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Empirical estimates of kinetic energy from some recent U.S. tornadoes

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Abstract Data from some recent tornado damage assessments are used to compute the percentage of damage path area by enhanced Fujita (EF) rating and to estimate kinetic energy. Only a small fraction of the damage area gets the highest damage rating, and this fraction is lower than a model used by the U.S. Nuclear Regulatory Commission. However, estimates of kinetic energy derived from a characteristic wind speed for each EF rating and the fraction of area with that rating match kinetic energy estimates using the model percentages. On average, the higher the EF rating, the larger the kinetic energy, but there is large variability in the relationship. The average total kinetic energy over the EF1 tornadoes examined in the study is 0.61 TJ, which compares with an average of 2.37 TJ, 40.1 TJ, 36.5 TJ, and 50.4 TJ for the EF2, EF3, EF4, and EF5 tornadoes, respectively. The most energetic tornado examined had a maximum damage rating of EF3.

1. Introduction

The United States experiences more tornadoes than any country on Earth [*Grazulis*, 1990]. Advances in technology have improved forecast warnings; nevertheless, the active 2011 season with over 1700 tornadoes took the lives of more than 550 people [*Simmons and Sutter*, 2012]. The devastating societal impacts of tornadoes [*Brooks and Doswell*, 2001] makes it critical to understand their potential destructiveness.

What is known about tornadoes comes almost exclusively from available records. Tornado records in the United States date back to the seventeenth century [*Grazulis*, 1990]. More comprehensive records compiled by the National Weather Service (NWS) *Storm Data*, reviewed by the National Climate Data Center [*Doswell and Burgess*, 1988], and maintained by the Storm Prediction Center (SPC) date back to the middle twentieth century.

The records contain information on the location of first touchdown, damage path length and width, and maximum damage rating which are used to estimate local incidence rates [*Thom*, 1963; *Widen et al.*, 2014]. With additional assumptions about the variation in intensity along the length and across the width of a tornado, *Reinhold and Ellingwood* [1982] model local tornado wind speed probabilities in the United States. A similar approach is applied by the U.S. Nuclear Regulatory Commission [*Ramsdell and Rishel*, 2007] to model probabilities of extreme tornado winds at the building level. Using damage surveys from tornadoes during the 3–4 April 1974 outbreak and from tornadoes during April and May of 2011, *Standohar-Alfano and van de Lindt* [2014] develop an empirical model for the intensity gradient over the tornado path as input to a hazard analysis.

A destructive potential index that multiplies damage area by damage rating is developed in *Thompson and Vescio* [1998]. The index is reformulated in *Agee and Childs* [2014] by multiplying the square of the damage path width by the square of the mean wind speed for the maximum EF rating under the assumption that every location in the damage path receives the worst damage. Work has also been done in describing the distribution of tornado intensities [*Dotzek et al.*, 2003, 2005; *Brooks*, 2004] and the mass-specific kinetic energy [*Schielicke and Névir*, 2009] aggregated by EF rating category.

Recently, more comprehensive records of tornadoes have become available in a systematic way through the NWS Damage Survey Viewer (Damage Assessment Toolkit). These records contain additional information about the damage path including the total damage area, the damage area by damage rating, and duration of the tornado. This additional information makes it possible to estimate tornado energy for individual tornadoes without the assumption that the fastest winds occur across the entire path.

