Tornadoes without NWS Warning

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ABSTRACT

During a 5-yr period of study from 2000 to 2004, slightly more than 26% of all reported tornadoes across the United States occurred without an NWS warning being issued. This study examines some of the reasons behind why no warnings were issued with these tornadoes, and what climatological, storm classification, and sociological factors may have played a role in the lack of warnings. This dataset of tornado records was sorted by F scale, geographically by region and weather forecast office (WFO), hour of the day, month of the year, tornado pathlength, tornado-to-radar distance, county population density, and number of tornadoes by day and order of occurrence.

Results show that the tornadoes most likely to strike when the public is least likely to be aware were also those tornadoes with the greatest chance of not being warned. Singular tornado events (one tornado report per day within a WFO county warning area) and the first tornado report of the day were the most difficult scenarios on which to warn, with over half of all solitary tornado events not warned. Geographic areas that experienced a significant proportion of weak, solitary, and/or nocturnal tornadoes had a much higher ratio of missed warnings. In general, the stronger the tornado, as estimated from its F-scale rating and/or track length, the greater chance it was warned. However, the tornado distance from radar had a significant impact on tornado warning statistics. In addition, many weak tornadoes were not warned, and the overall ratio of missed tornado warnings to reported tornadoes actually increased over more densely populated regions, likely due to more complete postevent verification.

1. Introduction

The issuance of tornado warnings is one of several high-profile services provided by the National Weather Service (NWS). The general public, as well as many critical decision makers in media, emergency management, and the private sector, rely upon the NWS for advanced warning that a tornado will strike, and many expect additional information to accompany the warning, including tornado time of arrival, expected path, and intensity. However, about one-quarter of all tornadoes in this study occurred with no warning issued.

This study examines several of the reasons behind why some tornadoes are not warned, and what climatological, storm morphological, and sociological factors may have inhibited a warning from being issued. Only after the underlying factors for missed warnings are better understood can research and operations be more clearly focused to improve tornado warning capabilities. This study examines 5 yr of tornado data to identify any unique storm characteristics or associated circumstances that would have inhibited a warning. This paper is a companion article to Brotzge and Erickson (2009), which investigated the causes for tornado warnings with negative lead time.

2. Data

Five years of tornado data collected between 2000 and 2004 were obtained directly from the performance branch of the National Oceanic and Atmospheric Administration (NOAA)/NWS. These data included information
on all tornado records and their associated warnings, if any. The data contained the date and location of each tornado’s county segment, the time of the event, if and when the NWS warning was issued, the weather forecast office (WFO) that issued the warning, the county or parish location, the estimated F-scale rating, and the number of fatalities and estimates of damage. Additional information including tornado pathlength, width, and duration were obtained from the National Climatic Data Center. County population estimates were obtained from the 1 July 2000 population estimates produced by the Population Division of the U.S. Census Bureau (U.S. Census Bureau 2008).

Storm classification was determined by manual review of radar reflectivity data, using a simplified version of the classification scheme as suggested by Gallus et al. (2008). Each storm event was classified as either cellular, linear, tropical (hurricane, tropical storm), or undefined. No radar velocity data are needed for this classification scheme. The Gallus et al. classification scheme was chosen because it was based solely upon the radar reflectivity, had been applied recently for comparison with severe weather reports, and was used in the companion paper Brotzge and Erickson (2009). The purpose of the classification was to differentiate between storms that were primarily cellular, linear, or tropical related; the intention here was not to identify storms as supercellular or nonsupercellular.

### 3. Climatology

To better understand why some tornadoes are not warned for, a climatology of the 5-yr dataset of tornado reports was completed. The data were sorted by F scale, geographically by region and WFO, hour of the day, month of the year, tornado pathlength, tornado-to-radar distance, county population density, and number of tornadoes by day and order of occurrence. The database of tornado reports from 2000 to 2004 includes 5170 (73.6%) tornadoes with associated NWS warning and 1854 (26.4%) tornadoes without warning.

