Tornado Warnings, Lead Times, and Death

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Abstract

Intuitively people believe that when a tornado has longer lead time, there will be a higher probability of reducing fatalities in an event. Sutter and Simmons (2009) created a model to qualitatively prove the effects of lead time on death; however, the results were inconclusive due to finding no obvious trend. We examine the lead time for tornadoes warned in advance using data provided by the National Weather Service Performance Management Branch's verification system starting in January 1986 to December 2023 by creating probabilistic graphs. We come to three conclusions about the relationship between tornado warnings, lead time, and death: the distribution of lead time across the data set has changed little over time, forecasters are issuing more shorter lead times for weak tornadoes than ever before, and there is no statistically significant relationship between death and lead time.

1. INTRODUCTION

Tornado events in the US cause billions in damage each year, injuring thousands and unfortunately dozens die due to these vicious storms. Research over the past few decades has suggested extending the lead time may result in less fatalities; however, there is little research that suggests this relationship is significant. Intuitively people believe that the longer the lead time, the less deadly a tornado will be, but it is a difficult topic to quantify due to the various aspects of a tornado and what leads it to being deadly. One of the first papers' that examines this relationship qualitatively is Sutter and Simmons (2009) where they look at the number of fatalities from tornadoes from 1986 to 2002 to understand the relationship between lead time and death as well as lead time and injuries. The paper concludes that the longer the lead time the less injuries there will be, but the impacts of a longer lead time and reduction in fatalities is not conclusive. Their model shows that the longer lead times after 30 minutes become just as deadly as if the tornado were not warned in the first place (Simmons and Sutter 2008).

What made the Sutter and Simmons (2009) model complex was the need to control a variety of factors of the tornado to get results that showed the impacts of lead time. It is necessary to consider the characteristics of a tornado event to understand why tornado events may lead to casualties. The risk, defined as the probability of a tornado event occurring, and vulnerability, defined as the likelihood of a person experiencing harm (Strader, Haberlie, and Loitz 2021) is the starting point to understanding how these characteristics impact an event. Previous studies have examined the location, seasonality, and population's income to define the vulnerability. We specifically look at vulnerability being the strength of a tornado and the number of casualties due to the tornado event.

In addition to vulnerability and risk of tornadoes, there have been changes made by the National Weather Service (NWS) in how they issue tornado warnings. Beginning in October 2007, the NWS shifted from county-based warnings to storm based warnings, although there is little evidence that the performance of these issues changed (Brooks and Correia 2018). Instead, the largest adjustment and impact on tornado warnings happened after the 2011 outbreak when people called for the NWS to work on reducing false alarm rates (FAR) (Brooks and Correia 2018). Brooks (2004) describes the relationship between FAR and probability of

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detection (POD) are proportionally related to one another, as FAR decreases, the POD decreases as well. This in turn results in a reduction in lead time since forecasters may wait longer to issue warnings in order to be more confident in their decisions (Brooks and Correia 2018). Using data from the National Weather Service (NWS) Performance Management Branch's verification system (PMB) dating back to 1986 up until 2023, we create an analysis by examining if lead time has changed across the data but how probabilities of casualties' changes over time as well.

By comparing factors of the tornado to one another, including the strength of the tornado and whether a tornado resulted in death or not, we can create a qualitive understanding of the relationship between tornado warnings, lead time, and death. Furthermore, we can compare the early storm-based era and the late storm-based era by looking at the distribution of lead time and the differences of lead time distributions based on strength. A comparison between the county-based era and storm-based era to explore how lead time and the probability of a deadly tornado occurring at each lead time has changed throughout time. The benefits of understanding this relationship will be in helping policymakers decide where their focus should be when it comes to preventing deaths in violent tornadoes.

2. Data and Methods

We use the NWS PMB verification system from 1986 to 2023, as well as information on the casualties from the county-based era from National Centers for Environmental Information (NCEI). NWS officially evaluates tornadoes based on one-minute segments that the tornado is on the ground for, where unwarned segments are equal to zero. We define the lead time as the average of warned segments of a tornado. The NWS defines initial lead time as given an event has occurred, how long was a warning issued prior to the event taking place. Lead time would account for tornadoes warned during the event, where the initial lead time is only prior to the event. This study is specifically only using the initial lead time provided by the NWS.

