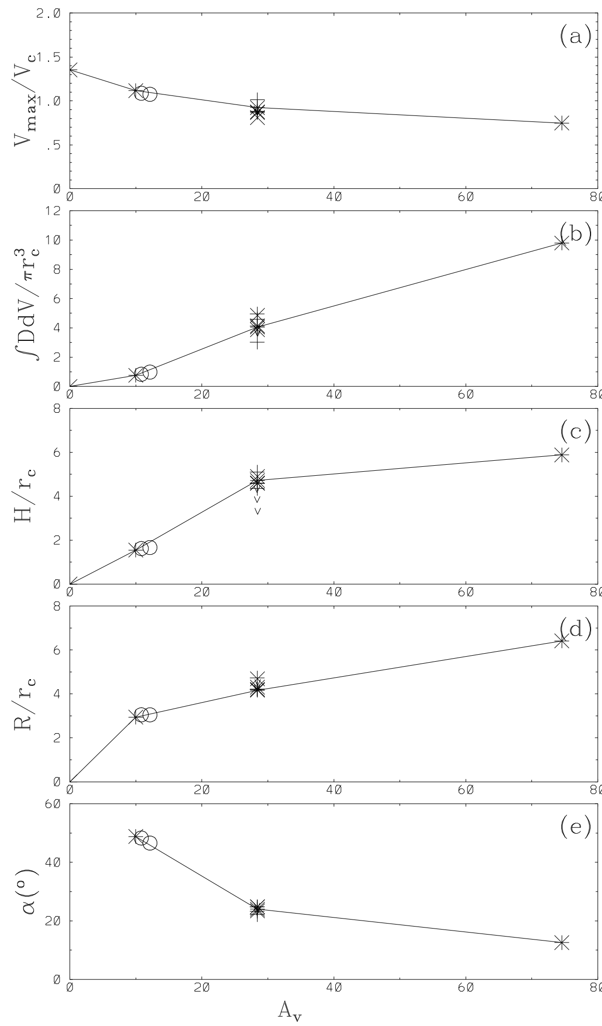

Figure 2: Mean quasi-steady results versus A_v for simulated medium swirl tornadoes with $A_a \approx 8.2$. Normalized (a) maximum mean swirl velocity; (b) debris cloud total mass; (c) debris cloud height; (d) radius; and (e) cone angle. Variations included changes in: d_p (*); g and ν (v); d_p and σ (o); surface pick-up parameters (x,+).

Results are shown for varying A_v (Fig. 2), varying A_a (Fig. 3) and varying S_c (Figs. 4, 5). For simplicity, the values of r_c and V_c from the appropriate simulations without debris are used in non-dimensionalizing quantities.

Not surprisingly, for fixed S_c and A_a, the debris cloud mass, height and radius increase with increasing A_v (figs 2b-d): a smaller particle terminal velocity relative to the tornado velocity scale will lead to more debris being lofted (and lofted to greater heights and for longer times). For increasing A_a (and fixed S_c, A_v) there are competing effects (figs 3b-d): increasing radial accelerations (and hence centrifuging) can

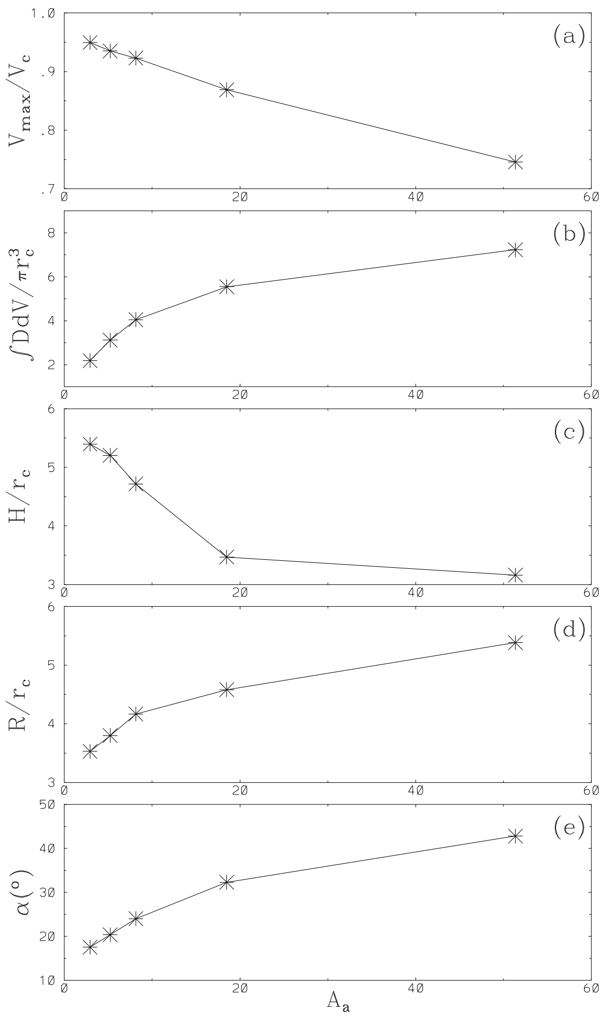

Figure 3: As in fig. 2 but versus A_a, with $A_v \approx 28.3$.