#### a. Sorted by F scale

The first hypothesis tested by the authors is that the larger and more violent a tornado, the more likely that tornado will be warned or observed visually by a spotter, or that the associated storm features will be recognized from radar. The dataset was sorted by F scale and by whether or not a warning was issued (Table 1). The results indicate that, in general, the stronger the tornado rating, the greater the chance that a tornado was warned. Weak tornadoes (F0, F1) have relatively high ratios of missed warnings (27.7%) when compared to stronger tornadoes (F2, 15.5%), while very strong tornadoes (e.g., F4s) have very low ratios of missed warnings (<10%). Many factors may influence why these stronger tornadoes are warned, including tornado duration, proximity to radar or population centers, F-scale classification, and tornado order, and these factors are discussed in later sections. All reported F3 and F4 tornadoes that occurred without warning between 2000 and 2004 are listed in Table 2.

While 26.4% of the documented tornadoes were not warned, fatalities caused from unwarned tornadoes accounted for only 11.1% of all tornado fatalities (Table 3). This is primarily because, as shown in Table 1, it is generally the weaker tornadoes (F0, F1) that are unwarned. The fatality rate for weak tornadoes among unwarned tornadoes was 47.6%, nearly double the rate expected, since unwarned tornadoes accounted for only about a quarter of all reported tornadoes. However, a much larger sample size is needed to determine the significance and impacts of unwarned tornadoes on the fatality rates from weak tornadoes (Doswell 2007).

#### b. Geographical distribution

A second hypothesis tested is that some tornadoes simply are much easier to detect and warn in some parts of the country than in others. To evaluate this assumption, the tornado reports were sorted among four broad geographic regions: southeast (SE), midwest–east (MW), plains, and west (Fig. 1). The distributions of tornadoes by region and warning are shown in Table 4. The plains region has a significantly lower ratio of unwarned tornadoes, just over 20% when compared to other regions, whereas the west has over double the ratio of unwarned tornadoes at 42%. Unwarned tornado

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1 The National Climatic Data Center’s (NCDC) tornado database uses county segments of tornado paths, instead of complete tracks, for those events crossing county and state borders. Mention of “tornadoes” hereafter implies “tornado segments” for any such events.
ratios for the southeast and midwest regions were similar to one another, at 28.4% and 32.0%, respectively.

As shown in Table 4, many more tornadoes were observed among the plains states than in other regions, perhaps thereby improving tornado warning operations experience and maintaining the necessity for active local spotter networks. Much of the plains region is also relatively flat and with less vegetation than other regions, allowing for much easier viewing of storms. Brotzge and Erickson (2009, hereafter BE09) show from a limited sample that the plains region also has a much higher ratio of cell-based storms than regions to the east, perhaps allowing for easier tornado feature identification from radar. On the other hand, the west region also has a high ratio of cell-based storms based on the sample from BE09, but has the highest ratio of missed events. The west has by far the fewest tornadoes reported compared to other regions, thereby limiting warning operations experience. The west also suffers from limited radar coverage due to spacing between radars and mountain blockage (e.g., Westrick et al. 1999), and tornadoes west of the Rockies are generally much shorter lived (as deduced from their average pathlengths) than in other regions. This is discussed further in section 3f.

Next, the tornado data were sorted by the WFO county warning area (CWA) in which each reported tornado occurred. The percentage of tornado reports without warning were calculated for each WFO and plotted against the total number of tornado reports within each CWA during the 5-yr period (Fig. 2a). In general, WFOs with a relatively small number of tornadoes documented during the 5-yr period (i.e., <25) have a relatively high percentage of unwarned tornadoes (F0 4510 2 1 50.0

<table>
<thead>
<tr>
<th>F-scale rating</th>
<th>Total No. of tornadoes</th>
<th>Total No. of fatalities</th>
<th>Fatalities from tornadoes without warning</th>
<th>Percentage of fatalities from tornadoes without warning</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>4510</td>
<td>2</td>
<td>1</td>
<td>50.0</td>
</tr>
<tr>
<td>F1</td>
<td>1786</td>
<td>19</td>
<td>9</td>
<td>47.4</td>
</tr>
<tr>
<td>F2</td>
<td>528</td>
<td>54</td>
<td>9</td>
<td>16.7</td>
</tr>
<tr>
<td>F3</td>
<td>162</td>
<td>107</td>
<td>4</td>
<td>3.7</td>
</tr>
<tr>
<td>F4</td>
<td>38</td>
<td>43</td>
<td>2</td>
<td>4.7</td>
</tr>
</tbody>
</table>
1991), and challenging radar-warning conditions for potentially tornadic minisupercells (e.g., Spratt et al. 1997). During 2004 alone, Florida was hit by five tropical systems (Bonnie, Charley, Frances, Ivan, and Jeanne), several of which spawned a significant number of tornadoes. During the study period within the CWAs of these four WFOs, tornadoes from tropical storms and hurricanes accounted for between 10% and 59% of the tornadoes without warnings. Furthermore, very weak tornadoes and waterspouts, which are rather unpredictable, isolated, and transitory, and common to the Gulf coast region, are notoriously difficult to warn.

