Nolan, D. S., 2025: Comments on "The strongest winds in tornadoes are very near the ground." *Electronic J. Severe Storms Meteor.*, **20** (1), 1–5.

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Comments on "The Strongest Winds in Tornadoes Are Very Near the Ground"

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ABSTRACT

Kosiba and Wurman (KW) investigated the vertical variations of windspeeds observed in tornadoes by mobile Doppler radars over the last 30 y. By comparing windspeeds observed at the lowest altitudes, including some within 15 m of the surface, KW conclude that the most extreme instantaneous winds in tornadoes occur very near the ground. Importantly, KW distinguish between this finding and recent studies using large-eddy simulations (LES) by Nolan et al. (N17) that show maximum azimuthally and temporally averaged windspeeds occurring at 30–70 m AGL. Here we show that, when the N17 model output is processed in a manner similar to KW, the same result is found: the most extreme instantaneous winds occur below 20 m AGL. This result strengthens the claims of KW, since LES produce the same result as their observational analysis.

1. Introduction

Reliable in-situ measurements of near-surface wind speeds in tornadoes are extremely rare (Blair et al. 2008; Blanchard 2013). However, due to the successful efforts of many field campaigns (Rasmussen et al. 1994; Wurman et al. 2012; Lyza et al. 2022), portable Doppler radars have sampled wind fields of hundreds of tornadoes. While the large majority of such observations occur 100 m or more above the ground, laboratory experiments (Ward 1972; Church et al. 1979; Zhang and Sarkar 2012), theory (Kuo 1971; Rotunno 2013), and numerical simulations (Nolan and Farrell 1999; Fiedler 1998; Lewellen et al. 2000) suggest that the strongest winds occur closer to the surface.

In a recent study, Kosiba and Wurman (2023; hereafter KW) used their large collection of Doppler radar observations of tornadoes to determine the altitude where the most extreme horizontal wind speeds in tornadoes occur. The maximum wind speed at each height was normalized by the maximum in each profile, and then composited to produce a representative vertical profile (see their Fig. 4). This profile shows that the fastest winds occur at the lowest analyzed level, just 15 m above ground level (AGL).

KW contrasted this finding with the results from the large-eddy simulations (LES) of Nolan et al. (2017; hereafter N17) that showed vertical profiles of temporally and azimuthally averaged winds in tornadoes of varying types. These profiles had maximum values at heights ranging from 30 to 70 m AGL.

The purpose of this comment is to show that when the wind fields in the LES of N17 and other recent studies are analyzed in the same manner as KW, they produce nearly identical results. This points to a converging picture of the low-level structure of tornadoes and the altitude where the most extreme wind speeds occur.

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Table 1: Properties of the LES tornadoes from N17 and D17 used in this study. The labels such as "60" and "40" refer to the thermodynamic speed limit (in m s^{-1}) associated with the convective forcing. The value for CTRL would be 80. $\{V\}_{max}$ is the maximum temporally and azimuthally averaged tangential wind speed.

Simulation	Tornado Type	Translation Speed (m s^{-1})	$\{V\}_{max}$ (m s^{-1})	Mean Max Inst. V_g (m s^{-1})	Height of Mean Max Inst. V_g (m)
CTRL	Medium swirl	0	93	139	8.75
W60M	Medium swirl	10	70	122	11.25
W40L	Low swirl	10	53	84	13.75
W40M	Medium swirl	10	47	84	8.75
W40H	High swirl	10	40	76	6.25

2. Recent large-eddy simulations

Bryan et al. (2017) and N17 presented a new set of three-dimensional large-eddy simulations of tornadoes. The computational domain was a closed, rotating chamber, 40 km on each side and 15 km deep. The tornadoes were generated by low-level convergence forced by a fixed vertical forcing function. Tornado intensity was controlled by modulating the strength of this vertical forcing, which is measured by the speed achieved by acceleration along the central vertical axis, equivalent to the so-called "thermodynamic speed limit" (Fiedler and Rotunno 1986; Rotunno 2013). Tornado structure was controlled by adjusting the environmental rotation rate.

