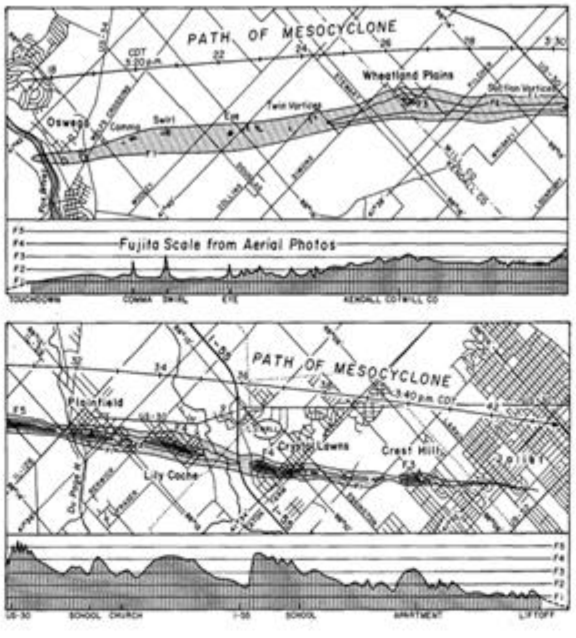
Tornado Intensity Estimation



Left (middle and bottom): Detailed map along the path of the Plainfield/ Crest Hill tornado. Maps this page courtesy: Dr. T. Theodore Fujita; University of Chicago.

Tornado Intensity Estimation: A History

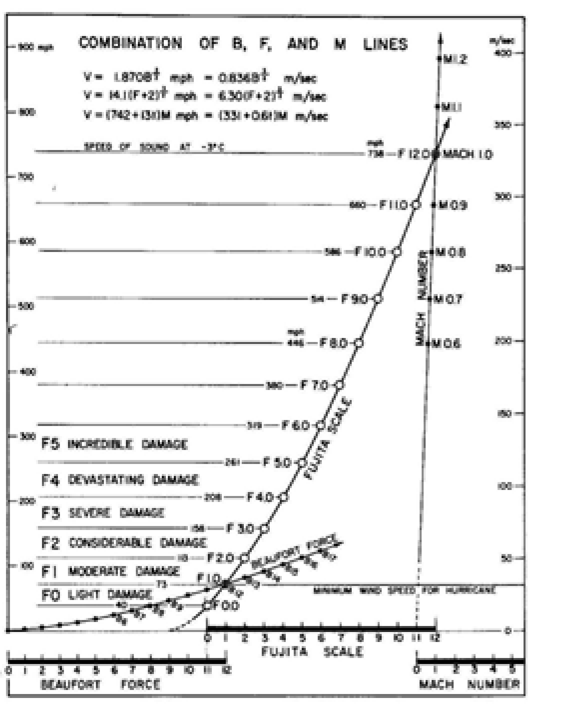


Fig. 1. Connection of Beaufort force, Fujita scale and Mach number. In deriving the equation for F-scale wind computation, the following considerations were made. (1) To connect Beaufort force 12 with Mach number 1 with a smooth curve, (2) To correspond B 12 with F 1 and M 1 with F 12, so that a 1 through 12 graduated scale, as in the case Beaufort force, covers the desired speed range. (3) Beaufort 0 indicates calm or no wind and Fujita 0 likewise denotes the wind speed causing no damage on most structures. (4) To give wider speed range as the speed increases because the faster the wind speed the wider the speed range to allow a visual distinction of damage from one scale to the next, and (5) An exponent 3/2 is likely to serve the above purpose. Furthermore, the square of the speed or the kinetic energy is proportional to the cube of F + 2. About 20 formulas to satisfy partial or total conditions listed above were examined before adopting Eq (2), the final equation, which was used to obtain the F-scale curve presented in this figure.

Fig. 1 from Fujita (1971) illustrating the Fujita scale in the context of the Beaufort scale and Mach number

- The Fujita Scale was developed in 1971 to quickly estimate tornado intensity from damage surveys
- Initially developed as a non-linear 12-step bridge between the end of the Beaufort scale (hurricane-force wind speed) and Mach 1 (the speed of sound)
- Various types of damage were then assigned to the first five levels (F1–F5) and F0 was added to account for tornadoes with wind speeds falling within the range of the Beaufort scale
- The NWS adopted the Fujita scale in the mid-1970s
- The Nuclear Regulatory Commission funded backfilling of the tornado record with Fujita scale ratings back to 1950, and Grazulis applied the scale to significant (F2+) tornadoes back to the 1870s/1880s

Tornado Intensity Estimation: A History

Original Fujita (F) Scale		
No.	Wind Speed (mph and ms^{-1})	Damage Description with respect to housing
F0	40-72 mph 18-32 ms^{-1}	Light damage: Some damage to chimneys
F1	73-112 mph 33-50 ms^{-1}	Moderate damage: Peel surfaces off roofs; mobile homes pushed off foundations or overturned.
F2	113-157 mph 51-70 ms^{-1}	Considerable damage: Roofs torn off framed houses; mobile homes destroyed.
F3	158-206 mph 71-92 ms^{-1}	Severe damage: Roofs and some walls torn from well-constructed houses.
F4	207-260 mph 93-116 ms^{-1}	Devastating damage: Well constructed houses leveled; structure with weak foundations blown off some distance.
F5	261-318 mph 117-142 ms^{-1}	Incredible damage: Strong frame houses lifted from foundation and carried considerable distances to disintegrate.

Table 1. Original Fujita (F) scale with wind speeds and damage description with respect to housing (after Fujita 1971).

Table 1 from WSEC (2006) summarizing the F-scale damage descriptions for each rating category

Fig. 3 from Fujita (1971) describing the Fujita scale wind speed ranges and the damage associated with them

Tornado Intensity Estimation: A History

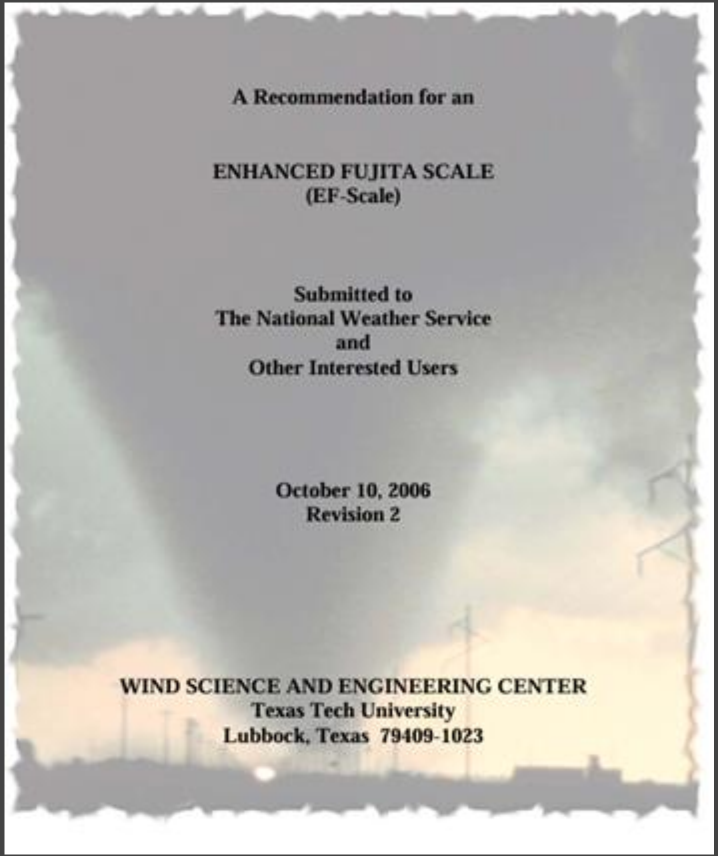
THE FUJITA TORNADO SCALE

		Little Damage	Minor Damage	Roof Gone	Walls Collapse	Blown Down	Blown Away
Damage f scale		f0	f1	f2	f3	f4	f5
Windspeed F scale		F0	F1	F2	F3	F4	F5
m/s		17–32	32–50	50–70	70–92	92–116	116–142
mph		40–73	73–113	113–158	158–207	207–261	261–319
To convert f scale into F scale, add the appropriate number							
Weak Outbuilding	-3	f3	f4	f5	f5	f5	f5
Strong Outbuilding	-2	f2	f3	f4	f5	f5	f5
Weak Framehouse	-1	f1	f2	f3	f4	f5	f5
Strong Framehouse	0	F0	F1	F2	F3	F4	F5
Brick Structure	+1	-	f0	f1	f2	f3	f4
Concrete Building	+2	-	-	f0	f1	f2	f3

From Fujita (1992) describing corrections to Fujita-scale ratings for construction quality

- Estimated “fastest ¼ mi wind speed at structure height” -> both of these vary substantially across affected structures and tornado intensities
- The original Fujita scale document (1971) did not account for construction quality
- Engineers quickly recognized that the more severe damage (F3–F5) associated with tornadoes could be attributed to wind speeds below those provided by the Fujita scale, particularly for structures of weaker construction
- Fujita’s first attempt to adjust Fujita scale ratings for construction quality was published as part of his memoirs (1992)

Tornado Intensity Estimation: A History


A Recommendation for an

ENHANCED FUJITA SCALE
(EF-Scale)

Submitted to
The National Weather Service
and
Other Interested Users

October 10, 2006
Revision 2

WIND SCIENCE AND ENGINEERING CENTER
Texas Tech University
Lubbock, Texas 79409-1023

