Analyzing tornado warning performance across storm lifetimes

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ABSTRACT: Tornadoes with inadequate warnings continue to present a threat to the public. In this study, outbreak events from 2008-2010 were gathered from the National Weather Service verification database to analyze their tornado warning performance. Utilizing Google Earth and an online radar viewer, we numbered the parent storms that produced those tornadoes. We then categorized these tornadoes into the order of sequence they were produced, called tornado order, to analyze their warning performance and lead time. Our primary hypothesis in doing this was to see whether the first tornado of every storm was more poorly warned than subsequent tornadoes on each storm. Furthermore, we analyzed differences in tornado-warning performance with respect to geographical region and the diurnal cycle. Our data shows a correlation with tornado order and warning performance. Warning rates and positive lead times increased with subsequent tornadoes after the first tornado. Tornado order with respect to their diurnal cycle showed a substantial difference between diurnal events (which had a better warning rate) and nocturnal events. No significant differences were evident between warning rates in different geographical regions. Our study shows evidence that tornado order and the diurnal cycle impact the warning performance of tornadoes.

1. Introduction

Throughout the United States, tornadoes can form at any given time of the year with the most frequent occurring during the spring. They present a hazard to the public with unfortunate lethal outcomes in some cases. It is the role of the National Weather Service (NWS) to prevent this outcome by issuing warnings well in advance of tornado formation. Unfortunately, isolated tornadoes and the first tornado of the day are the most likely to be inadequately warned (Brotzge and Erickson 2010). Factors influencing forecaster's confidence may play a role, including atmospheric conditions, geography, and the operations of the NWS.

The more isolated a tornado event is, the more likely the warning will have a reduced lead time, if any advanced warning was provided at all (Brotzge and Erickson 2009). This is consistent with Anderson-Frey et al's (2018) analysis showing that the probability of detection (POD) is lowest in non-outbreak events (59%) compared to outbreak events (80%). They also attributed higher POD with outbreak events due to atmospheric conditions more favorable for tornado development. This may increase warning lead time because the storms are likely stronger and more organized with a history of tornadic development (Brotzge and Erickson 2009). In general, the more tornadoes that are produced, the more likely the POD increases (Anderson-Frey et. al 2018).

Geography and the nature of the NWS may play an important factor in poor warnings. Regions that see far more tornado activity, such as the Plains, experiences fewer missed warnings possibly due to the heightened awareness and experience of the forecasters (Brotzge and Erickson 2010). The Plains region also experiences a higher level of positive lead time than any other part of the country (Brotzge and Erickson 2009), possibly due to the same reasons. In 2012, a NWS effort to curb false alarm warnings also reduced POD and warning lead time (Brooks and Correia 2018). This yields a few questions that motivate this study. Could the same curb be occurring in individual Weather Forecasting Offices before the first tornado of the day? Does the lead time increase with each subsequent tornado in the same storm? Along the same line, are the lead times of the first tornado of each storm generally lower? To begin answering these questions, we examine tornado warning statistics during outbreaks, which tend to have more fatalities and injuries than isolated events (Anderson-Frey et. al. (2018).

2. Data and methods

Tornado reports from 208-2010 were collected from the NWS tornado verification database. This includes the event ID, the local time of the event, the EF-scale rating of the tornado, the WFO that issued the warning, the tornadoes start and end latitude and longitude, the initial lead time of the tornado, and the percent event warned. We then filtered the dataset to include only “outbreak” tornadoes as defined by Anderson-Frey et al. (2018), yielding 1808 tornadoes. This was done for a few reasons: 1) we believe that any intra-storm trends in tornado warning performance are likely the largest for discrete, right-moving supercells, which are most common during outbreaks, 2) outbreaks are associated with more fatalities and injuries than other tornado events, and 3) to limit the sample size in order to complete the analysis during the 10-week summer program.