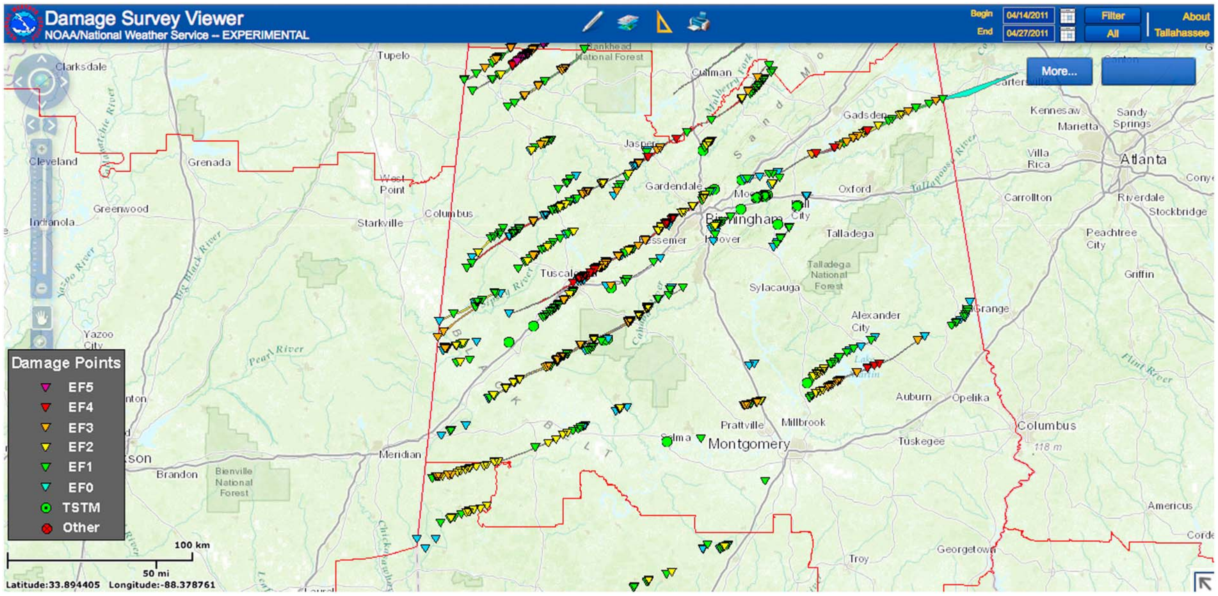

Figure 1. Screenshot of the data viewer. The data viewer is part of the NWS Damage Assessment Toolkit (DAT).

The purpose of the present study is to demonstrate a method for estimating kinetic energy from tornadoes where damage area information is available. These empirical energy estimates are compared with similar energy estimates made with the model assumptions of *Ramsdell and Rishel* [2007]. The approach allows comparisons to be made between tornadoes of different sizes and across different damage ratings. It also allows comparisons to be made between tornadoes and other destructive events (e.g., earthquakes). Our approach to estimating kinetic energy of tornadoes is similar to the approach taken by *Powell and Reinhold* [2007] for estimating the integrated kinetic energy of hurricanes.

The paper is organized as follows. In section 2 we describe the new tornado data available from the NWS Damage Survey Viewer. In section 3 we examine and compare the percent damage path area of the 18 available tornadoes by enhanced Fujita (EF) rating. In section 4 we compute total kinetic energy and rank the tornadoes. In section 5 we summarize the research and provide some concluding remarks.

2. NWS Damage Assessment Toolkit

Development of the NWS Damage Assessment Toolkit (DAT) has led to the creation of a new data set, which supplements the official Storm Data record with additional details of severe weather events [*Camp et al.*, 2013]. Created to standardize and streamline the collection of damage assessment data following severe weather events, the DAT facilitates the collection of data utilizing the EF scale criteria, where wind speeds are estimated by comparing damaged structures to a set of damage indicators and associated degrees of damage [*Washington State Energy Code (WSEC)*, 2006]. The EF scale ranges from EF0 indicating little structural damage to EF5 indicating complete destruction often with a concrete slab swept clean of debris.

The DAT consists of four primary components, including a central geospatially enabled database which stores the data. During a damage assessment, data are collected and transmitted to the central database via mobile apps and/or laptop-based software. The software utilizes GPS for positioning and allows for the inclusion of photographs from the damage site. Once in the central database, the data are edited and quality controlled through a web-based interface. The quality-controlled data are available for dissemination through Open Geospatial Consortium compliant web services, as well as through a web-based data viewer.

Figure 1 is a screenshot of the NWS Damage Assessment Toolkit. The toolkit has a filter button at the top right where specific storm dates can be selected. It also has a set of buttons across the top middle, which are used to extract and measure specific storms. On the left side of the toolkit the different damage points based on the damage rating are shown. There is also a tool for viewing and zooming on the map.

