TORNADO FALSE ALARMS ON DAYS WITH NO REPORTED TORNADOES: A CLIMATOLOGICAL AND RADAR SURVEY

Hannah Barnes[1,2], Dr. Jerry Brotzge[3], and Somer Erickson[4]

[1]National Weather Center Research Experience for Undergraduates
and
[2]University of Wisconsin – Madison, Madison, Wisconsin

[3]Center for Analysis and Prediction of Storms
University of Oklahoma, Norman, Oklahoma

[4]NOAA/National Severe Storms Laboratory, Norman, Oklahoma

ABSTRACT

A five-year study of tornado false alarms, as issued by the National Weather Service (NWS) from 2000 to 2004, found that 31.6 % of false alarms occurred on days when the Weather Forecast Office (WFO) was unable to confirm at least one tornado in their county warning area (CWA) from midnight to midnight (i.e., a zero day false alarm). Reviewing tornado warning data obtained from the National Atmospheric and Oceanic Administration (NOAA)/NWS, this study conducted a climatological and radar survey to diagnose situations when false alarms were issued on days with no confirmed tornadoes, i.e., marginally severe days that failed to produce tornadoes. The study was composed of three steps. First, zero day false alarms were compared to tornado day false alarms (days when tornadoes were confirmed within the WFO CWA). Climatological trends were identified in terms of time of day and year, geographic region, county population density, and distance from nearest WSR-88D radar. Second, the impact of the perceived large-scale tornadic potential was explored by an examination of Watch information from the Storm Prediction Center. Third, Level 2 radar data were examined. Reflectivity and velocity radar data were used to identify the impact of storm morphology, purple haze, and variations in circulation intensity with height.

This survey suggests four important trends: (i) zero day false alarms comprise a larger percentage of the total number of tornado false alarms in geographic regions less susceptible to tornadoes, (ii) zero day false alarms are more similar to one tornado day warnings than outbreak day false alarms in terms of the perceived large-scale tornadic potential, (iii) the circulation intensity of zero day false alarms and outbreak day false alarms at the lowest height scanned by a WSR-88D radar is notably weaker than those associated with one tornado day warnings, and (iv) purple haze may be a considerable factor in zero day false alarms and outbreak day false alarms.

1. Introduction

In 2008, 75% of tornado warnings issued by the National Weather Service (NWS) were false alarms (NWS 2009). Tornado false alarms are tornado warnings not associated with a confirmed tornado touchdown within the warning's spatial and temporal constraints. Despite attempts to reduce this figure, the tornado false alarm rate (FAR) has remained nearly constant for the last twenty years (NWS 2009). National Weather Service Weather Forecast Offices (WFO) issue tornado warnings for a county, or portion of a county, based upon a storm's environmental conditions, radar signature, and storm spotter reports (AMS 2003). The exact conditions that result in a tornado warning vary since a storm's tornadic potential is not absolute. For example, Doppler radars have enabled forecasters to locate mesocyclones: regions of rotation often associated with tornado development. However, tornadoes are neither an exclusive nor obligatory element of mesocyclones (AMS 2003).

A number of factors influence tornado false alarms. First, tornado false alarms are defined by the absence of a confirmed tornado touchdown. However, not every tornado touchdown is confirmed by the NWS. Tornadoes in rural areas and weak, short-lived, or isolated tornadoes are especially likely to remain unconfirmed. Thus, it is anticipated that some tornado false alarms are incorrectly classified. Second, the NWS

Corresponding author address: Hannah Barnes, 21401 W. Edinbourgh Dr., New Berlin, WI, 53146
E-mail: hcbarnes@wisc.edu

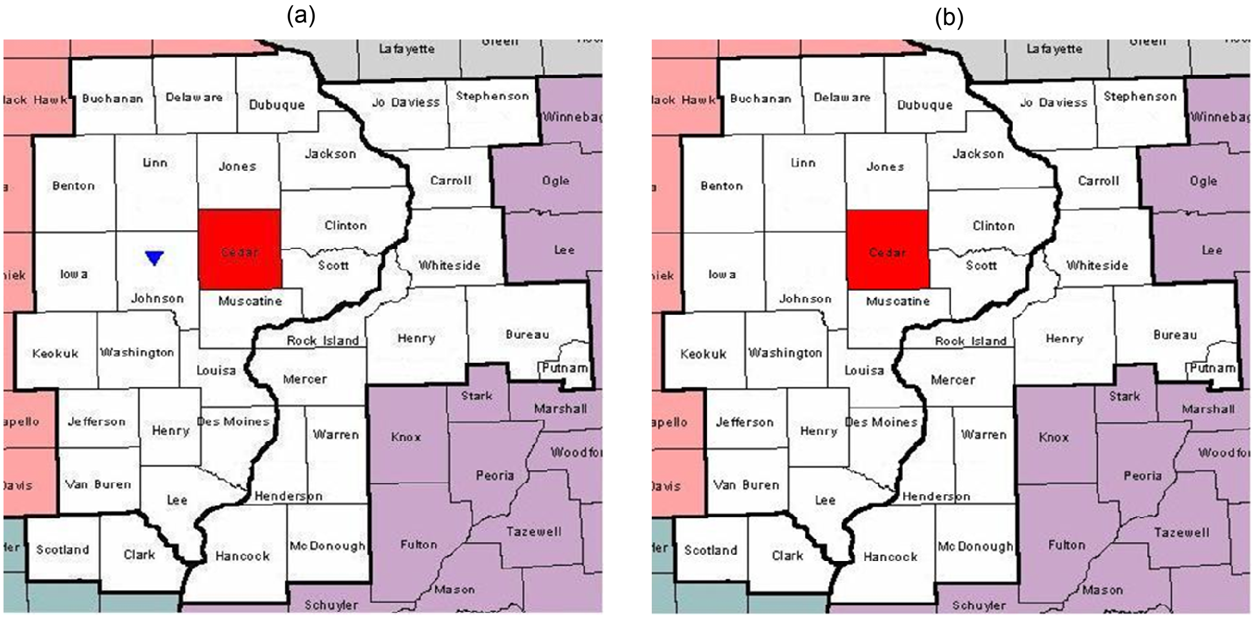

FIG.1. The Quad Cities CWA. Tornado warnings are represented by counties shaded in red. Confirmed tornadoes are represented by blue triangles. (a)Tornado day alarm. (b) Zero day alarm.

is most concerned that every tornado is warned. Recognizing that the public forgives false alarms more readily than missed tornadoes, forecasters may issue tornado warnings more liberally in marginal situations. This trend may be enhanced in highly populated regions where tornadoes pose an enhanced threat to public safety. Third, storm spotters may provide flawed or misleading information. Storm spotters represent a forecaster's best opportunity to issue a valid tornado warning. However, the expertise of the storm spotter is unknown and highly variable. Even with NWS training, a storm spotter may report a rotating wall cloud as a tornado and prompt a false alarm. Fourth, storm history may prompt a premature tornado warning. This factor may be enhanced during outbreaks. Rather than scrutinize each incoming spotter report and radar signature, the history of tornado development may prompt forecasters to liberally issue tornado warnings. Lastly, the distance between the tornadic storm and nearest radar may prompt a false alarm since low-level data diminishes with distance. Lacking low-level radar data on a distant storm, a forecaster may issue false alarm that could have been prevent if the storm was closer.

