Adjustments in Tornado Counts, F-Scale Intensity, and Path Width for Assessing Significant Tornado Destruction

ERNEST AGEE AND SAMUEL CHILDS

Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, Indiana

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ABSTRACT

The U.S. tornado record is subject to inhomogeneities that are due to inconsistent practices in counting tornadoes, assessing their damage, and measuring path length and path width. Efforts to improve the modern tornado record (1950–2012) have focused on the following: 1) the rationale for removing the years 1950–52, 2) identification of inconsistencies in F0, F1, and F2 counts based on implementation of the Fujita scale (F scale) and Doppler radar, 3) overestimation of backward-extrapolated F-scale intensity, and 4) a change in path-width reporting from mean width (1953–94) to maximum width (1995–2012). Unique adjustments to these inconsistencies are made by analyzing trends in tornado counts, comparing with previous studies, and making an upward adjustment of tornadoes classified by mean width to coincide with those classified by maximum width. Such refinements offer a more homogeneous tornado record and provide the opportunity to better evaluate climatological trends in significant (F/EF2–F/EF5) tornado activity. The median EF-scale (enhanced Fujita scale) wind speeds $V_{med}$ have been adopted for all significant tornadoes from 1953 to 2012, including an adjustment for overestimated intensities from 1953 to 1973. These values are used to calculate annual mean kinetic energy, which shows no apparent trend. The annual mean maximum path width $PW_{max}$ from 1953 to 2012 (adjusted upward from 1953 to 1994 to obtain a common lower threshold), however, displays an increasing trend. Also, the EF-scale median wind speeds are highly correlated with $PW_{max}$. The quantity $(V_{med} \times PW_{max})^2$ is proposed as a tornado destruction index, and, when calculated as an annual cumulative value, the three largest years are 2007, 2008, and 2011.

1. Introduction

Analyses of tornado intensities, their trends, and patterns of destruction through time are of great importance in the realm of climate science and to society in general. Scientists can be limited, however, by a lack of cohesive statistics in the modern tornado dataset (1950–2012). Considerable attention has been given to U.S. tornado statistics to determine the distribution function for their intensity, as well as the potential relationship of their intensity to path length and path width (Dotzek et al. 2003, 2005; Brooks 2004). The creation of the Fujita (F) and enhanced Fujita (EF) scales has introduced potential impacts on the interpretation of the U.S. tornado record. For example, both scales attempt to use tornado damage to quantify maximum wind speeds, but limitations exist in damage-assessment subjectivity and application, as well as in available targets and objects that can be damaged, as discussed by Doswell et al. (2009), Edwards and Brooks (2010), and Edwards et al. (2013). It is well known that maximum wind speed and the types of structures in the path, along with airborne debris and missiles, play a major role in causing tornado damage and as such are related to the ultimate assignment of F/EF-scale values. Thus, not only velocity $v$, but also $v^2$ and $v^3$, are important considerations in evaluating damage potential (Emanuel 2005). This study specifically chooses to use $v^2$, since dynamic-pressure wind loading onto barriers is directly proportional to the free-stream kinetic energy. There have been efforts to improve or establish more internationally recognized wind speed scales (Dotzek 2009), but there remain opportunities to adjust for discrepancies and to create a more homogeneous record of U.S. tornado events [for 1950–2012, as archived in Storm Data (described below), which is also accessible online from the Storm Prediction Center (http://www.spc.noaa.gov/wcm/)]. This study attempts to adjust for these discrepancies—to be specific, for significant tornadoes [$\geq$F/EF2; originally defined by Hales (1988)].
The proposed adjustments are based on the following: 1) establishing the best year for beginning the tornado record, 2) illustrating the heterogeneities in the F0 count for different periods of time, 3) identifying the undercounting of F1 events and the overcounting of F2 events that took place prior to 1974 and revising to establish a more homogeneous record, 4) making adjustments to inflated F-scale values (and thus speed estimates) from prior to 1974, and 5) establishing a more complete tornado record for maximum path width, recognizing that mean tornado path width was recorded in the years prior to 1995.

