People's thresholds of decision-making against a tornado threat using dynamic probabilistic hazard information

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Abstract

With pervasive use of smartphones for acquiring weather information and efforts of National Oceanic and Atmospheric Administration (NOAA) in developing a tool under the banner of the Forecasting a Continuum of Environmental Threats (FACETs) to disseminate probabilistic information about a tornado event, it is important to investigate people's probabilistic thresholds for taking protective action when presented with dynamic visual information about a tornado threat on a smartphone. We presented dynamic displays of probabilistic information of five hypothetical tornado scenarios to 109 college students on their smartphones and asked them to report at what moment they would take protective action (if any). After conducting Cox proportional hazard regression and Poisson regression, we found that proximity to the tornado, likelihood of the threat occurrence, and being inside vs. outside of the risk area played a significant role in people's decision-making. This study illustrated that regardless of tornado trajectory, as a moving probabilistic swath showing probabilistic forecast of the tornado becomes closer to the information recipients, around 12% of the participants would take protective action prior to being impacted by the probabilistic zone with more than 0% chance of the tornado occurrence. Almost half of them would take protective action before being impacted by the probabilistic zone with more than 20% chance, and around 88% of the participants would take protective action before being impacted by the probabilistic zone with more than 40% chance of the tornado occurrence. Our study corroborates previous relevant research that providing probabilistic hazard information to the public could enhance the warnings' effectiveness.

1. Introduction

Tornadoes are violently rotating windstorms capable of producing mass casualties (Ashley 2007; Fricker et al. 2017). In fact, over the period 1950—2012, tornadoes caused 108 fatalities annually in the United States (Shen and Hwang 2015).

In order to reduce the number of casualties in a hazardous natural disaster, people should be engaged in protective action (Grothman and Reusswig, 2006). According to the Protective Action Decision Model (PADM), different types of weather warnings can elicit different protective action from people (Lindell and Perry, 2012), mainly due to different levels of fear that they pose to the people (Lundgren, 1994). This theory suggests that for minimizing the risk in case of a tornado, people should be provided with effective weather information.

Issuing effective warnings in case of a tornado event has been under development in the last 50 years. In 2007, specific storm-based warnings were implemented by National Weather Service (NWS) to warn only people in the expected path of the tornado (Coleman et al. 2011) and reduce false alarms that could cause social disruption and economic losses (Simmons and Sutter 2011). Using this method, polygons are drawn to show areas at risk. According to NWS guideline, the areas inside the polygon have the same chance of being impacted by the tornado. When a recipient is outside of the polygon, he/she does not need to take protective action. It indicates that the risk in the area outside the polygon can be considered as negligible. The previous research works show that people’s interpretation and protective actions against these warning polygons are not consistent with NWS guideline (e.g. Montz 2012; Donner et al. 2012; Lindell et al. 2016; Jon et al. 2018).

Since the atmosphere is a chaotic system, any weather forecast involves a degree of uncertainty (Lorenz 1963). In order to further reduce the false alarm rate, it has been suggested that the uncertainty information should be communicated to the weather information users (NRC

2006, p. 2). Morss et al. (2008) conducted a nationwide survey to study how people interpret probability of precipitation in hypothetical situations. Their results showed that the majority of people in the U.S. (95%) were aware of existence of this uncertainty in weather forecasts. This result was corroborated by Joslyn et al. (2010) in an experiment to investigate how people in Washington and Oregon, USA could understand uncertainty in the weather information. Some other research works have found that weather-related decision-making is improved by including uncertainty information to the weather forecasts (e.g. Murphy 1998; Joslyn et al. 2007; Joslyn and LeClerc 2012, 2013).

To convey the probabilistic information and enhance accuracy of the weather information, a new method of issuing severe weather information is being prototyped at National Severe Storms Laboratory (NSSL) to transform weather information format from deterministic warnings to probabilistic information with a tool called Probabilistic Hazard Information (PHI).

According to Lazo et al (2009), the majority of people in the USA (72%) seek weather forecasts routinely to stay informed about the weather. With the advent of smartphones, use of mobile weather apps is a pervasive mean for acquiring information about the weather. A survey that was conducted in the USA in 2015 found that these apps are primary sources of acquiring weather information, surpassing television and radio tools (Hickey 2015). Understanding how people react to a visual probabilistic weather information if they receive the dynamic probabilistic information from PHI on their smartphones is an important research gap that needs to be addressed.