False alarm research has focused on assessing the validity of FAR as a performance measure and the public's perception. Barnes et al. (2007) argues that, by solely defining a warning as a success or failure, FAR does not give proper credit to forecasters. They contend that a tornado warning that misses by two minutes should be judged differently than one that misses by two hours. Thus, a conceptual model classifying severe weather events as unwarned, under-warned, perfectly warned, over-warned, or falsely warned based upon the degree of error in the intensity, location, and time is proposed. The majority of false alarm research has focused on the public's perceptions. False alarms are traditionally thought to reduce credibility, which is known as the cry-wolf or false alarm effect (Breznitz, 1984). As individuals ignore NWS warnings, this loss of credibility significantly threatens public safety. However, studies have also indicated that false alarms may not diminish credibility if the public understands the reason for the false alarm or perceives it as a valuable practice opportunity (Janis, 1962; Dow and Cutter, 1998). Even though the legitimacy of the cry-wolf hypothesis is debated, reducing FAR has the potential to increase the legitimacy of the NWS and save lives.

This research is approaching tornado false alarms from a new direction by concentrating on the climatological and radar characteristics of tornado false alarms that lack a confirmed tornado touchdown. Dr. Jerry Brotzge, Somer Erickson, and Dr. Harold Brooks are in the process of publishing a climatology of all tornado false alarms from 2000 to 2004. Within their study, 31.6% of all tornado false alarms occurred on what is called a zero tornado day. A zero tornado day false alarm, hereafter referred to as a ***zero day alarm***, is a subset of tornado false alarms that do not have a confirmed tornado touchdown within an entire WFO from midnight to midnight (FIG. 1). Categorized by the number of confirmed tornado touchdowns in a WFO during the day, zero day alarms make up the largest percentage of tornado false alarms. The present study seeks to discover how zero day alarms are fundamentally distinct from confirmed tornadoes and tornado false alarms with at least one confirmed tornado in the WFO that day, hereafter referred to as ***tornado day alarms***. Portions of the analysis include a comparison with one tornado positive lead time tornado warnings, which may reveal important distinctions in marginally severe atmospheric conditions. Climatologically this study strives to understand the distribution of zero day alarms in terms of time of day and year, geographical region, county population density, and distance from the nearest WSR-88D radar.

The Storm Prediction Center's (SPC) convective outlooks and watches are utilized to gain insight into the environment's perceived tornadic potential. Concluding the survey, radar imagery is analyzed to diagnose trends in storm morphology, purple haze, and how circulation intensity varies with height.

2. Data / Methodology

Obtained directly from the National Oceanic and Atmospheric Administration (NOAA)/NWS, data on 13,593 tornado false alarms from 2000 to 2004 were compiled. All the false alarms included in the data lacked a confirmed tornado touchdown during the warning's spatial and temporal confines. The date, issuance and expiration time in Central Standard Time, name and distance of nearest WSR-88D radar, county and state along with its latitude and longitude, and WFO was specified for each tornado false alarm. County population densities were acquired from the 1 July 2000 population estimates compiled by the Population Division of the U.S. Census Bureau. Following the scheme utilized by Brotzge and Erickson (2008), each false alarm was categorized into four geographic regions: Southeast, Midwest/East, Plains, or West (FIG. 2).

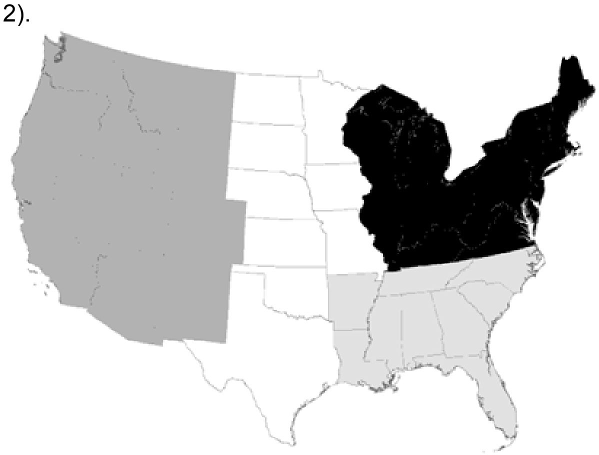

FIG. 2. All false alarms were divided among four geographic regions: Southeast, Midwest/East, Plains, and West.

Additionally, the number of confirmed tornadoes, tornado warnings, and tornado false alarms within the WFO from midnight to midnight were calculated for each false alarm. This information allowed us to compile a set of 4,300 zero day alarms.

For comparison purposes this study focused on outbreak tornado day false alarms and one tornado positive lead time tornado warnings. Satisfying conditions as specified by Galway (1977), a subset of1,683 outbreak day tornado false alarms was extracted from the tornado false alarm data. Hereafter referred to as ***outbreak day alarms***, these false alarms were defined as having occurred on days with at least ten confirmed tornadoes in a WFO from midnight to midnight. The five year tornado warning reports from 2000 to 2004 obtained from the NOAA/NWS were utilized to construct the one tornado positive lead time tornado warning data, hereafter referred to as ***one tornado day warnings***. All tornado warnings within these data had one confirmed tornado in a WFO from midnight to midnight with a positive lead time. This set of 605 tornado warnings specified the day, local standard time, and latitude and longitude of the tornado, along with the WFO, name of the nearest WSR-88D radar, and lead time.

Time restrictions required a subset of data be used in the analysis of the SPC convective outlooks and watches. To ensure that the subset sampled across the five year period this study utilized a semi-random approach. For the zero day alarms and outbreak day alarm subsets, data from 2003 and 2004 were listed chronologically in Central Standard Time and every fifth false alarm was selected. Utilizing the convective outlook archive maintained by the SPC, the closest prior outlook was chosen and the probability that at least one tornado will develop within 25 miles was manually evaluated for the warned county. Hereafter, the probability that at least one tornado will develop within 25 miles of any point is referred to as the SPC tornado probability. The analysis of the convective outlooks was limited to 2003 and 2004 since the SPC convective outlook archive began in 2003. The 2004 SPC convective watches were manually reviewed to identify if the county was included in a severe thunderstorm watch or tornado watch at the time of the false alarm. Despite the SPC watch archive beginning in 2004, 187 zero day alarms and 87 outbreak day alarms were manually reviewed. To gain further insight into the patterns associated with SPC convective watches the study manually reviewed all 146 one tornado day warnings in 2004.

