17.4B PRELIMINARY EVALUATION OF A REAL-TIME DIAGNOSTIC TORNADO DAMAGE INTENSITY ESTIMATION TOOL USED AT THE STORM PREDICTION CENTER

Bryan T. Smith*[1], Richard L. Thompson[1], Christopher D. Karstens[1,2], Jeremy S. Grams[1], Andrew R. Dean[1], Richard M. Mosier[1], and Andrew D. Lyons[1]

[1] NOAA/NWS/NCEP/Storm Prediction Center, Norman, Oklahoma
[2] School of Meteorology, University of Oklahoma, Norman, Oklahoma

1. INTRODUCTION

Tornado damage intensity nowcasting at the tornado-warning timescale remains a challenge (Smith et al. 2020b, their Fig. 5), and is partially due to tornado intensity changing along the tornado path and the limited ability to detect and account for these fluctuations in intensity (Smith et al. 2020a). Nonetheless, recent studies [e.g., Smith et al. 2015, Thompson et al. 2017, Cohen et al. 2018, Smith et al. 2020a, Smith et al. 2020b (hereafter S20a and S20b)] focused on the relationship between the near-storm environment, WSR-88D velocity signatures, and tornado damage intensity; while other studies (e.g., Kingfield and Ladue 2015, Gibbs 2016) have focused primarily on the correspondence between WSR-88D signature characteristics and tornado damage intensity. The National Weather Service (NWS) Warning Decision Training Division has included information from the aforementioned list of recent studies in its tornado warning training for NWS operational forecasters to better assess real-time tornado intensity.

The first indirect tornado intensity nowcast occurred when the NWS Norman/Oklahoma City Weather Forecast Office issued a severe weather statement containing the words, “Tornado Emergency” during the Bridge Creek-Moore-South Oklahoma City 3 May 1999 F5 tornado. The Greensburg, KS 4 May 2007 EF5 tornado also prompted a tornado emergency headline prior to striking the town. The NWS began issuing experimental Impact-Based Warning (IBW) tags for tornadoes in 2012 as an action-item response to the 22 May 2011 Joplin, MO EF5 tornado’s severe assessment recommendation (NWS Central Region 2011). Their recommendation #2: “NWS should explore evolving the warning system…should utilize a simple, impact-based, tiered information structure”. Formal training guidance for warning forecasters to issue tornado IBW tags was developed during the tornado IBW experimental phase and continued over the next several years. The tornado IBW-focused training included research findings highlighting the relationship between tornado damage intensity and radar characteristics, yet, tornado IBW discernment solely relied on a warning forecaster’s discretion to subjectively assess the tornado impact in a qualitative sense. Consequently, there remains a lack of explicit quantitative data (i.e., wind speeds) as a historically based layer of information for a tornado in tornado warnings. In contrast, other severe hazard phenomena (e.g., hail, thunderstorm gusts) are described quantitatively in severe thunderstorm warnings and different degrees of impact are byproducts of explicit quantitative thresholds. This study evaluates explicit quantitative information for tornado-damage intensity assessment during tornado-warning timescales.

2. DATA AND METHODOLOGY

Damage-survey information from a select sample of 125 tornadoes from 2020–2022 were initially extracted via the Damage Assessment Toolkit (DAT; Camp et al. 2010). Only wind-engineered damage indicators (DI) 1–28 based on the Enhanced Fujita (EF) Scale (WSEC 2006) were retained, resulting in 6553 individual DIs for 125 tornadoes.

WSR-88D level II radar data were analyzed using Gibson Ridge radar software for each parent storm and its associated tornado. Following the methodology of assigning 0.5° tilt single site WSR-88D rotational velocity (V_{rot}) to the storm-scale circulations of the tornadoes (refer to Smith et al. 2020a for more details), each storm was also examined as to whether a ρ_{HV} reduction area from a polarimetric tornadic debris signature [TDS; Ryzhkov et al. (2005)] was present. The date/time and location of the V_{rot} couplet centroids were

Corresponding author address: Bryan T. Smith, NOAA/NWS/NCEP/Storm Prediction Center, 120 David L. Boren Blvd., Suite 2300, Norman, OK 73072
Bryan.Smith@noaa.gov

matched to the closest grid point of archived Storm Prediction Center (SPC) mesoanalysis data (Dean et al. 2006) for the hour immediately preceding the V_{rot} scan.

The archived SPC mesoanalysis data (Bothwell et al. 2002) were based on the 0-h Rapid Refresh (RAP; Benjamin et al. 2016) model output adjusted for a 2-pass Barnes scheme of surface observations. The maximum effective-layer STP value within 80 km (STP80km) was used to characterize the mesoscale environment (S20a,b). Only the DI with the highest wind speed was kept after each DI was spatiotemporally matched to the nearest V_{rot}. As a result, a unique data point containing a date/time and location information was linked to peak DI, STP, and V_{rot} and is referred to as a 0.5^{o} DI scan. For discussion regarding the spatiotemporal matching of the nearest DIs to each of the 0.5^{o} DI scans and the ability for DIs to represent the potential wind damage field and underlying assumptions therein, refer to S20a.