After extracting tornadoes that occurred during outbreaks, we analyzed each outbreak event individually in order to match each tornado with its parent storm. Tornado reports were gathered and plotted using Google Earth. They are then matched with the Storm Forcster archived radar map (available freely online), where individual tornadic storms are tracked every 5 minutes (i.e., the time between successive radar volume updates). Within each outbreak, each storm that produces at least one tornado is then assigned a number. In cases that the same storm produces more than one tornado, that storm retains the same number. Merging tornadic storms are denoted using the lowest storm number between the two. This was done to retain the warning history of the earliest (and therefore theoretically the most mature) storm before the merge occurred. Splitting storms, or storms with a history of producing tornadoes that then split into two separate cells, are indicated by their original number and a corresponding decimal of 1 or 2 to differentiate them.

These methods yielded a dataset containing tornadoes matched with their parent storm. To our knowledge, this is the first study to explicitly relate tornado occurrence and warning characteristics on a storm-by-storm basis. We used this study to address the question posed in Section 1, as described below.

3. Results

We begin our analysis examining tornadoes with their associated warning performances. The focus will be on whether tornado order alone, geographical regions, and/or the diurnal cycle would influence warning potential. Lastly, our second analysis will investigate lead time differences in tornado warnings within their respective order.

a. Tornado Order

Figure 1 shows a bar graph separating tornadoes based on their order. While Only events are similar to First Order events, in which they are both essentially “first” tornado of a storm, we chose to separate the two to analyze their relative performance. In the First order, the percentages of tornadoes given a warning was 68% compared to the Middle order (86%) and Last order (78%). Only events faired far worse with 55% warned. Comparing the First order and the Middle order shows a meaningful rise of 18%, signaling an improvement in warning POD after the first tornado of the storm occurred. Interestingly, a modest decrease of about 8% occurred between the Middle mean and the Last tornado; however, the Last warning performance was still higher than the First. While Middle and Last tornadoes had better warning performances (a decrease in missed events); roughly one-third of the First tornadoes associated with each storm and roughly one-half of Only tornadoes had no warnings at all.

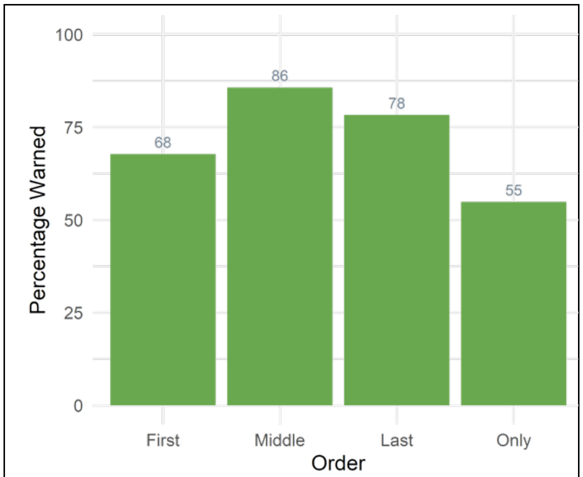

Fig. 1. A bar graph representing the different orders in a tornado. Tornado order are the first, last, middle sequence of tornadoes in a storm. Only tornadoes are isolated events.

b. Geographical Region

We next examined whether geographical region played a role in whether a tornado was warned. Terrain, regional tornado favorability, and forecasting experience are some factors that may influence whether a region has an increase chance of issuing a warning during a tornado. To examine this, the same data collected to create Fig. 1. are plotted with respect to the tornado's geographical location (Fig. 2). In general, the trends in the percent warned and tornado order in Figs 1 and 2 are similar. Figure 2 shows some subtle differences in warning performance between regions, particularly with respect to First tornadoes. While the Central (66%) and Southern (68%) regions show very little change in the percentage warned, the Eastern region differs (77%) with an increase of roughly 10%. The same cannot be said for the Middle tornadoes, where all regions show similar percentages, signaling possibly no geographical relations with warning performances. Remarkably, the percentage warned in the Last Order continues to be somewhat similar in the Central (82%) and Southern (76%) regions. In parallel to the First Order, the Eastern region differs significantly from the other regions with a difference of 8% in the Southern region and 14% in the Plains. We believe that the Eastern region and other regions is more likely due to the smaller sample size of the outbreak tornadoes rather than physical differences.

"Only" tornadoes appear to moderately favor the Southern region compared to their Central and Eastern counterparts. Overall, Isolated tornadoes in general have the worst warning rate out of any order while the Middle order performed the best. When comparing the Central and Southern regions performance from Figure 2 with Figure 1, they trended similar. This suggests that topography doesn't play a role in warning performance.

