P10.2 TRANSONIC VELOCITIES IN TORNADOES?

W. S. Lewellen*, J. Xia and D. C. Lewellen
West Virginia University, Morgantown, WV.

1. INTRODUCTION

There has long been speculation about what maximum wind speeds are achievable in extreme tornadoes. A recent review (Davies-Jones et al. 2001) indicates a limit on observations of between 125 m/s and 140 m/s, with these values somewhat larger than the so-called *thermodynamic speed limit* based on convective available potential energy in the storm environment.

Here we suggest that much higher transonic velocities may occur in small regions of time and space. The 3 key points covered here that lead to this suggestion are: (1) That based on the results from compressible, large–eddy simulations of corner flow dynamics in a tornado (Xia, 2001), the basic flow field structure is not drastically changed when velocities reach or exceed the local speed of sound; (2) Large near-surface intensification factors can be achieved, so transonic velocities do not require extremely large pressure drops or velocities to be created by the storm in the upper core; and (3) Any transonic regions would be small and situated where observation would be very difficult, so that existence is not ruled out by any known measurements.

2. REVIEW OF COMPRESSIBLE RESULTS

An instantaneous view of simulated velocity distributions in a low-swirl, high-Mach number tornado is shown in fig. 1. The velocities are normalized by the maximum swirl velocity, V_c , in the flow above the corner flow, and the lengths by $r_c = (V \cdot r)_o/V_c$ for ease of comparison with the view of such a vortex breakdown for incompressible flow (Lewellen et al. 2000a) (hereafter LLX). The views are quite similar with the most striking difference the increase in the height of the breakdown by approximately a factor of 4 in this high-Mach number case. This is associated with an increase of approximately 40% in the time-averaged maximum vertical velocity, Wmax, below the vortex breakdown, while the time-averaged maximum swirl velocity, Vmax, is increased less than 5%. This leads to the highest Mach numbers occurring near the centerline where both the highest velocities, and lowest values of speed of sound occur, and where the velocity is nearly vertical.

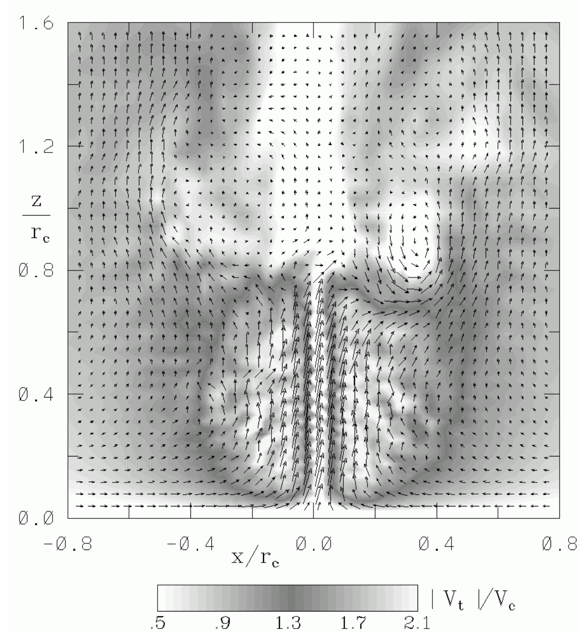

Figure 1: Instantaneous vertical cross section of compressible low-swirl tornado vortex at large Mach number showing normalized swirl velocity (grayscale) and magnitude of the velocity vector in the r-z plane (arrows, interpolated onto a uniform grid for clarity; maximum length corresponds to $V_{rz}/V_c = 3.60$).

The axisymmetric, time-averaged, Mach number contours for the same simulation represented in fig. 1 are shown in fig. 2. Although the maximum time averaged Mach number, M_{max} , for this case exceeds 1, the region within which $M > 0.5$ is relatively small. $M_{max} = 1.24$ occurs on the axis about midway between the vortex breakdown and the surface. The maximum swirl velocity occurs at this same height at $r \sim 0.1\ r_c$ where the axial and vertical velocities are roughly equal. Note that the breakdown height is unsteady with an average height of $\sim 0.6\ r_c$, while the instantaneous value at the time of fig. 1 is somewhat higher.