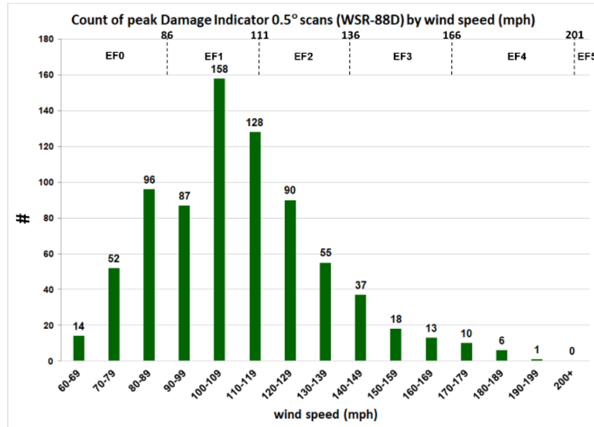

Figure 1. Count of peak damage indicator 0.5^{o} DI scans by wind speed (mph) in 10 mph bins.

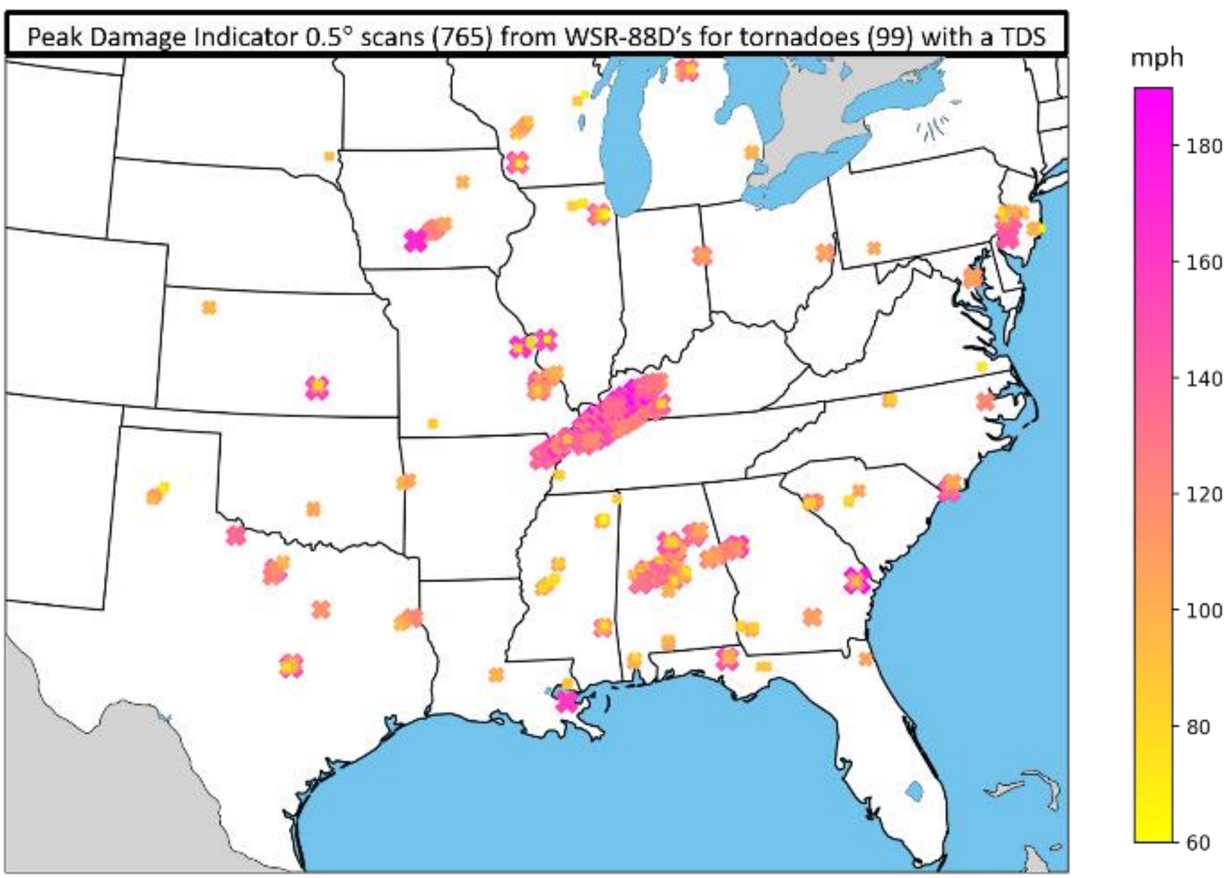

Figure 2. Spatial plot of 765 peak 0.5° damage indicator scans by wind speed (mph).

Finally, in order to better emulate a real-time tornado warning scenario in which a tornado can be confirmed (e.g., radar, visually by spotters or local authorities), we restricted analysis of calculating tornado damage intensity with wind speed ranges to 1) only tornadoes with a TDS (99 of the possible 125), and 2) during the periods when a TDS detection occurred. Included within the 26 filtered tornadoes was one short-path tornado that did not exhibit a TDS until after tornado demise (Schultz et al. 2012).

A sample of 765 0.5º DI scans (Fig. 1) were analyzed and the majority of 0.5º DI scans were EF1–2 and spatially located from the parts of the Great Plains eastward across the Mississippi Valley to the Mid-Atlantic States and the Southeast (Fig. 2).