To refrain from issuing too many tornado false alarms, some forecasters may adopt a general policy of waiting to issue a tornado warning until after a tornado has been confirmed visually by storm spotters. For others, their warning confidence for a given situation simply may be too low to issue a warning until after a tornado has been confirmed. Previous research has showed that the first tornado of the day has a much lower rate of warning (Bieringer and Ray 1996). This analysis also demonstrates that relationship. The percentage of first-tornado-of-the-day events without warning was plotted as a function of the total number of tornado days (Fig. 2b). Overall, the first tornado of the day has a much higher ratio of missed warnings than does the overall warning average. This is discussed in more detail in section 3i.

d. Seasonal climatology

Next, the total numbers of warned and unwarned tornado reports were sorted by month of year (Fig. 4a), and monthly average percentages of tornadoes without warning were calculated (Fig. 4b). Similar to the results shown from BE09 for negative lead time events, those months with the greatest numbers of tornado reports (e.g., May) have among the lowest ratios of unwarned tornadoes, while those months with relatively few tornado reports (e.g., January) have the highest ratios of unwarned tornadoes. The more solitary (nonoutbreak) tornado events most common during nonpeak tornado months make warning more difficult and are discussed in more depth in section 3i.

e. Storm classification

As demonstrated by the high ratio of unwarned tornadoes across Florida, the morphology of a given storm can impact warning operations. For this study, a sample of 110 positive lead time events, 110 negative lead time events, and 90 “no warning” tornado events were classified. All the data were listed in chronological order; every 40th event was classified from the positive lead time warning dataset, every 10th event was classified from the negative lead time warning dataset, and every 20th event was classified from the no-warning dataset. This sampling was done to ensure the representative

TABLE 4. Distribution by region of all reported tornadoes between 2000 and 2004 with and without NWS warnings shown by column.

<table>
<thead>
<tr>
<th>Region</th>
<th>Total no. of tornadoes</th>
<th>Tornadoes with warning</th>
<th>Tornadoes without warning</th>
<th>Percentage of tornadoes without warning (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southeast</td>
<td>1960</td>
<td>1403</td>
<td>557</td>
<td>28.4 ± 2.0</td>
</tr>
<tr>
<td>Midwest</td>
<td>1323</td>
<td>899</td>
<td>424</td>
<td>32.0 ± 2.5</td>
</tr>
<tr>
<td>Plains</td>
<td>3253</td>
<td>2589</td>
<td>664</td>
<td>20.4 ± 1.4</td>
</tr>
<tr>
<td>West</td>
<td>483</td>
<td>279</td>
<td>204</td>
<td>42.2 ± 4.4</td>
</tr>
</tbody>
</table>
annual variation of the population and to extract a roughly equal number of events from each category for comparison. The time required to classify each storm limited the number of events that could be studied.

Each event was reviewed manually using mosaic radar data (displayed online at http://www.mmm.ucar.edu/imagearchive/), and, when not available, level II radar data (Crum et al. 1998) archived at the National Climatic Data Center were used. The mosaic images are regional radar composites provided by the Precipitation Diagnostics Group within the Mesoscale and Microscale Meteorology Division of the National Center for

Fig. 2. (a) Reports of tornadoes (%) without an NWS warning plotted against the total no. of tornadoes confirmed by that WFO during the 5 yr of study. (b) Reports of first tornadoes of the day (%) without NWS warning plotted against the total no. of tornado days. Note that each dot represents one WFO.