We can view the data in two groups, one starting in 1986 to September 2007 and the other starting in October 2007 and onwards. This is due to changes made by NWS in how they issue tornado warnings. During the first group (1986–Sept. 2007), the NWS used county-based warnings, whereas starting in October 2007 the NWS started issuing warnings using polygons associated with the storm, also referred to as the storm-based warning era. Brooks and Correia (2018) show in their study that there is no significant difference in many aspects of the performance between these two warning eras, for that reason, both groups define the lead time as the initial lead time. A warned tornado will have any initial lead time greater than zero and a tornado not warned has an initial lead time of zero. For the remainder of this paper, the definition of lead time is only the initial lead time.

Additional information on the event from the NWS includes the end and start time/date, the state and county the tornado warning was issued, 1-minute segments, number of segments warned, Enhanced-Fujita (EF) scale rating, direct injuries, direct deaths, and damage to property and crops in United States dollars (USD).

Sutter and Simmons (2008) created a model of death using the defining characteristics of the tornado, with the focus being on the number of deaths. We will be taking a different approach to the topic, by looking at the number of tornadoes per minute of lead time based on a variety of factors. The benefit of this distribution method is the capability to control outliers in the data set. Tornadoes are rare events, and it is even rarer to have fatalities as a result, so when an event that results in numerous deaths it can cause sharp increases in the data and create outliers. By reducing the number of tornadoes instead of the number of deaths we can reduce the sensitivity of the data. Using probabilistic graphs shows the likelihood these events will occur at specific lead times, which paints an important picture of the possible impact longer lead times can have on the number of casualties. A probability density function (PDF) displays the likelihood of an event taking place at an exact time value, whereas a cumulative distribution function (CDF) displays the likelihood of an event happening at a less than or equal time value, with more events towards the left. In addition to PDF and CDF, plots of probabilities of an event occurring based on specific conditions.

To see the likelihood of the events being different to other probabilities in the graph, we can calculate the 95% confidence interval (CI) and plotted with the probabilities using the Wald's interval. Wald's equation is defined as:

$$\hat{p} \pm z_{(1+L)/2}\sqrt{\frac{\hat{p}(1-\hat{p})}{n}}$$

Where $\hat{p}$ is the probability, the n is the sample size and the z is the normal distribution quantile, this is the portion that decides the percentage of the CI Since we are focusing on the 95% CI, the z value is equal to 1.96.

Tornadoes are complicated storm systems with factors that impact the vulnerability and risk of people and the surrounding area. Exploring these factors can help int understanding the relationship between tornado warnings, lead times, and death. While the data set offers numerous characteristics, our study specifically uses the year the events occurred, strength, and casualty data only. There are different ways these features can be implemented and examined which we can break down piece by piece.

2.1 LEAD TIME AND TORNADO FEATURES

The best plots to look for differences in short versus long lead times is to the distribution using PDF and CDF plots. In addition to just the lead time, different conditions can sperate the data into two groups to compare them by asking if an event meets. One comparison is the strength of the tornado, weak versus strong, where the weak tornadoes are EF-0, EF-1, and EF-Unknown and strong tornadoes are EF-2 and higher. The second comparison is the distribution of lead times for tornadoes with fatalities and tornadoes with no fatalities. In addition to comparisons, we can look at the probability of a deadly tornado given lead time with a 95% CI.

2.2 EARLY VS LATE STORM-BASED ERA

When the NWS switched from county-based warnings to storm-based warnings there was no significant changes in the performance of tornado warnings; however, there was a large performance change in 2012 (Brooks and Correia 2018). Brooks and Correia (2018) associate the change with the threshold of warnings being issued due to the emphasis in reducing the number of false alarm rates (FAR) as well as the duration of tornadoes getting smaller, where a larger fraction of warnings lasted 45 minutes during the county-based warning era and now more warnings last for 30 minutes.

To see the effects this has on the lead time distribution, comparing the tornado storm-based events by the early storm-based era, from October 2007 to December 2011, and the late storm-based era, from January 2012 to December 2023. From there we can look at the lead time distribution for strong and weak tornadoes between the two different periods. This will show the effect of the threshold change and the impacts it has on the amount of time given to people in the path of a tornado.