Upon finding and implementing adjustments to the above, the opportunity exists to reexamine tornado intensity trends through time, particularly in significant tornado counts, their kinetic energy, and maximum path width (as well as the possible relationship of the median EF-scale wind speed value with maximum path width). Further, to provide a way to better assess the magnitude of tornado damage on the basis of F/EF-scale wind speed estimates, this study introduces a tornado destruction index (TDI). It is noted that this index does not explicitly consider the geography of population distribution and construction practices along the path of individual tornadoes. Analysis of the annual cumulative values of the TDI parameter (TDIC) is also made to look for evidence of climatological trends and/or idiosyncrasies in archiving method.

2. Data accountability, adjustments, and analysis

The Storm Prediction Center maintains a modern tornado data record, compiled from the Storm Data archive at the National Climatic Data Center (NCDC), and currently includes tornado attributes for the period of 1950–2012. Numerous efforts have been made to provide the most accurate data [the most recent being the introduction of the EF scale; see assessment by Edwards et al. (2013)], but there remain succinct biases in a number of the attributes, some of which have been addressed (Schaefer and Edwards 1999; McCarthy 2003; Doswell 2007). Specifically applicable to this study are biases that exist in both reported count and damage magnitude of tornadoes throughout the period that inhibit accuracy of analysis and/or require the omission of large portions of the data record to avoid such biases. Differences in path-width reporting (from mean to maximum) are also addressed.

a. Homogeneous versus heterogeneous records

One of the concerns to be examined is associated with the first three years of the modern tornado data record: 1950–52. Efforts to extend the tornado record back in time to before the establishment of the National Severe Storms Forecast Center in 1953 have been pursued with support from the U.S. Nuclear Regulatory Commission (Tecson et al. 1979) and independently by Grazulis (1993). These efforts involved searching newspaper reports and old photographs—useful but limited resources that may not allow for accurate tornado attributes (Doswell and Burgess 1988; Schaefer and Edwards 1999). Figure 1 shows the annual tornado count through time, which has been increasing since 1950 as a result of a variety of factors (population growth, increasing numbers of storm chasers and observers, verification methods,
technological advancements, etc.). It is evident from this and subsequent figures that the 1950–52 data record may have credibility issues (based in part on the assessment method and the long period of elapsed time in compiling data). The decision to eliminate these three years of data from the study is discussed below, along with subsequent analyses that support such action.

Another source of heterogeneity comes from improved tornado counting (especially for weaker tornadoes) with the implementation of the Weather Surveillance Radar-1988 Doppler (WSR-88D) network, which occurred during the early 1990s and was completed in 1997 (Crum et al. 1998). Doppler radar allows for the possibility of detecting a vortex circulation that coincides with local wind damage of F/EF0 strength. Agee and Hendricks (2011) have shown evidence of a similar technological effect in the climatological data of hurricane-induced tornadoes. Figure 2 shows the count of F/EF0 tornadoes for 1950–2012 and an apparent discontinuity in the data in the early 1990s (supported by the \( t \)-test comparison of means, significant at the 0.01 confidence level), coinciding with the implementation of the Doppler radar network. This technological advancement has allowed meteorologists to better detect mesocyclones that may produce weak tornadoes and consequently to record more events than during the pre-Doppler era. Although Verbout et al. (2006) note that nearly all of the increase in tornado reports during the past 50 years can be attributed to increased reporting of F/EF0 tornadoes that is largely due to population increase, it is noted that the magnitude of the increase in the early 1990s (Fig. 2) cannot be explained by population growth. It is also interesting to note that there is an increase in both counts and variability in the F/EF0 record after the implementation of Doppler radar, as depicted by the “fanning” pattern of data.

A third area of concern, and most applicable to the current study, is that of the overcounting and overrating the intensity of F2 versus F1 tornadoes, specifically before the implementation of the F scale in 1974, as noted by Grazulis (1993). Figure 3a shows the F/EF1 tornado counts from raw data files and illustrates the general undercounting of F1 tornadoes prior to 1974, as well as a cluster of low values for 1950–52. The F/EF1 tornado counts from 1974 to 2012 show a more homogeneous, stationary pattern (with an average of 336 tornadoes per year), accompanied by random variability (correlation coefficient squared \( r^2 = 0.0144 \)). Contrary to the F/EF0 record, no spike in reporting is seen during the time of Doppler radar implementation. Further, as seen in Fig. 3b, the F2 count prior to 1974 is noticeably elevated, except for the cluster of the three years 1950–52. Coupling the observations of too few F1s and too many F2s for the period of 1953–73, when compared with the subsequent years, allows the authors to draw a reasonable conclusion that there was an assignment of excessively high values of wind speed range for many of the F2 events. When all
data are combined (see Fig. 3c for F/EF1–F/EF5), the record appears to be mostly homogeneous and stationary [as reported by Verbout et al. (2006)]. This conclusion does not follow, however, since the potentially overestimated F2 and underestimated F1 counts have been added together, masking the real signal.

