CORRESPONDENCE

Reply to “Comments on ‘The Regulation of Tornado Intensity by Updraft Width’”

ROBERT J. TRAPP, GEOFFREY R. MARION, AND STEPHEN W. NESBITT

Department of Atmospheric Sciences, University of Illinois at Urbana–Champaign, Urbana, Illinois

(Manuscript received 10 September 2018, in final form 18 September 2018)

1. Introduction

Motivated in part by the tornado observational record, Trapp et al. (2017, hereinafter TMN17) posed a simple hypothesis linking tornado intensity to rotating-updraft width. TMN17 evaluated this hypothesis using a set of idealized numerical simulations of supercell thunderstorms, which ultimately revealed robust linear correlations between peak near-surface vertical vorticity and updraft area at midlevels ($\sim 3\text{--}7$ km above the ground).

Coffer and Markowski (2018, hereinafter CM18) have questioned whether this hypothesis and the model-evaluated correlations are valid for storms in the ensemble of higher-resolution quasi-idealized simulations presented by Coffer et al. (2017, hereinafter C17). We refer to the simulations as quasi-idealized because they had initial and boundary conditions based on a real (composite) sounding rather than the analytic profiles of wind, temperature, and humidity used by TMN17. The C17 ensemble itself was based on small perturbations of the composite wind profile, and thus it was composed of simulations that span a very small range of environmental wind shear.

Here we will address CM18's concerns using an independent set of high-resolution simulations patterned after those of TMN17. We will concede that adjustments in TMN17's analysis method are necessary to account for the higher transience and spatial variability in these simulations, but otherwise we will show that the simulated storms still exhibit robust correlations between relevant variables as in TMN17. We will then demonstrate that CM18's failure to find such correlations is likely due to data dependence. Finally, we will use

this opportunity to further clarify some key points of TMN17.

2. Analysis methodology

As described in more detail by Marion and Trapp (2018, manuscript submitted to *J. Geophys. Res.*), the aforementioned set of new simulations are conducted with version 18 of Cloud Model 1 (CM1; Bryan and Fritsch 2002), over a $180\text{ km} \times 180\text{ km} \times 20\text{ km}$ computational domain, with uniform horizontal and vertical grid spacings of 125 m, and a free-slip lower boundary. The cloud and precipitation microphysical processes are parameterized using the NSSL double-moment scheme (Mansell et al. 2010), and turbulent mixing is parameterized using a 1.5-order turbulence kinetic energy closure approximation (Deardorff 1980). C17 used a stretched horizontal and vertical grid, a semislip lower boundary condition, and an adaptive time step, but otherwise their model setup is essentially the same as that used here.

The experiments of TMN17 spanned a relatively large range in 0–6-km bulk wind shear: $21\text{--}36\text{ m s}^{-1}$. Our new experiments (see Table 1) also span this range of bulk shear, and additionally are conducted over a $1000\text{--}3000\text{ J kg}^{-1}$ range of mixed-layer convective available potential energy (CAPE), and over three different mixed-layer depths (MLDs). In contrast, the C17 experiments have a bulk-shear variation of only 2 m s^{-1} (from 24 to 26 m s^{-1} in their “nontornadic” profile, and from 30 to 32 m s^{-1} in their “tornadic” profile).

Following TMN17, peak near-ground vertical vorticity ζ_{peak} in the new experiments is quantified within a $25\text{ km} \times 25\text{ km}$ box about the updraft of the storm of interest, and all other quantifications are performed prior to the occurrence of ζ_{peak} . Midlevel updraft,

Corresponding author: Robert J. Trapp, jtrapp@illinois.edu

DOI: 10.1175/JAS-D-18-0276.1

© 2018 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).

TABLE 1. Values of environmental characteristics—namely, MLD (m), level of maximum buoyancy z_B (m), CAPE (J kg^{-1}), and hodograph radius u_0 (m s^{-1})—used in the new set of simulations. The sounding generation procedure follows that of Warren et al. (2017), and the hodograph generation procedure is as described in TMN17.

MLD (m)	z_B (m)	CAPE (J kg^{-1})	u_0 (m s^{-1})
500	7000	2000	8
750	7000	2000	8
1000	6000	1000	10
1000	7000	1000	6
1000	7000	1000	8
1000	7000	2000	6
1000	7000	2000	10
1000	8000	2000	8
1000	8000	3000	6

mesocyclone, and downdraft areas are defined as contiguous areas exceeding thresholds of $w = 20 \text{ m s}^{-1}$, $\zeta = 10^{-2} \text{ s}^{-1}$, and $w = -8 \text{ m s}^{-1}$, respectively, at heights of $z = 6.25, 6.25$, and 3.25 km , respectively. Because of the increased variability within the vorticity field near the surface in these higher-resolution simulations, we define the near-surface mesocyclone area as a contiguous area exceeding an Okubo–Weiss parameter (e.g., Markowski et al. 2011) value of 10^{-2} s^{-1} . Thus, we consider only a vortex near the surface, rather than the various “filaments” of vertical vorticity extending outward from the low-level updraft. We then require that resultant near-surface mesocyclones have a duration of at least 10 min (two model output times) prior to the occurrence of ζ_{peak} . This is consistent with observations of tornadic low-level mesocyclones and serves to eliminate highly transient features that would not be considered “tornado-like.”