Almost all 0.5º DI scans (748) were associated with supercells as the parent storm type, with damage-estimated peak wind speeds ranging from 60–190 mph (EF0–EF4). Only 4 out of 99 tornadoes were associated with QLCSs. Most of the 0.5º DI scans for supercells overlapped with the range of QLCS' peak damage-estimated winds of 60–142 mph (EF0–EF3). Similar to the findings from S20a,b, the notable difference between the two convective modes is the prevalence of 0.5º DI scans with supercells in the 136–190 mph range (EF3–EF4). The majority of 0.5º DI scans were sampled below 6000 ft above radar level (ARL; Fig. 3). Each of the 99 tornadoes had a peak wind speed associated with the final damage rating (Fig. 4), and 90% were between 90–165 mph (EF1–EF3). It is acknowledged that this study's sample is not representative of the distribution of all tornadoes during the period, but there was a focus to primarily examine characteristics of more intense tornadoes (EF1+).

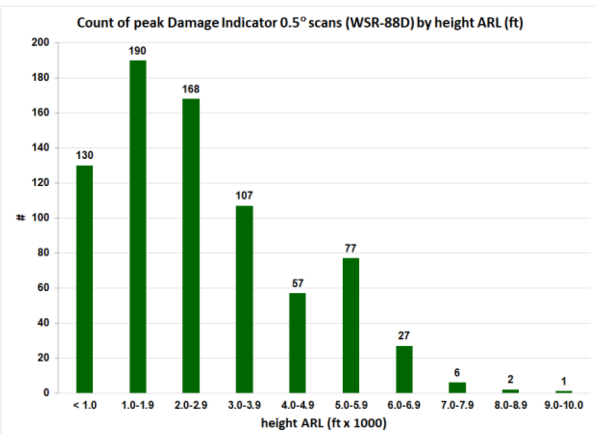

Figure 3. Same as Fig. 2 except for above radar level (ARL) in 1000 ft bins.

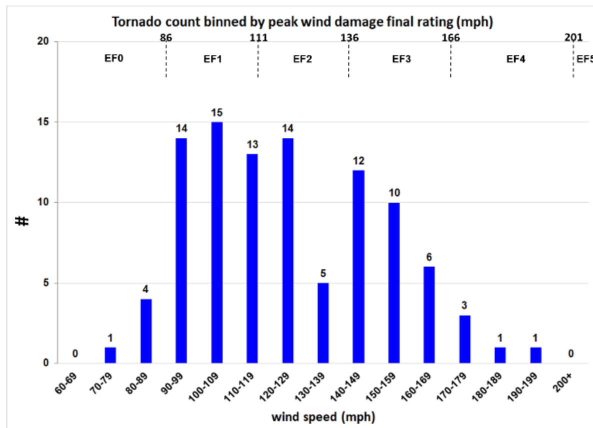

Figure 4. Similar to Fig. 1 except for the 99 tornadoes' final EF rating damage-based peak wind speed.

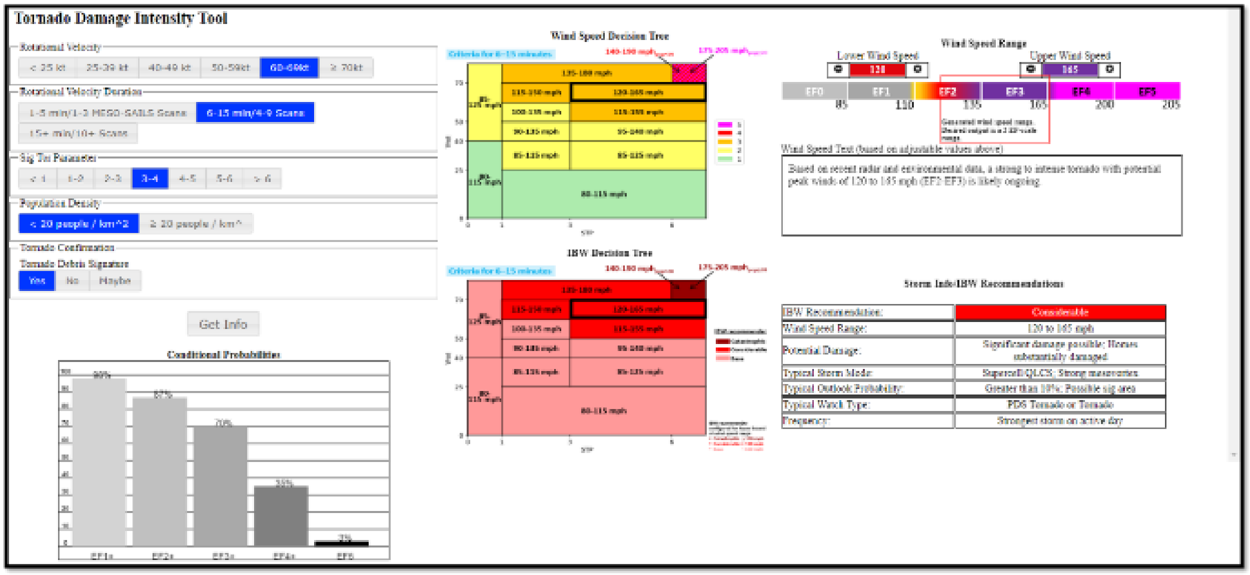

Figure 5. SPC tornado qIDSS tool.