As noted, the cluster of the three years 1950–52 appears to be outside the distributions for particular tornado counts in each of Figs. 1, 2, and 3a–c, and it follows that the authors have elected to begin their study with 1953. Note that Verbout et al. (2006) start their analysis with 1954, which is also reasonable.

A fourth area of concern is the shift in the data record for reporting tornado path width. Although there was some gradual overlap of both mean and maximum path-width reporting, it was not until 1995 that the change was completed, as noted by Brooks (2004). A method is introduced below for building a maximum path width record from 1953 to 2012.

b. Refinements and method

1) COUNTS

Significant tornadoes (F/EF2–F/EF5) produce the greatest destruction. In accord with this situation, it is assumed that the contemporary significant tornado statistics (1974–2012) are more reliable than those from the earlier period, because of increased knowledge, as well as more complete field investigation and documentation. Figure 4 is presented to show comparisons between pre-F-scale and post-F-scale counts for equal time periods (1953–73 and 1974–94, respectively), and it is reasonable.
to consider making adjustments to the data. The specific focus is on F2 events, which account for 85% of the total significant tornado difference (between the two adjoining 21-yr periods), as previously explained in Fig. 3b. The method for adjustment (Table 1) begins with calculating the mean counts of F1 and F2 tornadoes for the two periods, which establishes an F1:F2 ratio for each period. To remove the overcounting of F2s in the early period, their count is lowered (and the F1 count consequently raised) until the ratios are equal. New mean counts for F1 and F2 tornadoes are found following the adjustment, and the percent change in F1 mean counts is found to be 27.6%:

\[
\text{Count correction factor} = \frac{\mu_2 - \mu_1}{\mu_1} = \frac{310 - 243}{243} = 0.2757 \rightarrow 27.6\%.
\]

This is the factor by which F2 counts are lowered (and F1 counts raised) in the 1953–73 period. There was not sufficient rationale to make comparable types of adjustments to the small differences in F3–F5 tornado counts, because of the infrequency of their occurrence (Verbout et al. 2006). The annual plot of adjusted significant tornado counts is presented in Fig. 5. With the adjustment, the mean count of significant tornadoes for the pre-F-scale era (1953–73) is lowered from 243 to 191, which is closer to the mean count of 158 for the post-F-scale era (1974–2012). Still, a weak decreasing trend in significant tornado counts exists, which is consistent with previous research (Doswell et al. 2009). Fewer significant tornadoes does not necessarily imply a decrease in destruction from tornadoes, however (a topic discussed in a later section).

2) INTENSITY AND WIND SPEED

Since actual maximum wind speeds of tornadoes are estimated, the approach used in this study is to adopt the median wind speed value \( V_{\text{med}} \) (from the EF scale) for each of the respective EF ratings of all significant tornadoes (except for the EF5 rating, where the minimum estimated wind speed is used because of the infrequency of events). These median wind speeds are equivalent to the mean of the estimated wind speeds of the upper and lower bounds for that particular EF rating [e.g., for EF2 rating, \( V_{\text{med}} = (111 \text{ mi h}^{-1} + 135 \text{ mi h}^{-1})/2 \), converted to meters per second]. The EF scale, being a more recent way to estimate tornado intensity than the F scale [see assessment by Edwards et al. (2013)], is used throughout this study for assessing median wind speeds and calculating kinetic energy. Further, Widen et al. (2013) have noted that the F scale and the EF scale can be considered to be equivalent for climatological studies. Not only have

| TABLE 1: Count-correction method for adjusting F2 tornado counts for 1953–73, using the more accurate 1974–94 data. |
|---------------------------------|-------------------|-------------------|
|                                | 1953–73           | 1974–94           |
| F1 mean count                  | 243               | 332               |
| F2 mean count                  | 187               | 128               |
| F1:F2 ratio                    | 1.3               | 2.6               |
| Corrected mean count: F1       | 310               | 332               |
| Corrected mean count: F2       | 120               | 128               |
| Corrected F1:F2 ratio          | 2.6               | 2.6               |
the F2 counts been revised, but also the representative median wind speeds have been adjusted (per the EF scale) because all counts are viewed as having overestimated wind speeds (even the fraction that is retained in the F2 category). The magnitude of the wind speed adjustment is determined by the change in percent of the total F1 and F2 counts that is attributed to F2 tornadoes following the count adjustment (see Table 1):