WSR-88D reflectivity and velocity radar data was reviewed for each data subset. Selected subsets of zero day alarms, outbreak day alarms, and one tornado day warnings were manually reviewed using WDSS-II. In constructing the subsets, zero day alarms and outbreak day alarms were chronologically listed in Central Standard Time. Every 43rd zero day alarm and 17th outbreak day alarm, from 2000 to 2004, was selected. This produced a set of 100 zero day alarms and 100 outbreak day alarms that spanned the five year period. Then, every fourth false alarm was selected from the sets of 100 in order to produce two sets of 25 false alarms. The subset of one tornado day warnings was obtained by listing the tornado warnings in chronological order by local standard time and selecting every twenty-fourth from 2000 to 2004. The radar data for the three subsets was obtained from the National Climatic Data Center (NCDC) level II radar inventory. Reflectivity and velocity radar data were reviewed to diagnose storm morphology, the presence of purple haze, and circulation intensity at the lowest elevation and nearest three kilometers. The storms were classified as cellular, linear, or tropical based upon the scheme suggested by Gallus et al (2008).

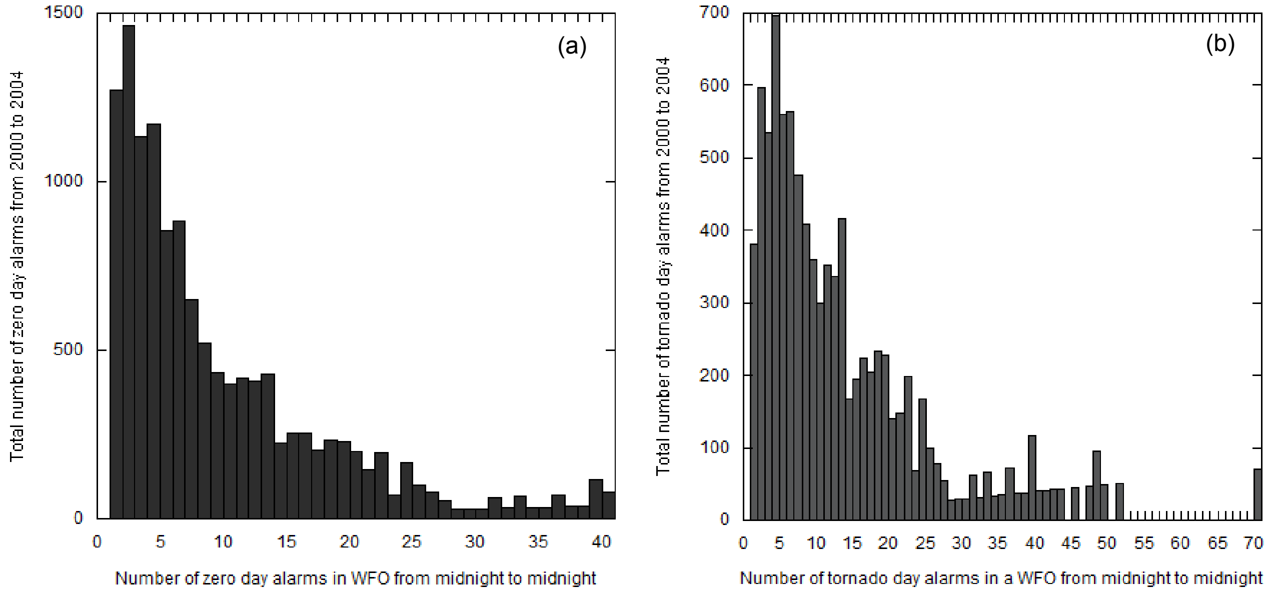

FIG. 3. Number of (a) zero day alarms and (b) tornado day alarms issued by a NWS WFO from midnight to midnight during the 5 year period.

3. Results

3.1 Climatology

To formulate an improved comprehension of the differences between tornadic and non-tornadic false alarms, a climatology comparing zero day alarms to tornado day alarms was completed. While the 4,300 zero day alarms lack a confirmed tornado within a WFO from midnight to midnight, the remaining 9,293 false alarms had at least one confirmed tornado in the WFO during that same day. The climatology addresses distributions with respect to the time of day and year, geographic region, county population density, distance from the nearest WSR-88D radar, and the perceived large-scale tornadic potential.

a. Diurnal Climatology

How does the number of zero day alarms issued by a WFO compare to the number of tornado day alarms? Histograms of the number of zero day alarms and tornado day alarms issued by a WFO in one day were produced (FIG. 3a, FIG. 3b). The number of zero day alarms and tornado day alarms are similarly distributed. However, Fig. 3a and Fig. 3b reveal two notable outliers. A summary of these events are as follows:

1) On 18 February 2000, the Weather Forecast Office in Nashville, Tennessee issued 40 zero day alarms throughout central Tennessee from 1845 to 2241 EST. A strong pre-frontal squall line, forced by the right entrance region of an upper level jet streak, was moving across the lower Mississippi Valley. With strong vertical shear and low-level flow transporting moisture into the region, the complex was expected to continue to produce severe storms in the Tennessee Valley. While persistent tornadic supercells were reported in Arkansas and Northern Mississippi, Central Tennessee was expecting mainly high winds and large hail. Despite this volatile atmosphere, SPC storm reports did not report any high winds, large hail, or tornadoes in Central and Eastern Tennessee.
2) On 15 September 2004, the Weather Forecast Office in Tallahassee, FL issued 70 tornado day alarms along with 18 confirmed tornado touchdowns associated with Hurricane Ivan. While the category 3 hurricane officially made landfall in Gulf Shores, AL at 0150 CDT on 16 September, the storm's strong northeast quadrant struck the Florida panhandle and southern Alabama during the evening of 15 September.

These two outliers highlight the great difficulty in distinguishing tornadic storms from nontornadic storms. The dynamics of tornadogensis remain vastly unknown, despite extensive research. This lack of knowledge is a substantial factor in tornado false alarms. It must be accepted that, for unknown reasons, a storm displaying prominent tornadic capabilities will fail to spawn a tornado and generate a false alarm.

In terms of time of day, when are zero day alarms most prevalent? Given that tornadoes climatologically occur in the afternoon and early evening hours, the study hypothesized that both zero day alarms and tornado day alarms would follow this trend. The number of zero day alarms and tornado day alarms was plotted by hour (FIG. 4). Fig. 4 indicates that both types of tornado false alarms occur most frequently between 1300 and 2100 local time, which supports the hypothesis.