3. Results

Figure 1 reveals robust linear correlations between peaks in midlevel updraft-core area and midlevel mesocyclone area (Fig. 1a), near-ground mesocyclone area and midlevel mesocyclone area (Fig. 1b), midlevel updraft area and near-ground vertical vorticity (Fig. 1c), and midlevel updraft area and midlevel downdraft area (Fig. 1d). Each of these correlations have comparable coefficient of determination (R^2) values to those in TMN17. If we regress time-averaged values of area instead of peak values, then we also find robust correlations (Fig. 2). Indeed, in light of the increased temporal variability in these higher-resolution experiments, time averaging is probably a better approach.

CM18 (p. 4049) noted that peak values in their simulations occurred “sometimes as much as 25 min apart.”

FIG. 1. Scatterplots showing relationships between (a) peak midlevel updraft area (km^2) and peak midlevel mesocyclone area (km^2), (b) peak midlevel mesocyclone area (km^2) and peak near-ground mesocyclone area (km^2), (c) peak midlevel updraft area (km^2) and peak near-ground vertical vorticity (s^{-1}), and (d) peak midlevel updraft area (km^2) and peak downdraft area (km^2).

FIG. 2. As in Fig. 1, except for time averages of the maximum values over the 30-min period preceding the time of peak near-ground vertical vorticity.

CM18 (p. 4049) also noted that when they analyzed values “at the time of tornadogenesis/tornadogenesis failure,” minimal to no correlations were found. In fact, per the physical reasoning presented by TMN17, we

would not have expected high correlations between contemporaneously analyzed values (which, incidentally, is why we did not pursue the type of analysis that CM18 conducted in their Fig. 1). To illustrate the expected time lag between, for example, peak mesocyclone area and peak low-level vertical vorticity, consider the following exercised derived from Davies-Jones (1982): Assume a circular mesocyclonic vortex with radius r_M at some initial time $t = 0$. Under a uniform field of horizontal convergence C , assume that circulation is conserved over the time interval τ that the mesocyclonic vortex is contracted into a tornado with radius r_T . The equation that governs this simple problem is

$$\frac{1}{A} \frac{dA}{dt} = -C,$$

where A is the time-dependent area of the vortex. It can be integrated from $t = 0$ to $t = \tau$ and then solved for τ , yielding

$$\tau = \frac{1}{C} \ln\left(\frac{r_M^2}{r_T^2}\right).$$

If we let $r_M = 3000$ m, $r_T = 100$ m, and $C = 5 \times 10^{-3} \text{ s}^{-1}$, we find that $\tau = 23$ min.

Perhaps the larger question is why, even when CM18 followed the basic methodology of TMN17 (i.e., as presented in CM18, their Fig. 4), did their regressions yield relatively low R^2 values? We believe the answer lies in the relative lack of an experimental range in the C17 ensemble (i.e., 2 m s^{-1} range in bulk shear, which is less than 10% of the bulk-shear magnitude). The C17 experiments were meant to show how small perturbations in the environmental wind could yield different realizations of tornadic and weakly tornadic storms. While appropriate for that purpose, the C17 experiments do not provide for an appropriate test of the TMN17 ideas.

To illustrate, we present two simple regression analyses. In both, we compare values in nondimensional quantity A to those in nondimensional quantity F/m . By definition, these quantities are linearly related. But let us assume that we measure the value of A given some value F/m and assume further that our measurement uncertainty is $\sim 10\%$. If the experimental range in F/m is comparable to the uncertainty (as in C17), then the regression yields a low R^2 (Fig. 3a), even though we know that the correlation should be perfect. If, on the other hand, the experimental range in F/m is much larger (as in TMN17), then even with the same error/uncertainty in A , the regression yields a much higher R^2 (Fig. 3b). The essence of the issue in Fig. 3a, and in C17, is that the experimental data are not sufficiently independent (e.g., Wilks 2006).

FIG. 3. Scatterplots showing relationships between two nondimensional, linearly related quantities A and F/m . (a) The hypothetical experimental range in F/m is 0.1, which is comparable to the assumed uncertainty in A . (b) The hypothetical experimental range in F/m is 2, with the same assumed uncertainty in A .