Wind speed correction factor
\[ = 100 \left( \frac{n_{F2}}{n_{F1} + n_{F2}} \right)_{\text{before}} - 100 \left( \frac{n_{F2}}{n_{F1} + n_{F2}} \right)_{\text{after}} \]
\[ = 15.6 \rightarrow 15.6\% , \]

where \( n_{F1} \) and \( n_{F2} \) are the number of F1 and F2 counts, respectively. Thus, the principle now invoked (viz., correction of overestimation of F2 counts as a result of a perception of higher maximum wind speeds than what actually occurred) results in a 15.6% reduction in the median wind speed for the EF2 rating. It is reasonable to note for consistency that all significant tornado scales should receive a similar adjustment for the 1953–73 period (Table 2). Figure 5 shows that this approach and adjustment yield more homogeneous records and stationary patterns than are seen in the raw data. This adjustment may not create the perfect set of wind speed data, but it is an improvement.

3) PATH WIDTH

The U.S. tornado database provides the mean path width of tornado events from 1950 to 1994 but provides maximum path width from 1995 to the present. Figure 6 shows the annual mean values of significant tornado path widths for the two periods (1953–94 and 1995–2012), which reveals a discontinuity jump in their respective lower thresholds of approximately 209 m (supported by a \( t \) test comparing different population means, significant at the 0.01 confidence level). In an attempt to equate these two different populations, mean width values have been increased by 209 m and are renamed “maximum” width values. The entire record (1953–2012) is now represented by a single lower threshold (as shown in Fig. 7), and the mean values of maximum path width for each of the four significant EF-scale ratings have been matched by making an upward adjustment of 52 m (209/4) for the period of 1953–94. The trend of path widths through time shows increasing variability with a recent uptick toward wider tornadoes; improved methods of measuring path widths may be responsible for some of the variability, however.

### Table 2. Intensity corrections made to the EF-scale intensity ratings for 1953–73.

<table>
<thead>
<tr>
<th>Intensity</th>
<th>Velocity range (mi h(^{-1}))</th>
<th>( V_{med} ) (mi h(^{-1}))</th>
<th>( V_{med} ) (m s(^{-1}))</th>
<th>( V_{adj} ) (m s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF2</td>
<td>111–135</td>
<td>123</td>
<td>55.0</td>
<td>46.4</td>
</tr>
<tr>
<td>EF3</td>
<td>136–165</td>
<td>150.5</td>
<td>67.3</td>
<td>56.8</td>
</tr>
<tr>
<td>EF4</td>
<td>166–200</td>
<td>183</td>
<td>81.8</td>
<td>69.0</td>
</tr>
<tr>
<td>EF5</td>
<td>&gt;200</td>
<td>200*</td>
<td>89.4*</td>
<td>75.5*</td>
</tr>
</tbody>
</table>

* Minimum speed is used for EF5 intensity because of the difficulty in assigning a median value.
4) Maximum Path Width and Tornado Intensity

From previous results, it is now possible to examine the relationship of the adjusted maximum path width to the median value of EF-scale wind speeds (Fig. 8). The linear distribution of these data points shows an approximately 170-m increase in maximum tornado path width for each 10 m s\(^{-1}\) increase in \(V_{\text{med}}\) (with an \(r\) value of 0.981), which is a plausible result since one might expect wider tornadoes to have higher ratings because of the increased opportunity to impact more buildings of greater structural integrity. Minimal uncertainty in this relationship exists, as expressed by the error bars in Fig. 8, except for EF5, which is characterized by a small number of events. Also, many tornadoes are not steady-state systems, multiple vortices can be present, and the aero-dynamics of surface boundary layer vortex spinup can differ, all of which represent opportunities to produce variation in maximum path width versus intensity rating. It is noteworthy, however, that although this result is derived from a different method it is consistent with the
3. Kinetic energy and tornado destruction

Although kinetic energy and related quantities for tornadoes have been considered in past studies (e.g., Dotzek et al. 2005; Dotzek 2009), the adjustments to the U.S. tornado record presented in this study now allow for reinvestigation of such quantities. To be specific, the focus is on kinetic energy for significant tornadoes for the period of 1953–2012, as well as the introduction of a new quantity for examining the TDI.

a. Kinetic energy

As discussed in the introduction, this study has chosen $v^2$ for addressing tornado damage, because of its relationship to dynamic pressure buildup on obstacles to the flow. Further, Dotzek et al. (2005) noted that tornado intensities are exponentially distributed over the peak wind speed squared ($v^2$), particularly for significant tornadoes. Even if this study had chosen the advective transport of kinetic energy ($v^3$), used in calculating power dissipation, the results would provide the same conclusion.