- The Fujita scale was also extremely limited in the damage indicators that could be used to estimate tornado intensity
- To adjust estimated wind speeds for intense tornadoes to better match the wind speeds needed to cause observed damage and to develop a larger catalog of damage indicators for estimating tornado intensity, the Enhanced Fujita Scale was developed in the early–mid 2000s and adopted by the NWS on 1 February 2007
- *While wind speed ranges were changed, the goal was to make the rating meaningfulness stay the same (e.g., F5 = EF5 for climatological purposes)*

Tornado Intensity Estimation: A History

Table 5. EF-Scale Wind Speed Ranges Derived from Fujita-Scale Wind Speed Ranges

Fujita Scale			EF Scale	
Fujita Scale	Fastest 1/4/-mile Wind Speeds, mph	3-Second Gust Speed, mph	EF Scale	3-Second Gust Speed, mph
F0	40 - 72	45 - 78	EF0	65 - 85
F1	73 - 112	79 - 117	EF1	86 - 109
F2	113 - 157	118 -161	EF2	110 - 137
F3	158 - 207	162 - 209	EF3	138 - 167
F4	208 - 260	210 - 261	EF4	168 - 199
F5	261 - 318	262 - 317	EF5	200 - 234

Table 6. Recommended EF-Scale Wind Speed Ranges

Derived EF Scale		Recommended EF Scale
EF Classes	3-Second Gust Speed, mph	3-Second Gust Speed, mph
EF0	65 - 85	**65 - 85**
EF1	86 - 109	**86 - 110**
EF2	110 - 137	**111 - 135**
EF3	138 - 167	**136 - 165**
EF4	168 - 199	**166 - 200**
EF5	200 - 234	**>200**

From WSEC (2006)

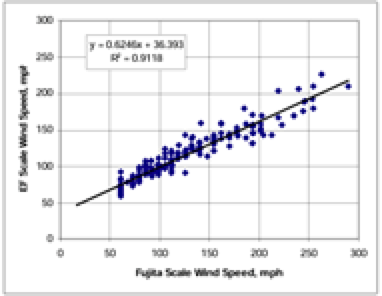


Figure 1. Correlation of Fujita-Scale and EF-Scale Wind Speeds

- Six steps in the creation of the EF scale:
  a. The expected wind speeds needed to cause the degrees of damage (DODs) for each damage indicator (DI) were developed through an iterative "expert elicitation" process, in which a panel of experts were repeatedly polled to estimate the wind speeds for each DI/DOD combination until very few poll–poll changes were noted
  b. An independent group of damage survey experts were polled to provide wind speed estimates for each DI/DOD combination using F-scale criteria
  c. A linear regression was fit between the EF-scale and F-scale wind speed estimates for each DI/DOD combination, which was found to have very strong correlation between the two independent expert groups (R^2 = 0.91)
  d. The F-scale rating wind speed ranges were converted from the "fastest ¼-mile" gust values to 3-s gust values
  e. The 3-s gust values for the F-scale rating wind speed ranges were converted to their EF-scale 3-s gust values
  f. The converted wind speed ranges were rounded to the nearest 5-mph increment to establish the finalized EF-scale wind speed ranges for each rating level

Tornado Intensity Estimation: A History

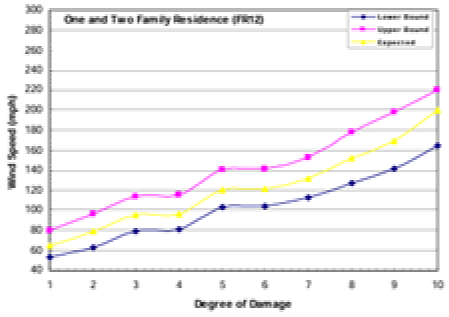
2. ONE-AND TWO-FAMILY RESIDENCES (FR12)
(1000 – 5000 sq. ft.)

Typical Construction

- Asphalt shingles, tile, slate or metal roof covering
- Flat, gable, hip, mansard or mono-sloped roof or combinations thereof
- Plywood/OSB or wood plank roof deck
- Prefabricated wood trusses or wood joist and rafter construction
- Brick veneer, wood panels, stucco, EIFS, vinyl or metal siding
- Wood or metal stud walls, concrete blocks or insulating-concrete panels
- Attached single or double garage

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	53	80
2	Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding	79	63	97
3	Broken glass in doors and windows	96	79	114
4	Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward; failure of porch or carport	97	81	116
5	Entire house shifts off foundation	121	103	141
6	Large sections of roof structure removed; most walls remain standing	122	104	142
7	Exterior walls collapsed	132	113	153
8	Most walls collapsed, except small interior rooms	152	127	178
9	All walls	170	142	198
10	Destruction of engineered and/or well constructed residence; slab swept clean	200	165	220

* DOD is degree of damage



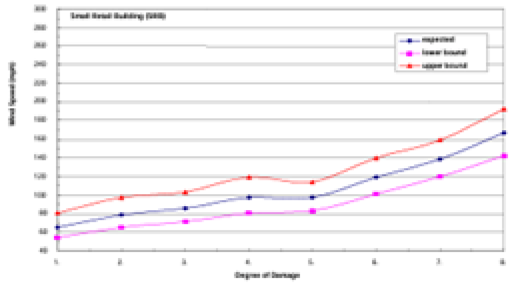
8. SMALL RETAIL BUILDING (SRB)

Typical Construction

- Best example is fast-food restaurant
- Flat, hip, gable, mansard or monoslope roof
- Asphalt shingles, metal panels, slate, tile, single-ply or BUR roof covering
- Plywood/OSB roof decking
- Wood or metal roof structure consisting of trusses or rafters and joists
- Wood or metal stud walls
- Typically have large areas of window glass and double entry doors
- Canopies, covered walkways or porches
- Wood, brick veneer, metal or vinyl siding, concrete blocks, EIFS or stucco wall cladding

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	54	81
2	Loss of roof covering (<20%)	78	65	98
3	Broken glass in windows and doors	86	72	103
4	Uplift of roof decking; significant loss of roof covering (>20%)	98	81	119
5	Canopies or covered walkways destroyed	98	83	114
6	Uplift or collapse of entire roof structure	119	101	140
7	Collapse of exterior walls; closely spaced interior walls remain standing	138	120	159
8	Total destruction of entire building	167	143	193

* DOD is degree of damage



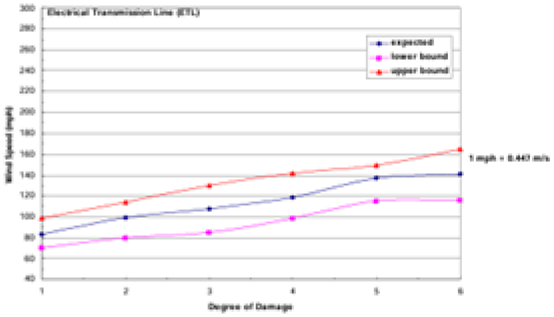
24. ELECTRICAL TRANSMISSION LINE (ETL)

Typical Construction

- Single wood poles with wood cross arms
- Single steel or concrete poles with metal cross arms
- Metal trussed towers

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	83	70	98
2	Broken wood cross member	99	80	114
3	Wood poles leaning	108	85	130
4	Broken wood poles	118	98	142
5	Broken or bent steel or concrete poles	138	115	149
6	Collapsed metal truss towers	141	116	165

* DOD is degree of damage



Full document:
https://www.depts.ttu.edu/nwi/Pubs/EnhancedFujitaScale/EFScale.pdf

Examples of EF0 damage

19 Apr 2023 Etowah, OK
DI 3, DOD 2, 75 mph

27 Apr 2024 Goldsby, OK
DI 2, DOD 2, 79 mph

19 Apr 2023 Etowah, OK
DI 1, DOD 1, 65 mph

Examples of EF1 damage

6 May 2024 Oklahoma City, OK
DI 8, DOD 4, 100 mph

24 Mar 2023 Rolling Fork, MS
DI 2, DOD 4, 97 mph

19 Apr 2023 Pink, OK
DI 27, DOD 3, 110 mph

Examples of EF2 damage

31 Mar 2023 Hookers Bend, TN
DI 2, DOD 5, 121 mph

19 Apr 2023 Etowah, OK
DI 2, DOD 7, 132 mph

31 Mar 2023 Clifton, TN
DI 27, DOD 4, 120 mph

Examples of EF3 damage

19 Apr 2023 Pink, OK
DI 24, DOD 6, 141 mph

22 Mar 2022 Damascus, MS
DI 2, DOD 9, 145 mph

31 Mar 2023 Hookers Bend, TN
DI 27, DOD 5, 145 mph

Examples of EF4 damage

24 Mar 2023 Rolling Fork, MS
DI 21, DOD 8, 175 mph

24 Mar 2023 Rolling Fork, MS
DI 2, DOD 9, 190 mph

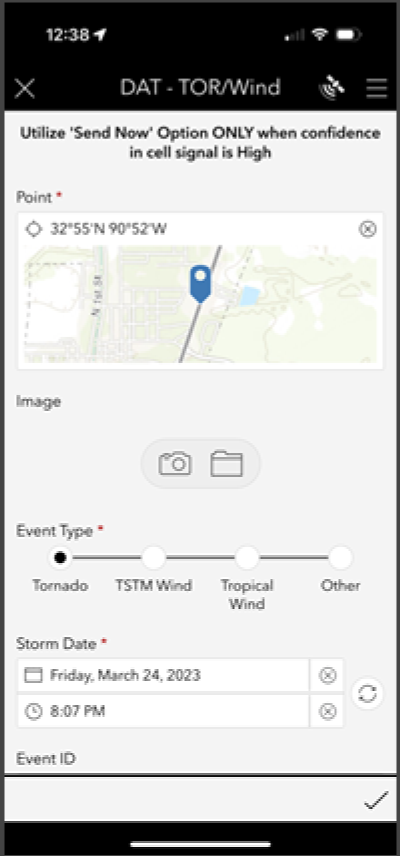
24 Mar 2023 Rolling Fork, MS
DI 27, DOD 5, 167 mph