* *Corresponding author address:* W. Steve Lewellen, MAE Dept., WVU, Morgantown, WV 26506-6106; e-mail: WSLewellen@mail.wvu.edu

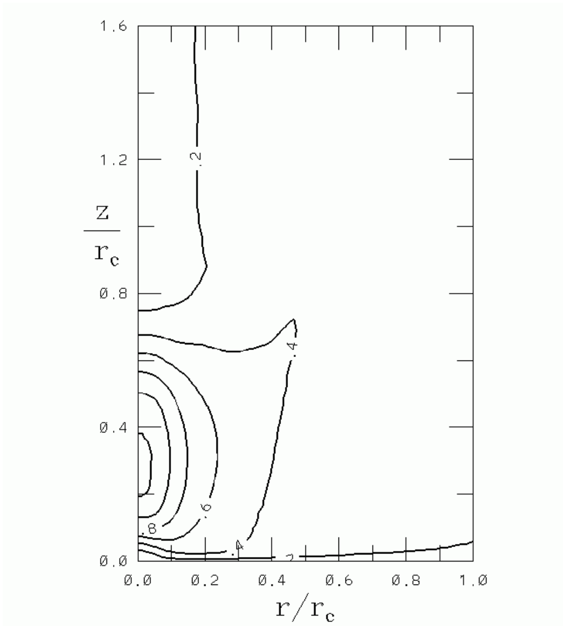

Figure 2. Axisymmetric, time-averaged contours of local Mach number for the same simulation as represented in fig. 1.

The compressibility effects in the time averaged distributions for medium or high swirl corner flows are substantially weaker than those shown for low swirl, since they are essentially limited to influencing the secondary vortices where the highest Mach numbers are found in these cases. The appearance of the secondary vortices remain qualitatively similar to that for incompressible simulations, as exhibited for example for high swirl in fig. 8 of LLX, even when the peak Mach number exceeds one in the strongest secondary vortices. The potential for transonic velocities in the secondary vortices was suggested by Fiedler (1996), who used an axisymmetric, laminar model to argue that speeds in a tornado need not be limited to the speed of sound.

3. SURFACE INTENSFICATION

Our simulated M_{max} occurs relatively close to the surface where the dynamics of the flow in the surface layer turning upward into the core can yield a local intense region of minimum pressure. Here we distinguish between the results for quasi-steady flow and that for unsteady conditions where the surface intensification can become much stronger.

3.1 Quasi-steady intensification

The ratio of the maximum low-level pressure drop across the tornado vortex to that above the interaction with the surface is limited to approximately a factor of 4 for the simulation represented in fig. 2, roughly the same as for a similar incompressible case.

The maximum time-averaged Mach number is shown in fig. 3 as a function of the maximum time-averaged swirl velocity well above the surface, V_c , divided by the speed of sound in the undisturbed atmosphere, a_o. A series of points from Xia (2001) are plotted for corner flows with low, medium, and high swirl ratios, along with the corresponding lines that represent an isentropic approximate transform from incompressible results for velocity intensification due to surface interaction.

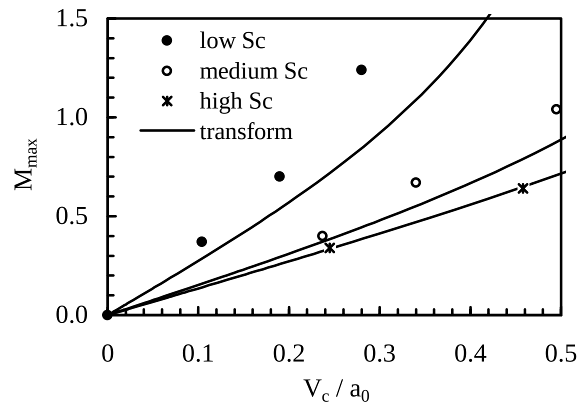

Figure 3. Maximum time-averaged Mach number within the tornado versus V_c/a_o for low, medium, and high corner flow swirl ratios.

The largest intensification of the time-averaged Mach number occurs for corner flows with low swirl ratios with the intensification factor increasing as V_c increases. For higher swirl ratio corner flows the time-averaged Mach number intensification is greatly reduced, as the secondary vortices with their instantaneous higher Mach numbers are essentially averaged out. The upper numerical data point comes from the same simulation as fig.1 and 2. It shows a time-averaged surface interaction amplification of the Mach number by a factor of 4.4. The corresponding incompressible run shows a maximum velocity amplification of 2.7. This velocity ratio is increased to 3.7 in the compressible simulation represented by this particular point on the curve by the drop in density in the region of the highest velocity. The remaining increase of approximately 20% in the Mach number amplification is contributed by the decrease in local speed of sound associated with the decreased local temperature.

Figure 3 suggests that local regions of transonic velocity may occur if values of swirl velocity greater than ~ 90 m/sec in the region above the surface interaction are combined with a low swirl ratio corner flow near the critical value. Since the corner flow swirl ratio is essentially controlled by flow in the surface layer below approximately 100 m (LLX), and since 90 m/sec is within the range supportable by a mesocyclone, there is a chance that some reported velocities above 90 m/sec may have occurred in combination with a low swirl ratio corner flow. Our model predicts that transonic velocities can occur in small regions of such tornadoes.