The method for calculating the annual total kinetic energy for the period of 1953–73 is presented in Table 3, which incorporates the noted adjustments (reduction in F2 counts and 15.6% reduction in $V_{med}$). In a similar way, Table 4 shows calculations for the unadjusted period of 1974–2012. The range of wind speeds for the respective EF-scale rating has been used for all years in establishing median values $V_{med}$, and the square of these values gives the kinetic energy per intensity rating. Multiplying this value by the respective number of events per intensity rating and then summing the four (EF2–EF5) totals gives a total kinetic energy for each period. A mean kinetic energy per significant tornado per year can then be computed, as shown in Tables 3 and 4.

### Table 3. Kinetic energy (KE) calculations for 1953–73. On the basis of this table, one obtains $\frac{KE_{sig,torn}}{4} = 2.58 \times 10^6$ m$^2$ s$^{-2}$ and $KE_{sig,torn}/year = (2.58 \times 10^6)/21 = 1.23 \times 10^5$ m$^2$ s$^{-2}$.

<table>
<thead>
<tr>
<th>Intensity</th>
<th>$N_{raw}$</th>
<th>$N_{adj}$</th>
<th>$V_{med}$ (m s$^{-1}$)</th>
<th>$V_{adj}$ (m s$^{-1}$)</th>
<th>KE ($V_{adj}^2$)</th>
<th>KE $\times N_{adj}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF2</td>
<td>3929</td>
<td>2845</td>
<td>55.0</td>
<td>46.4</td>
<td>2152.96</td>
<td>6.13 $\times 10^6$</td>
</tr>
<tr>
<td>EF3</td>
<td>937</td>
<td>937</td>
<td>67.3</td>
<td>56.8</td>
<td>3226.24</td>
<td>3.02 $\times 10^6$</td>
</tr>
<tr>
<td>EF4</td>
<td>212</td>
<td>212</td>
<td>81.8</td>
<td>69.0</td>
<td>4761.00</td>
<td>1.01 $\times 10^6$</td>
</tr>
<tr>
<td>EF5</td>
<td>26</td>
<td>26</td>
<td>89.4</td>
<td>75.5</td>
<td>5700.25</td>
<td>1.48 $\times 10^5$</td>
</tr>
<tr>
<td>Totals</td>
<td>5104</td>
<td>4020</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1.03 $\times 10^7$</td>
</tr>
</tbody>
</table>

### Table 4. Kinetic energy calculations for 1974–2012. On the basis of this table, one obtains $\frac{KE_{sig,torn}}{4} = 5.46 \times 10^6$ m$^2$ s$^{-2}$ and $KE_{sig,torn}/year = (5.46 \times 10^6)/39 = 1.40 \times 10^5$ m$^2$ s$^{-2}$.

<table>
<thead>
<tr>
<th>Intensity</th>
<th>$N$</th>
<th>$V_{med}$ (m s$^{-1}$)</th>
<th>KE ($V_{med}^2$)</th>
<th>KE $\times N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF2</td>
<td>4539</td>
<td>55.0</td>
<td>3025.00</td>
<td>1.37 $\times 10^7$</td>
</tr>
<tr>
<td>EF3</td>
<td>1289</td>
<td>67.3</td>
<td>4529.29</td>
<td>5.84 $\times 10^6$</td>
</tr>
<tr>
<td>EF4</td>
<td>298</td>
<td>81.8</td>
<td>6691.24</td>
<td>1.99 $\times 10^6$</td>
</tr>
<tr>
<td>EF5</td>
<td>32</td>
<td>89.4</td>
<td>7992.36</td>
<td>2.56 $\times 10^5$</td>
</tr>
<tr>
<td>Totals</td>
<td>6158</td>
<td>—</td>
<td>—</td>
<td>2.18 $\times 10^7$</td>
</tr>
</tbody>
</table>
approach, Fig. 9 shows the adjusted total significant tornado kinetic energy per year for the entire record, which is stationary (see linear-fit dashed line). This is further supported by the mean kinetic energy per significant tornado per year being very similar (1.23 $\times 10^5$ m$^2$ s$^{-2}$ for 1953–73 vs 1.40 $\times 10^5$ m$^2$ s$^{-2}$ for 1974–2012), as shown respectively in Tables 3 and 4. Two years, 1974 and 2011, are noted outliers, with all other departures randomly distributed from the fitted line ($r^2$ = 0.0026), as characteristic of a stationary time series.