That said, there is some independence revealed in the CM18 analyses, namely, between their tornadic data cluster and their nontornadic/weakly tornadic data cluster (their Fig. 4). Indeed, Fig. 4c in CM18 shows a fairly clear separation between the larger updraft areas and stronger near-ground vertical vorticity in the tornadic data cluster, and the relatively smaller updraft areas and weaker near-ground vertical vorticity in the nontornadic/weakly tornadic data cluster. This separation is consistent with, and supportive of, the TMN17 hypothesis.

We would like to reiterate here that the large range in bulk shear considered in the experiments of TMN17—equivalent to the 10th–90th-percentile values of bulk shear in spring-season tornadic environments (Grams et al. 2012)—resulted in a large range of supercell-updraft widths, which ultimately provided for an evaluation of the response of the low-level vertical vorticity field to the updraft widths. The comparable range in bulk shear (and also a large range of CAPE) in experiments with higher resolution (125-m grid lengths) likewise provided for an evaluation of the response of vertical vorticity characteristics to updraft width. In other words, the basic conclusions of TMN17 seem to be

relatively insensitive to grid spacing, with the concession that some adjustments in the analysis methodology are necessary to account for spatiotemporal variability, particularly in the vertical vorticity field.

To conclude, we concur with CM18 that, as with any new idea, continued testing of the TMN17 hypothesis with relevant datasets will help to refine it. In addition to new simulations, we are also using observational datasets toward this end.

Acknowledgments. This research was initially supported by the Department of Energy through Grant DE-SC0014101. Further support has been provided by NOAA through Award NA17OAR4590195. Resources from the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation and the state of Illinois, contributed to this research.

REFERENCES

- Bryan, G. H., and J. M. Fritsch, 2002: A benchmark simulation for moist nonhydrostatic numerical models. *Mon. Wea. Rev.*, **130**, 2917–2928, [https://doi.org/10.1175/1520-0493\(2002\)130<2917:ABSFMN>2.0.CO;2](https://doi.org/10.1175/1520-0493(2002)130<2917:ABSFMN>2.0.CO;2).

- Coffer, B. E., and P. M. Markowski, 2018: Comments on “The regulation of tornado intensity by updraft width.” *J. Atmos. Sci.*, **75**, 4049–4056, <https://doi.org/10.1175/JAS-D-18-0170.1>.
- , M. D. Parker, J. M. L. Dahl, L. J. Wicker, and A. J. Clark, 2017: Volatility of tornadogenesis: An ensemble of simulated nontornadic and tornadic supercells in VORTEX2 environments. *Mon. Wea. Rev.*, **145**, 4605–4625, <https://doi.org/10.1175/MWR-D-17-0152.1>.
- Davies-Jones, R., 1982: Tornado dynamics. *Thunderstorm Morphology and Dynamics*, E. Kessler, Ed., Vol. 2, *Thunderstorms—A Social, Scientific, and Technological Documentary*, NOAA/U.S. Department of Commerce, 297–362.
- Deardorff, J. W., 1980: Statocumulus-capped mixed layers derived from a three-dimensional model. *Bound.-Layer Meteor.*, **18**, 495–527, <https://doi.org/10.1007/BF00119502>.
- Grams, J. S., R. L. Thompson, D. V. Snively, J. A. Prentice, G. M. Hodges, and L. J. Reames, 2012: A climatology and comparison of parameters for significant tornado events in the United States. *Wea. Forecasting*, **27**, 106–123, <https://doi.org/10.1175/WAF-D-11-00008.1>.
- Mansell, E. R., C. L. Ziegler, and E. C. Bruning, 2010: Simulated electrification of a small thunderstorm with two-moment bulk microphysics. *J. Atmos. Sci.*, **67**, 171–194, <https://doi.org/10.1175/2009JAS2965.1>.
- Markowski, P. M., Y. Richardson, M. Majcen, J. Marquis, and J. Wurman, 2011: Characteristics of the wind field in three nontornadic low-level mesocyclones observed by the Doppler on Wheels radars. *Electron. Severe Storms Meteor.*, **6** (3), <http://www.ejssm.org/ojs/index.php/ejssm/article/view/75/63>.
- Trapp, R. J., G. R. Marion, and S. W. Nesbitt, 2017: The regulation of tornado intensity by updraft width. *J. Atmos. Sci.*, **74**, 4199–4211, <https://doi.org/10.1175/JAS-D-16-0331.1>.
- Warren, R. A., H. Richter, H. A. Ramsay, S. T. Siems, and M. J. Manton, 2017: Impact of variations in upper-level shear on simulated supercells. *Mon. Wea. Rev.*, **145**, 2659–2681, <https://doi.org/10.1175/MWR-D-16-0412.1>.
- Wilks, D. S., 2006: *Statistical Methods in the Atmospheric Sciences*. Academic Press, 678 pp.