a. SPC Tornado qIDSS per-scan method

Based on S20b's distributions of 0.5º DI scans (i.e., their figs. 9–10, 15), a tornado damage-based intensity estimation tool was developed (Fig. 5). The quantitative impact-based decision support services (qIDSS) tool estimates a wind speed range based on input data (i.e., binned values of V_{rot} & STP80km) for each 0.5º DI scan concurrent with a TDS. A real-time or instantaneous damage-based wind speed range, featuring a lower-bound (LB) and upper-bound (UB) wind speed, was recorded and termed the SPC *per-scan* method. For example, a 65-kt V_{rot} and 3.2 STP80km would translate to the 60–69 kt V_{rot} bin and the 3–4 STP bin as input parameters, respectively. The resulting LB and UB wind speed (e.g., 115 mph, 155 mph) correspond to the damage-based wind speed range (115–155 mph).

b. SPC Tornado qIDSS per-tornado method

A second approach was designed for skillfully predicting the tornado's final EF rating damage-based peak wind speed. The SPC Tornado qIDSS per-tornado method includes an additional time component of varying combinations of 0.5º DI scans with binned V_{rot} & STP80km. In contrast to the per-scan method, a peak wind speed range for the duration method is a cumulative approach in which the LB and UB can iteratively increase during the time of the tornado if higher binned parameter combinations warrant. Using the prior example of 60–69 kt V_{rot} and the 3–4 STP, the duration component of these criteria increasing from 1–5 minutes to 6–15 minutes increases the wind speed range from 115–155 mph to 120–165 mph, respectively (e.g., Figs. 4–5). The duration was calculated based on a sum of accumulated interval time between 0.5º DI scans (rounded to the previous minute) possessing the V_{rot} & STP80km combinations and did not have to occur sequentially.

	Scan 0	Scan 1	Scan 2	Scan 3	Scan 4	Scan 5
0.5º scan time (UTC)	16:30:05	16:32:19	16:34:51	16:37:01	16:39:10	16:40:58
Vrot	46	61	65	55	64	49
STP80km	3.2	3.2	3.2	3.2	3.2	3.2
Accumulated time	N/A	1 min	3 min	5 min	6 min	7 min
Per scan range (mph)	N/A	115–155	115–155	110–145	115–155	90–130
Per tornado range (mph)	N/A	115–155	115–155	115–155	120–165	120–165
TDS	No	Yes	Yes	Yes	Yes	Yes

Table 1. Hypothetical example of accumulated time (rounded to the previous minute) for the SPC Tornado qIDSS per-tornado method for the 60–69-kt V_{rot} and 3–4 STP80km bins.

c. Tornado qIDSS recommended warning type

The qIDSS component to the SPC tornado qIDSS tool was developed as a first-guess decisional aid, and it was built atop the damage-based wind speed data serving as the foundational meteorological information for the tool. The LB wind speed of the wind speed range was used for binning the wind speed range data into recommended tornado IBW categories (e.g., no-tag tornado warning, considerable-tag tornado warning, catastrophic-tag tornado warning), and based on at least the degree of damage at those wind speeds being met by the qIDSS tool and to generally be characteristic of the language embedded in those different tornado IBW tags. The base-tier (no tag) tornado warning was used for LB wind speeds below 110 mph. The qIDSS tool used 110 mph through 139 mph as the LB wind speed, in increments of 5 mph, for recommending a considerable-tag tornado warning. A catastrophic-tag tornado warning required a minimum of 140 mph as the LB wind speed.

3. RESULTS

a. SPC Tornado qIDSS per-scan method

The SPC Tornado qIDSS tool was used to compute the LB and UB wind speed for 99 tornadoes with a TDS. The tool-output wind speed range was compared to each tornado's DAT-based, damage-derived wind speed. The per-scan method, acting as a real-time damage intensity estimate, provided a wind speed range in which two-thirds of the 765 0.5º DI scans (Fig. 6a) had a peak DI wind speed that fell within the specified range, which are typically 35–45 mph. Based on the previously described example of when a TDS is observed, the SPC Tornado qIDSS per scan method using a 65 kt V_{rot} and an STP value of 3 results in 115–155 mph wind speed-damage estimate for that particular 0.5º DI scan. If the verifying peak wind speed damage estimate was 110 mph, a slight over-forecast resulted. Nearly 10% of the 0.5º DI scans had small over-forecast errors <10 mph.