b. Tornado destruction index

Kinetic energy trends give a sense of how the strength of tornadoes is changing through time, but they fail to account for the trend in tornado widths, which reveals how much area is being influenced and possibly damaged at a given point in time. As noted by Thompson and Vescio (1998), the potential for tornado damage should be related to tornado intensity, path width, and path-length. In fact, they introduced a destruction potential index (DPI) for measuring potential damage associated with a single tornado outbreak. Their index multiplies the tornado intensity rating and the total area of each given track, all of which are summed for a single outbreak and compared (e.g., Palm Sunday 1965 vs 3 April 1974). The parameter for estimating the intensity of tornado destruction presented in the current study is different than DPI and has an objective that considers all significant tornadoes on an annual basis for the entire tornado record. TDI is directly proportional to the pressure exerted by wind loading on barriers to the flow [which is proportional to $(V_{med})^2$ for the given EF-scale intensity] as well as the maximum path width $(PW_{max})^2$ that defines a unit of area containing such obstacles:

$$TDI = (V_{med} \times PW_{max})^2.$$  \hspace{1cm} (1)

As shown in Fig. 8, the magnitude of tornado destruction *at the time of maximum intensity* increases as EF rating increases. Given that the tornado has its maximum velocity rating $V_{med}$ as it advances across the area $PW_{max}^2$, it is appropriate to assume that every point in this unit area is exposed to maximum local damage. It is noted that the outer boundaries of the maximum width area obviously do not receive the maximum wind speed, but this physical property of the vortex is characteristic of all events (and the individual TDI calculations are systematically made for all events). Further, this “collateral” damage should be related to tornado intensity and path width. Therefore, a cumulative parameter for significant tornadoes can now be defined as $TDI_C$, the cumulative tornado destruction index:

$$TDI_C = \sum_{n=2}^{5} (N_n V_{med}^2) \times (PW_{max}^2),$$  \hspace{1cm} (2)

where $N_n$ is the number of events per rating, $V_{med}$ is the median EF-scale wind speed, $PW_{max}$ is the mean maximum path width per rating, and $n$ is the EF-scale intensity.

The annual totals of $TDI_C$ are presented in Fig. 10, which suggests a quasi-stationary pattern through 2006, with 1965 holding the record for highest $TDI_C$. It is noteworthy, however, that three of the last six years (2007,
2008, and 2011) have produced record values of $TDI_{C}$, which is due in part to greater values of $PW_{\text{max}}$. The results in Fig. 10 show a possible trend in $TDI_{C}$ and the increasing variability in total annual tornado destruction. Note that the ratio of significant tornadoes to total tornadoes has gone from 7.2% in 2004 to 13.2% in 2012, despite the decrease in significant tornadoes (see Fig. 5). The maximum path width may be contributing to this upturn in $TDI_{C}$, however (see Fig. 10). Also worthy of consideration is the possible movement of intensity ratings toward the middle categories (EF2 and EF3) with the introduction of the EF scale (Edwards and Brooks 2010). Continual monitoring of $TDI_{C}$ provides an opportunity to detect changes in tornado destruction on a climatological time scale.

4. Summary and conclusions

Although several improvements to the modern U.S. tornado record (1950–2012) have been offered in past and current work, issues with the tornado archive remain that may be difficult to address. Doswell et al. (2009) discuss a systematic underrating of tornadoes in the most recent decade that is due to policy changes at the National Weather Service, and it is further noted that concerns related to the EF scale have been raised by Edwards and Brooks (2010). Verification policies that were implemented during NWS modernization and the Doppler upgrade may also influence interpretation of the tornado data. Also, attention needs to be given to societal influences on tornado statistics and the nature of damage accounts for individual events. Factors such as population density, structural integrity of buildings and homes, human response, and geographic differences in a multitude of factors can potentially affect the tornado record [see Ashley (2007) and numerous references within that publication]. In addition, Brotzge and Donner (2013) cite several societal and cultural challenges in how the public is made aware of and heeds a tornado warning. These include personalized risk, knowledge from past experience, income differences, and feasibility of taking action to protect life and property.