Fig. 3. (a) Warned and unwarned tornadoes (No.) plotted by hour of day. (b) The percent dev calculated by subtracting the hourly percentage dev from the daily percent average of tornadoes without warning (26.4%) plotted by hour of day.
Atmospheric Research (NCAR). Reflectivity composites are available every 30 min. As described in section 2 and in Gallus et al. (2008), each storm event was classified as line, cell, tropical, or undefined. Broken lines of individual storm cells were classified as “cell,” while “line” events were generally solid convective squall lines. Undefined events primarily were stratiform regions with embedded convective elements. Storm classification was valid only at the time of tornado formation; many storms were in the process of evolving from clusters or lines of cells to more solid convective lines.

The classification of the sample events for warned and unwarned tornadoes is shown in Fig. 5. In general, the tornadoes without warning include a slightly greater ratio of linear events than those with warning. During manual classification of these events, many of the unwarned cases were found to be more difficult to classify than those storms with warning lead time. Many of the storms were in the process of evolving into lines or were lines of discrete cells, and unlike the warned events, very few of the unwarned cases could be classified as discrete supercells. However, because of the relatively small samples used in this study and the inherent uncertainty

fig. 4. (a) As in Fig. 3, but for month. (b) Mean percentage of tornadoes without warning plotted by month.

fig. 5. The storm classification percentages from a subsample of (a) 110 tornadoes with positive lead time warning, (b) 110 tornadoes with negative lead time warning, and (c) 90 tornadoes with no warning.
in the classification, these results may not be representative of the storm population (Doswell 2007).

f. Impacts of pathlength

Another hypothesis tested is that long-track tornadoes have a much greater warning percentage than do short-track tornadoes. This study binned all tornado data by pathlength and then calculated the percentage of tornadoes warned. The longer the path, the greater the chance that a tornado was warned (Fig. 6). About 70% of all tornadoes with a track length <2 km were warned, whereas 85% of tornadoes with a tornado track of >10 km were warned. The mean pathlength of a warned tornado was 4.1 km with a median of 1.4 km and a sample size of 5092. The mean pathlength of an unwarned tornado was 2.4 km with a median of 0.0 km and a sample size of 1846. Note that for the data used in this study, all pathlengths <1 km were assigned a length of 0.0 km.

As discussed in section 3b, geographic differences in tornado warning statistics may be influenced by differences in storm morphology or tornado behavior. Some indication of these differences in tornado climatology may be discerned from an examination of the average tornado pathlength among the four disparate geographic regions (Table 5). Results indicate some regional differences in the tornado climatologies. The relatively short tracks in the west region may mean that forecasters have less time to detect and warn on each event. While an examination of the total tornado duration also was possible, time estimates of tornado start and end times are inherently uncertain, and a tornado pathlength can be estimated more confidently from postevent damage surveys.

g. Impacts of population density

A fifth hypothesis tested was that tornadoes in rural areas are “underwarned,” meaning that tornadoes in

<table>
<thead>
<tr>
<th>Region</th>
<th>Percentage of tornadoes without warning</th>
<th>Tornado track</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean (km)</td>
</tr>
<tr>
<td>Southeast</td>
<td>28.4</td>
<td>4.6</td>
</tr>
<tr>
<td>Midwest</td>
<td>32.3</td>
<td>4.2</td>
</tr>
<tr>
<td>Plains</td>
<td>20.4</td>
<td>3.1</td>
</tr>
<tr>
<td>West</td>
<td>42.4</td>
<td>1.7</td>
</tr>
</tbody>
</table>
less populated areas occur more frequently than are officially reported. For this study, each tornado was binned according to the population density of the county of initial tornado formation. Results indicate that the ratio of tornadoes not warned actually increases with increasing population density (Fig. 7). Those reported tornadoes in counties with $<5$ persons km$^{-2}$ were warned 75.3% of the time while tornadoes in counties with $\geq 50$ persons per km$^2$ were warned only 66.0% of the time. Tornadoes in counties with $\geq 400$ persons km$^{-2}$ were warned only 59.1% of the time. Those tornadoes that occurred in counties with populations $\geq 100$ persons km$^{-2}$ have a statistically lower rate of warning than those verified in counties with $<50$ persons km$^{-2}$. In other words, the greater is the county population density, the smaller is the percentage of recorded tornadoes that were warned.