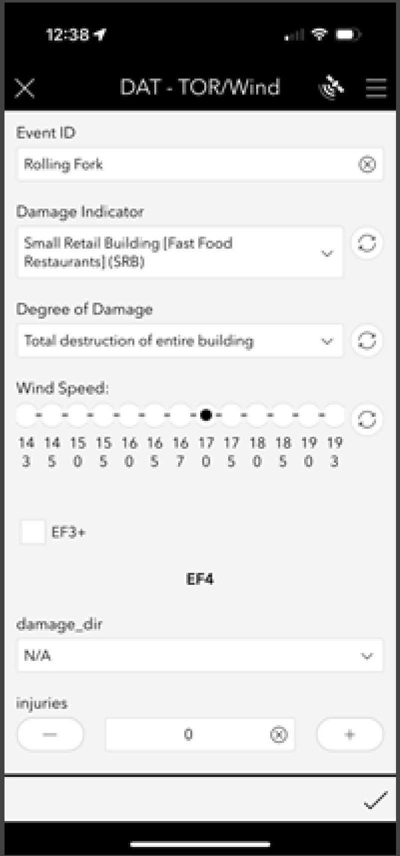
Examples of EF5 damage

20 May 2013 Moore, OK
DI 2, DOD 10, 201 mph

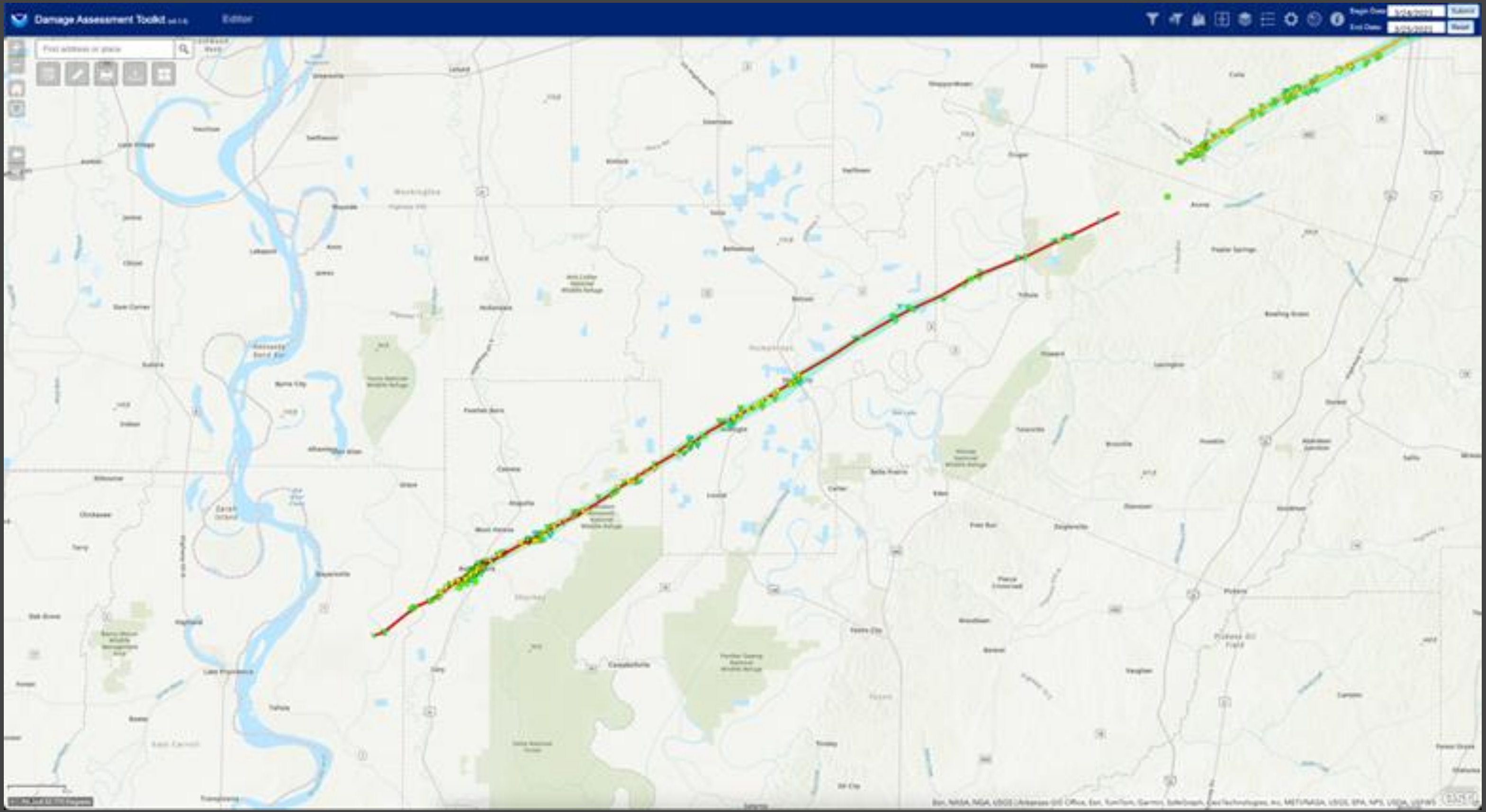
27 Apr 2011 Smithville, MS
DI 2, DOD 10, 205 mph

How the EF Scale is applied today





How the EF Scale is applied today



EF Scale Application: The Good, the Bad, and The Ugly

Table 3. Damage Indicators for EF Scale

DI No.	Damage Indicator (DI)
1	Small Barns or Farm Outbuildings (SBO)
2	One- or Two-Family Residences (FR12)
3	Manufactured Home – Single Wide (MHSW)
4	Manufactured Home – Double Wide (MHDW)
5	Apartments, Condos, Townhouses [3 stories or less] (ACT)
6	Motel (M)
7	Masonry Apartment or Motel Building (MAM)
8	Small Retail Building [Fast Food Restaurants] (SRB)
9	Small Professional Building [Doctor's Office, Branch Banks] (SPB)
10	Strip Mall (SM)
11	Large Shopping Mall (LSM)
12	Large, Isolated Retail Building [K-Mart, Wal-Mart] (LIRB)
13	Automobile Showroom (ASR)
14	Automobile Service Building (ASB)
15	Elementary School [Single Story; Interior or Exterior Hallways] (ES)
16	Junior or Senior High School (JHSH)
17	Low-Rise Building [1-4 Stories] (LRB)
18	Mid-Rise Building [5-20 Stories] (MRB)
19	High-Rise Building [More than 20 Stories] (HRB)
20	Institutional Building [Hospital, Government or University Building] (IB)
21	Metal Building System (MBS)
22	Service Station Canopy (SSC)
23	Warehouse Building [Tilt-up Walls or Heavy-Timber Construction] (WHB)
24	Electrical Transmission Lines (ETL)
25	Free-Standing Towers (FST)
26	Free-Standing Light Poles, Luminary Poles, Flag Poles (FSP)
27	Trees: Hardwood (TH)
28	Trees: Softwood (TS)

- The Good
  - Many more DIs and DODs to estimate tornado wind speeds
  - Wind speed estimates that better match the wind speeds needed to cause structural damage based off of improved engineering knowledge over time
  - The Damage Assessment Toolkit (DAT) greatly improves the efficiency of tornado damage surveys
  - DAT collection also allows for highly detailed surveys to be conducted in a much more timely fashion for major events
  - Wind speed estimates are assumed to be of a standard elevation (10 m AGL) and gust duration (3-s)

EF Scale Application: The Good, the Bad, and The Ugly

.TORNADO #2: LUTTS, TENNESSEE...

RATING:	EF-3
ESTIMATED PEAK WIND:	157 MPH
PATH LENGTH /STATUTE/:	50.6 MILES
PATH WIDTH /MAXIMUM/:	800 YARDS
FATALITIES:	0
INJURIES:	7
START DATE:	DECEMBER 23, 2015
START TIME:	652 PM CST
START LOCATION:	2.5 MI SW OF LUTTS/WAYNE COUNTY, TN
START LAT/LON:	35.1368, -87.9362
END DATE:	DECEMBER 23, 2015
END TIME:	752 PM CST
END LOCATION:	2.0 MI SW OF MT. PLEASANT/MAURY COUNTY, TN
END LAT/LON:	35.5377, -87.2381

SURVEY SUMMARY:

THIS EF-3 TORNADO TOUCHED DOWN JUST EAST OF THE HARDIN COUNTY/WAYNE COUNTY LINE ABOUT 2.5 MILES SOUTHWEST OF THE TOWN OF LUTTS. AT TOUCHDOWN...HUNDREDS OF TREES WERE SNAPPED AND UPROOTED BEFORE THE TORNADO REACHED ITS PEAK STRENGTH ABOUT ONE HALF MILE WEST-SOUTHWEST OF LUTTS ALONG LUTTS RD WHERE THE TORNADO REACHED A WIDTH OF 800 YARDS AND EF3 STRENGTH. A POST OFFICE AND CHURCH...BOTH BRICK BUILDINGS...WERE DESTROYED ALONG WITH MULTIPLE HOMES SWEPT FROM THEIR FOUNDATIONS. FOUR PEOPLE WERE INJURED HERE IN LUTTS. AS THE TORNADO CONTINUED NORTHEAST...HUNDREDS OF TREES WERE SNAPPED AND UPROOTED ALONG ITS PATH TO WHERE A CONCENTRATED AREA OF TREES WERE DESTROYED ABOUT 5 MILES NORTH OF COLLINWOOD. THE TORNADO CONTINUED SNAPPING AND UPROOTING TREES UNTIL THE HIGHWAY 64 AND NATCHEZ TRACE PARKWAY INTERSECTION. AT THIS LOCATION...AN OUTBUILDING WAS DESTROYED ALONG WITH THE ROOF OF A MOBILE HOME. FURTHER NORTHEAST INTO LAWRENCE COUNTY ALONG NAPIER RD...A HOUSE WAS SWEPT OFF ITS FOUNDATION WHERE 3 PEOPLE WERE INJURED. AS THE TORNADO TRAVELED NORTHEAST...SEVERAL HOMES WITH ROOFS COMPLETELY REMOVED OR DAMAGED HEAVILY WERE FOUND ALONG LINVILLE ROAD. THE TORNADO WEAKENED AS IT CROSSED INTO MAURY COUNTY WHERE A BARN WAS DESTROYED AND MANY TREES WERE SNAPPED AND UPROOTED ALONG JOY ROAD...2 MILES SOUTHWEST OF MOUNT PLEASANT.