Three data types can be created in the DAT for an event. Damage points are primarily collected in the field with the mobile software and contain EF damage rating information for individual structures, along with

Table 1. Tornadoes Available From the DAT That Have Contours of Damage by EF Rating

Name	Length (km)	Width (m)	Rating	EF0 (%)	EF1 (%)	EF2 (%)	EF3 (%)	EF4 (%)	EF5 (%)
Argo, AL/GA (2011)	115	1609	EF4	42	33	18	5	2	
Hackleburg, AL/TN (2011)	1207	1320	EF5	35	28	18	13	4	2
Hayleyville, AL (2011)	51.2	1207	EF3	48	38	12	3		
Lake Martin, AL (2011)	71.18	805	EF4	34	29	23	12	2	
Pocahontas, IA (2011)	5.15	537	EF4	68	26	6	0.4	0.07	
Sawyerville-Eoline, AL (2011)	1609	1760	EF3	30	25	38	7		
Shottsville, AL (2011)	29.7	1207	EF3	51	44	3	2		
Floyd County, GA (2011)	20.4	183	EF2	62	27	12			
Creston, IA (2012)	26.7	549	EF2	82	17	1			
New Virginia, IA (2012)	1.61	46	EF1	91	9				
Oskaloosa, IA (2012)	2.09	69	EF1	66	34				
Rake, IA (2012)	1.30	83	EF1	96	4				
Cobb County, GA (2012)	2.25	137	EF1	67	33				
Edmond, OK (2013)	7.24	823	EF1	92	8				
Newcastle-Moore, OK (2013)	22.5	2092	EF5	43	30	16	8	3	0.1
Shawnee, OK (2013)	32.2	1931	EF4	57	34	9	0.7	0.07	
Adairsville, GA (2013)	35.1	823	EF3	64	32	3	0.5		
Cherokee, GA (2013)	20.8	183	EF1	68	32				

optional photographs. Damage paths and damage polygons are created through subjective analysis of the damage points using the web-based editor. Damage paths (polylines) are created to follow the approximate centerline of the path of a tornado. Damage paths may consist of multiple segments along the path and store damage rating information about the event. Damage polygons outline the spatial extent of the damage associated with a tornado. The polygons are used to create contours of damage consistent with each damage category.

In this study, damage contours are downloaded using the Extract Toolbox as a single shapefile. The file contains nested polygons by EF scale rating. We import the shapefile to R using the readOGR function from the rgdal package [*Bivand et al.*, 2014]. Some EF ratings covered more than one polygon, but each is assigned a unique identifier. We compute the area for each polygon using a planar projection and sum by EF rating. We also compute the total damage path area and the percent area by rating.

3. Percent Damage Area

Table 1 is a chronological list of the 18 tornadoes examined in this study and their damage path percentages. These tornadoes were chosen because they have damage polygons available in the DAT. Tornadoes were included only if the damage path could be produced as a conformal shapefile with contours by EF damage rating. At the time of writing only these 18 tornadoes met these requirements.

The data set includes tornadoes from 2011 to 2013 throughout multiple states including Alabama, Georgia, Iowa, Oklahoma, and Tennessee. There are eight tornadoes from the 2011 season, five from the 2012 season, and five from the 2013 season. The eight tornadoes from 2011 occurred on 27 April 2011 across the south. There was a total of 145 tornadoes on that day [*Elsner et al.*, 2014] with total damage losses exceeding $10 billion US [*National Climatic Data Center (NCDC)*, 2012].

Percentages of the damage path having an EF0 rating range from a low of 30% for the EF3 Sawyerville-Eoline, AL (2011) tornado to a high of 96% for the EF1 Rake, IA (2012) tornado with a median of 64%. As a comparison, percentages of the damage path having an EF1 rating range from a low of 4% for the EF1 Rake, IA (2012) tornado to a high of 44% for the EF3 Shottsville, AL (2011) tornado with a median of 29%.

Table 2 lists the number of tornadoes in the study by maximum EF rating and the median and range of the percent area affected by the maximum rating. For comparison the table includes the percent area used by the U.S. Nuclear Regulatory Commission's (NRC) model [Table 3-1] and the percent area used in the empirical model of *Standohar-Alfano and van de Lindt* [2014]. The percentage areas in the NRC report are based on a weighted average of a theoretical model (stationary Rankine vortex) [$\frac{1}{3}$ weighting] and empirical estimates [$\frac{2}{3}$ weighting] from the *Reinhold and Ellingwood* [1982, Table 7c] report on tornado damage risk assessment.