To better explain this trend, data were sorted by county population density, lead time, and F-scale rating (Fig. 8). Similar to the trend shown in Fig. 7, the ratio of weak (F0 and F1) tornadoes not warned increases with increasing population density. Counties with $\geq 50$ persons km$^{-2}$ have a significantly smaller ratio of tornadoes warned than those counties with $<50$ persons km$^{-2}$. However, for strong to violent (F2–F4) tornadoes, the ratio of unwarned tornadoes remains nearly steady with respect to the county population density at around 17%.

These results may reflect the possibility that relatively weak tornadoes in urban areas almost always are verified while some weak tornadoes in rural areas may not be reported. In more populated counties, there are naturally more eyewitnesses and damage indicators, thereby leaving evidence behind for postevent damage surveys and storm verification. In rural areas, tornadoes often occur without damage and so even when verified,
their F-scale rating could be underestimated (Doswell and Burgess 1988; Anderson et al. 2007). Thus, the smaller unwarned fraction in rural areas may result from missed tornadoes and misclassifications of tornadoes rather than better warning performance.

h. Impacts of distance from radar

Radar is one of the primary tools used in the detection and warning of tornadoes. The introduction of the Weather Surveillance Radar-1988 Doppler (WSR-88D) dramatically improved tornado warning lead times (Bieringer and Ray 1996; Simmons and Sutter 2005). Thus, a sixth hypothesis tested herein is that tornado warning operations must deteriorate with storm distance from radar.

From the 5-yr dataset used in this study, the distances of all tornado events to the nearest WSR-88Ds were calculated and then sorted by lead time and whether or not a warning had been issued. The results indicate that the tornado to radar distances had little impact on lead time, but a significant impact on whether or not a warning was issued. The ratio of positive lead time tornadoes to the total number of tornadoes decreased with range at a rate of 3.3% (100 km)$^{-1}$. The ratio of negative lead time (or zero lead time) tornadoes to the total number of tornadoes decreased with range at a rate of 2.4%. However, the ratio of unwarned tornadoes to the total number of tornadoes increased with range at a rate of 5.7% (100 km)$^{-1}$.

Due to the relatively small sample size, the data were sorted into four bins representing 0–50-, 50–100-, 100–150-, and 150–200-km tornado-to-radar ranges. The ratio of unwarned tornadoes to the total number of tornadoes was computed for each bin, and a 95% confidence interval was calculated for each category (Fig. 9). The ratios of unwarned tornadoes for the 0–50- and 50–100-km ranges were statistically lower than in the 100–150- and 150–200-km range at the 95% confidence level. Tornadoes are about 4.7% more likely to remain unwarned when located 100 km or more from a WSR-88D compared to those tornadoes located within 100 km of a radar. During the 5 yr of study, this translates into approximately 118 tornadoes nationwide that were not warned due to the distance from radar, or on average about 24 tornadoes per year. Using the statistics from Table 1, this equates to two to three strong to violent (F2 or greater) tornadoes per year that remained unwarned due to radar distance, approximately 0.2% of reported tornadoes overall.

Next, the warnings were sorted by radar distance, lead time, and F-scale rating. For F0 and F1 tornadoes (Fig. 10a), the ratio of unwarned tornadoes to the total number of tornadoes increased with range at a rate of 4.9% (100 km)$^{-1}$. For tornadoes rated F2 or greater (Fig. 10b), the ratio of unwarned tornadoes to the total number of tornadoes increased with range at a rate of 10.2% (100 km)$^{-1}$. In summary, the distance of a storm from a radar had a modest and linear impact on the tornado warning performance for both weak and strong to violent tornadoes.

Surprisingly, even the ratio of weak to strong tornadoes appeared to be a function of radar-to-tornado distance. The number of F0 and F1 tornadoes increased by approximately 2.3% (100 km)$^{-1}$ relative to the number of tornadoes rated F2 or greater (Fig. 11a). The ratio of F0 and F1 tornadoes within 0–50 km of a radar was statistically lower than the ratio of F0 and F1 tornadoes 150 km or more from a radar at the 90% confidence level. Because most WSR-88Ds were placed purposely in or near metropolitan areas (Leone et al. 1989), the population density and associated infrastructure decrease with distance from a radar in many areas. Population densities, when plotted against tornado-to-radar distance, showed a steady drop in population density with distance from a radar (Fig. 11b). Thus, with less infrastructure to hit, postevent damage surveys in some rural areas may have underestimated the true intensity of tornadoes during the study period, assuming the climatology is not expected to change within 150 km of the radar. Doswell et al. (2009) cite irregularities in historical trends of Fujita and enhanced Fujita (EF) scale ratings.
and, in particular, a reduction in F4 and F5 tornadoes after 2003.