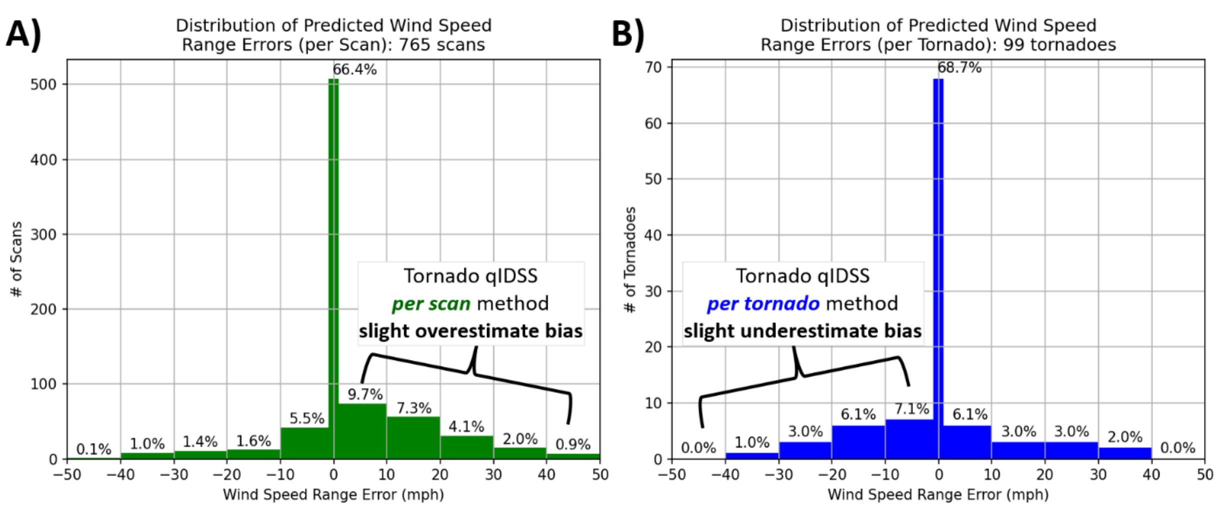

Figure 6. Histogram of the SPC Tornado qIDSS per scan and per tornado predicted wind speed range errors in 10 mph bins. Positive (negative) values indicate an overestimate (underestimate) of wind speed compared to wind speed-based damage verification.

The percentage of over-forecast 0.5º DI scans lessened as errors became larger (e.g., 10–19 mph vs. 40–49 mph) between the per-scan wind speed ranges and verifying damage-based peak wind speeds. Under-forecasts accounted for <10% of the 0.5º DI scans. Since both forecast wind speed ranges and observed damage-based peak wind speeds can be compared, metrics for a 2x2 contingency table were utilized on a performance diagram (Roebber 2009). A "hit" occurs when a peak DI wind speed is within the forecast wind speed range. A "miss" (under-forecast) is represented by an observed peak DI wind speed higher than the forecast wind speed range. A "false alarm" (over-forecast) is represented by an observed peak DI wind speed weaker than the forecast wind speed range. This contingency table configuration is based on the rationale of the so-called asymmetric penalty (Doswell 2004), whereby the penalty for missing an event is higher than false-alarming. The per-scan method's critical success index (CSI) or threat score is 0.664 (Fig. 7).

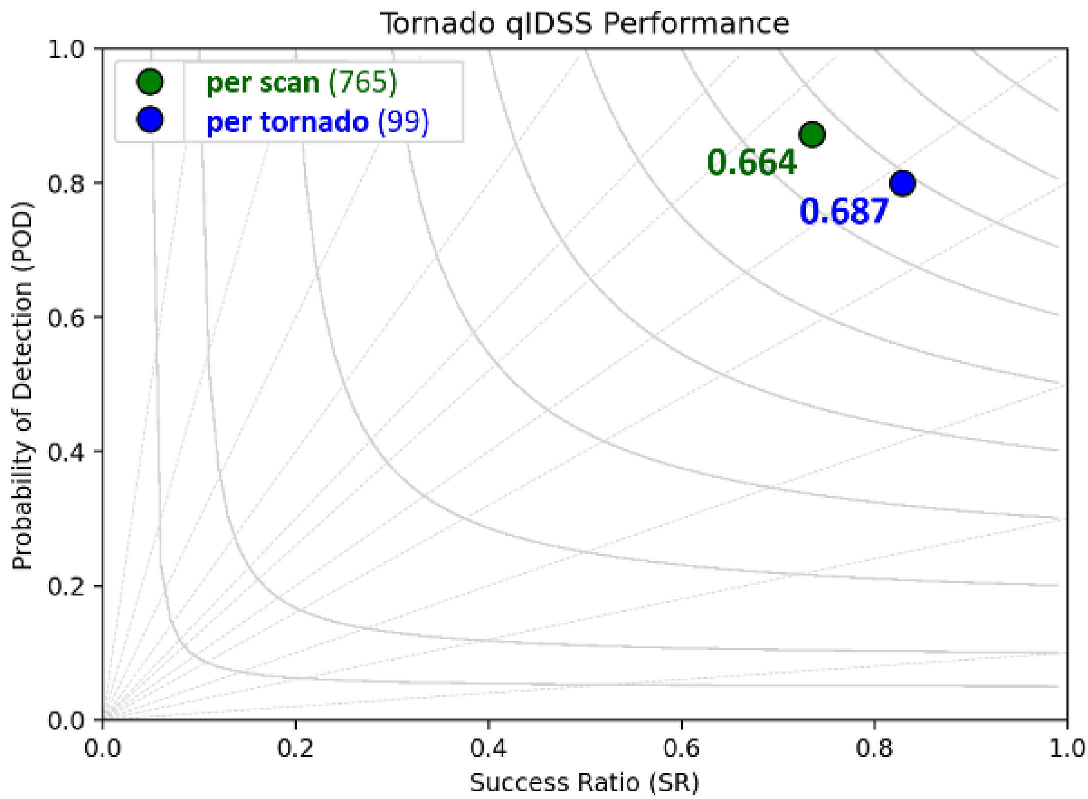

Figure 7. Performance diagram with probability of detection (y-axis), success ratio [1–false alarm (x-axis)], bias (dashed lines), critical success index (curved lines) of the SPC Tornado qIDSS per-scan (green) and per-tornado method (blue).