2.3 COMPARING MODERN DATA TO PAST DECADES

Since Sutter and Simmons (2008) is a main motivator for this study, we can use previous decades to compare with the modern era. We break the data into four groups, the two from the previous section, the early and late storm-based eras, as well as the early county-based era being January 1986 to December 1996 and the late county-based era being January 1997 to December 2007. As seen there is a three month overlap for the groups with 2007; however, this should not impact any results since between October to December 2007 there were only four tornado events.

We examine the lead time distribution and distribution in the strengths across the data in the same way as the previous section. In addition to the distributions, comparing across the data of the probability of a deadly tornado given a lead time with a 95% CI is plotted.

3. RESULTS

3.1 LEAD TIME, STRENGTH, AND DEATH DISTRIBIUTION

From October 2007 to December 2023, 43% (9698/22587) of tornado events were unwarned, with less than 1% of those resulting in casualties. Distributions of tornado events with fatalities across lead time are much more sporadic in comparison to the events with no fatalities due to the sample size of deadly tornado events (Fig. 1). A cumulative distribution is favorable to smooth out the data and to see what the most common lead time is in the data set (Fig. 1). Of all the tornadoes in the data set, 0.4% were deadly and 23% of those were unwarned. Out of the warned deadly tornadoes, 93.3% of those tornadoes are strong. The most common lead time for deadly tornadoes is 18 minutes, whereas a tornado that is not deadly is approximately 13 minutes (Fig. 1).

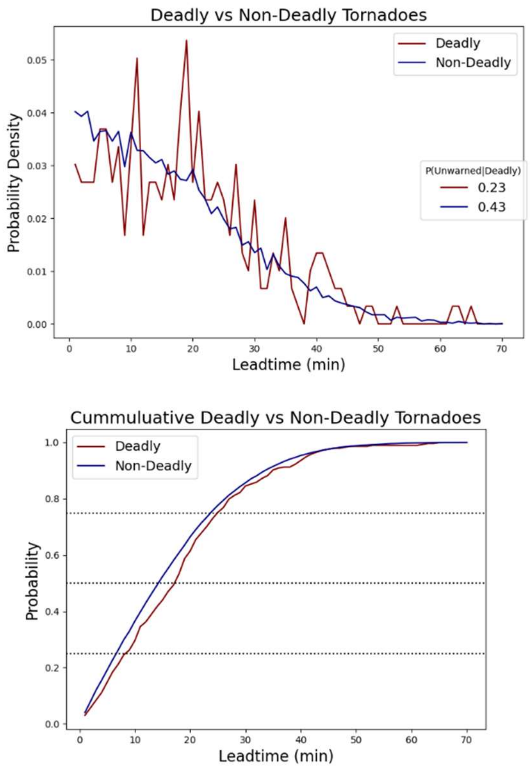

Figure 1. The probability density function (PDF) on the left and cumulative distribution function (CDF) on the right of the warned tornadoes that resulted in at least one death versus warned tornadoes that had no deaths given a lead time.

In addition to looking at the distribution of lead times for deadly tornadoes, we want to look at how lead time is impacting the number of fatalities from an event. We will do this by taking the number of deadly tornadoes divided by the total number of tornadoes given a lead time to get the probability a deadly tornado will occur at a specific lead time. In addition to the probability, we use Wald's 95% CI to look at the likelihood the probability will occur and how similar it is to other probabilities. Due to the sample size being small, we aggregate the lead time into 5-minute groups (1-5, 6-10, 11-15…) with the last group being all the events having a lead time greater or equal to 35 minutes (Fig. 2). The unconditioned probability of a warned tornado resulting in a death is 0.022 and the probability of an unwarned tornado being deadly is 0.008.

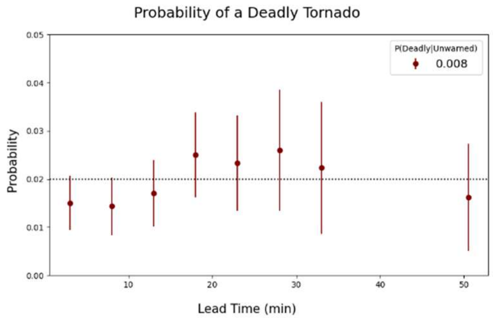

Figure 2. The probability graph of the likelihood a deadly tornado event will occur at a lead time with the dots representing the probability and the lines being the 95% confidence interval. Each point represents an aggregate of lead time (1-5, 6-10…) and the last point represents everything longer than 35 minutes. The black dotted line is the average probability and in the legend is the probability of a deadly unwarned tornado occurring.