3.2 Unsteady Overshoots

Under certain unsteady conditions (Lewellen et al. 2000b; Lewellen and Lewellen, 2002) the Mach number intensification induced by surface interaction can be much larger than that expected for quasi-steady tornadoes given in fig. 3. When a simulation similar to that given by Lewellen et al. (2000b) is repeated for compressible flow, fig. 4 shows that although the peak overshoot in pressure drop may be significantly reduced relative to the incompressible prediction, the overshoot can still be strong enough to produce transonic velocities.

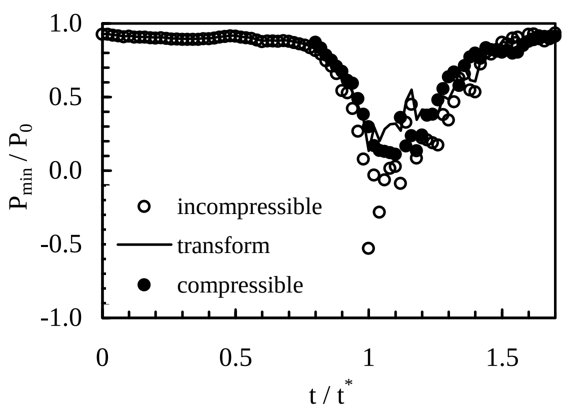

Figure 4. Comparison of minimum perturbation pressures as a function of time during the temporal overshoot discussed in the text. The pressure estimated from the isentropically transformed incompressible pressure is also shown.

The transformed approximation shown in fig. 4 agrees reasonably well with the full solution. It captures the effect of the density drop in the momentum equation, but misses the choking effect imposed by continuity which forces both the vertical velocity and core size to be increased. Conditions in the immediate spatial and temporal vicinity of minimum pressure are somewhat similar to those occurring in the quasi-steady simulation shown in fig. 1, but they are occurring for much more modest velocities and pressure drop well above the surface.

The incompressible case does not depend on the total pressure, but for purposes of fig. 4, a constant pressure has been added so that the total pressure is the same for both cases. The compressible result yields a decreasing central density that imposes a limit on minimum vortex core size as the Mach number increases. This limit on the minimum radius in turn constitutes a limit on the minimum pressure. Examination of the local Mach number in the vicinity of the minimum pressure shown in fig. 4, shows that a value of ~ 2 has been reached. Although the dynamics of transonic swirling flow are quite different from that of simple 1-D transonic flow, with Mach numbers permitted to exceed 1 within the minimum flow cross section (Lewellen et al. 1969), it still imposes a modified choking condition, which restricts the pressure drop within this minimum flow cross section.

Note that even in this rather extreme example where the minimum pressure drops as low as 20% of P_o, much lower than generally expected to be associated with any tornado, maximum pressure drops above 1 km for the simulation shown in fig. 4 do not exceed approximately 5% of P_o. When scaled so that a_o = 347 m/sec on a 1 km domain radius, t* = 50 seconds, and the time over which the low level pressure drops below 0.8 P_o is ~ 30 seconds. During this temporal overshoot, the small region of lowest pressure is effectively shielded from higher pressures aloft by the combination of a vortex breakdown and a conical region of flow. This transient flow pattern provides an efficient pressure recovery in the vertical, swirling flow away from the region of minimum pressure, and thus retards the rate at which the evolving downdraft from above can fill the low level region of extremely low pressure.

The incompressible results for a range of unsteady overshoots (Lewellen and Lewellen, 2002) show that the ratio of the peak near-surface, swirl velocity to the upper V_c can easily exceed 6, with the peak vertical velocity ~ 1.4 times larger. This suggests the ratio of the near-surface peak M to the upper level V_c /a_o may be of order 10.

4. OBSERVATIONAL DIFFICULTIES

If velocities can exceed sonic velocity, why haven't such high velocities been observed? Recording such high velocities is extremely difficult for several reasons. First, in a low swirl corner flow where such high Mach numbers appear most likely to occur, the region of any transonic velocities is expected to be well inside a heavy cloud of debris. Second, the highest velocities will be essentially in the vertical direction, which is the most difficult velocity component to be directly observed by Doppler radar. Third, this high Mach number is predicted to occur within ~ 100 m of the surface which makes it extremely difficult to observe from a safe distance. Fourth, the small spatial and temporal scale of the highest velocities insures considerable reduction of the measured value by time and space averaging for current radars.