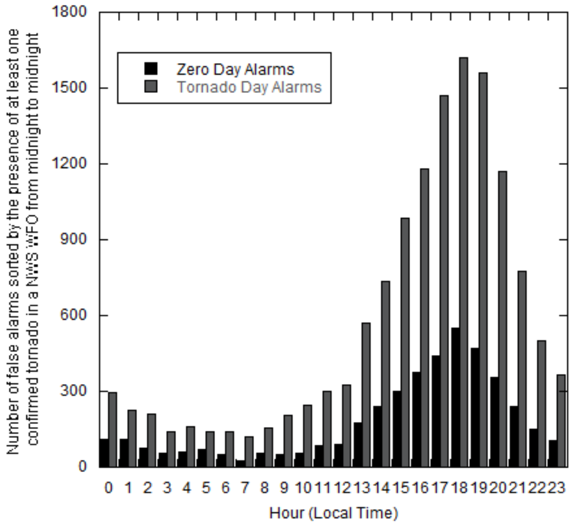

FIG. 4. Number of tornado day alarms and tornado day alarms issued each hour during the 5-year study.

b. Seasonal Climatology

Do certain periods of the year experience enhanced susceptibility to zero day alarms? Months with climatologically fewer observed tornadoes are hypothesized to have a larger percentage of tornado false alarms occurring on zero tornado days. This percentage will hereafter be referred to as the ***zero day alarm percentage***. The number of zero day alarms and tornado day alarms was plotted by month (FIG. 5a). To aid interpretation, the percentage of false alarms that occurred on zero tornado days was also plotted per month (FIG. 5b). Both zero day alarms and tornado day alarms have an absolute maximum in May and relative maximum in November, as indicated in Fig. 5a. However, note that in Fig. 5b, May and November have some of the lowest zero day alarm percentages: 25.2% and 21.5%, respectively. This supports the seasonal hypothesis that zero day alarms are more likely during less active tornado periods. Compared to summer and winter, days displaying tornadic potential in spring or fall are more likely to produce at least one tornado in a WFO and not result in zero day alarm.

c. Geographic Climatology

Does the zero day alarm percentage vary significantly between geographic regions? Only the West and Plains were anticipated to display significant disparity. To assess the validity of this prediction, the false alarms were divided into four geographic regions (FIG. 2) and a table depicting the zero day alarm percentages per region was constructed (Table 1). Evaluating the 95% confidence interval from each geographic region reveals that the percentage of false alarms occurring on zero tornado days was significantly different in all regions expect between the West and Midwest / East. The percentage of zero day alarms was particularly distinct between the West and Plains. While the 43.1% of tornado false alarms in the West occurred on zero tornado days, the zero day alarm percentage was only 26.4% in the Plains. This distinction likely reflects the fundamentally different climatologies of the West and Plains. With fewer tornadic storms, more short-lived, transient tornadoes, and poorer radar coverage, the West is more likely to lack a confirmed tornado touchdown in a WFO on a given day.

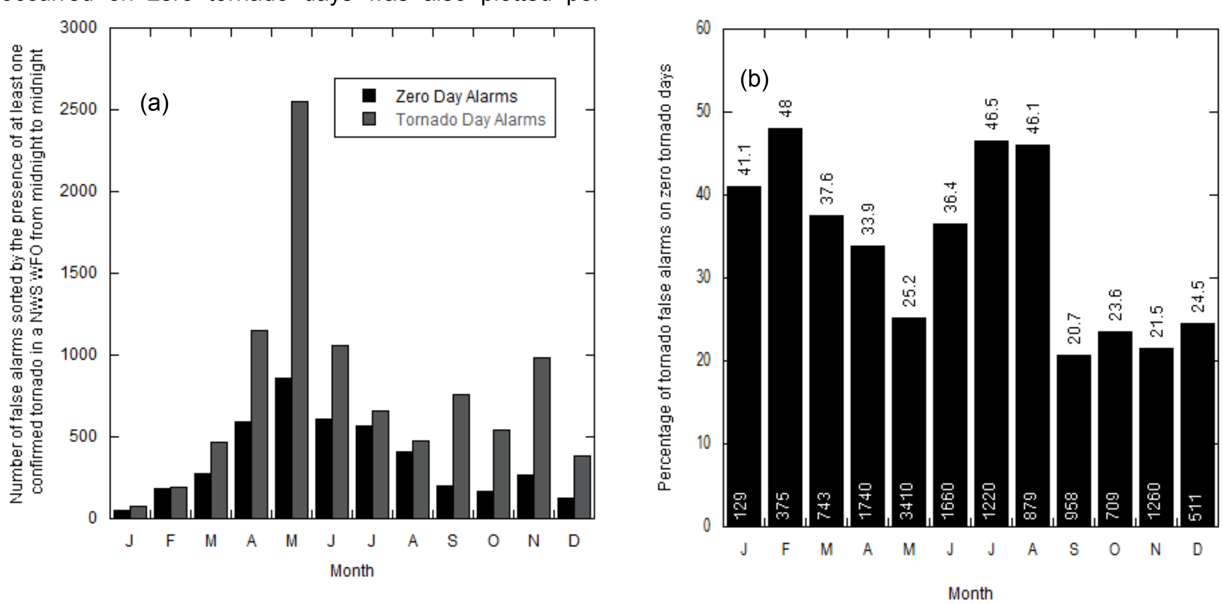

FIG. 5. (a) Number of zero day alarms and tornado day alarms plotted as a function of month of the year. (b) Percentage of all tornado false alarms occurring on zero tornado days each month. Note that the values on (b) indicate the total number of false alarms that month.

Table 1. Tornado false alarm statistics listed as a function of geographic region

Geographic region	False alarms on tornado days	False alarms on zero tornado days	Total number of false alarms	Zero day alarm percentage	Confidence interval
Southeast	3520	1650	5170	31.9	33.2 – 30.6
Midwest / East	1690	1030	2720	7.9	36.1 – 39.7
Plains	3710	1330	5040	26.4	25.2 – 27.6
West	377	286	663	43.1	39.3 – 46.9

d. Impact of County Population Density

The climatology of tornado false alarms, pending publication by Brotzge, Erickson, and Brooks, suggests that false alarms occur more frequently in highly populated areas. Does this pattern persist when tornado false alarms are separated into zero day alarms and tornado day alarms? With decreasing county population density, the percentage of zero day alarms was hypothesized to decrease faster than tornado day alarms. The percentage of tornado false alarms occurring on zero tornado days, along with its 95% confidence interval, was plotted with respect to the county population density in persons per square kilometer (FIG. 6a). The same process was also done for tornado day alarms (FIG 6b). While FIG. 6a indicates that the zero day alarm percentage decreases with decreasing population density, Fig. 6b suggests that the percentage of tornado day alarms increases with decreasing county population density. Note, in counties with 5 to 24 people per square kilometer, the percentage of zero day alarms is significantly different from counties with more than 24 people per square kilometer. Thus, zero day alarms are significantly less common in low population counties. This trend may indicate how mitigating factors influence the issuance of tornado false alarms. In highly populated areas, forecasters may display an increased tendency to warn on marginal storms or questionable storm spotter reports in order to ensure a high degree of public safety.

e. Impact of Radar Distance

Compared to tornado day alarms, how are zero day alarms affected by the county's distance from the nearest WSR-88D radar? Radars tend to be located near metropolitan areas. Given the impact of county population density, it was hypothesized that the zero day alarm percentage would decrease and the tornado