Along with very fine grid spacing in the center of the domain (5 m in the horizontal, 2.5 m in the vertical), these simulations introduced a new feature of "eddy injection" to ensure that the boundary layer flow was fully turbulent before arriving at the inner core of the tornado. Similar to previous studies, N17 used these simulations to measure the ratio of the tornado intensity, as defined by the temporally and azimuthally averaged tangential wind speeds, to the thermodynamic speed limit. In addition N17, Dahl et al. (2017; hereafter D17), and Dahl and Nolan (2018; hereafter D18) used these simulations to explore the relationships between azimuthally averaged winds above the surface, azimuthally averaged winds at 10 m AGL, and peak 3-s gusts at fixed 10-m AGL points.

N17 computed the ratios of the maximum 3-s gusts at 10 m to the temporal-azimuthal-mean tangential winds and found that the average fastest 3-s gusts over a 5-min interval were 10–25% greater than the maximum mean winds aloft, and that the fastest individual 3-s gusts over the 5-min interval were 29–72% greater than the mean winds aloft. Very extreme 3-s gusts frequently occurred in these simulations, often >100 m s^{-1} and even reaching 180 m s^{-1}. Subsequently, D18 generated simulated radar observations and compared them to the 3-s surface gusts occurring directly below the observation. They found that the median underestimates of surface winds by simulated radar measurements varied from 75% to 60% for ranges of 0.3–10.5 km (Fig. 18 of D18). While these calculations were not applied to instantaneous winds, N17 found that instantaneous 10-m windspeeds were 20–100% faster than 3-s gusts (Fig. 2 of N17). Therefore, the D18 radar underestimates of instantaneous 10- m winds would be significantly greater.

3. Comparison to KW

KW, of course, used radar observations of real tornadoes, and sought to find the fastest instantaneous windspeeds at any level. To show that our simulated tornadoes provide nearly identical results, we use model output from five of the LES produced in N17 and D17. The simulations and their properties are listed in Table 1. Each dataset consists of the three-dimensional wind fields every 1 s for 300 s. During this period, the structure and intensity of each tornado was in a quasi-steady state.

First, the model data was processed in a manner closely following KW. For each output time, the maximum ground-relative horizontal windspeed (V_g) at each level was computed, and then the values were normalized by the maximum value of V_g between the surface and (z = 100 m) to make $|V_g|$. For each of the five simulations, $|V_g|$ profiles from three randomly selected output times were plotted to create Fig. 1, which is intended to replicate Fig. 2 of KW. While the colors of the lines in KW indicate the altitude at which the maximum V_g occurs for each profile, we use colors to indicate from which of the five simulations each profile was taken. Nonetheless, our Fig. 1 is very similar to Fig. 1 of KW. One outlier from the W40L simulation appears with much slower windspeeds below 50 m, but coincidentally, a similar outlier appears in KW (note their thin blue line that starts near $|V_g|$ = 0.6).

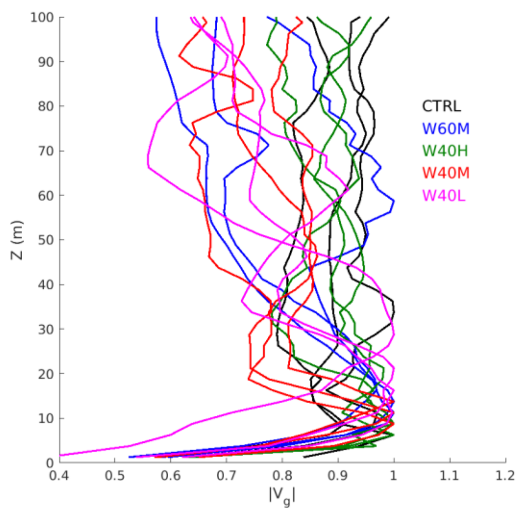

Figure 1: Vertical profiles of maximum instantaneous windspeeds in the simulated tornadoes. Each curve shows one snapshot of the maximum ground-relative wind speed at each level, normalized by its maximum value below 100 m ($|V_g|$). Three samples are shown for each simulation.

With limited data, KW sought to create single, representative profile of windspeed as a function of height for tornadoes, by compositing the vertical derivatives $d|V_g|/dz$ of the profiles in four different height ranges. They then vertically integrated the composite $d|V_g|/dz$ values to produce the profile shown in their Fig. 4. Our simulations provide three-dimensional wind fields, making a similar calculation of $d|V_g|/dz$ unnecessary. We instead show vertical profiles of the maximum V_g averaged over all 300 outputs at each level, separately for each simulation. This is useful because their different intensities and structures allows them to be easily compared on the same plot, as shown in Fig. 2. The 95th-percentile values are also shown.