- The Bad
  - Old Fujita Scale method: assign rating first, then estimate wind speed
  - This was the method typically applied during the early EF-Scale era (2007–2013), prior to the deployment of the DAT
  - EF Scale application method with the DAT: estimate wind speed first, then allow rating to fall out of wind speed estimate
  - Still tremendous uncertainty in structural failure-wind speed relationship
  - *Survey results often convey more confidence in the accuracy of wind speed estimates than we actually have because wind speed estimates are often taken straight from the DAT*

EF Scale Application: The Good, the Bad, and The Ugly

F5	261-318 mph 117-142 ms^{-1}	Incredible damage: Strong frame houses lifted from foundation and carried considerable distances to disintegrate.

2. ONE-AND TWO-FAMILY RESIDENCES (FR12)
(1000 – 5000 sq. ft.)

Typical Construction

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- Wood or metal stud walls, concrete blocks or insulating-concrete panels
- Attached single or double garage

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6	Large sections of roof structure removed; most walls remain standing	122	104	142
7	Exterior walls collapsed	132	113	153
8	Most walls collapsed, except small interior rooms	152	127	178
9	All walls	170	142	198
10	Destruction of engineered and/or well constructed residence; slab swept clean	200	165	220

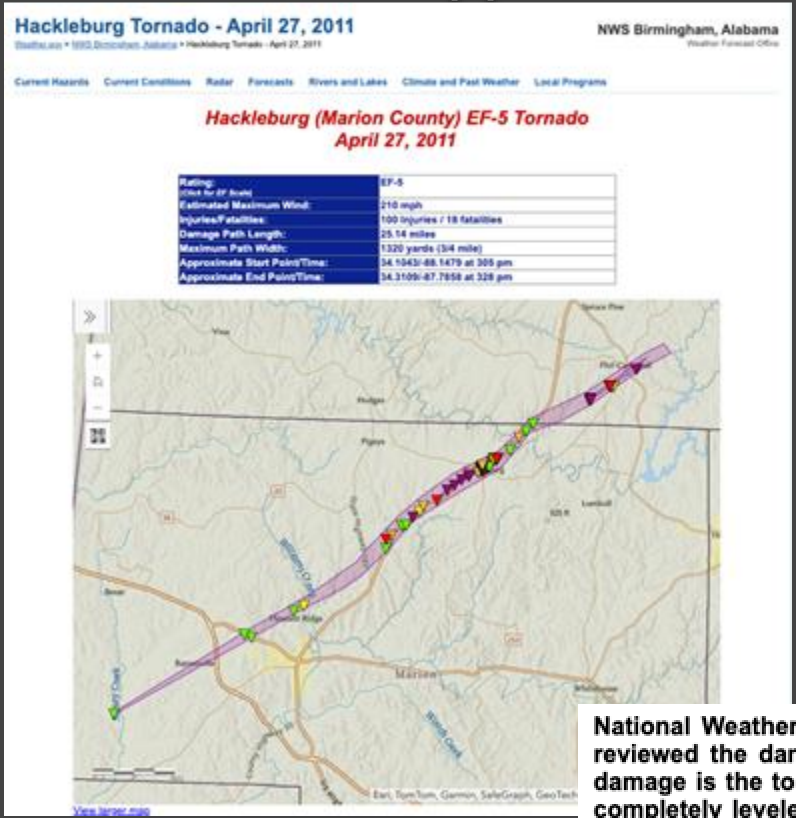
* DOD is degree of damage

Table 6. Recommended EF-Scale Wind Speed Ranges

Derived EF Scale		Recommended EF Scale
EF Classes	3-Second Gust Speed, mph	3-Second Gust Speed, mph
EF0	65 - 85	**65 - 85**
EF1	86 - 109	**86 - 110**
EF2	110 - 137	**111 - 135**
EF3	138 - 167	**136 - 165**
EF4	168 - 199	**166 - 200**
EF5	200 - 234	**>200**

- The Ugly: EF5
  - The standard for F5 damage on the Fujita Scale was a "strong frame house lifted from foundation and carried considerable distances to disintegrate" (i.e., swept away)
  - On the EF scale, the "expected value" or starting point wind speed for this level of damage is 200 mph
  - Before the wind speed ranges for each EF-Scale category were rounded, 200 mph was the start of EF5
  - However, the 5-mph rounding of each EF-Scale wind speed increment was applied to the top of each rating range; so instead of 200 mph being the start of EF5, it is now the end of EF4
  - *This represents a fundamental break between the Fujita and EF Scales at the 4/5 threshold!*

EF Scale Application: The Good, the Bad, and The Ugly


Hackleburg Tornado - April 27, 2011
NWS Birmingham, Alabama
Current Hazards Current Conditions Radar Forecasts Rivers and Lakes Climate and Past Weather Local Programs

Hackleburg (Marion County) EF-5 Tornado
April 27, 2011

Rating: (Click for EF Scale)	EF-5
Estimated Maximum Wind:	210 mph
Injuries/Fatalities:	100 injuries / 18 fatalities
Damage Path Length:	25.14 miles
Maximum Path Width:	1320 yards (3/4 mile)
Approximate Start Point/Time:	34.1043/-88.1479 at 305 pm
Approximate End Point/Time:	34.3109/-87.7858 at 328 pm

- The Ugly: EF5 (continued)
  - The break between how swept-away single family homes are handled between the Fujita and EF scales presents a fundamental discontinuity between the Fujita and EF scales as a whole
  - Before the deployment of the DAT, EF5 ratings were often assigned through evaluating a combination of swept-away homes and the context of the surrounding landscape
  - However, the precision provided by the DAT has amplified the impacts of this breakpoint

National Weather Service meteorologists, along with the foremost expert in storm damage assessment reviewed the damage in Hackleburg in Marion County. The main indicators of Hackleburg having EF-5 damage is the tossing of vehicles upwards of 150-200 yards, one well built home with 4 sides brick was completely leveled and the debris from the home was tossed to the north over 40 yards, and there was large amounts of wind rowing, the strewing of building materials in straight lines, around the city of Hackleburg.

EF Scale Application: The Good, the Bad, and The Ugly

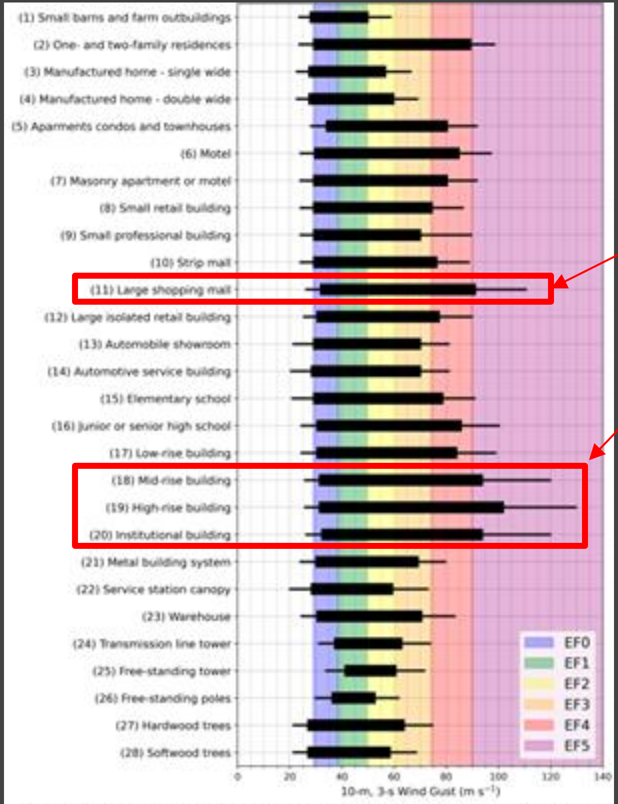
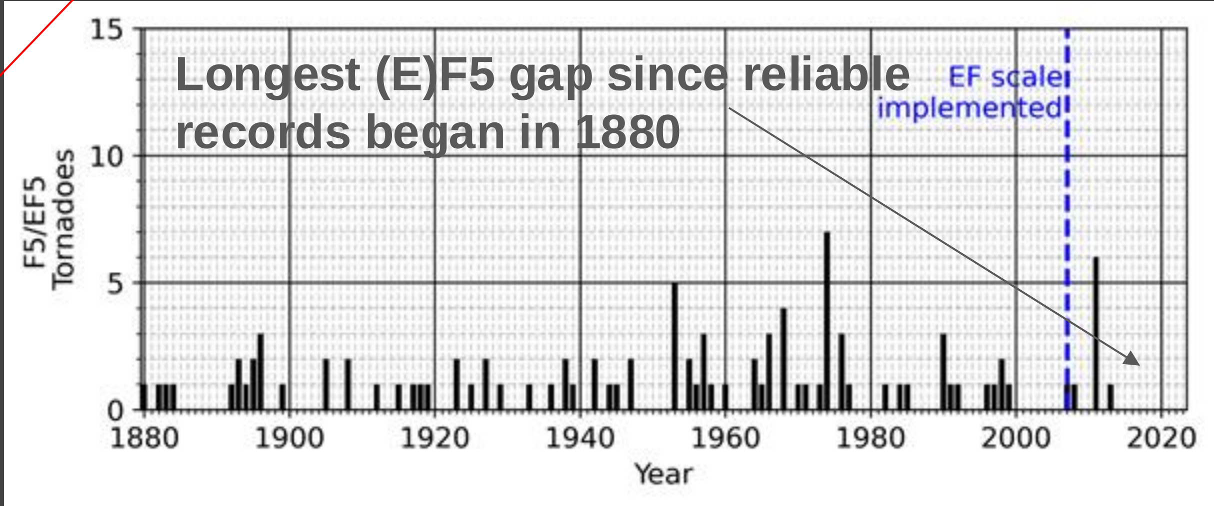