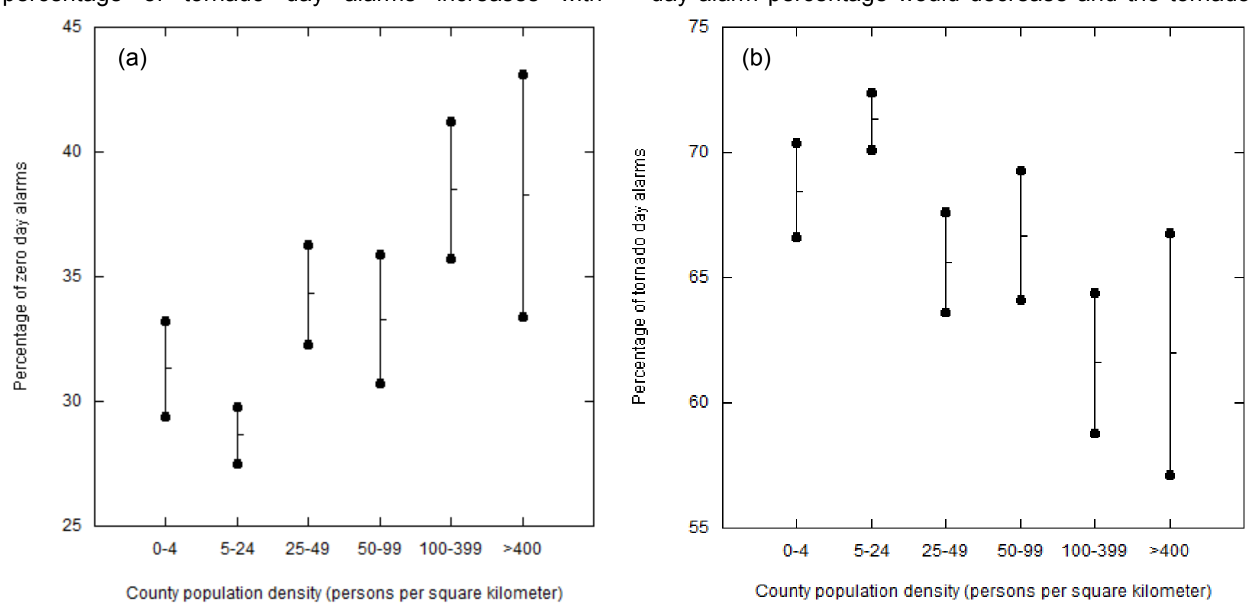

FIG. 6. (a) Percentage of zero day alarms and its 95% confidence interval plotted as a function of county population density (persons per square kilometer). (b) Same as (a) but for tornado day alarms.

day alarm percentage would increase with distance. Tornado false alarms were first separated by distance from the nearest WSR-88D radar in 50 kilometer increments through 150 kilometers. Then, the percentage of tornado false alarms occurring on zero tornado days and tornado days was calculated. Both zero day alarms and tornado day alarms were not found to have a statistically significant relationship with respect to distance from the nearest WSR-88D radar. However, previous studies have indicated that tornado reports are directly related to the distance from the nearest WSR-88D radar (e.g., Ray et al. 2003). Given that tornado false alarms are dependent on the absence of a confirmed tornado touchdown, flaws in the data may have influenced these results.

f. Impact of Perceived Tornadic Potential

Understanding the large-scale atmospheric conditions is imperative when issuing a tornado warning. A storm may display tornadic potential; however, in unfavorable atmospheric conditions a forecaster may refrain from issuing a tornado warning until further evidence materializes. In order to comprehend the influence of the perceived tornadic potential the study focused on three types of tornado warnings: zero day alarms, outbreak day alarms, and one tornado day warnings. The variability within tornado false alarms may be highlighted by comparing zero day alarms to outbreak day alarms. Comparing one tornado day warnings to zero day alarms may reveal important distinctions in marginally severe atmospheric conditions. Since the SPC primarily utilizes large-scale atmospheric conditions to assess the hazardous weather potential across the nation, their convective outlooks and watches were employed. However, the implications of these results are limited since the analysis was restricted to two years of convective outlook data and one year of convective watch data.

When atmospheric conditions are perceived by SPC to be marginally severe, do the subsequent SPC discussions and watches make the NWS more susceptible to issuing zero day alarms? This question was assessed by evaluating the SPC tornado probability that was issued as a part of their daily convective outlooks. The SPC tornado probability is the probability that at least one tornado will develop within 25 miles of any point during the convective outlook. This study hypothesized that the SPC tornado probability would be lower for zero day alarms than outbreak day alarms. The percentage of zero day alarms and outbreak day alarms were plotted as a function of SPC tornado probability (FIG. 7a, FIG. 7b). Given that tornadoes occur relatively infrequently, a 5% or greater SPC tornado probability represents a significant tornado threat. While 69% of zero day alarms had at most a 2% SPC tornado probability, only 13% of outbreak day alarms were similarly associated. These results suggest that the large-scale atmospheric conditions associated with zero day alarms were considered less suitable for tornado development than outbreak day alarms. During zero day alarm situations, these results suggest that the SPC correctly forecasted the expected tornado threat and local NWS offices would have incurred fewer false alarms if had they followed the advice from SPC.

Is there an identifiable distinction between zero day alarms and one tornado day warnings in terms of large-scale atmospheric conditions? SPC convective watches were hypothesized to indicate a significant difference. The percentage of zero day alarms and one tornado day warnings, during 2004, were plotted as a function of the presence of a valid severe thunderstorm watch or