Reviewing Figs. 7, 9, and 11, the impacts of population density and radar distance on warning are additive and yet generally apply to different geographic areas, relative to the radar location. Areas of high population density (generally within 100 km of the radar) incur a higher than average percentage of missed warnings due to much easier (more frequently available) post-event verification. On the other hand, areas far from the radar (greater than 100 km) have limited low-level (<3 km AGL) radar coverage, thereby limiting the

Fig. 10. (a) Percentage of all weak (F0 and F1) tornadoes classified as having positive or negative lead times or unwarned, binned by distance from nearest WSR-88D. (b) As in (a), but for strong to violent (F2–F4) tornadoes.

Fig. 11. (a) Percentage of all tornadoes classified by F-scale rating, binned by distance of tornado from radar (km). (b) The mean and median of the population density of counties where tornadoes occurred, binned by distance of tornado from radar (km).
detection of low-level rotation from radar. A relative lack of storm spotters also inhibits real-time warnings in rural areas. In summary, areas near the radar may have higher than average missed warning percentages due to more frequent postevent verification, while areas far from radar have higher than average missed warning percentages due to the lack of low-level radar coverage and fewer storm spotters.

To clarify this interaction between warning, radar distance, and population density, a table of 24 categories was constructed from the binned categories as shown in Figs. 7 and 9, and the percentage of reported tornadoes warned was calculated for each category (Table 6). As shown, the percentage of reported tornadoes warned varied significantly at any given range as a function of the county population density. Likewise, for any given population density, the percentage of reported tornadoes warned varied as a function of the distance of the tornado from a radar. Note the large increase in the percentage of unwarned tornadoes with distance from a radar, reaching nearly 50% for distances $>100$ km from a radar for population densities of $>50$ persons km$^{-2}$. However, for areas with $<50$ persons km$^{-2}$, fewer spotters, less damage, and sparse postevent verification translate to lower percentages of missed warnings at all radar distances.

### Table 6. Percentage of documented tornadoes unwarned, as a function of radar distance (km) and county population density (persons km$^{-2}$). Sample size for each category is shown in parenthesis.

<table>
<thead>
<tr>
<th>Population density</th>
<th>Distance (km)</th>
<th>(0–50 km)</th>
<th>(50–100 km)</th>
<th>(100–150 km)</th>
<th>$&gt;150$ km</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.00$ km$^{-2}$</td>
<td>(0–50 km)</td>
<td>35.5% (110)</td>
<td>26.5% (268)</td>
<td>22.2% (212)</td>
<td>23.1% (238)</td>
</tr>
<tr>
<td>$50.00$ km$^{-2}$</td>
<td>(50–100 km)</td>
<td>46.3% (80)</td>
<td>35.3% (266)</td>
<td>30.6% (314)</td>
<td>23.3% (459)</td>
</tr>
<tr>
<td>$100.00$ km$^{-2}$</td>
<td>(100–150 km)</td>
<td>62.5% (8)</td>
<td>51.3% (117)</td>
<td>45.7% (116)</td>
<td>30.0% (263)</td>
</tr>
<tr>
<td>$&gt;150$ km$^{-2}$</td>
<td>$&gt;150$ km</td>
<td>0% (0)</td>
<td>48.3% (29)</td>
<td>39.1% (23)</td>
<td>51.6% (31)</td>
</tr>
</tbody>
</table>

* Sample size of zero.

### Table 7. Tornado statistics listed as a function of the number of documented tornadoes per “tornado day” per WFO, with and without NWS warning.