To date, there has been little research that has investigated the effect of probabilistic information about the tornado occurrence on people’s decision-making. Some researchers have considered static displays of probabilistic weather information about tornado occurrence in hypothetical scenarios and investigated people’s expected responses to each display (e.g. Ash et al. 2014; Miran et al. 2018b). None of them, however, have investigated people's reaction to the probabilistic weather information in a dynamic setting in which people receive the probabilistic information on their smartphones, so the people's thresholds for taking protective actions can be derived.

a. Research objective

The research goal of the current study is to investigate laypeople's probabilistic thresholds for taking protective action against a probabilistic tornado information presented with dynamic displays. Understanding the effects of proximity to the tornado, the likelihood of being impacted by the threat, and being inside vs. outside of the warning area on people's decision-making can shed more lights on understanding people's thresholds for taking protective action.

2. Background

a. Probabilistic Hazard Information (PHI)

PHI prototype tool, is a software that was developed as part of a broader Forecasting a Continuum of Environmental Threats (FACETs) program (Karsten et al. 2015; Rothfusz et al. 2014). It allows forecasters to produce probabilistic weather forecasts pertaining to multiple weather hazard types including severe thunderstorm, lightning, and tornado (Karsten et al. 2015). With PHI prototype tool, a weather forecaster draws a moving color-coded swath consisting of several overlapping cones with different sizes to show the areas at risk, and then determines its future movement direction. The color of each cone is associated with the probability of the threat occurrence within that cone (see Fig.1). The location of threat at the moment is most likely within the smallest cone and close to its small end, and the biggest cone's large end most likely represents the expected location of the hazard at a certain amount of time into future (e.g. 60

min). Using PHI, the weather information recipients know not only their proximity and the lead time to the threat but also the probability of being impacted by the threat in their locations at each moment. It is expected that the end-users could coordinate their protective action with the probabilistic information (Karsten et al. 2014) and make more appropriate decisions.

b. Literature Review

Effects of using probabilistic information in communication of tornado and other weather-related risks has been investigated in several research studies (Baker 1995; Broad et al. 2007; Morss et al. 2008; Hirschberg et al. 2011; Meyer et al. 2013; Wu et al. 2014; Cox et al. 2013; Ash et al. 2014; Marimo et al. 2015; Morss et al. 2016). No research has investigated people's probabilistic thresholds for decisions-making against a tornado threat. In the current section, we review the papers that we used to design our research.

1) INFLUENCING FACTORS ON THE TORNADO RESPONSE

Many researchers have studied people's responses to tornado warnings from different perspectives (e.g. Senkbeil et al. 2012; Lindell et al. 2013; Durage et al. 2014; Schumann et al. 2017; Casteel et al. 2018). Some research studies have investigated the effect of different factors on people's behavioral responses in course of a tornado event. A few studies have investigated the effect of availability of tornado warnings on the people's protective action and found that the likelihood of taking protective action has a positive correlation with the number of warning sources (e.g. Colman et al. 2011; Luo et al. 2015; Miran et al. 2018a). Some other studies considered the effects of prior experience of tornadoes and sociodemographic characteristics of the warning recipients on their responses (e.g. Silver et al. 2014; Sherman-Morris 2010; Senkbeil et al. 2012; Comstock et al. 2005; Schmidlin et al. 2009). The results of these studies are not consistent. One possible reason for such an inconsistency can be the lack of consistency of the studies' context.

Several research works have studied the effect of proximity to the tornado on people's protective action in a hazardous event and concluded that knowledge of tornado path could play a significant role in people's decision making. Balluz et al. (2000) conducted an empirical research to investigate factors associated with people's response to tornado warnings during tornado events in Arkansas, U.S. in 1997. The authors found that if people knew that their locations were on a tornado path, they were significantly more likely to take shelter. Miran et al. (2018a) investigated factors influencing people's protective action in three tornado events, which occurred in Oklahoma in 2013. They found that the likelihood of taking protective action for people on the tornado path was significantly higher than that of people 5 miles far from the path. They concluded that proximity to the tornado can be a determining factor for people's protective behavior in the course of a tornado event.