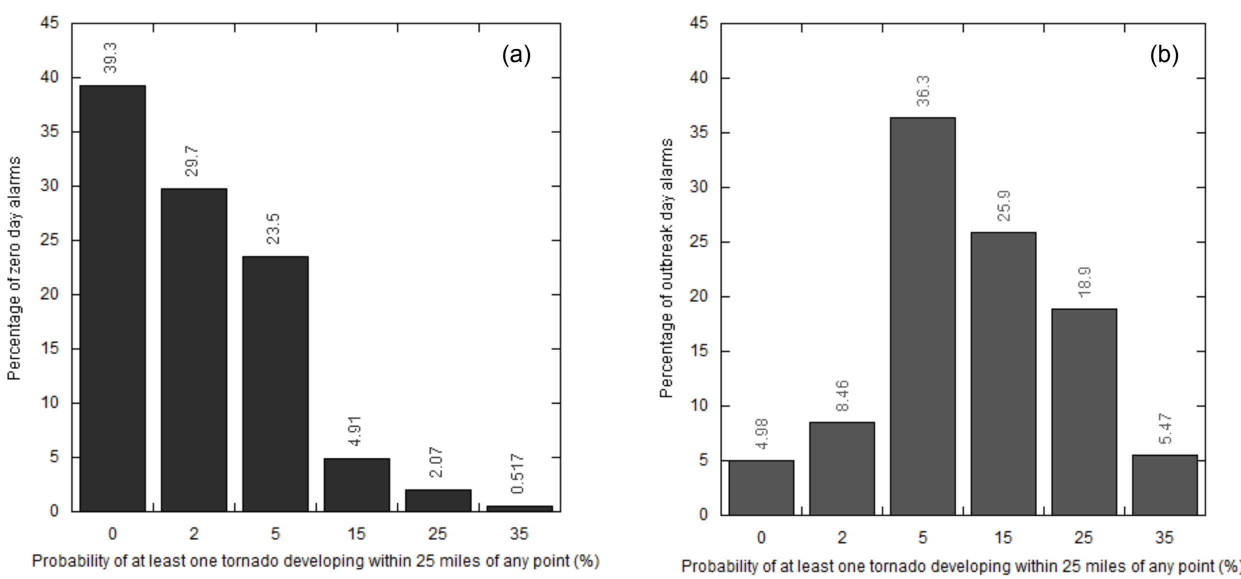

FIG. 7. (a) For a subset of 387 zero day alarms, the percentage of zero day alarms plotted as a function of the probability that a tornado will develop within 25 miles of any point as assigned by the SPC. (b) Same as in (a) but for a subset of 201 outbreak day alarms.

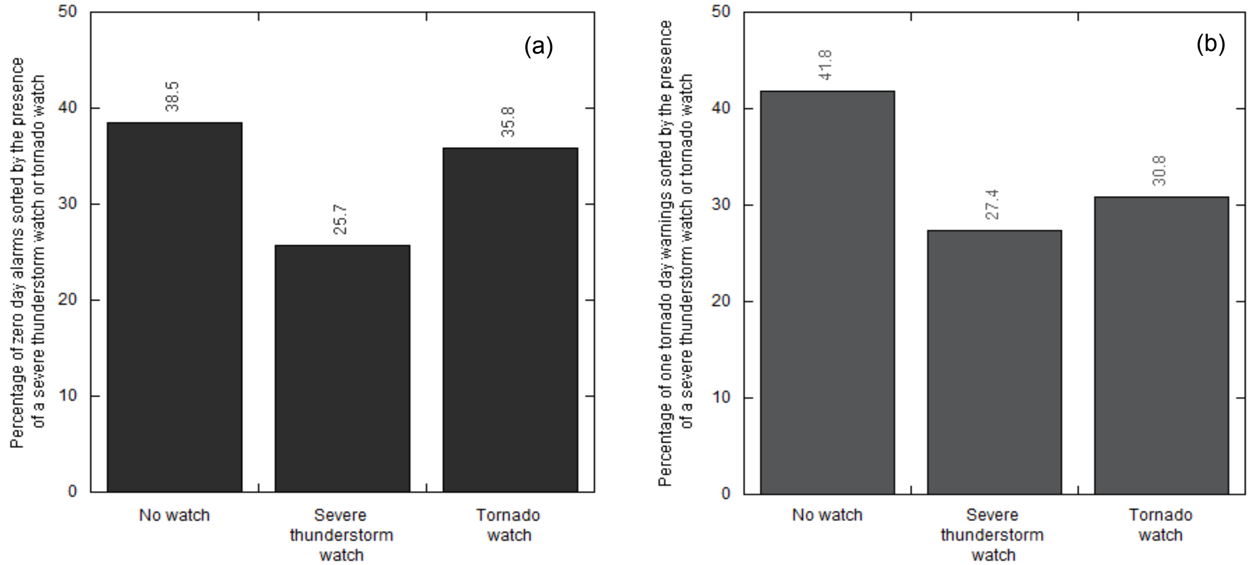

FIG. 8. (a) For a subset of 387 zero day alarms, the percentage of zero day alarms plotted as a function of the probability that a tornado will develop within 25 miles of any point as assigned by the SPC. (b) Same as in (a) but for a subset of 201 outbreak day alarms.

tornado watch at the time of the warning (FIG.8a, FIG. 8b). Comparing Fig. 8a to fig 8b does not reveal a significant difference between zero day alarms and one tornado day warnings in terms of the presence or type of convective watch. From a large-scale atmospheric perspective, these results suggest that in 2004 one tornado day warnings were not perceived to have an enhanced tornadic threat with respect to zero day alarms. It is noteworthy that outbreak day alarms were similarly analyzed. In an unshown figure, 87.4% of outbreak day alarms were under a tornado watch. These results appear to highlight the marginal atmospheric conditions associated zero day alarms and one tornado day warnings as well as the great difficulty in assessing the tornadic potential of a given storm.

3.2 Radar

Reflectivity and velocity radar data are some of the most prominent tools employed during tornado warning situations. This study seeks a greater comprehension of the distinct radar trends associated with zero day alarms through a comparison with outbreak day alarms and one tornado day warnings. An analysis of reflectivity and velocity radar data focused on diagnosing trends in storm morphology, assessing the infraction of purple haze on velocity radar data, and investigating how circulation intensity varies with height. It is important to note that implications of these findings are preliminary since each of type of tornado warning included only 25 storms from 2000 to 2004.

a. Impact of Storm Morphology

Based upon a manual classification of the dominant storm structure, are tornadic and non-tornadic storms dominated by cellular, linear, or tropical morphologies?

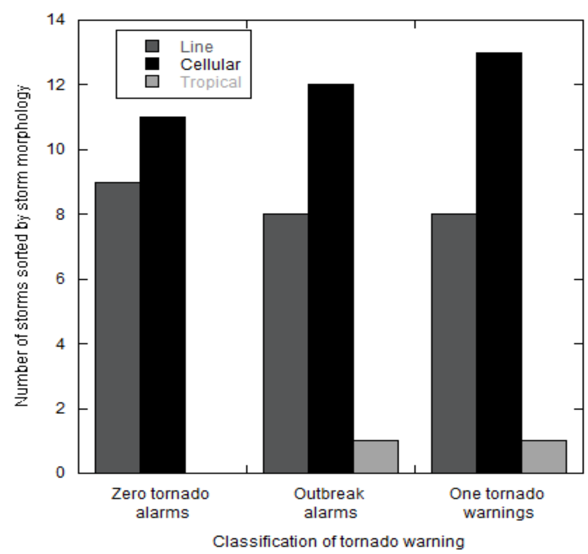

FIG.9. For zero day alarms, outbreak day alarms, and one tornado day warnings, the number of linear, cellular, and tropical storms.