Much like Fig. 4 of KW, our Fig. 2 also indicates that the most extreme windspeeds in tornadoes occur very close to the ground. We can also see that the locations and relative values of the most extreme windspeeds, as compared to winds aloft, vary with tornado intensity and structure. The heights of the fastest windspeeds decrease with increasing swirl of the tornado, similar to the heights of fastest the azimuthal-mean winds in N17, but are within 20 m of the surface (Table 1).

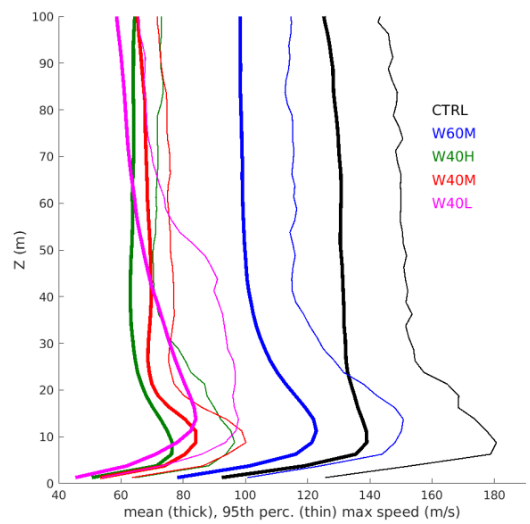

Figure 2: Averages of the maximum horizontal wind speed at each height over the 300 output times (thick), with 95th-percentile values (thin).

The simulations also can provide profiles of average maximum vertical velocities. These are shown in Fig. 3. While the updraft intensities generally increase with height, all the simulations show a local enhancement of maximum updrafts near the surface, between 8–20 m. W40L is an outlier, with its mean maximum updraft exceeding 80 m s^{-1} at 13.75 m height. This is even greater than the mean maximum for CTRL, which had convective forcing twice as strong. This suggests that low-swirl tornadoes have the most extreme low-level updrafts and the greatest propensity for lofting large debris, which is consistent with previous studies (Baker and Stirling 2017; Miller et al. 2024).

4. Conclusions

A caveat that may apply to both the observational and numerical results is that the tornadoes studied were in relatively "open" environments, without buildings or substantial tree coverage at the tornadic base (which radar beams would not penetrate). Depending on their size and number, the presence of obstacles could change the distribution of extreme winds drastically (e.g., Kawaguchi et al. 2020). In addition, significant debris loading, which would be likely to occur in suburban and urban environments, can reduce the low-level wind speeds (Lewellen et al. 2008; Bodine et al. 2016).

Nonetheless, the main conclusion of this paper is that the simulations of N17 and D17 produce essentially the same results as the KW observational analysis, which means it is very likely that both are physically correct.

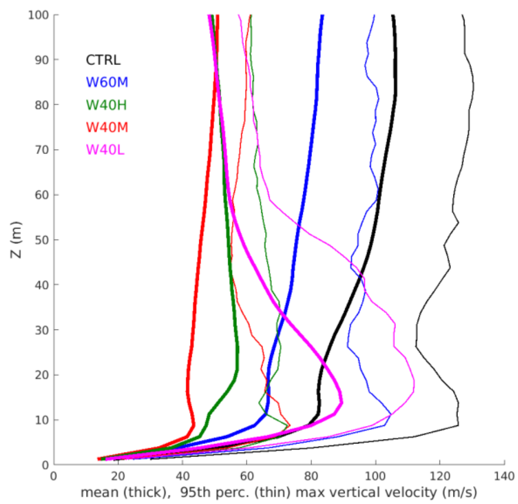

Figure 3: Averages of the maximum vertical velocity at each height over the 300 output times (thick), with 95th percentile values (thin).

ACKNOWLEDGMENTS

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Reply

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We are encouraged by the agreement concerning the heights above ground of the maximum tornado winds between the observational findings of Kosiba and Wurman 2023 (KW23) and the reanalyzed numerical modeling results of Nolan et al (2017) presented in Nolan 2025 (N25). Only recently have accumulated efforts from decades of field observations resulted in statistically meaningful numbers of cases for intercomparison and analysis [Wurman et al. 2021 (W21), which presented an analysis covering 120 distinct tornadoes and KW23], to provide context for rare reliable in-situ observations inside tornadoes (Wurman 2008; Blanchard 2013; Kosiba and Wurman 2013; Wurman et al. 2013; Kosiba and Wurman 2016). N25's reanalysis of model output in a fashion that parallels the methodology applied to radar data in K23, W21, and Kosiba and Wurman 2013, specifically examining shorter-period windspeed fluctuations, adds substantial confidence to the results of K23.