Table 2. Median Percent Area by Maximum EF Rating[a]

Rating	Wind Speed ($m\ s^{-1}$)	Midpoint Speed ($m\ s^{-1}$)	Number of Tornadoes	Median % Area	Range % Area	NRC % Area	SAvdL % Area
EF1	38.4–49.6	44.0	6	20.7	(4.1, 33.9)	22.8	26.6
EF2	49.6–60.8	55.2	2	6.1	(0.7, 11.5)	11.5	17.4
EF3	60.8–74.2	67.5	4	2.3	(0.5, 7.0)	6.7	10.8
EF4	74.2–89.4	81.8	4	.9	(0.1, 1.9)	3.2	5.8
EF5	89.4–104.6	96.1	2	.8	(0.1, 1.6)	1.7	4.1

[a]NRC refers to the model used by *Ramsdell and Rishel* [2007], and SAvdL refers to the empirical estimates of *Standohar-Alfano and van de Lindt* [2014].

The median percent area of the maximum EF rating is lower than the NRC model and considerably lower than the empirical estimates from *Standohar-Alfano and van de Lindt* [2014] all five EF ratings. The discrepancy is largest for the higher EF rating with the model percent above the highest percentage for the EF4 and EF5 tornadoes. Figure 2 illustrates the comparison of the empirical data with the NRC model for an EF3 tornado.

The model and actual data are represented as sets of nested rectangles. There is large variability in percentages at all rating levels. The EF0 percentages range from a minimum of 30% for the Sawyerville-Eoline tornado to a maximum of 64% for the Adairsville tornado. The EF1 percentages range from 25% for the Sawyerville-Eoline tornado to 44% for the Shottsville tornado. The EF2 percentages range from 3% for both the Adairsville and Shottsville tornadoes to 38% for the Sawyerville-Eoline tornado, and the EF3 percentages range from 0.5% for the Adairsville tornado to 7% for the Sawyerville-Eoline tornado.

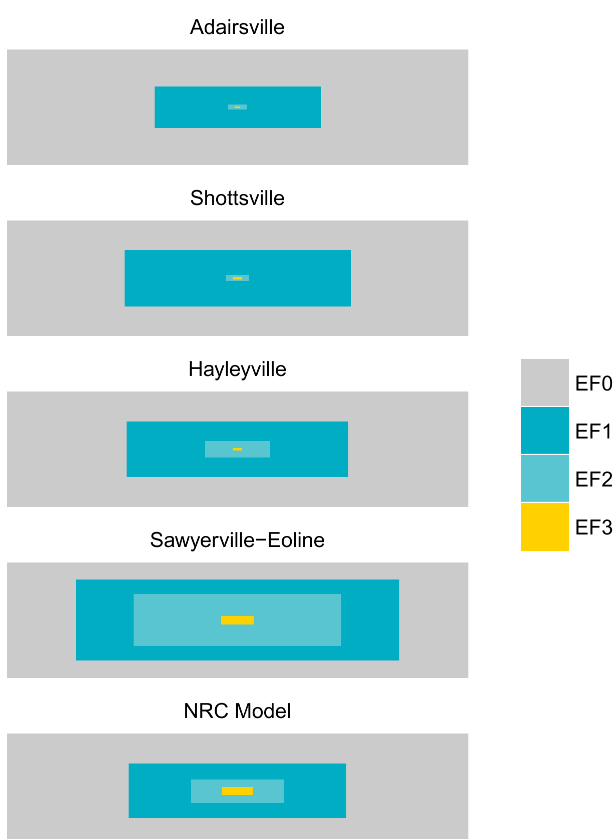

Figure 2. Comparison of percent area by damage rating for the four EF3 tornadoes in our study. For comparison the NRC 2007 model is shown.