While outbreak day alarms were expected to be dominated by cellular storms, linear storms were hypothesized to categorize most zero day alarms and one tornado day warnings. The number of storms dominated by a cellular, linear, or tropical structure was plotted for each type of tornado warning (FIG. 9). Given that the storms were manually classified, as described in section 2, this analysis was highly subjective. Cellular storms comprised over half of the storms in each data set: 55% of zero day alarms, 57.1% of outbreak day alarms, and 59.1% of one tornado day warnings. Zero day alarms experienced the greatest percentage of linear storms: 45%. However, outbreak day alarms

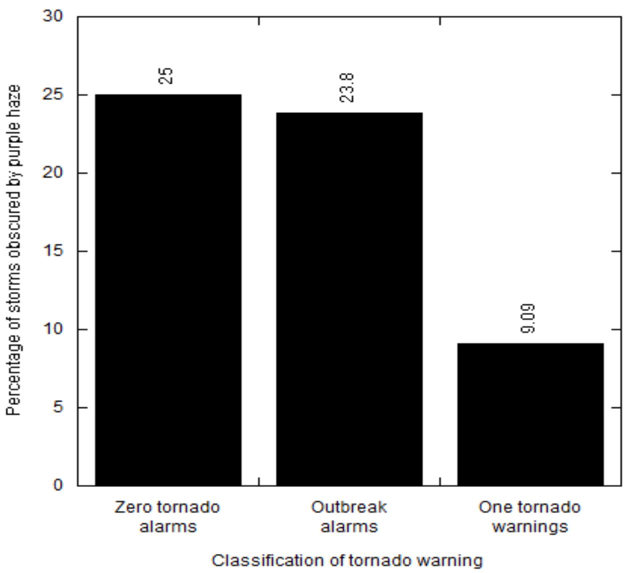

FIG. 10. For the 25 zero day alarms, outbreak day alarms, and one tornado day warnings, the percentage of storms whose velocity data was obscured by purple haze.

experienced nearly the same percentage of linear storms as one tornado day warnings: 38% and 36.6%, respectively. Fig. 9 begins to suggest that cellular storms are perceived to have the greatest tornadic potential, regardless of tornado occurrence.

b. Impact of Purple Haze

With the advent of Doppler radar, velocity radar data became a valuable tool to identify regions of rotation and enhanced tornadic potential. However, quality control issues such as range-velocity mitigation may color code the velocity data as purple. These areas are often designated as “purple haze.” Are zero day alarms and outbreak day alarms more severely impacted by this purple haze than one tornado day warnings? Initially, the study was hypothesized to indicate that purple haze would not significantly impact any type of tornado warning. To assess the hypothesis’ validity, the percentage of storms obscured in purple haze was plotted for each type of tornado warning (FIG. 10). While 25% of zero day alarms and 23.3% of outbreak day alarms were negatively impacted by purple haze, only 9.09% of one tornado day warnings were similarly afflicted. Despite the limited sample size, these results begin to suggest that purple haze is a noteworthy factor in tornado false alarms. This result likely reflects the crucial role of velocity radar data in the tornado warning decision making process.

c. *Impact of Circulation Intensity and Height*

In terms of magnitude and vertical depth, are circulations associated with zero day alarms weaker than outbreak day alarms and one tornado day warnings? To assess this question WSR-88D velocity data at a 0.5° elevation angle was used to determine if gate-to-gate shear or a couplet was discernable at the lowest height and near three kilometers above ground level (AGL). For the purposes of this study, a couplet was considered to have gate-to-gate shear less than 10 ms^{-1}. Expecting most zero day alarms to lack gate-to-gate shear, zero day alarms were hypothesized to have the weakest circulation intensity. First, the

Table 2. Circulation intensity statistics listed as a function of tornado warning classification for the lowest height scanned by a WSR-88D radar at a 0.5º elevation angle.

Tornado warning classification	Percent with gate-to-gate shear	Percent with couplet	Percent without a discernable circulation
Zero day alarms	45	20	35
Outbreak day alarms	47.6	19.1	33.3
One tornado day warnings	63.4	13.6	22.7

Table 3. Circulation intensity statistics listed as a function of tornado warning classification for the scan nearest to 3 km taken by a WSR-88D radar at an 0.5° elevation angle.

Tornado warning classification	Percent with gate-to-gate shear	Percent with couplet	Percent without discernable circulation
Zero day alarms	27.8	11.1	61.1
Outbreak day alarms	46.7	5.6	46.7
One tornado day warnings	52.6	10.5	36.9

percentage of zero day alarms, outbreak day alarms, and one tornado day warnings associated with gate-to-gate shear, a couplet, or no discernable circulation was computed at the lowest height and nearest three kilometers (Table 2, Table 3). Quantitatively, at the lowest height, the circulation intensities of zero day alarms and outbreak day alarms differed substantially from those correlated with one tornado day warnings. 45% of zero day alarms and 47% of outbreak day alarms were associated with gate-to-gate shear, while 63% of one tornado day warnings were similarly affiliated. These percentages begin to suggest that the velocity radar data of zero day alarms are very similar to outbreak day alarms. However, while manually reviewing the velocity radar data, the circulations associated with outbreak day alarms were significantly easier to identify than the circulations of zero day alarms. This perceived discrepancy may reflect the small sample size and subjectivity of the circulation intensity classification. Near three kilometers, the data did not indicate clear distinctions between zero day alarms, outbreak day alarms, and one tornado day warnings. This may be explained by inadvertent biases in the subsets. 38% of outbreak day alarms did not have a scan below three kilometers, while only 10% of zero day alarms and 13.6% one tornado day warnings were similar afflicted. The circulation intensity was recorded only at the lowest height in these cases, which unequally reduced the sample size of outbreak day alarms

Comparing Table 2 and Table 3 seemingly indicates that one tornado day warnings have a stronger circulation through three kilometers than zero day alarms. While the percentage of zero day alarms lacking a discernable circulation nearly doubled between the lowest scan and the scan nearest to three kilometers, it increased by a mere 9% for one tornado day warnings. For reasons stated above conclusions concerning outbreak day alarms could not be determined.

Gate-to-gate shear is considered a principle indicator of tornadic potential. The percentage of storms with gate-to-gate shear exceeding 10 ms^{-1} at the lowest scan and nearest three kilometers is plotted for zero day alarms, outbreak day alarms, and one tornado day warnings (FIG. 11). 47.4% of the one tornado day warnings have gate-to-gate shear at both levels,

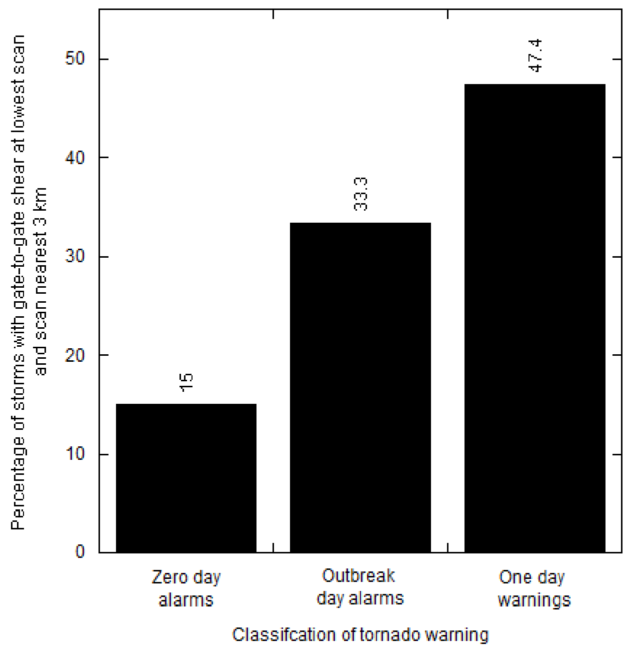

FIG.11. For zero day alarms, outbreak day alarms, and one tornado day warnings, the percentage of storms with gate-to-gate shear at the lowest height and near 3 km as detected by a WSR-88D radar at a 0.5° elevation angle.

compared to just 15% of zero day alarms. Thus, Fig. 11 supports the theory that zero day alarms have characteristically lower circulation intensities than one tornado day warnings.