FIG. 1. Graphic highlighting the wind speed ranges for the 28 DIs of the EF scale. The bold black bars represent the range from the expected value of the lowest DOD to the expected value of the highest DOD, and the thin black tails represent the range from the lower bound of the lowest DOD to the upper bound of the higher DOD. The EF-scale wind speed ranges corresponding to each rating are shaded for reference.

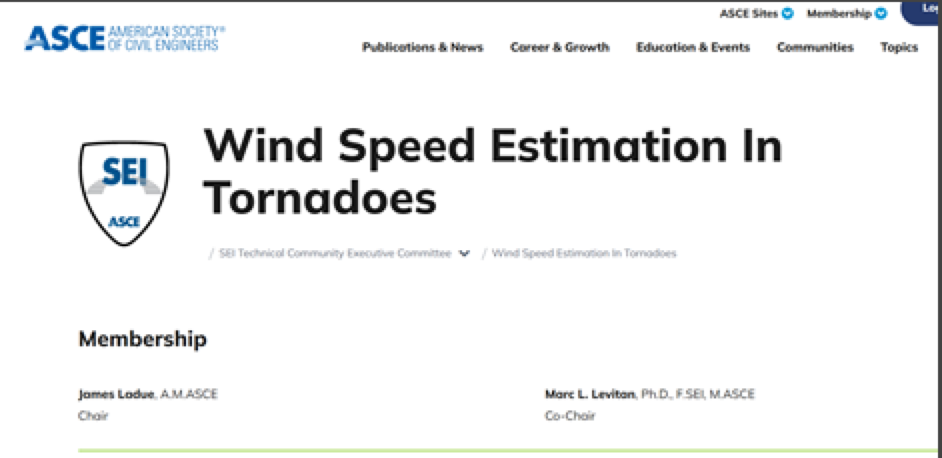
From Lyza et al. (2024)

- The Ugly: EF5 (continued)
  - Only 4 of the 28 DIs of the EF Scale can yield an EF5 wind speed estimate based on an “expected value” DOD application
  - The end result: no EF5 tornadoes since the Moore tornado on 20 May 2013



From Lyza et al. (2025)

Other Methods for Tornado Intensity Estimation



- While the EF Scale is the most readily usable and consistent way to estimate tornado intensity, it has obvious shortcomings
- Advances in technology and knowledge are allowing for the development of numerous additional tornado intensity estimation techniques
- The American Society of Civil Engineers (ASCE) and the American Meteorological Society (AMS) have a formed a committee to develop a standard for estimating tornado intensity using a variety of methods
- The ASCE Standards Committee for Wind Speed Estimation in Tornadoes (WSE Committee)

Other Methods for Tornado Intensity Estimation

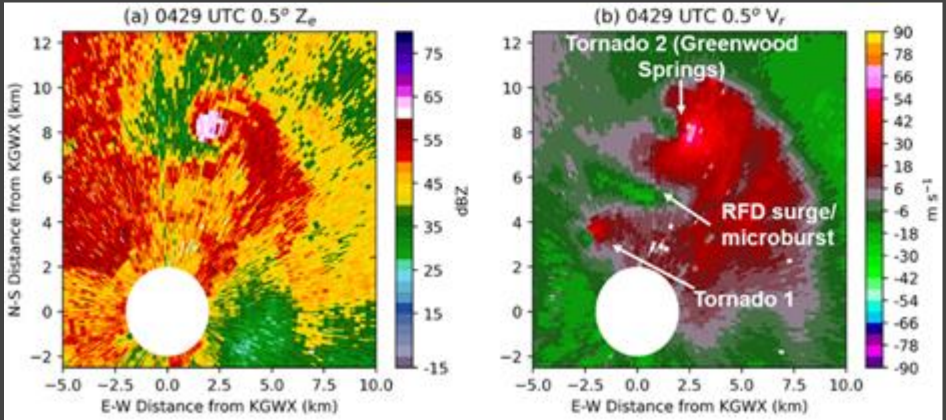


FIG. 14. (a) 0.5° PPIs of Z_e and (b) V_r at 0429 UTC 14 Apr 2019, showing the location of the rear-flank microburst relative to the Greenwood Springs tornado ("Tornado 2"), as well as the initial tornado associated with the parent supercell ("Tornado 1").

From Lyza et al. (2022)

- Six methods in development by the WSE Committee
    - Revised EF Scale (preliminary target: 2026)
    - **Tree-fall pattern method**
    - **Radar measurements**
    - **In-situ observations**
    - Forensic engineering analyses
    - **UAS and satellite remote sensing applications**

Tree-fall Pattern Method

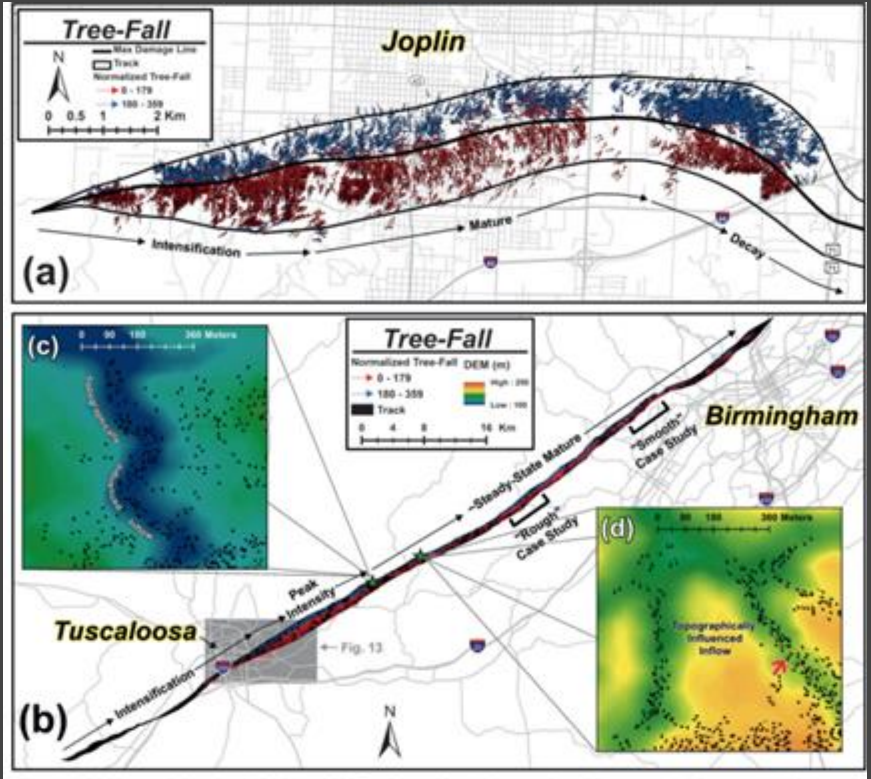


FIG. 1. Digitized tree fall from the (a) Joplin and (b) Tuscaloosa–Birmingham tornadoes. The arrow colors denote track-relative tree-fall direction that has utility in identifying locations of converging or diverging tree-fall patterns. (c),(d) Zoomed-in areas of the damage path where the tree-fall patterns appear to have been strongly influenced by the underlying topography (background DEM). The red arrow in (d) denotes the photograph location of Fig. 11, which is described in section 3c.