For the set of EF2 tornadoes, the EF0 percentages range from a minimum of 62% for the Floyd County tornado to a maximum of 82% for the Creston tornado. The EF1 percentages range from 17% for the Creston tornado to 27% for the Floyd County tornado, and the EF2 percentages range from 1% for the Creston tornado to 12% for the Floyd County tornado. For the set of EF4 tornadoes, the EF0 percentages range from a minimum of 34% for the Lake Martin tornado to a maximum of 68% for the Pocahontas tornado. The EF3 percentages range from 0.4% for the Pocahontas tornado to 12% for the Lake Martin tornado.

4. Total Kinetic Energy

Damage path area together with the percent area by EF rating allows us to estimate per tornado kinetic energy. The kinetic energy per unit mass (mass specific KE) of the tornado is given by $\frac{1}{2}v^2$ where v is the wind speed [*Schielicke and Névir*, 2009]. Here we use the midpoint wind speed on the EF operational damage scale so that $v_{EF0} = 33.8\ m\ s^{-1}$ and $v_{EF5} = 96.1\ m\ s^{-1}$ (see Table 2). The wind speeds represent an average over 3 s. The upper bound on the EF5 rating is from the derived EF scale.

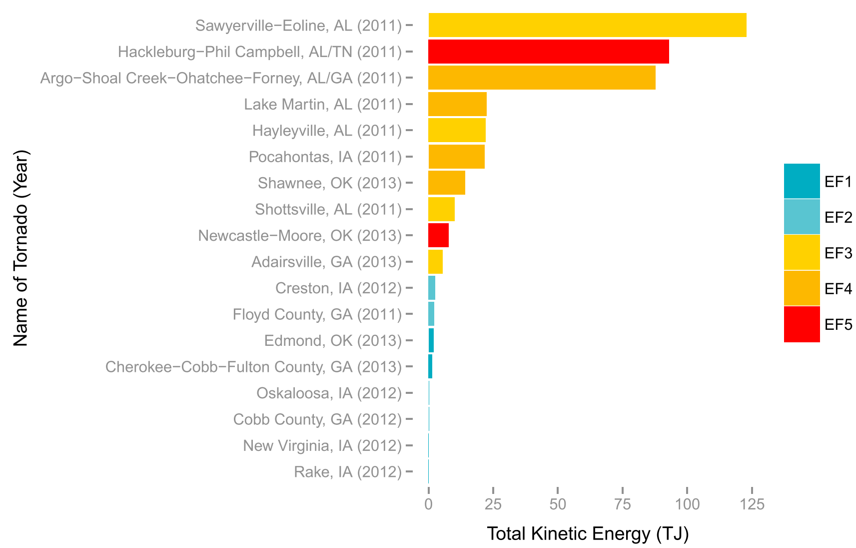

Figure 3. Tornado kinetic energy. The bar colors correspond to the highest EF rating.

We compute a weighted average of the midpoint wind speed using the corresponding fractions of total damage footprint area as weights. One half this average wind speed squared is the total mass specific kinetic energy. We convert this mass specific kinetic energy to units of Joules by multiplying by air density (1 kg m^{-3}) and tornado volume using the path area and assuming a height of 1 km. Tornado height likely varies considerably perhaps by as much as a factor of 10, but without additional information we give it a fixed value.

Figure 3 shows the tornadoes ordered by total kinetic energy (TKE). The most powerful tornado in our study is the Sawyerville-Eoline, AL tornado from the 27 April 2011 outbreak. We estimate that the tornado had a total kinetic energy of 123 TJ. For comparison the Hiroshima bomb had a blast yield of 67 TJ. The second most powerful tornado is the Hackleburg-Phil Campbell, AL tornado with an estimated TKE of 93 TJ, followed by the Argo-Shoal Creek-Ohatchee-Forney, AL/GA tornado with an estimated TKE of 88 TJ. The destructive Newcastle-Moore, OK tornado ranked ninth with an estimated TKE of 7.7 TJ. For the Newcastle-Moore OK tornado only a small fraction of the area of the damage footprint had an EF5 rating (0.1%). This fact, along with its limited path length and duration, is the reason for the relatively low-energy ranking in this study.