3.2 EARLY VS LATE STORM-BASED ERA

We split the data from the storm-warning era into two: 6872 tornado events from the early storm-based era being October 2007 to December 2011 and 15715 tornado events from the late storm-based era being January 2012 to December 2023. The early storm-based era has 34% of unwarned tornadoes and 47% of the late storm-based era is unwarned tornadoes. The percentage of unwarned tornadoes resulting in fatalities is 1.3% in the early storm-based era and less than 1% in the late storm-based era.

The most common lead time in the early storm-based era was 8-minute lead time, while the late storm-based era had 1-minute lead time being the most common (fig. 3a). The most common lead time for early storm-based era is approximately 17 minutes and 11 minutes in late storm-based era (Fig. 3a). Both sets of events have approximately 83% weak tornadoes and 16% strong tornadoes each.

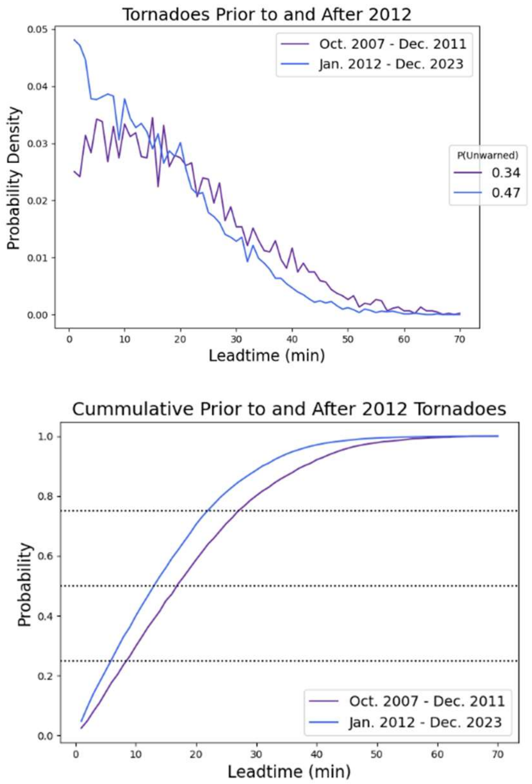

Figure 3a. The probability density function (PDF) on the left and cumulative distribution function (CDF) on the right of the warned tornadoes early storm-based era versus later storm-based era.

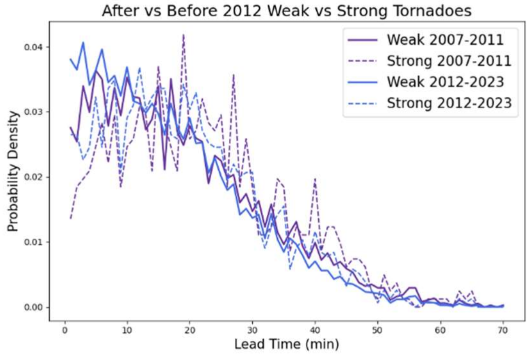

Figure 3b. The PDF graph of the prior versus late storm-based era separated by the strength of the tornado. The solid lines are weak (EF-0, EF-1, and EF-U) and the dotted lines are strong (EF-2+), with the blue being late storm-based era and purple being early storm-based era.

3.3 MODERN VS OLDER PERIODS

We split the data into four groups based on the warning era and if it was the earlier or later portion of the eras: early county-based is 1986 to 1996, late county-based is 1997 to 2007, and the early and late storm-based eras defined previously. Both county-based eras have the most common lead time of around 15 minutes, while the early storm-based era is approximately 18 minutes, and the late storm-based era is around 13 minutes (Fig. 4). In addition to the most common lead time, the probability of issuing a warning with a long lead time has little differences for both county-based and the early storm-based eras (Fig. 4). Taking the distribution of lead time, we broke it down by the strength of the tornado for each set of data and plotted the cumulative distribution (Fig. 5). The most common lead time for weak