Consider the finescale radar measurements of the Dimmitt, Texas tornado (Wurman and Gill, 2000) to see how a region of transonic velocity might be masked. For approximately the first 2 minutes of their data they report a two-cell vortex with a central downdraft above 400 m combined with a one cell vortex below 300 m. This is consistent with our model of a "low-swirl corner flow", at least potentially similar to fig. 1 and 2. It is interesting to attempt to interpret their data as coming from a tornado similar to our compressible transonic simulation.

They reported a peak raw DOW-measured velocity of 74 m/s near the beginning of the period at a height of ~ 600 m. In their equation for adjusting this velocity for beam resolution (quoted as 61 m), we use $r = 0.6\ r_c$ from the simulation and $(V\ r)_o \sim 18000\ m^2/s$ taken from their fig. 21 at 1 km radius. The upper level observation and simulation would then be consistent for $V_c = 83$ m/s and $r_c = 216$ m. With $a_o = 340$ m/s, fig. 3 yields $M_{max} \sim 1$ and fig. 2 suggests this occurs in the vertical velocity on the axis ~ 90 m AGL. Less than 4% of this vertical velocity would be seen with the radar antenna set at 2^o to make the scan. The strongest simulated swirl velocity of ~175 m/s occurring at r ~ 20 m would be reduced to ~ ½ this value in the raw radar data due to the beam width. There would also be a difference in the maximum recorded velocities on opposite sides of the axis of ~ 10 m/s due to the ~ 4% contribution from the vertical velocity at that location.

The net result is that the low-level peak velocity reported (also 74 m/s) is only modestly smaller than that indicated (~ 90 m/s) for the "simulated" recordings. When the data reduction complications of dealiasing the signal and debris velocities not necessarily representing air velocities are added, it leaves room to question whether transonic velocities might have been masked in a small region of this tornado for a brief time at the beginning of their observation period. This possibility is further strengthened by the early, relatively rapid, tornado evolution that could be associated with further temporal intensification in an even smaller low-level region.

5. CONCLUDING REMARKS

We suggest that velocities in some tornadoes may achieve significantly higher values than generally believed. Compressible large–eddy simulations of corner flow dynamics in a tornado indicate that there are no apparent physical barriers to transonic speeds occurring within small regions of real tornadoes for brief time periods. Such conditions appear most likely to occur for corner flows within the low-swirl regime, where locally intensified velocities in a relatively small region below a vortex breakdown allow Mach numbers to be more than 4 times greater than that at higher levels directly supported by storm dynamics. Even larger local levels of intensification in Mach numbers may occur during the sharp temporal overshoot in near-surface intensity that simulations indicate may occur while a tornado's corner flow evolves from a very low swirl to a high swirl.

There may be effects not currently included in our model that could act to reduce the strong surface intensification to such an extent that transonic velocities can not occur. For example, our idealization of the surface boundary as having a fixed uniform aerodynamic roughness may significantly under predict turbulence and dissipation generated by the interaction with the surface. A more complex, realistic simulation of the interaction of the corner flow with the surface may be required when great amounts of debris are being ripped from the surface and carried upward hundreds of meters. Thus, we leave the question of whether transonic velocities actually occur in any tornado open.

ACKNOWLEDGEMENT

This study was funded by NSF Grant ATM-9876450.

REFERENCES

Davies-Jones, R., R. J. Trapp, and H. B. Bluestein, 2001: Tornadoes and Tornadic Storms. *Severe Convective Storms*, C. A. Doswell, Ed., Amer. Meteor. Soc., 167-221.

Fiedler, B. H., 1996: The sonic speed limit of tornadoes. Proc. of the AMS 18th Conf. on Severe Local Storms, 19-23 Feb., San Francisco, CA. 385-386.

Lewellen, W. S., W. J. Burns and H. J. Strickland, 1969: Transonic Swirling Flow. *AIAA .l.*, **7**, 1290-1297.

Lewellen, D.C., and W. S. Lewellen, 2002: Near-surface intensification during unsteady tornado evolution. Paper 12.8 in this Proceedings.

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, Proc. of the AMS 20th Conf. on Severe Local Storms, Orlando, FL. 265-268.

Wurman, J. and S. Gill, 2000: Finescale radar observations of the Dimmitt, Texas (2 June 1995), tornado. *Mon. Wea. Rev*., **128**, 2135-2163.

Xia, J., 2001: Large-eddy simulation of a three-dimensional, compressible tornado vortex. WVU PhD Thesis, Available from: http://etd.wvu.edu/templates/showETD.cfm?recnum=2216