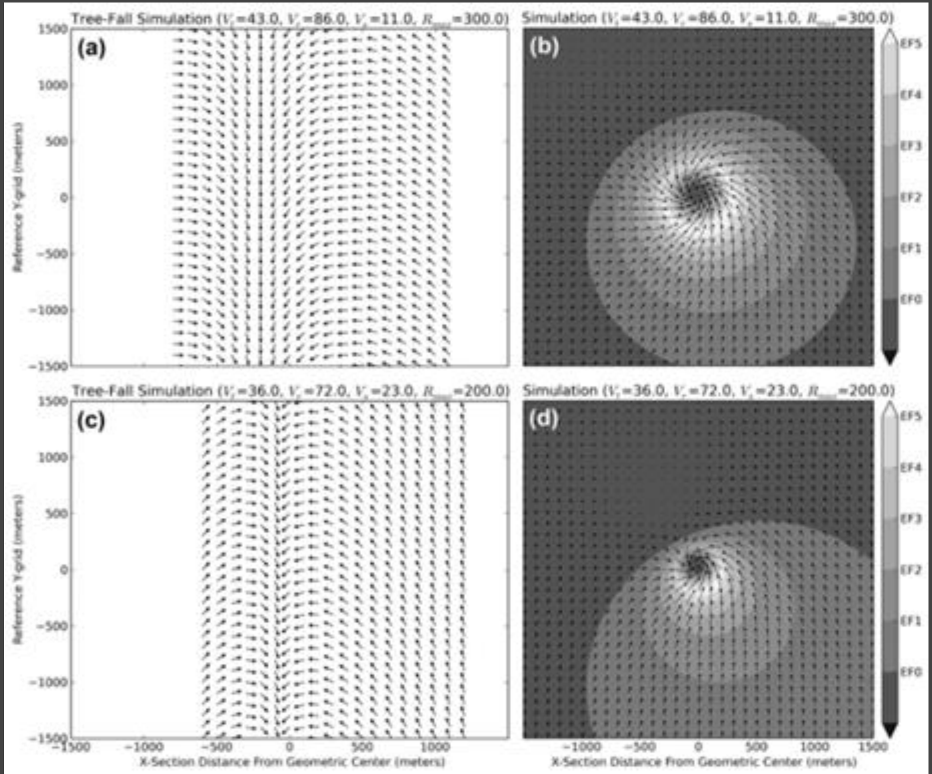


FIG. 9. Best-fit simulations of idealized tornado-induced tree fall and the resulting analytical vortex wind field corresponding to the peak-intensity period for (a),(b) the Joplin tornado (observations shown in Fig. 8b) and the (c),(d) Tuscaloosa–Birmingham tornado (observations shown in Fig. 10b, below).

Figs. 1 and 9 from Karstens et al. (2013)

Radar Observations of Tornadoes

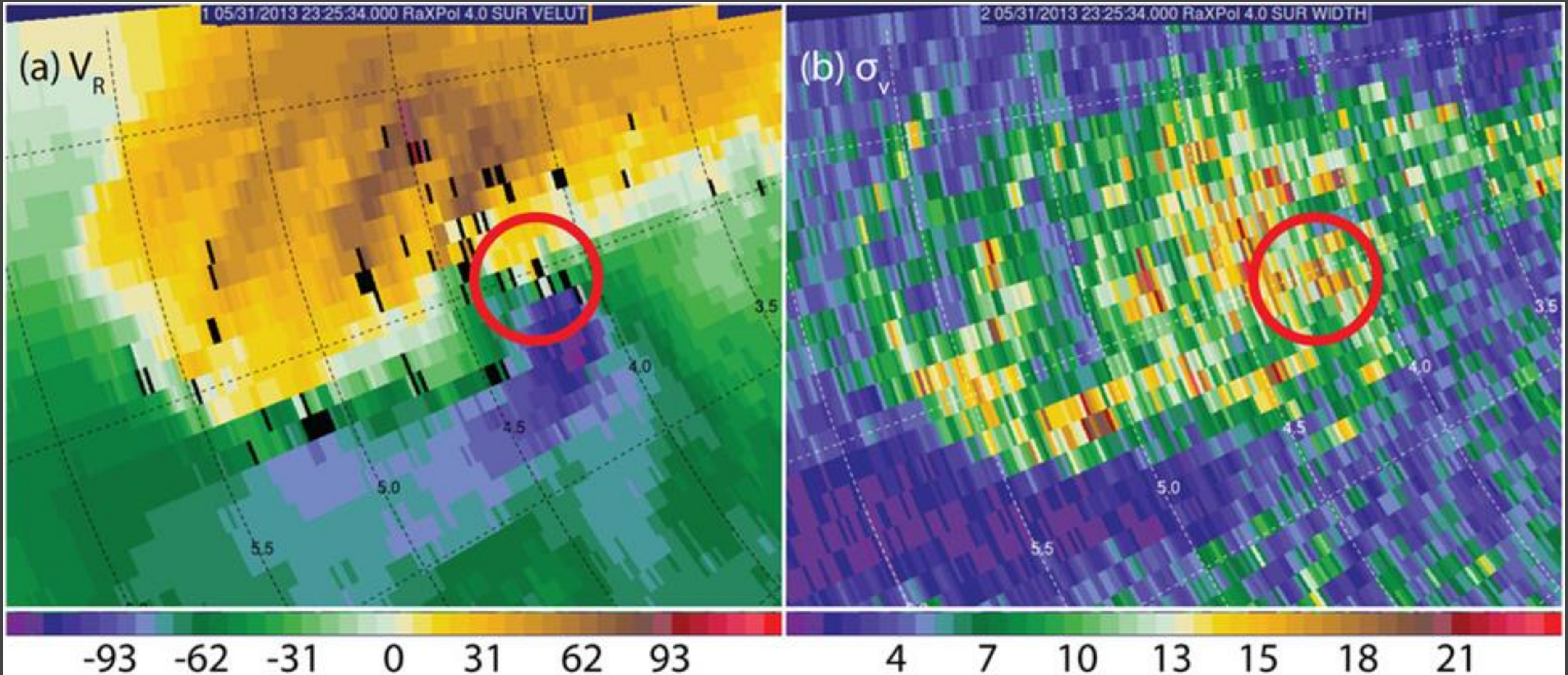


Fig. 8 from Snyder and Bluestein (2014)
31 May 2013 El Reno, OK tornado; peak Vr of -126.5 m s^{-1}

Radar Observations of Tornadoes

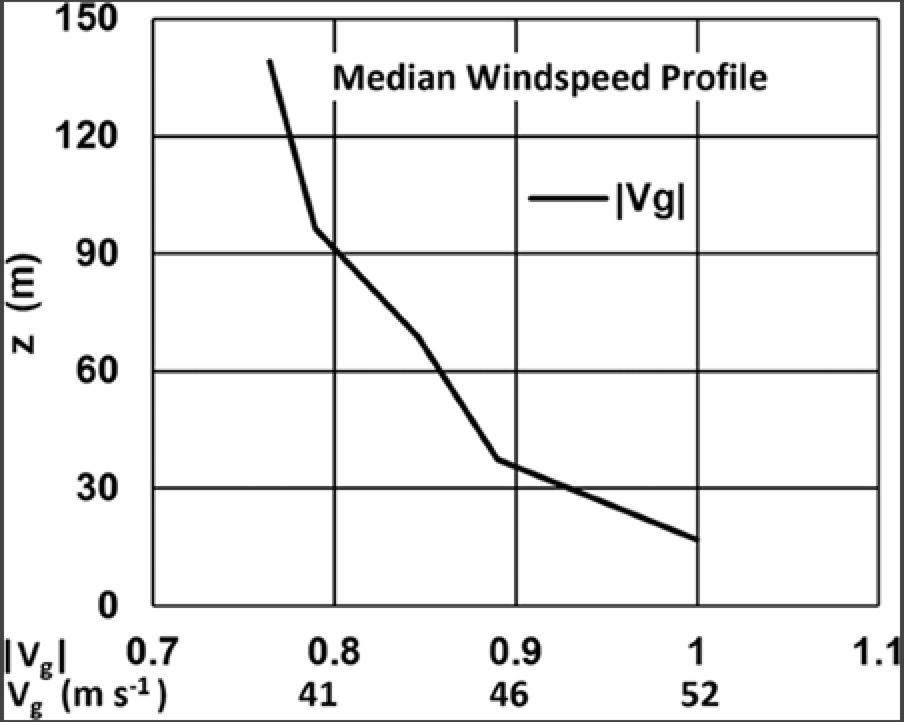


Fig. 4 from Kosiba and Wurman (2023).

- Radar estimation of tornado wind speeds is of particular interest since radar has a unique ability to detect wind components throughout the entire vortex at relatively high-resolution
- Work by Kosiba and Wurman (2023) used a radar climatology of tornadoes sampled with Doppler on Wheels (DOWs) to illustrate that tornado winds may be strongest near the ground (consistent with past modeling studies)