Seeking a more comprehensive understanding of these relationships, the percentage of storms whose circulation intensity increased, decreased, or remained constant was calculated for zero day alarms, outbreak day alarms, and one tornado day warnings (Table 4). However, a conclusive relationship cannot be concluded from Table 4. The disorganized nature of these results may reflect the study's limited sample size. Additionally, our results may be reflecting the limited amount of radar data available below three kilometers. Out of the 63 cases manually reviewed, only 50.7% of them had at

TABLE 4. Based upon WSR-88D radar data taken at an 0.5° elevation angle, statistics on the variation of circulation intensity between the lowest scan and nearest 3 km listed as a function of tornado warning classification.

Tornado warning classification	Percent with increasing circulation intensity	Percent with decreasing circulation intensity	Percent with constant circulation intensity
Zero day alarms	27.8	38.9	33.3
Outbreak day alarms	20	66.7	13.3
One tornado day warnings	31.6	36.8	31.6

least two kilometers between their lowest level and the scan closest to three kilometers.

The numerical results above cannot support that a significant difference in circulation intensity exists between zero day alarms and outbreak day alarms. However, the results begin to suggest that one tornado day warnings experience circulation intensities of greater magnitude and depth than zero day alarms.

4. Conclusions

This study completed a comprehensive survey seeking to diagnose the climatological and radar circumstances associated with zero day alarms from 2000 to 2004. From a statistical and climatological perspective, the study endeavored to discover how zero day alarms are distinct from tornado day alarms. Large-scale atmospheric conditions were evaluated using the SPC convective outlooks and watches, while storm dynamics were analyzed using reflectivity and velocity radar data. These aspects of the study focused on how zero day alarms deviated from outbreak day alarms and one tornado day warnings. The results are summarized as follows:

- Zero day alarms follow the same diurnal trend as tornadoes, with most occurring between 1300 and 2100 local time.
- The percentage of false alarms occurring on zero tornado days is lowest in May and November, when tornadoes are climatologically most common. Given the synoptically and thermodynamically superior conditions in spring and fall, it is less likely that a day displaying significant tornadic potential will not produce at least one tornado.
- The percentage of false alarms occurring on zero tornado days is statistically different in each geographic region except between the West and Midwest /East. Additionally, the geographic distribution of zero day alarms follow tornado climatology. The West has the highest percentage of false alarms occurring on zero tornado days, while the Plains experience the lowest zero day alarm percentage.
- This study has indicated that, despite zero day alarms being more common in highly populated regions, there is no significant trend associated with distance from the nearest WSR-88D radar. This contrasts previous studies that indicate tornado reports are directly related to county population density and distance from the nearest radar since radars are often located near metropolitan areas (Ray et al. 2003). Given that tornado false alarms are dependent on confirmed tornado reports, flaws in the dataset may be impacting our analysis.
- In terms of large-scale atmospheric conditions, zero day alarms appear more similar to one tornado day warnings than outbreak day alarms. The SPC convective outlooks and watches suggest that zero day alarms and one tornado day warnings occur on days perceived to be marginally severe. However, outbreak day alarms occur predominantly on days considered to have a significant tornado threat.
- A quantitative analysis of the circulation intensity manually derived from velocity radar data suggests that zero day alarms are more similar to outbreak day alarms than one tornado day warnings at the lowest levels. However, during the manual analysis areas of circulation were significantly more difficult to identify in storms associated with zero day alarms than outbreak day alarms.
- 50.7% of the storms did not have at least two kilometers between the lowest scan of a WSR-88D radar at a 0.5° elevation angle and the scan nearest to three kilometers.
- 25% of zero day alarms and 23.3% of outbreak day alarms were obscured by purple haze, while only 9.09% of the one tornado day warnings were similarly afflicted. This limitation in the radar's ability may significantly influence tornado false alarms.

By 2014, the NWS strives to reduce FAR to 70% (NWS 2009). In the past, however, the NWS has struggled to reduce FAR. In a climatology of tornado false alarms, pending publication by Brotzge, Erickson, and Brooks, zero day alarms comprised the largest percentage of tornado false alarms in terms of the number of confirmed tornadoes in a WFO in a single day. Thus, reducing the number of zero day alarms may significantly aid the NWS in reaching its goal. This study suggests that storms displaying tornadic potential should be scrutinized especially in geographic regions that are climatologically less susceptible to tornadoes. Additionally, despite the radar analysis' small sample size, the results of this study begin to suggest that radar imagery represents the NWS best opportunity to reduce FAR. First, before issuing a tornado warning specific attention should be given to the gate-to-gate shear at the lowest level. This suggests that increasing radar coverage of the lowest kilometers of a storm may reduce FAR. Furthermore, efforts to reduce the amount of purple haze in the velocity radar data should be increased.

The strength of the implications suggest by this study are limited. First, the data employed may be flawed due to its dependence on confirmed tornado touchdowns. Numerous tornadoes each year are unconfirmed by the NWS. Tornadoes that are short-lived, weak or isolated are particularly susceptible to this error. Thus, there exists a high likelihood that some tornado warnings are incorrectly classified as false alarms. Second, by defining a tornado day from midnight to midnight the data biased the early morning hours. Future work should remove this bias by defining a tornado day as any 24 hour period with twelve hours before and after the tornado warning. Third, the analysis of the SPC convective outlooks and watches is temporally limited. The two years of convective outlook data and one year of convective watch data will need to be expanded before definite conclusions may be reached. Fourth, the small sample size of this study's radar analysis can only begin to imply trends. In order to strengthen this aspect of the study, each of the zero day alarms, outbreak day alarms, and one tornado day warnings data sets should contain at least 100 storms. Additionally, the radar analysis employed highly subjective in classifying storm morphology and circulation intensity.

Finally, this study has illuminated a number of avenues for future research into zero day alarms. While analyzing the SPC convective outlooks and watches suggests how the large-scale atmospheric environment is perceived by forecasters, this does not reveal the storm specific atmospheric conditions. A comparison of proximity soundings associated with zero day alarms, outbreak day alarms, and one tornado day warnings may reveal important distinctions. An analysis of parameters such as CAPE, CIN, and storm-relative helicity could be particularly revealing. Additionally, documenting which warnings resulted from information provided by storm spotters would prove invaluable in improving warning operations. The percentage of zero day alarms that were driven by storm spotter reports as well as the geographic and temporal distributions would be particularly insightful.

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