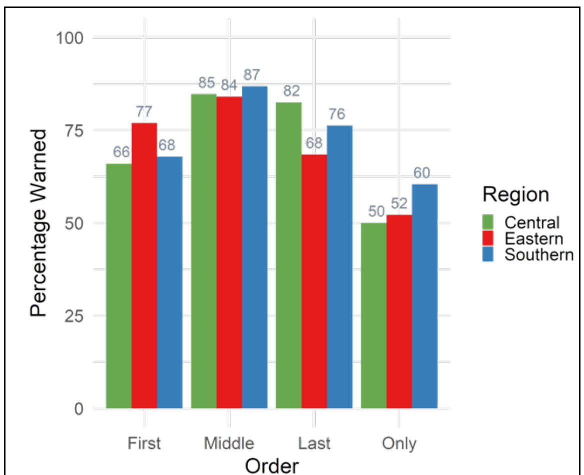

Fig. 2. Four regions were denoted in this analysis: The Central, Eastern, Southern, and Western sectors of the United States. The Order of the tornadoes, described in *Tornado Order*, are replicated within each

corresponding region. Tornadoes in the Western sector were not located when compiling the data and thus are not included in the bar graph.

c. Diurnal Cycle

The differences in Day and Night have a profound effect on our weather. Typically, nocturnal thunderstorms become rarer as night falls possibly due to the lack of daytime heating and instability. In addition, visibility becomes nullified as day passes into night making it harder to verify active tornadoes. With these issues in mind, does the diurnal cycle affect warning performances?

For this analysis, we examined the tornado order with respect to the diurnal cycle. Figure 3 shows that warning performance decrease at night compared to their daytime counterpart, except for the First tornadoes of each storm. In the other categories, the differences between day and night are rather large. For the Middle tornadoes, the differences are about 16%, while the Last tornadoes shows a decline of roughly 20%. Isolated events fared somewhat better with a drop off rate closer to 12%. Interestingly, the drop rate for the First tornadoes was rather minimal, showing no correlation with the diurnal cycle. This suggests that an increase in warning performance that one might expect for daytime outbreak compared to a nighttime outbreak may not hold true for the first tornadoes of each storm. Similar with Fig 1. and Fig 2., Isolated tornadoes continued to exhibit warning performances that are dwarfed in comparison with the other orders. Inverting the graph shows a dangerous trend in no-warnings associated with nocturnal tornadoes. For example, over half of Only tornadoes that occur overnight are not warned.

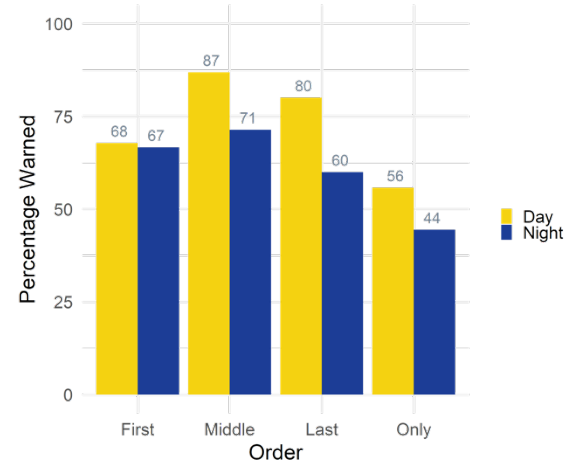

Fig 3. Shows a graph of the diurnal effect on warning performances in conjunction with tornadic order.

d. Lead Time

Figure 4 shows warning lead time within their respective orders as in previous figures. As anticipated, the amount of advanced warning for the First tornadoes (15 min) and Only tornadoes (15 min) are smaller than the Middle (22 min) and Last (19 min) tornadoes. This shows that even during better-warned tornado outbreaks, the first tornadoes of each storm are more poorly warned than subsequent tornadoes with each storm. If a storm produces subsequent tornadoes, the lead time of those tornadoes, on average, increases by roughly 7 mins with respect to the first tornado of that storm.