Radar Observations of Tornadoes

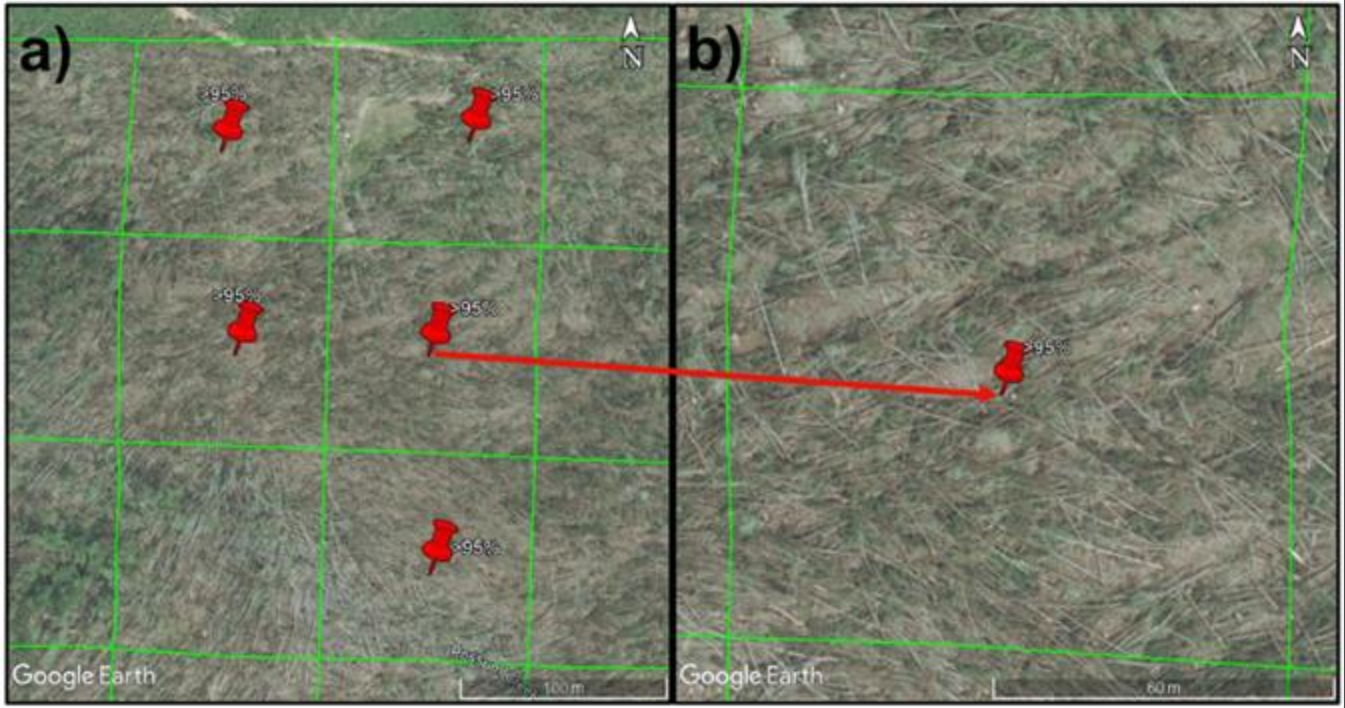


FIG. 8. (a) Overview of the five 100 m × 100 m plots estimated to feature >95% tree fall in the analyzed cross sections of the Greenwood Springs tornado track. (b) Zoomed depiction of the right-center plot (as indicated by the red arrow).

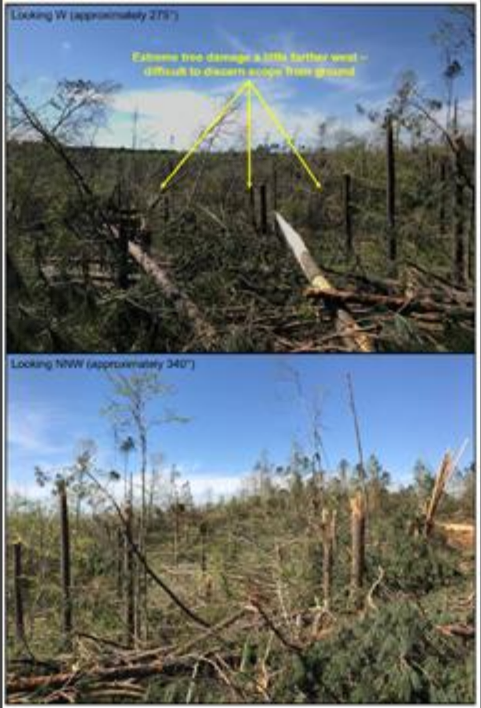


FIG. 3. Images of severe tree damage found by the UAH ground survey team along Brown Taylor Road NNE of the GWX radar. (top) What appeared as likely extreme tree damage just west of the road is noted.

Figs. 8 and 3 from Lyza et al. 2022; Greenwood Springs, MS EF4 tornado of 13 Apr

Radar Observations of Tornadoes

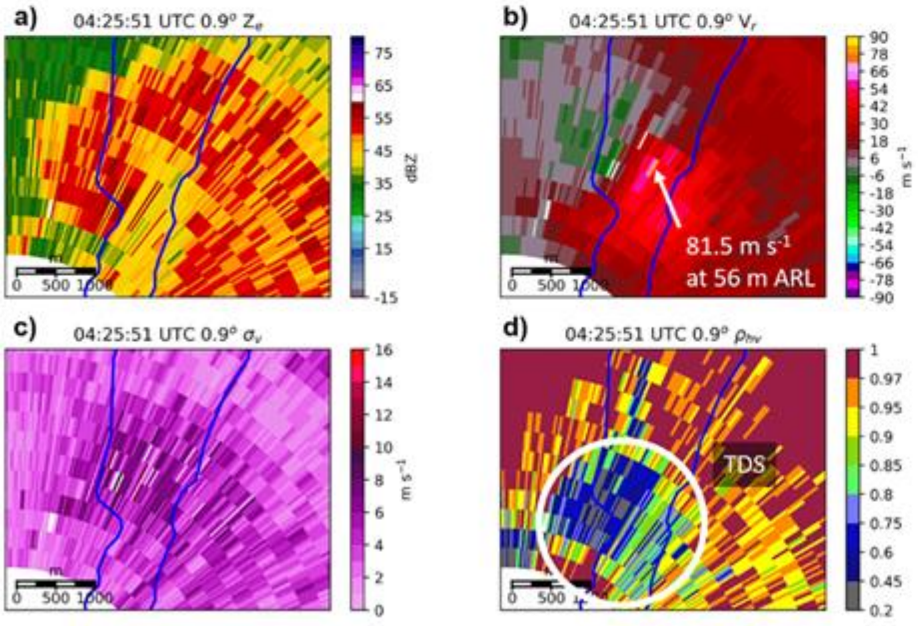


FIG. 11. Plan-position indicator (PPI) plots of (a) equivalent reflectivity factor (Z_e), (b) manually de-aliased radial velocity (V_r), (c) spectrum width (σ_v), and (d) copolar correlation coefficient (ρ_{hv}) from the 0.9° GWX sweep at 0425:51 UTC 14 Apr 2019, the time of the highest V_r value observed during the Greenwood Springs tornado. The EF0 damage contour of the tornado track is outlined in blue.

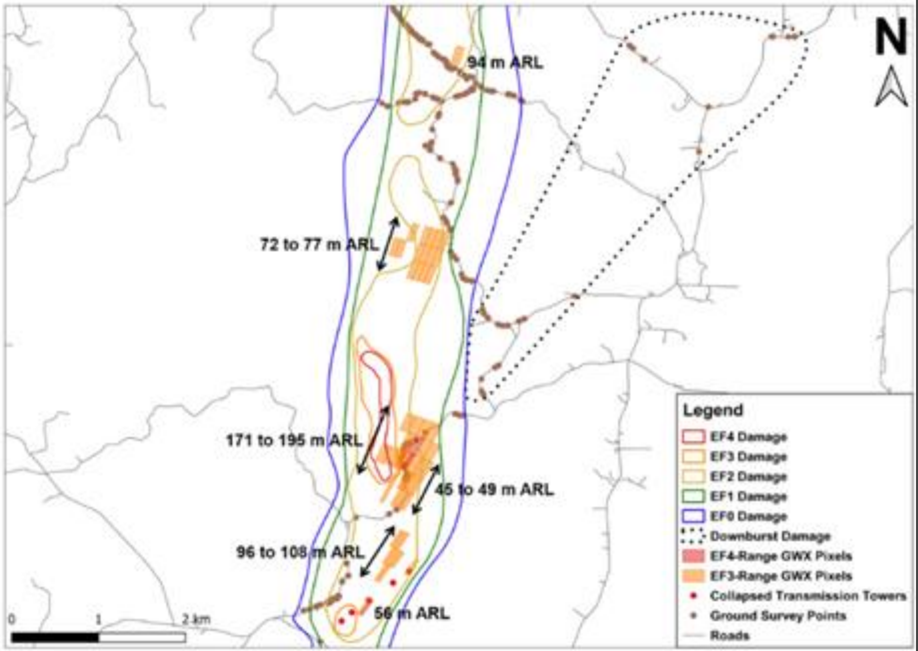


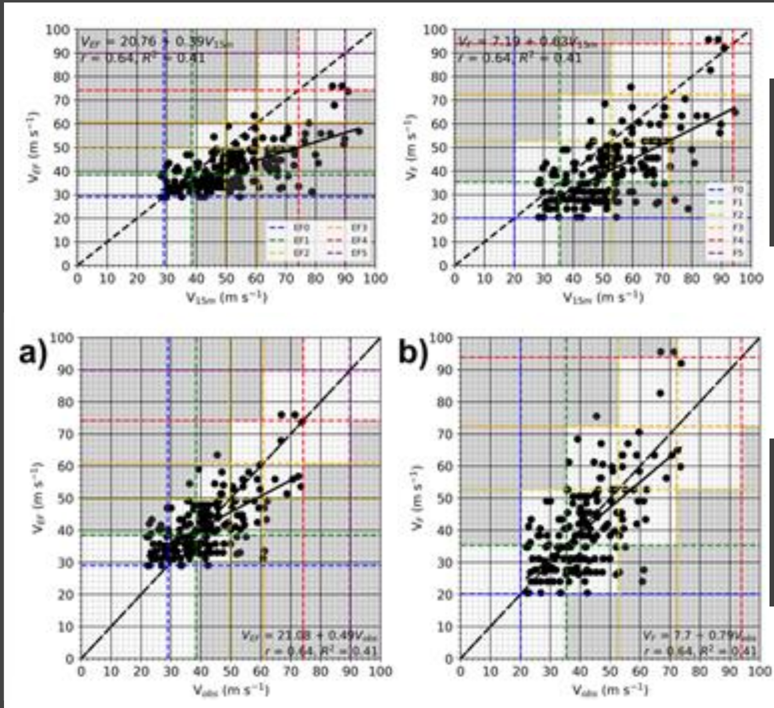
FIG. 19. Zoomed-in map of the most intense damage region of the Greenwood Springs tornado with GWX pixels featuring V_r values in the EF3 or EF4 wind speed range overlaid. The elevation values indicate the range of estimated beam heights for pixels in each GWX sweep where EF3+ V_r values are detected.