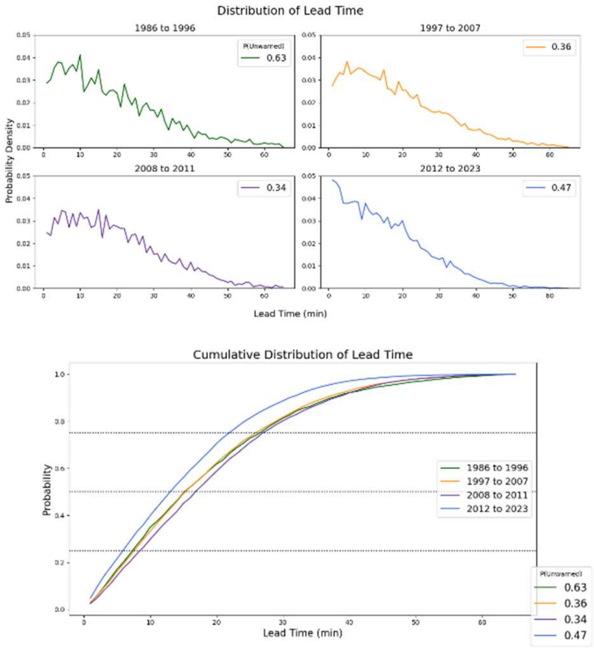

Figure 4. The probability density function (PDF) on the top and cumulative distribution function (CDF) on the bottom of the warned tornadoes for four different periods: 1986 to 1996 (early county-based), 1997 to 2007(late county-based), 2008 to 2011 (early storm-based), and 2012 to 2023 (late storm-based).

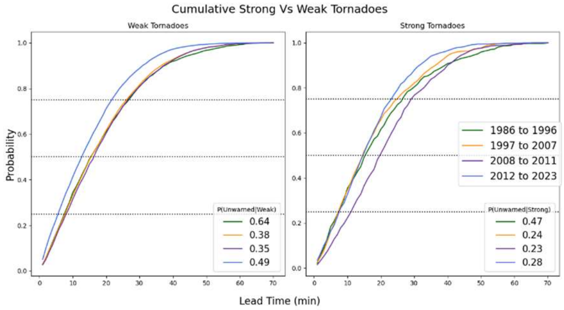

Figure 5. The cumulative distribution function (CDF) of the weak (left) and strong (right) tornadoes for both county-based and storm-based warnings. The bottom right legend on both graphs is the probability of an unwarned tornado being weak (left) or strong (right).

The most common lead time for weak tornadoes for all but the late storm-based era is around 15 minutes, and the late storm-based era is around 10 minutes (Fig. 5). The most common lead time for the early storm-based warning is approximately 18 minutes while the other eras are all approximately 10 minutes (Fig. 5).

Similar to the previous section, we examine the probability of a deadly tornado occurring given a lead time in addition to the distributions (Fig. 6). The most common probability of a deadly tornado warning in advance for the early county-based era is 0.014, the early storm-based era is 0.031, and both late storm-based and late county-based eras are 0.020 (Fig. 2). The probability of an unwarned tornado being deadly for the early county-based era is 0.014, late county-based era and early storm-based era is 0.012, and late storm-based era is 0.008 (Fig. 6).

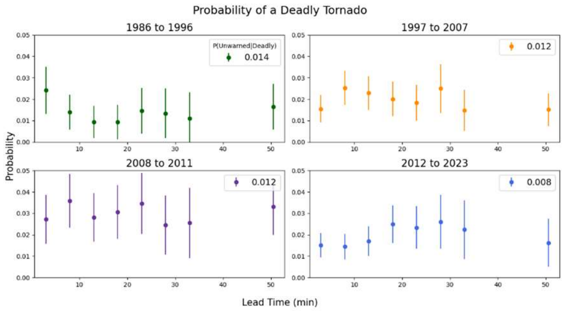

Figure 6. Probability of a deadly tornado occurring across four decades with the 95% confidence interval. Each point is five minutes pooled together, except for the last point being greater than 35 minutes. In the top right corner on each panel is the probability of an unwarned tornado being deadly.

4. DISCUSSION

4.1 GENERAL LEAD TIME AND DEATH

The first step to understanding the relationship between tornadoes warned in advance and the number of casualties is to examine the differences in lead time between tornadoes that resulted in deaths or not. Out of the 12889 tornadoes warned, 298 of them have at least one death. Since there is such a small amount of fatal tornado events, plots of the data without either cumulating the data or aggregating the minutes will be difficult to interpret (Fig. 1). If the intuitive idea that tornadoes warned farther in advance was less deadly, we would see that the most common lead time would be less than the tornados that resulted in no deaths. This is not true, with the most common lead time for deadly tornadoes being around 18 minutes and non-deadly tornado events being approximately 13 minutes (Fig. 1).