b. SPC Tornado qIDSS per-tornado method

The per-tornado method utilized duration of V_{rot}/STP combinations to quantify the peak damage-based wind speed estimate for each tornado by using the maximum LB and UB wind speeds for the wind speed range. Using the aforementioned case example of 60–69 kt V_{rot} and an STP value of 3 for a time accumulation of 8 minutes (i.e., 6–15 minutes), the SPC Tornado qIDSS tool results in a 120–165 mph maximum EF-rating wind speed estimate based on peak DI data from the tornado (Table 1). Over two-thirds of the final, maximum damage-based wind speed estimates for the 99 tornadoes were correctly within the predicted damage-based wind speed range (Fig. 6b). There was nearly an even distribution of binned forecast wind speed overestimates and underestimates, along with decreasing probabilities as difference errors between the forecast wind speed range and the verifying wind speed increased. The forecast error of wind speed less than 10 mph from the predicted wind speed range resulted in >80% of the tornadoes having a final maximum damage-based wind speed estimate within 10 mph of the predicted wind speed range, similar to the per-scan method. The error or difference between the qIDSS-generated wind speed range versus the actual maximum damage-based wind speed estimate for each tornado is displayed in Fig. 8. The qIDSS-estimated wind speed range captured the damage-based wind speed for most of the longer-track tornadoes, and a smaller fraction of these medium to longer track tornadoes were slight forecast underestimates. The per-tornado method was analyzed with a performance diagram, and it is nearly unbiased statistically (i.e., bias ~1) and the CSI is 0.687 (Fig. 7).

c. Recommended warning type vs. NWS warnings

The highest-tier tornado warning IBW from the qIDSS tool-based wind speed range were compared to the highest tier of NWS warning for the 99 tornadoes using the per-tornado method. The tornado warning–no tag type of warning was the most common NWS warning type and recommendation from the SPC Tornado qIDSS tool output (Fig. 9). Both the per-tornado method recommended warning type and the NWS warnings exhibited substantial overlap for the tornado warnings with no tags and considerable tags. The overlap may at least be partially a result of use of previously published work by WFOs. However, the upper part of the distribution (i.e., 75^{th}, 90^{th} percentiles) was lower for the qIDSS per-tornado method compared to the NWS warnings with no tags, which is a slight improvement. Also, the absence of a qIDSS per-tornado catastrophic tag below 140 mph, while three NWS warnings have a catastrophic tag in this range, suggests that using the objective-based qIDSS per-tornado approach may be able to help reduce false alarms for the catastrophic tag in NWS tornado warnings.

4. DISCUSSION

It is important to remember that although outlier tornado events using the SPC Tornado qIDSS methods are statistically infrequent and in the tails of the distributions (e.g., Fig. 6), the large number of tornadoes and DI scans during a tornado lifespan over the CONUS each year still results in a non-negligible number of poorer-performing events. One notable outlier occurred with a sharp coastal front on the evening of 15 February 2021 near Wilmington, NC. Stable conditions were analyzed onshore over the NC coastal plain by the SPC mesoanalysis. However, moist/unstable conditions were analyzed over the adjacent Atlantic waters. An EF3 with the actual maximum damage-based wind speed of 160 mph occurred along the frontal zone near the coast where a warm sector penetrated immediately inland. Likely due in part to relatively coarse grid resolution of the SPC mesoanalysis, it is suspected the buoyancy of the RAP-based SPC mesoanalysis data mischaracterized the near-storm environment by under-representing buoyancy and thereby negatively influencing the maximum STP within 80 km (i.e., 0 value). The maximum STP value within 185 km was a 3.2 value. The qIDSS per-tornado method resulted in a 75–115 mph wind speed estimate, and which proved to be a large underestimate compared to a 120–165 mph range when including an STP 3–4 bin value in the qIDSS tool. The Wilmington, NC, case likely provided the largest noteworthy example of STP value sensitivity within this sample of events when mischaracterizing the mesoscale environment.

The veracity of these results may not necessarily be applicable especially at ARL heights sampling the mid-levels of the storm (6000 ft ARL or higher) at far ranges from WSR-88Ds. Future work may include adding tornado cases relatively far from the nearest WSR-88D to better assess the application of the SPC Tornado qIDSS techniques at high ARL heights (i.e., 6,000–10,000 ft). However, data from S20a,b suggest some utility in estimating tornado-damage intensity is possible at a 60–100 mi range (6,000–10,000 ft ARL) from the nearest WSR-88D. Yet, known radar limitations such as beam broadening and velocity sampling issues at increasing height degrade the radar's ability to resolve with relatively high fidelity the circulation parent to the tornado. Consequently, a meteorologist's ability to distinguish between a weak versus an intense tornado can be limited when using a meteorologist-over-the-loop approach, such as the SPC Tornado qIDSS tool, which was developed using a sample of tornado radar scans $\leq$ 10,000 ft ARL. A recent example is the Lamar County, TX–Choctaw County, OK EF3 (160 mph) tornado on 4 November 2022. The Fort Worth, TX (KFWS), Fort Smith, AR (KSRX), and KSHV (Shreveport, LA) WSR-88Ds were nearly equidistant (i.e., 120–140 mi) from the tornado and scanned the tornadic circulation no less than 13,000–14,000 ft ARL. Very strong velocity gates were sampled by KFWS (e.g., >70-kt V_{rot}) but the author's confidence in selecting appropriate velocity gates for V_{rot} was substantially lessened by a broad, erratic 2-D velocity field, which tends to become more common at distant radar range. Therefore, the application of extrapolating higher V_{rot} to generally equating to more intense tornadoes at very distant radar range, is likely case-by-case dependent. The findings from this work raise the question about how meteorologists can estimate tornado damage intensity at increasingly far radar range (e.g., 60–100+ mi) where known low-level (e.g., <6,000 ft ARL) WSR-88D radar gaps exist, and the equitable implications that can result from this reality. A present-day pragmatic solution can include a default 70–110 mph wind speed range, which results in a recommended base-tier tornado warning with no IBW tag, unless substantive evidence exists to the contrary (e.g., combination of visual confirmation, supporting near-storm environment, supercell convective mode, very strong V_{rot}, etc.). In the 4 November 2022 EF3 case, the aforementioned strategy may have been utilized since only a no-IBW-tag tornado warning was issued.