Figs. 11 and 19 from Lyza et al. 2022; Greenwood Springs, MS EF4 tornado of 13 Apr 2019

Radar Observations of Tornadoes

EF-Scale Wind Speed Estimate from Damage

F-Scale Wind Speed Estimate from Damage



Wind speed *increasing* from radar beam to near-ground

Wind speed *constant* from radar beam to near-ground

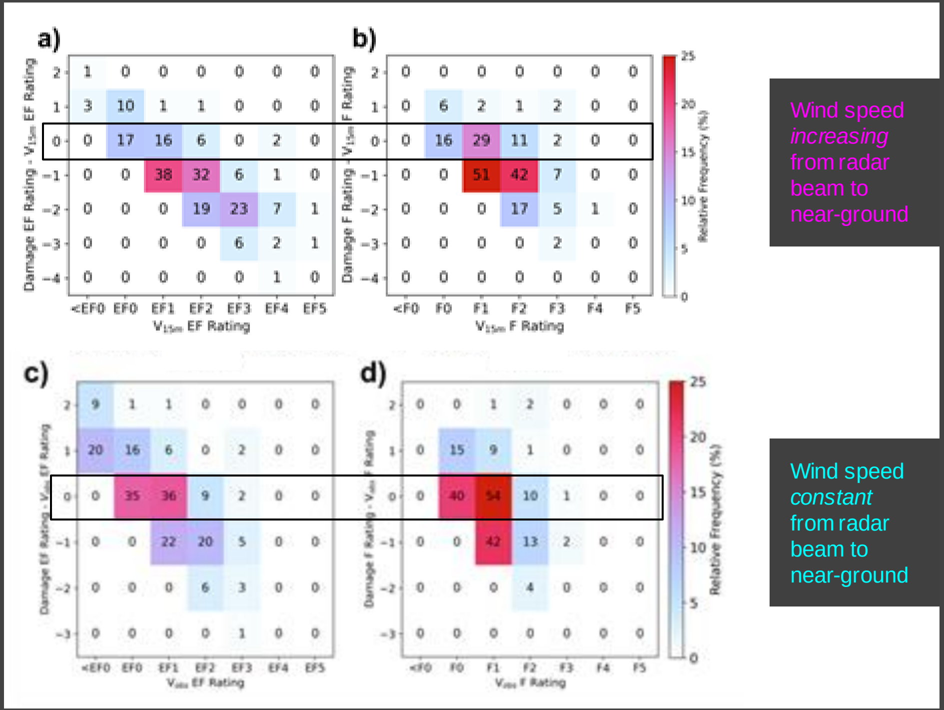
Adapted from Figs. 6, 12, and 17 of Lyza et al. (2024; MWR)

- Lyza et al. (2024) gathered 194 observations from 105 different tornadoes that had observations from WSR-88D radars 150 m AGL and compared those observations to both EF and F-scale estimates of wind speed from damage
- Applied two different assumptions to estimate winds near the ground: (1) that wind speeds increase along the Kosiba and Wurman (2023) curve and (2) that wind speeds remain constant from radar beam height to the surface
- For both assumptions, radar-based intensity estimates of near-ground winds increase more quickly than wind speed estimates from damage from the EF scale as vortex intensity increases
- Damage-based wind speed estimates from EF scale more closely match radar for weak tornadoes, while wind speed estimates from the F scale more closely match radar for strong–violent tornadoes; however…

Radar Observations of Tornadoes

EF-Scale Wind Speed Ranges

F-Scale Wind Speed Ranges



Adapted from Figs. 14 and 17 of Lyza et al. (2024; MWR)

The official tornado climatology is still based on the ratings of tornadoes.

When the radar-based wind speed estimates and damage-based wind speed estimates are both binned into their respective EF and F scale ratings, the F scale yields **less rating error** than the EF scale across the entire range of tornado intensities.

<u>Key Takeaway:</u> Tornado intensity estimation is still a very difficult task, and damage-based estimates of tornado intensity can still contain a lot of error. <u>*Estimates of tornado intensity from the EF scale likely yield lower-bound estimations of actual tornado intensity in many cases, especially for stronger tornadoes.*</u>

UAS and Satellite Remote Sensing

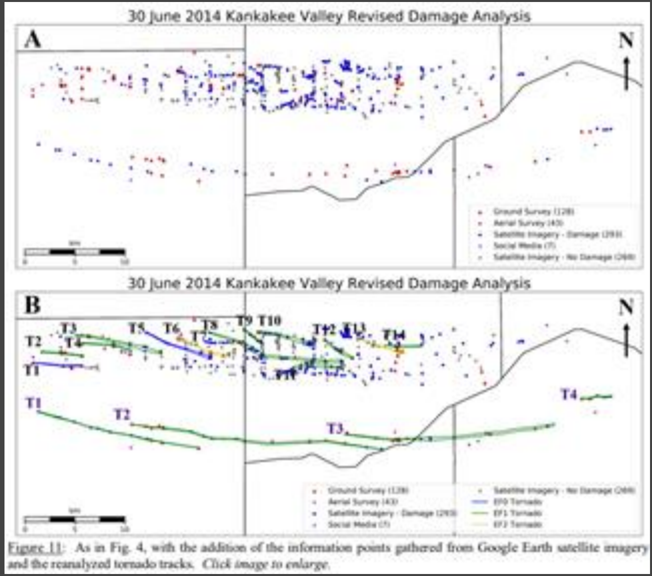


Figure 11: As in Fig. 4, with the addition of the information points gathered from Google Earth satellite imagery and the reanalyzed tornado tracks. *Click image to enlarge.*

Figs. 11, 8, and A2
Reanalysis of the Kankakee Valley, IL/IN, QLCS EF0–EF2 tornado tracks of 30 June 2014

In-situ Observations

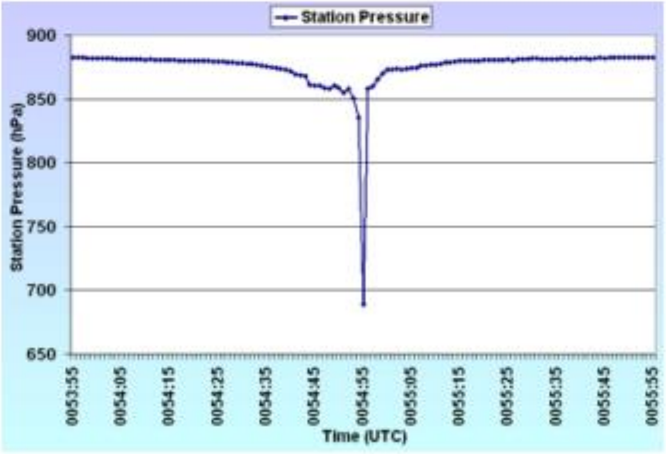


Figure 11: Station pressure (hPa) trace at 2.6 m AGL during a 120 s sample period (0053:55 to 0055:55 UTC). *Click image to enlarge.*

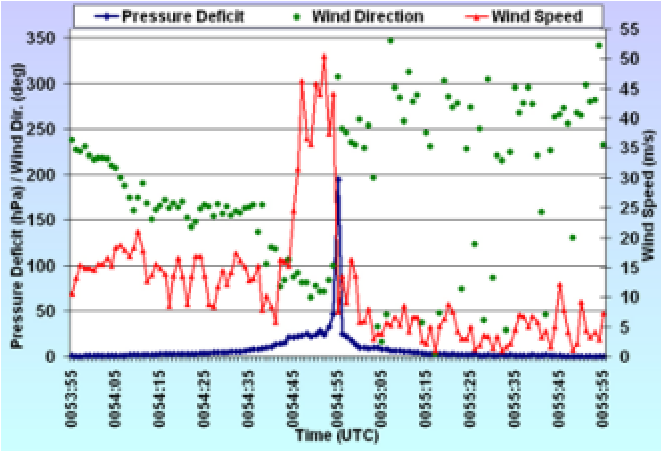


Figure 12: Combination of wind speed (red line, $m\ s^{-1}$) and direction (green dot, azimuthal degrees) at 2.9 m AGL and station pressure deficit (blue line, hPa) at 2.6 m AGL during a 120 s sample period (0053:55 to 0055:55 UTC). *Click image to enlarge.*

Figure 17: Aerial images of the tornado damage within the industrial region of Tulia. The yellow arrows denote the location of the MM vehicle. View is looking to the east (a), west (b). Highway 87 serves as a north-south reference. Photos by NOAA/NWS Lubbock, Darrin Davis and Zane Price. *Click image to enlarge.*

Figs. 11, 12, and 17 from Blair et al. (2008)
Observations from inside the Tulia, TX EF2 tornado of 21 Apr 2007

Tornado Intensity Estimation: Summary

Power pole dragged ~18” through an embankment at Rolling Fork, MS, 24 Mar 2023; rated EF3

- Many advances have been made in tornado intensity estimation since the 1970s
- However, there are still many uncertainties in estimating tornado winds, particularly for the strongest of tornadoes
- Recent downturn in higher-end tornado ratings are a byproduct of survey practices, not a weakening of tornadoes over time
- Critical to keep the uncertainties in tornado intensity estimation in mind when using past tornado intensities in climatological risk assessment!