The study presented here offers unique adjustments to improve the analysis and interpretation of tornado data and associated statistical inferences. To be specific, the years 1950–52 are shown to be inappropriate for inclusion in the data analyses presented. Identification of inconsistencies in F0, F1, and F2 counts are found to coincide with the beginning of the F-scale method, as well as the implementation of Doppler radar. The F0 counts prior to Doppler are noticeably low, but with Doppler the counts are much higher with greater variability. It is conjectured that higher F0 counts are largely due to the capability of detecting radar vortex structures for areas of relatively weak tornado damage (that otherwise might not have been labeled as tornadic). Next, the F1 counts are too low, prior to the introduction of the F-scale method, and the F2 counts are too high for the same period. Refinements have been presented that move 27.6% of the inflated F2 counts down to the F1 category. Although previous work (e.g., Verbout et al. 2006) states that the F1–F5 annual tornado counts are stationary, the current work shows how this record can be viewed as stationary once the adjustments to F1 and
F2 counts are made [consistent with the findings by Grazulis (1993)].

Because of the obvious importance of significant tornadoes in producing death and destruction, considerable attention has been given to these data trends for 1953–2012. Even with the adjustments to the F2 counts before 1974, the significant tornado annual totals are trending down [as noted by Doswell et al. (2009)], raising the question of the possible cause for such a trend. The size of these destructive tornado events has also been brought into consideration, however. From 1953 to 1994, the mean tornado path width was recorded, but from 1995 to present it has been replaced with the maximum path width. Lower thresholds for each time period have been identified, and an adjustment of 209 m has been added to the annual mean path width for 1953–94 (thereby providing a longer and more homogeneous record of maximum tornado path width). This lower threshold adjustment also resulted in each of the four significant EF-scale ratings having an addition of 52 m (i.e., 209/4) to their mean maximum path widths. Although significant tornadoes are trending down, the annual mean maximum path width does not show a downward trend, and in fact its three highest values occur in 2007, 2008, and 2011.

To better evaluate the destructive potential of significant tornadoes (at the time of their maximum intensity), a method was adopted to assign the median wind speed for each EF-scale rating to each tornado event from 1953 to 2012, after adjustments were made to the 1953–74 period. A simple plot of $PW_{\text{max}}$ versus $V_{\text{med}}$ shows a strong linear correlation ($r = 0.981$), with an approximately 170-m increase in $PW_{\text{max}}$ for each 10 m s$^{-1}$ increase in $V_{\text{med}}$. Also, the error-bar analysis presented supports the validity of this relationship.

Considerable attention in the past has been given to $\nu$, $\nu^2$, and $\nu^3$ when examining possible tornado destruction. This study has chosen $\nu^3$ to calculate an adjusted kinetic energy value for the entire period of 1953–2012, which shows a stationary record (with the exception of two outliers, 1974 and 2011). The adjusted kinetic energy is given respectively for 1953–73 and 1974–2012 as $1.23 \times 10^9$ and $1.40 \times 10^9$ m$^2$.s$^{-2}$ per significant tornado event per year. Recognizing that the destructive potential from significant tornadoes should consider both maximum wind speed and maximum size for the total annual record, a new parameter, tornado destruction index, has been defined as $(V_{\text{med}} \times PW_{\text{max}})^2$. This parameter is calculated for a unit area at the time of its maximum intensity, using the median value of the assigned EF-scale rating. Further, the annual cumulative total of TDI (defined as TDI$_C$) has been presented to evaluate the magnitude of destruction of significant tornadoes and shows a quasi-stationary pattern yet captures three record high events in the past 6 yr (2007, 2008, and 2011). This also illustrates the potential value of TDI$_C$ in monitoring the climatological trend of any increasing risk of tornado destruction, an important consideration in the climate science community today.

REFERENCES


Hales, J. E., 1988: Improving the watch/warning system through the use of significant event data. Preprints, 24th Conf. on Severe Local Storms, Baltimore, MD, Amer. Meteor. Soc., 165–168.