5. FORECASTER NOTES

The SPC Tornado qIDSS techniques provide an objective first-guess diagnosis and assessment of tornado damage intensity and offer an example of bridging the Research to Operations (R2O) gap. It is important to keep in mind that properly assessing of velocity data for V_{rot}, using a representative 0-hr or 1-hr forecast sounding of the near-storm inflow environment and its associated STP value, monitoring a potentially changing near-storm environment and its controlling influence on STP, and confirming information about an ongoing tornado (e.g., TDS, visual confirmation), are each crucial components of the forecast process. Each of these variables or considerations are fluid and require a meteorologist-over-the-loop to properly account for an array of circumstances unique to each individual tornado. It would therefore be unrealistic to expect a statistically skillful, first-guess tornado damage intensity tool alone—which provides a static tool-based determination—to provide additional value that a meteorologist using the qIDSS tool information can provide and optimally fuse the meteorologist-machine mix. These preliminary results with a limited sample are loosely analogous to the statistical skill of the tropical cyclone track forecast cone [2/3 probability ellipse based on climatology (Neumann 1972)]. The qIDSS tool has been deployed at the SPC for several years. The qIDSS-generated wind speed range and modifications to the LB and UB have been evaluated on a case-by-case basis during real-time tornado events by the authors, and they have anecdotally found that improved damage-based intensity estimates are possible using the meteorologist-machine mix.

Applied research with operational applications too often fails to complete the “last mile” for full operational implementation. The work presented herein is at a critical stage in the R2O process, and the opportunity is available to incorporate quantitative data (i.e., wind speed range) as a foundation or base-layer of information for IBW tornado warnings. The R2O application of this work and its initial results provide a path for the operational community to both conceptually and practically improve real-time identification of rare-event tornado forecasting. By adopting this scientific approach, the IBW tornado warnings within the NWS warning program can be more consistent and statistically skillful by using these quantitative data, ultimately leading to credible messaging of rare ongoing tornadic events and their impacts.