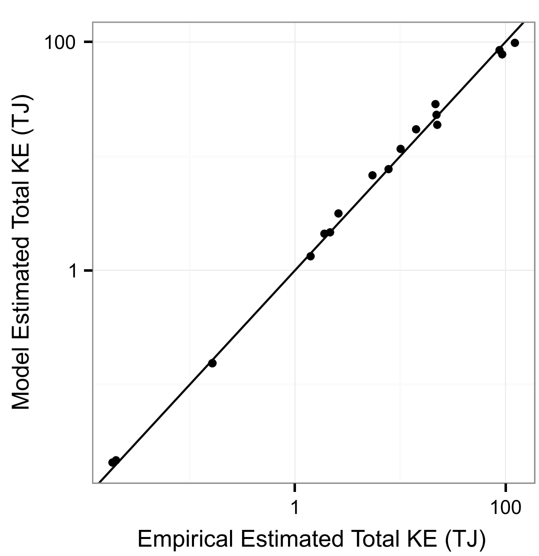

Figure 4. Model versus empirical estimated total kinetic energy.

On average the higher the EF rating the larger the kinetic energy, but there is large variability in the relationship. The average TKE over the EF1 tornadoes is 0.61 TJ, which compares with an average of 2.37 TJ, 40.1 TJ, 36.5 TJ, and 50.4 TJ for the EF2, EF3, EF4, and EF5 tornadoes, respectively. The most energetic tornado had a maximum damage rating of EF3. The most energetic of the EF2 tornadoes was Creston, IA (2012) with an estimated TKE of 2.6 TJ and the most energetic of the EF1 tornadoes was Edmond, OK (2013) with an estimated TKE of 1.9 TJ.

We compute the TKE using the NRC model for the percent areas and compare the values with our empirical estimates in Figure 4. The plot shows an excellent correlation between our empirical estimates and the NRC derived values. The correlation between the two estimates exceeds 0.99.

As noted above the empirical percent areas are lower than the model percentages at the highest EF rating. However, the empirical percentages tend to be larger at the middle ratings for the two strongest tornadoes. For example 13% of the path of the EF5 Hackleburg-Phil Campbell, AL/TN tornado had EF3 damage which compares with 6.5% for the EF5 NRC model. There are too few cases to evaluate whether these differences represent a real bias in the model.

5. Summary and Conclusions

Tornadoes leave behind a swath of destruction. Data from modern damage assessments provide an opportunity to compare recent tornadoes based on energy. Damage contours by EF rating are available as shapefiles from the NWS's Damage Assessment Tool. Here we use these data to compute the percentage of the damage path by EF rating and to estimate the tornado's total kinetic energy (TKE). Comparisons are made between our empirical estimates and estimates made using a standard model of percentages.

For a given EF rated tornado the percent area by EF rating varies considerably. We find the percent area in the highest ratings to be consistently below the percent area given by the NRC model and much below the percent area given in *Standohar-Alfano and van de Lindt* [2014] with the underestimates largest for the most damaging tornadoes. Since our sample size is small, we hesitate to draw definitive conclusions, but the results suggest that the most damaging winds might be spatially more restrictive than previously thought. More research on this topic is needed.

TKE for each tornado is estimated from these percent areas and a characteristic wind speed for each EF rating. Based on these estimates the three most powerful tornadoes in our data set include the Sawyerville-Eoline, AL tornado with a TKE of 123 TJ, the Hackleburg-Phil Campbell, AL tornado with a TKE of 93 TJ, and the Argo-Shoal Creek-Ohatchee-Forney, AL/GA tornado with a TKE of 88 TJ. These empirical estimates of TKE match very well with the estimates based on the theoretical/empirical model used by the NRC. The estimate of TKE makes use of the middle wind speed for each EF rating. While this provides a simple working procedure to estimate energy, improvements can be made by assuming a distribution of speeds conditional on rating.

As previously mentioned the study is limited by the small number of tornadoes with damage area information. Repeating our analyses on additional tornado events will provide robust statistics on path area percentages and tornado energy. This limitation notwithstanding, the present work provides a framework for estimating energy of historical tornadoes from path characteristics and EF rating. Finally, while our approach of including wind speed variation over the damage path is an improvement over the simpler approach of using a single wind speed, it does not consider the fact that at least some tornadoes have multiple vortices and other local-scale eddies [*Agee et al.*, 1976]. However, we assume that these disturbances produce locally faster and slower winds that average out over the tornado's life span.

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