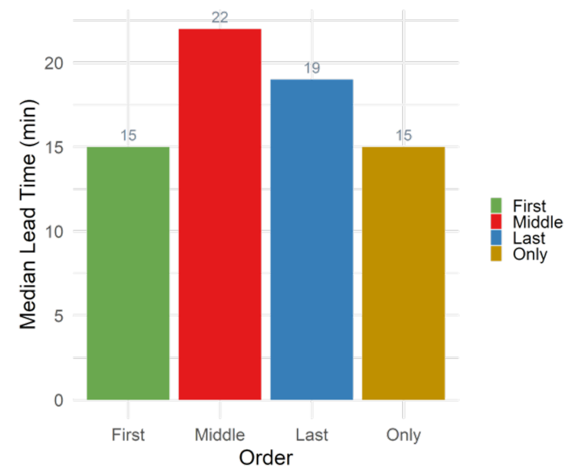

Fig. 4 A bar graph representing the lead time performance of tornadoes with respect to their order of occurrence.

4. Discussion and Summary

Tornado data from 2008-2010 were gathered by the NWS verification database. We used Google Earth to plot the tornado's locations and Storm Forcster to relate them to the storms that produced the tornadoes. During an outbreak event, each storm that produced at least one tornado were assigned a number. In total, 37 outbreaks and 1808 tornadoes were analyzed. The goal of this project was to determine if the order of a tornado within its parent storm affects warning performance, and subsequently whether geographical location and/or the diurnal cycle influence these relationships. Our most important findings are summarized below.

1. *The impact of tornado order does influence warning performance.*

The First and Only tornadoes performed the worst whereas the Middle and Last orders had substantially better results. In particular, the Middle and Last tornadoes within a cyclic storm tended to have 4-7 mins more lead time than the first tornadoes within the storm. This finding collaborates Brotzge and Erickson (2009, 2010) in that Isolated and the First tornadoes of the day are difficult to warn.

We speculate forecaster confidence may play a role in the evolving tornado warning performance during a cyclic storm's lifetime. The idea is that a storm, with a history of producing multiple tornadoes, may allow forecasters to become less reluctant in issuing warnings, hence better warning performances. So, why would forecaster become hesitant when issuing a warning? The threat of broadcasting a false alarm, a warning with no associated tornado, unfortunately does occur leaving the public dismayed. If there are subsequent false alarm, this may lead the public to become alarm fatigued. To prevent this, forecasters may become cautious when issuing warnings during the first tornado (including isolated events), whereas subsequent tornadoes may lower their hesitancy.

In our analysis, we choose to separate the First and Only tornadoes for better examination; however, Only tornadoes can still be considered the "first" tornado of a storm. If this is the case, why do the Only tornadoes perform worse than First tornadoes, at least in percentage warned? We speculate that this may be due to the storms that produce Only tornadoes occurring along the periphery of the primary outbreak (but are still included within the "outbreak" definition). Some of these "lone wolf" tornadoes may be hundreds of miles away from the main event while continuing to still be part of the same synoptic system. It is possible that forecasters are not focused on the possibility of tornado production far away from the main cluster of storms.

2. *Geographical regions do not strongly influence tornado warning performance.*

This somewhat contradicts the findings of Brotzge and Erickson (2010) where they suggest tornadoes without warnings are higher in the Midwest than in the Plains region. It is possible that our sample size (37 outbreaks and 1808 tornadoes) is too limited, especially in the Eastern region, to extract differences in warning performance in different regions. Brotzge and Erickson (2010) paper conducted a 5-year study for all tornadoes while we accounted for outbreak type events in a three-year study. This reasoning could also explain why the Eastern regions performed comparably well under the First tornadoes and poorer in the Last tornadoes

3. *Tornado Warning Performance is sensitive to the time of day*

Middle, Last, and Only tornadoes are much more likely to be warned during the daytime, whereas the likelihood of First tornadoes being warned does not change between daytime and nighttime. This is important because roughly 26% of all outbreak tornadoes occur overnight (Anderson-Frey et al. 2018).

4. *The order of the Tornado with its parent storm does influences warning lead time.*

Our original goal for this study was to compare the lead times of tornadoes with respect to their order of sequence in each storm. Median positive lead time for the First tornadoes of each storm is roughly 15 minutes, while the median positive lead time for the Middle tornadoes of each storm is around 22 minutes.

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