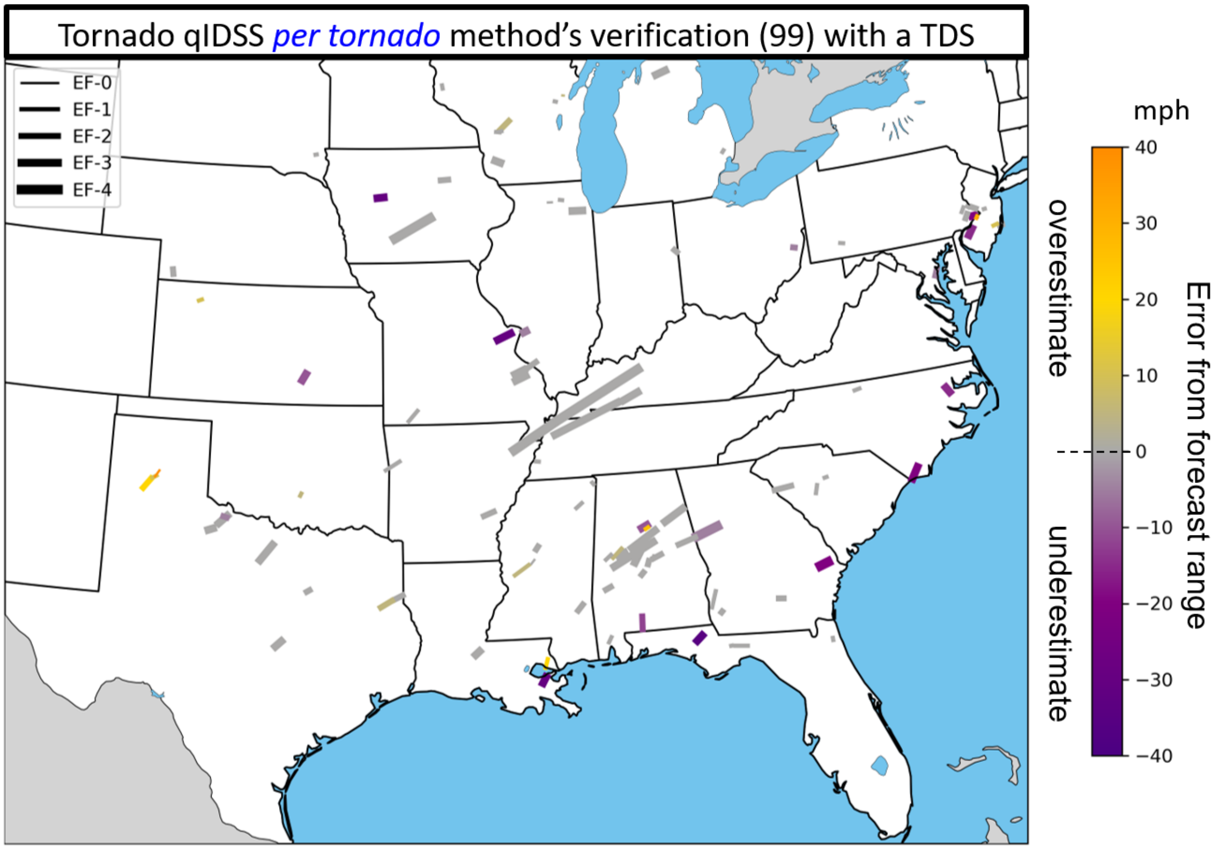

Figure 8. Spatial plot of 99 tornadoes and their Tornado qIDSS per tornado method's predicted damage-based wind speed range compared to the final, maximum damage-based wind speed estimate (mph).

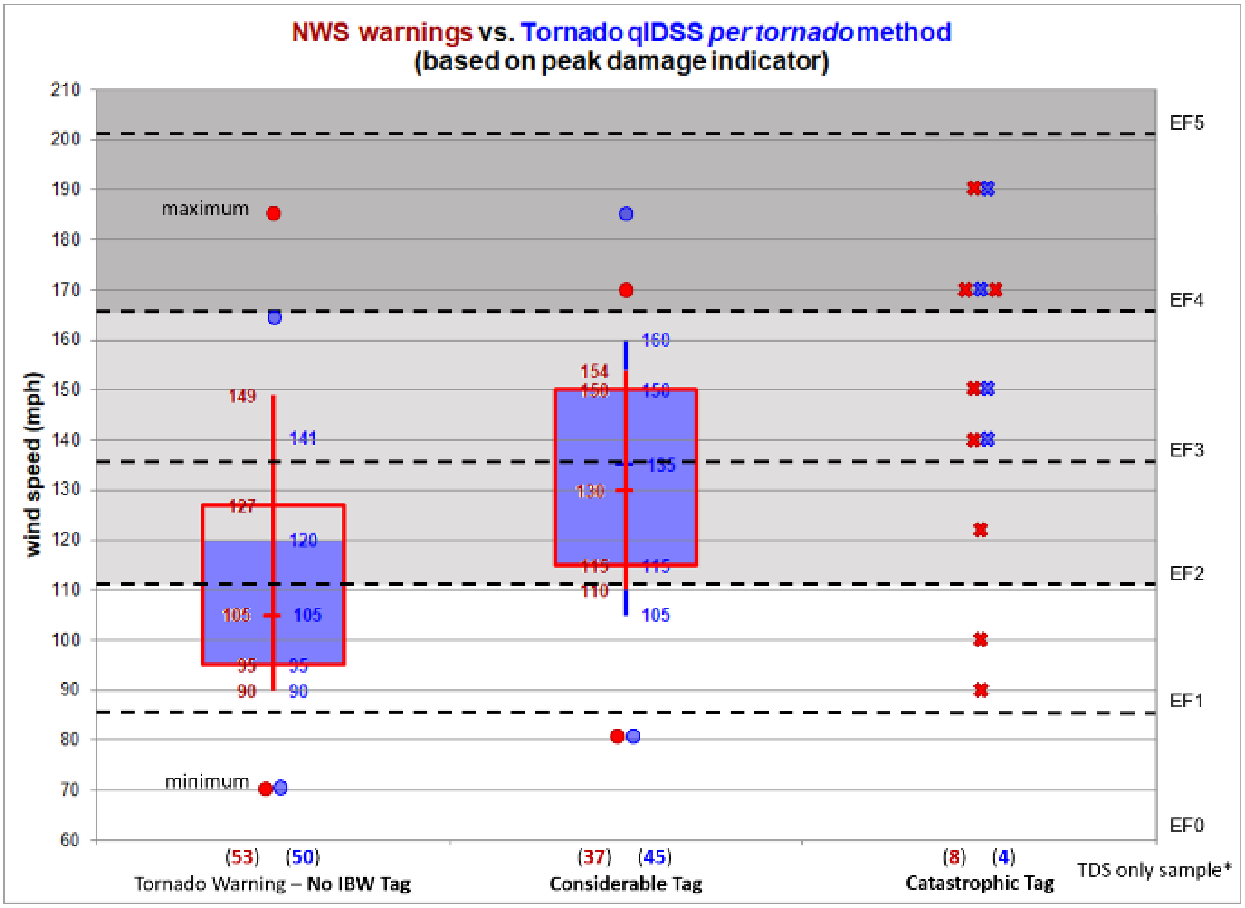

Figure 9. Box-Whisker comparison between the Tornado qIDSS per tornado method's IBW warning type (blue fill) versus NWS warnings (red overlay). Verifying data for the final, maximum damage-based wind speed estimate (mph) for 99 tornadoes are plotted. Boxes represent the 25th and 75th percentiles, medians, and whiskers extend to the 10th and 90th percentiles. Maximum and minimum values are denoted with circles. Filled X's represent individual events in the catastrophic-tag IBW category.

6. ACKNOWLEDGEMENTS

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