throw the rising debris out of the strongest updrafts, dropping H/r_c but increasing R/r_c; overall the total mass increases. There are competing effects as well when S_c is varied for fixed A_v and A_a (figs 4, 5c-e, 6). The relative vertical velocities are highest for low-swirl conditions but the area on the surface over which they occur is smallest; the reverse holds for high-swirl conditions. As a result the intermediate S_c case produced the largest dimensionless debris cloud mass.

The interior cone angle is a function of the relative importance of swirl velocities to vertical velocities (hence increasing with S_c, fig. 5f) and the relative importance of centrifuging (increasing with increased radial accelerations and hence increasing A_a, fig. 3e, or with increasing w_t and hence decreasing A_v, fig. 2e). All of these effects contribute to the visual appearance of debris clouds (fig. 6).

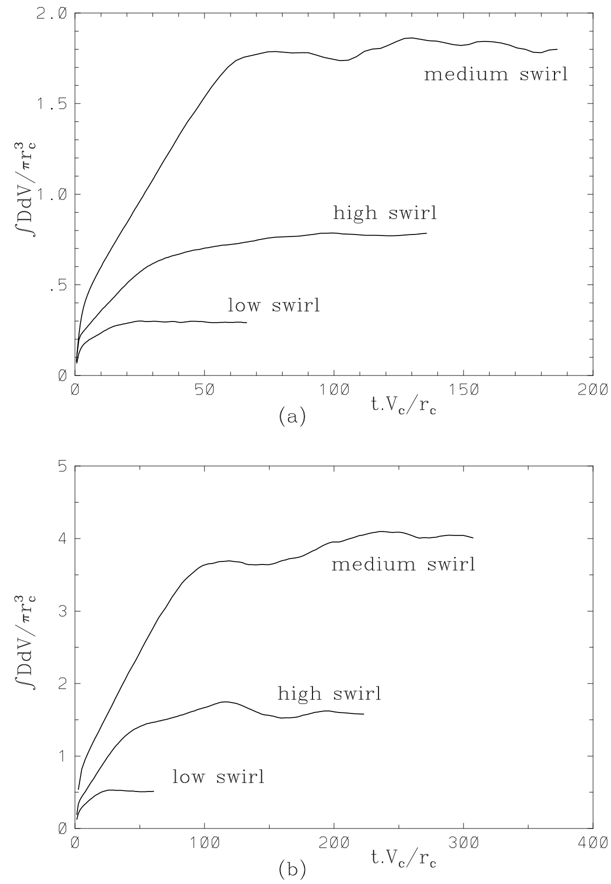

Figure 4: Time histories of normalized total debris mass for different swirl ratio tornadoes with: (a) $A_v \approx 22.9$, $A_a \approx 2.8$; (b) $A_v \approx 28.3$, $A_a \approx 8.6$.

4.2 *Effects on Air Flow*

Regardless of how it is achieved we have found that an increase in total debris loading generally produces a decrease in peak swirl or vertical velocities in the corner flow region (e.g., fig. 2a,b; 3a,b). The reduction is generally largest for low-swirl conditions. The presence of debris can lead to significant structural changes in the flow as well. Figure 7 illustrates one example. A high-swirl tornado corner flow that has multiple strong secondary vortices in the absence of debris (e.g., fig. 7a) will loft debris primarily within the secondary vortices if the velocity scale is modest and/or debris larger or denser (fig. 7b), but, given smaller or lighter debris (fig. 7c) and/or higher velocity scale (fig. 7d), will reach sufficient debris loading in the main updraft annulus to severely weaken or even destroy the secondary vortices.