<table>
<thead>
<tr>
<th>Tornadoes per tornado day</th>
<th>Total No. of tornadoes</th>
<th>No. of tornadoes without NWS warning</th>
<th>Percentage of tornadoes without NWS warning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1332</td>
<td>739</td>
<td>55.5</td>
</tr>
<tr>
<td>2</td>
<td>930</td>
<td>310</td>
<td>33.3</td>
</tr>
<tr>
<td>3</td>
<td>699</td>
<td>172</td>
<td>24.6</td>
</tr>
<tr>
<td>4</td>
<td>520</td>
<td>114</td>
<td>21.9</td>
</tr>
<tr>
<td>5–9</td>
<td>1785</td>
<td>342</td>
<td>19.2</td>
</tr>
<tr>
<td>10–19</td>
<td>1199</td>
<td>126</td>
<td>10.5</td>
</tr>
<tr>
<td>$&gt;20$</td>
<td>559</td>
<td>51</td>
<td>9.1</td>
</tr>
</tbody>
</table>

4. **Conclusions**

A climatology of tornado and warning statistics from 2000 to 2004 highlighted those tornadoes that occurred without NWS warning. Tornado data were sorted by F-scale rating, geography, WFO, time of day, month, storm type, pathlength, county population density, distance from radar, and tornado order during multiple tornado events. Our results are summarized as follows.

- The first tornado of the day and solitary tornado events were the most difficult situations on which to warn.
Over half of all singular tornado events were not warned (Table 7). On days with four or more tornadoes, the first tornado of the day had a miss ratio of over 44% (Table 8). BE09 found that the first tornado of the day and solitary tornado events also led to the greatest percentage of negative lead time warnings. The stronger a tornado, as indicated by its F-scale rating and track length, the greater chance that it was warned. Significant (≥F2) tornadoes had nearly half the ratio of unwarned tornadoes compared to weak tornadoes (F0 and F1; Table 1). Less than 10% of long-track tornadoes (≥20 km path) remained unwarned, yet over 30% of short-track tornadoes (<2 km path) were unwarned (Fig. 6).

- **Regional differences in tornado climatology impacted warning statistics.** A high frequency of tropical storms and hurricanes, as well as short-lived, weak tornadoes, likely contributed to a high ratio of unwarned tornadoes across Florida and along the Gulf coast (Fig. 2). Many solitary and weak, short-track tornadoes likely contributed to a high ratio of unwarned tornadoes across the west region (Tables 4 and 5). An examination of storm classification indicated linear storms may lead to a higher ratio of unwarned tornadoes (Fig. 5), and diurnal statistics showed an above-average number of unwarned tornadoes at night and during the morning (Fig. 3). Geographic regions with a high number of solitary, weak, linear, and/or nocturnal tornadoes can expect an above-average number of unwarned tornadoes.

- **The tornado-to-radar distance had a significant impact on tornado warning operations.** The tornado-to-radar distance had little impact on lead time but a significant impact on whether or not a warning was issued. Tornadoes ≥100 km from a WSR-88D had a statistically significant lower rate of warning than did tornadoes across Florida and along the Gulf coast (Fig. 2).

### Table 8. Tornado statistics listed as a function of the number of documented tornadoes per day per WFO with and without NWS warning. Statistics are for those tornado days with four or more tornadoes.

<table>
<thead>
<tr>
<th>Order of tornado occurrence</th>
<th>Total No. of tornadoes</th>
<th>No. of tornadoes without NWS warning</th>
<th>Percentage of tornadoes without NWS warning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>2549</td>
<td>1127</td>
<td>44.2</td>
</tr>
<tr>
<td>2nd</td>
<td>1217</td>
<td>287</td>
<td>23.6</td>
</tr>
<tr>
<td>3rd</td>
<td>752</td>
<td>130</td>
<td>17.3</td>
</tr>
<tr>
<td>4th</td>
<td>519</td>
<td>82</td>
<td>15.8</td>
</tr>
<tr>
<td>5th–9th</td>
<td>1246</td>
<td>148</td>
<td>11.9</td>
</tr>
<tr>
<td>10th–19th</td>
<td>562</td>
<td>58</td>
<td>10.3</td>
</tr>
<tr>
<td>≥20th</td>
<td>179</td>
<td>22</td>
<td>12.3</td>
</tr>
</tbody>
</table>

**Fig. 12.** (a) Tornadoes (%) within each region binned by no. of tornadoes per tornado day. (b) Tornadoes (%) without warning, binned by no. of tornadoes per tornado day.
within 100 km of a radar, and increased for both weak and strong tornadoes (Figs. 9–11). The rate of unwarned tornadoes increased 4.7% for those tornadoes 100 km or more from a WSR-88D. This translates to an approximate average of 24 tornadoes per year that remained unwarned due to the distance from a radar, including two to three strong to violent tornadoes (F2 or greater) per year. However, these estimates appear to be significantly underestimated due to the difficulty of verification in some rural areas (Table 6).