From there, we want to analyze the probability of a deadly tornado given a lead time (Fig. 2). As previously mentioned, the data set is incredibly small, in order to understand the significance of a probability given a lead time, it is necessary to aggregate the time (1-5, 6-10…) with the last point representing all warnings longer than 35 minutes (Fig. 2). Overall, there is no strong trend suggesting a longer lead time is less deadly; instead, there is a small trend of increasing the probability when increasing lead time (Fig. 2). This is not suggesting that a longer lead time is going to result in more deaths, the sample size is small, so the 95% CI are overlapping each other. This result does suggest that for storm-based warnings, there is no significant relationship in a longer lead reducing the number of deaths. We can see if this idea has changed throughout time by comparing the storm-based eras with the county-based eras later on.

4.2 EARLY VS LATE STORM-BASED ERA

The change with warnings in 2012 is a threshold change, not a performance change, in fact the difference between these two decades has to do with FAR and POD. Brooks and Correia (2018) describe that after the 2011 outbreak, people wanted to reduce the number of false alarms issued. In addition, most tornado warnings have a duration of 45 minutes in the early storm-based era, while in the last storm-based era most warnings have a duration of 30 minutes (Brooks and Correia 2018). There is a positive correlation between FAR and POD, meaning as the FAR reduced, the POD did as well (Brooks 2004). We can suggest that forecasters may have reduced FAR by holding off on issuing a warning until it became clearer that a tornado would form. This could explain why the lead times in the later storm-based era decreased (Fig. 3a); however, it does not explain the extreme increase in 1-minute lead times in the later part of the era. The peak in lead times for tornadoes in the late storm-based era is around 1-minute and the early storm-based era is closer to 13-minutes (Fig. 3a), this difference is huge in comparison to the rest of the lead times, where after 10 minutes the probability of a weak or strong tornado occurring given a lead time is not vastly different.

To understand where this change is occurring, we look at the weak and strong tornadoes in comparison to the early and late storm-based eras (Fig. 3b). We notice that the largest gap between the eras is at the start, where there are more 1-minute warnings for the weak tornadoes in the later period (Fig. 3b). The weak tornadoes are not the only ones that have shorter lead times, as the strong tornadoes in the late storm-based era have also decreased in lead time. It may not be as drastic as the weak tornadoes due to how few there are, but there are still shorter lead times for tornadoes late storm-based era in comparison to prior. Overall, it appears that between the beginning of the storm-base era and the latter half, the lead time for both strong and weak tornadoes have decreased; however, we are issuing shorter lead time warnings for weak tornadoes.

4.3 COUNTY-BASED VS STORM-BASED ERAS

We relooked at Sutter and Simmons (2009) originally did in simpler terms, rather than creating a model to show for variables, we looked at the distribution of lead time across the decades can show how warnings may or may not have changed over the years (Fig. 4). As previously stated, in the late storm-based era there was a large jump in shorter lead times in comparison to the early storm-based era; we also know now that this is true throughout both county-based and storm-based eras, with the largest difference being a higher probability of a warnings being issued one to five minutes prior to the event for the late storm-based era (Fig. 4). After these first five minutes though, the distribution along the lead times does not appear to drastically change over time, in fact the most common lead time does not change for the both county-based warnings with 15 minutes and the early storm-based warning is 18 minutes (Fig. 4). It appears that since 1986, the lead time distribution has not significantly changed, except for lead times in the first five minutes. While forecasters have changed the way warnings are issued, the lead time distribution has changed slightly, with the largest difference being the late storm-based eras issuing warnings with shorter lead times.

It is not just an overall change, but significantly weaker tornadoes. The most common lead time for weak tornadoes in the late storm-based era is around 10 minutes whereas every other set is around 15 minutes (Fig. 5). In comparison, the most common lead time for strong tornadoes in the early storm-based era is 15 minutes and the other eras are all around 10 minutes (Fig. 5). The weak tornadoes have a shorter lead time in the late storm-based era in comparison to the other eras and then the lead time for strong tornadoes goes down from the earlier portion of the era. This puts an emphasis on the point made in the last section that in the most recent years, forecasters have been issuing more warnings with short leads time for specifically weak tornadoes in comparison to any other era. Additionally, the lead time for strong tornadoes has gone back down to be similar to the county-based warning eras. We conclude that while the distribution of lead time overall has changed slightly throughout the data, the most recent period shows there has been a drastic increase in warnings with short leads specifically for weak tornadoes, but strong tornadoes as well.