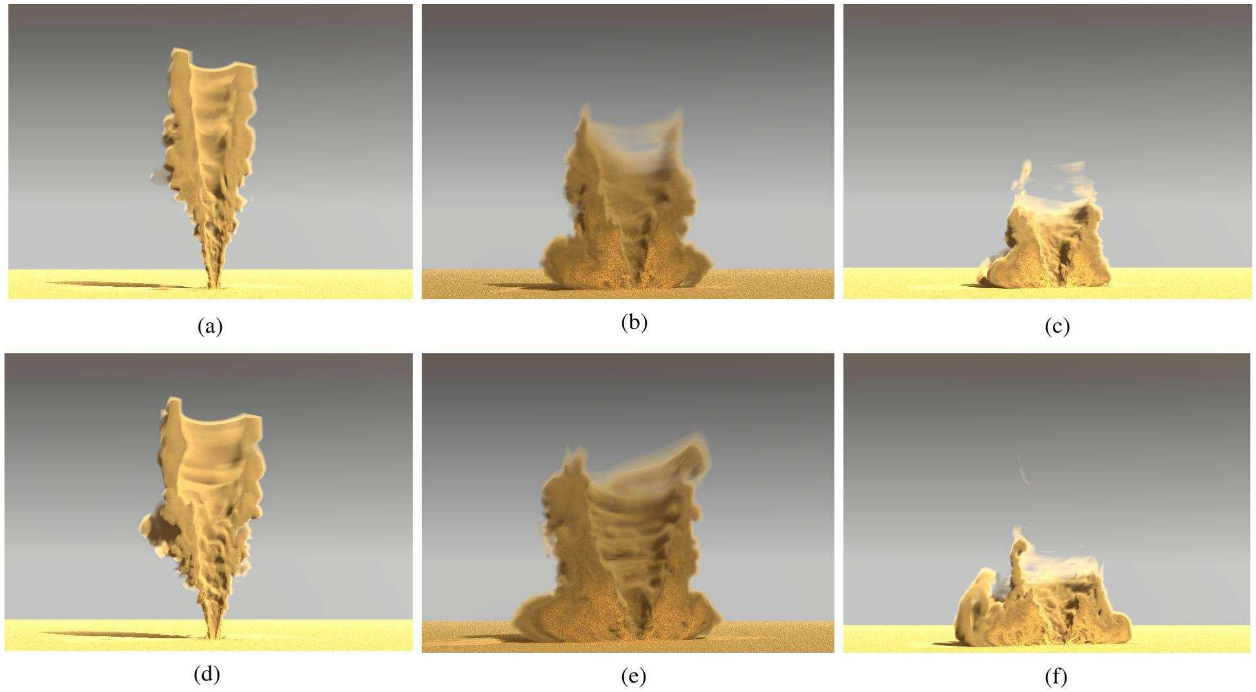

Figure 6: 3-D cut-away views of the debris cloud for different simulated tornadoes with: $A_v \approx 22.9$, $A_a \approx 2.8$ (a-c) ((a) $S_c = 1.0, V_c = 75m/s, d_p = 0.5mm$; (b) $S_c = 3.2, V_c = 56m/s, d_p = 0.38mm$; (c) $S_c = 10.6, V_c = 73m/s, d_p = 0.5mm$) and $A_v \approx 28.3$, $A_a \approx 8.6$ (d-f) ((d) $S_c = 1.0, V_c = 136m/s, d_p = 0.8mm$; (e) $S_c = 3.3, V_c = 93m/s, d_p = 0.5mm$; and (f) $S_c = 10.0, V_c = 133m/s, d_p = 0.8mm$).

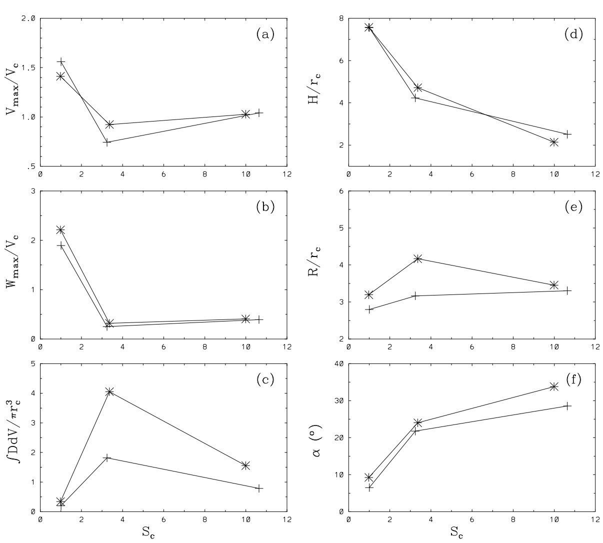

Figure 5: Normalized maximum mean swirl velocity (a), maximum mean vertical velocity (b), total debris mass (c), debris cloud height (d), radius (e) and cone angle (f) versus S_c. (+) $A_v \approx 22.9$, $A_a \approx 2.8$; (*) $A_v \approx 28.3$, $A_a \approx 8.6$.

5 CONCLUDING REMARKS

The present work reinforces our earlier conclusions that the presence of debris can significantly affect tornado cornerflow structure. These effects, as well as debris cloud properties, are sensitive to a host of physical parameters, many of which we have explored to date only in simple limits. In particular, the present study has focused on quasi-steady results, and a single debris species at a time, with unrestricted availability at the surface. Given the sensitivity of the results to debris type, and some of the longer timescales involved in the debris cloud dynamics, it is important to extend these results by treating realistic spectra of debris, keeping track of its pickup and deposition on the surface, and considering evolving debris clouds in more detail.