- **Many weak tornadoes were missed, even in densely populated regions.** The ratio of reported tornadoes not warned increased with increasing county population density (Fig. 7). However, this pattern only held for weak (F0 and F1) tornadoes (Fig. 8). A review of warning rates as a function of population density and radar distance (Table 6) showed that over 35% of tornadoes are not warned in very densely populated areas (>400 persons km⁻²) within 50 km of the radar. This suggests that many more tornadoes occur in less populated areas that are never verified. This rate increased to well over 50% for ranges beyond 100 km from a radar, pointing toward a much greater impact from radar distance than is suggested from Fig. 9. These results are consistent with Anderson et al. (2007), who found a likely underestimate of F0 and F1 tornadoes in some but not all rural areas. In summary, these trends indicated (i) more comprehensive, post-event validation from damage surveys was done in higher population density areas and/or (ii) weak tornadoes simply were not observed or were much more difficult to verify in more rural areas. As shown in Table 1, weak tornadoes had a lower ratio of being warned, and Figs. 7–11 hint that perhaps only in the most urban areas were most weak tornadoes verified.

Several implications result from these findings. First, these tornado warning statistics are encouraging for public safety. The most intense tornadoes (e.g., those with the longest path tracks, rated as F2 or greater) have the lowest ratio of missed warnings. Those times (e.g., during the late afternoon) and months (e.g., May) when most tornadoes occur have a much higher chance of being warned than during nonpeak periods. Those areas of the country with the most tornadoes have the lowest ratio of missed warning events. In general, advance warnings are being issued during most outbreak scenarios.

Unfortunately, **those tornadoes most likely to strike when the public is least likely to be aware are also those tornadoes with the greatest chance of not being warned.** Those tornadoes occur during the night, during nonpeak tornado months of the year, and during nonoutbreak events. Thus, the public may be especially vulnerable in these situations. As Ashley (2007) and Ashley et al. (2008) have shown, nocturnal tornadoes are twice as likely to cause fatalities than those during the day. Gaps in the observing network may pose an additional problem for forecasters. As shown in Table 6 and Figs. 9 and 10, the percentage of tornadoes not warned increases with distance from a radar for both weak and strong tornadoes.

Tornado warning verification statistics have improved significantly over the past several decades (e.g., Brooks 2004; Simmons and Sutter 2005). However, these statistics are not a reflection of the true number of tornadoes occurring. Although the verification program currently is being restructured, the verification process remains suspect. Results from this study show that the most violent and longest-track tornadoes have a relatively high ratio of being warned. However, further improvement in our tornado warning capabilities will require significant advances in warning on weak and/or solitary tornado events, warning on events far from radars, warning on the first tornado of the day, and warning during nonpeak hours such as at night and morning.

One solution for addressing these problems is for increased storm spotter participation (Doswell et al. 1999). Spotter networks would be especially critical at night, at positions far from WSR-88D sites, and on marginal tornado days. Such field reports likely would increase the probability of detection, reduce the number of false alarms, and greatly improve warning confidence. For less populated regions, new advances in weather radar show promise in measuring more directly those mesoscale features influencing tornado potential (e.g., Brotzge et al. 2010). Dual-polarization radar is able to sense debris directly, thereby confirming tornado touchdown remotely for those vortices that loft debris to beam height (Ryzhkov et al. 2002). Rapidly scanning radars would provide forecasters with much greater temporal resolution, capturing the most transient circulations now so often missed, and adaptively sensing radars could fill gaps in current weather radar coverage (e.g., McLaughlin et al. 2009). More versatile scanning with the WSR-88Ds [e.g., scans with negative elevations; Brown et al. (2002)] could also fill some low-level gaps in the current radar coverage. However, only mesoscale numerical weather prediction and “warn on forecast” (Stensrud et al. 2009) ultimately can predict tornado-genesis prior to development, a critical step in providing the necessary positive lead time required for public response. Fortunately, some recent modeling efforts are starting to demonstrate such tornado prediction is possible (e.g., Hu and Xue 2007).
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REFERENCES