Tornadoes are rare events and tornadoes with deaths are even rarer. By only doing the number of deaths, as seen by Sutter and Simmons (2009), it can make the data sensitive when big events occur. To combat that we simply look at the number of events with deaths over the decade to find the probability of a deadly tornado event occurring (Fig. 6). To understand any changes in the probability over time, we can examine the probability by era and then compare awards. The early county-based era shows the probability starting to decrease up to 15 minutes, after those 15 minutes there is not much to say, with the confidence intervals overlapping with one another and are not distinguishable between one another; something that Sutter and Simmons (2009) originally saw in their study (Fig. 6). The late county-based era shows a slight increase between the first and second 5-minute bins (1-5 and 6-10), but after that it seems to constantly decrease up until 25 minutes and then becomes too sporadic to say anything about it (Fig. 6). The early storm-based era is harder to show any significant difference between any aggregate lead time (Fig. 6). This group has the least number of years, meaning it has a smaller number of events and as a result the sample sizes for the points are small. This explains why the confidence intervals are much larger in this era than any other; there is nothing to interpret as a result (Fig. 6). That leaves us with the most recent era, the late storm-based era. It is constant in the first fifteen minutes, but after that it increases the probability of a deadly event; however, the sample sizes at later lead times are much smaller and lead to overlapping CI's (Fig. 6). This means that there is nothing significant between the lead times, there is no concrete evidence suggesting that a longer lead time will increase the number of fatalities; however, there is no evidence showing that a longer lead time decreases the number of fatalities. Overall, there has been no data to back up the claim that lead time strongly impacts fatalities in a tornado event. Each era shows there is no significant difference in the probability of a warned deadly tornado occurring will decrease as time increases. This conclusion provides information to policy makers that will go into decision-making surrounding tornadoes and reducing the number of fatalities.

5. CONCLUSION

The rarity of tornadoes makes the relationship between tornado warnings, lead times and death an extremely complex task. Sutter and Simmons (2009) introduced the first study exploring this relationship where the results were inconclusive. Many people believe increasing lead time will lead to fewer deaths. Our results counter this idea. We come to three main conclusions: the distribution of lead time across multiple decades are almost the same, there has been a substantial increase in issuing shorter lead times after 2011, and there is no statistically significant relationship between lead time and death. While intuitively there is an expectation to see a significance in lead time and death, there is no statistical proof to support this claim. It is not to say that tornado warnings are not significant, instead it questions the importance of longer lead times.

There are limitations to this study, with data about tornado events being difficult to access and the characteristics of an event. The NWS provides detailed information on the event, like location and time of day. Future studies should examine if lead time has a significant impact on an event at a specific location or time of day. Numerous studies describe the vulnerability in the Southeastern region of the US (Strader, Haberlie, and Loitz 2021; Strader and Ashley 2018; Strader et al. 2022; Sutter and Simmons 2010), understanding the lead time could be fundamental in reducing the risk and vulnerability. In addition, it would be important to see if there is a significant difference in the slopes across the eras, in the future probability tests would show if there were a statistical difference in distributions. Additionally, limitations in the size of the data become a challenge when interpretating data. Tornadoes are rare events and having a death occur is rarer, this holds limitations in the sample size of the data. Aggregating the data to five-minute groups can help increase the sample size, but the number of events with lead times greater than 35 minutes is incredibly small.

The results of this study can help policymakers and researchers alike. Main motivators for tornado research have been towards extending the lead time in hopes to reduce deaths; however, when there is no evidence a longer lead time makes a difference. It means that solutions to reducing the number of fatalities is not by increasing lead time and has to do with other factors.

6. ACKNOWLEDGMENTS

This research was inspired from the model created by Sutter and Simmons (2009). This material is based upon work supported by the National Science Foundation under Grant No. AGS-2050267. Thank you to both Dr. Daphne LaDue and Alex Marmo for the support throughout the program.

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