6 ACKNOWLEDGMENTS

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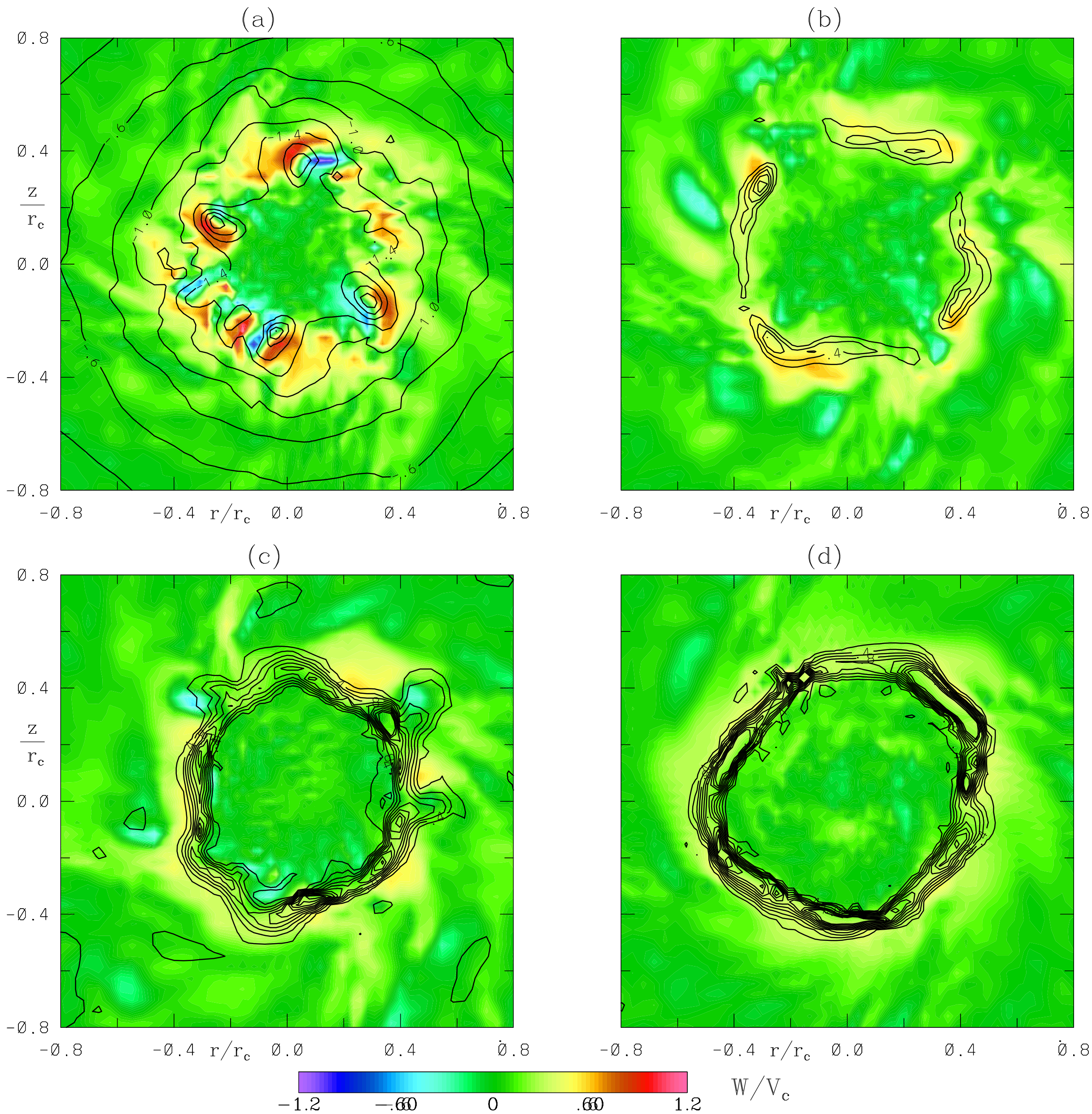

Figure 7: Instantaneous horizontal cross section of simulated tornadoes at a height of 0.12 r_c showing: (a) normalized vertical wind velocity (color) and pressure (contours in units of ρV_c^2, 0.2 interval) for tornado without debris; (b-d) normalized vertical wind velocity (color) and debris loading (contours, 0.2 interval) for (b) V_c = 73 m/s, d_p = 2.0 mm; (c) V_c = 73 m/s, d_p = 0.5 mm; (d) V_c = 133 m/s, d_p = 2.0 mm.

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