We agree with N25, and stated explicitly in several radar studies (e.g., W21) that radar sampling of low-level winds in tornadoes is biased towards winds occurring in open conditions. This is because non-open environments (e.g., towns, forests) have, by definition, objects (e.g., trees, buildings) which obstruct radar beams and thus windspeed observations. It is extremely challenging, to say the least, to obtain below-obstruction-height radar observations between buildings, interior to forests. This is particularly impactful when comparing low-level radar windspeed observations with windspeed inferences from from documented damage in towns (e.g., Wurman et al. 2024; Wurman and Alexander 2005).

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We also note that quantifying swirl ratio in tornadoes is particularly challenging "in the wild". Efforts have been made (e.g., Wurman 2002; Alexander and Wurman 2005; Kosiba and Wurman 2010; Kosiba and Wurman 2013), but defining, observing and quantifying low-level, near-surface flow and geometry are problematic.

While actual field observations in real world tornadoes provide the ultimate validation of conceptual models of tornado structure, such observations will likely always be limited by the transience, wide distribution and violence of tornadoes. Tornado observations in nature are necessarily uncontrolled. Controlled laboratory simulations of tornadoes (e.g., Church et al. 1979; Refan et al. 2017; Haan et al., 2008) have struggled to produce fully realistic tornadoes. Numerical models, especially when analyzed in fashions lending to comparisons with actual observations (N25), offer an extremely valuable complement to observations. Every individual method exhibits advantages and limitations. Comprehensive deconvolving of the causal relationships among intensity, surface roughness, thermodynamic influences, vortex structure, vertical and horizontal and temporal variations of wind velocities, turbulence, and other factors, depends upon synergy between observations, laboratory, and conceptual and numerical modeling.

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REVIEWER COMMENTS
(For Nolan Manuscript)

[Authors' responses in *blue italics.*]

REVIEWER A (Robin L. Tanamachi):

Initial Review:

Recommendation: Accept with minor revisions.

General comments: Low-altitude radar observations of tornadoes (KW) and simulations of tornado-strength convective vortices (N17) appear to be telling a convergent story about wind speeds near the ground in deep convective vortices. I have given considerable thought to whether alternative explanations exist for the convergence, and I honestly can't think of any. I recommend this Comment be accepted once the following minor comments have been addressed.

[Minor comments omitted...]

REVIEWER B (Daniel T. Dawson):

Initial Review:

Reviewer recommendation: Accept with minor revisions.

General Comment: This short comment describes a reanalysis of several recent LES simulations of tornadoes by the author (Nolan et al. 2017; N17) that is designed to match as closely as possible the analysis methodology of Kosiba and Wurman (2023; KW) as applied to vertical wind profiles from the mobile Doppler radar observations. The results of the reanalysis are in agreement with those of KW in that the height of the maximum horizontal wind speeds in the simulated tornadoes lies very close to the ground, at or below 20 m AGL, in contrast to the original analysis which suggests heights between 30–70 m.

Overall the comment is well-written and the methodology and results are robust. The main concern I have with the paper in its current form is that the original methodology of N17 and most specifically why the results of that analysis differ from the new analysis is not sufficiently explained. While this information could be obtained by consulting N17, (and of course the reader should be referred to that paper for the details), I think a paragraph or two is warranted to compare and contrast the two approaches to make the current paper more self-contained. This and other more minor comments are included in the enclosed "tracked changes" version of the original manuscript. My overall recommendation is accept with minor revisions.

The results of the analysis in N17 does not differ with what is shown here, they are just showing different measurements of the wind. N17 emphasized the height of the time-azimuthal mean wind, while KW sought to find the altitude of the most extreme instantaneous winds. The fact that this might not clear to the Reviewers bolsters the point that this should be explained more carefully. An additional paragraph of text about the setup and motivation for the N17 simulations has been added to section 2.

This doesn't really explain well why the original N17 simulations showed a height of maximum tangential winds of 30–70 m. This information should be provided and an appropriate transition made to the reanalysis following the KW methodology.

I have added additional text emphasizing that the N17 focused on the time-azimuthal mean winds as the primary metric of tornado intensity. Beyond that, I don't think more should be added.

[Minor comments omitted...]