2) EFFECT OF VISUAL PROBABILISTIC INFORMATION ON TORNADO RESPONSE

There is a few research studies that have investigated the effect of presenting visual probabilistic information about a tornado occurrence on people's decision-making. In her experiment, Klockow (2013) considered two types of warning displays for a hypothetical tornado event. Each display consisted of a polygon showing the areas at risk along with a symbol identifying the location of the warning recipient on the display relative to the polygon. One set of displays were deterministic, without differentiation of risk of the tornado occurrence. The other set was probabilistic in which the polygons were color-coded in a way that each color conveyed a certain level of risk in the corresponding area. The author found that the uncertainty visualization, the proximity to the tornado, and the existence of the warning boundary had significant effects on the risk decision-making.

Ash et al. (2014) designed two types of deterministic and probabilistic swaths, showing the areas at risk of a hypothetical tornado threat, and designated different locations for the weather information recipients on the display, inside and outside the swath. For the probabilistic swaths, they used two different color schemes, red-scale, different shades of color of red, and multiple-hue, each color depicting the risk of tornado occurrence in the respective area. They showed the static displays to the participants and asked them to report their level of fear and likelihood of taking protective action in different locations for the recipients. The researchers found that the strongest protective action can be expected from the riskiest area, and there is a significant negative relationship between strength of protective action and the risk of the respective area. The results also showed that taking the expected protective action was more likely when the recipient's location was inside the swath rather than outside. Many participants did not consider the areas outside the swath as risk-free zone.

In another study, Miran et al. (2018b) investigated the effect of providing the probabilistic information about a hypothetical tornado occurrence through PHI on people's protective action. They designed static displays of two types of weather information and asked the participants to report their expected protective action in different locations on the displays. There was a set of probabilistic color-coded PHI swaths, denoting the areas that are likely to get impacted by the threat, and a deterministic polygon, showing the areas at risk of the tornado occurrence. Different colors on the swath denoted a probability range of tornado occurrence in the respective area. Two color schemes were chosen for the swaths, namely "five-color" using multiple hues, and "red-scale" using different shades of red. The researchers instructed their participants to assume that both deterministic polygon and probabilistic swaths could inform the recipients about their proximity to the tornado but only swaths could provide the probabilistic information about the tornado occurrence. The authors found that both proximity to the tornado and the likelihood of the threat occurrence had significant effects on people’s protective action. They noted that only when the chance of the tornado occurrence was higher than chance of non-occurrence, providing the probabilistic information incited stronger protective actions from the people. They also found that using both types of deterministic and probabilistic displays, the percentage of people who reported that they would immediately take shelter increased exponentially as their distance to the threat decreased. The authors asserted that this finding is limited to people’s taking shelter behavior right after receiving the weather information and does not reflect people’s probabilistic thresholds for taking protective action in a dynamic setting that people can see forecasted movement of the threat.

3) PROBABILISTIC THRESHOLD FOR WEATHER-RELATED DECISION-MAKING

In a research study, Morss et al. (2010) conducted a nationwide survey in the U.S. and investigated people’s probabilistic thresholds for taking protective action in different weather-related scenarios. Among different questions that they posed, the participants were asked to report at what forecast chance they would take protective action against a potential rain or frost. The results showed that individual differences of participants and the context of the weather information had a significant role in the people’s thresholds. Combining all scenarios, the probabilistic threshold of decision making for 26% of the participants was less than 20%, and the threshold for 36% of the participants was between 20% and 40%. The authors’ analysis showed that as the percentage-chance forecast increases, the likelihood of taking protective action increases and vice versa. The authors find that different people had different thresholds at which they would take protective action, consistent with Joslyn et al. (2010).

Researchers have studied people’s response to probability information on other types of natural hazards. Doyle et al. (2014) conducted a research, based on a volcanic eruption forecast, to investigate how framing of probabilities affects people’s decisions to evacuate a hypothetical town during a volcanic event. The researchers recruited 179 participants and presented them two different scenarios of a volcanic event with different probabilities of occurrence and different lead time. In the first scenario, they stated that there is a "73–83% probability of an eruption occurring within the next 2 weeks", and in the second scenario in which the volcanic event was more likely than scenario 1, they stated that "there is a 45–55% probability of an eruption occurring within the next 3 days". They translated these phrases to their equivalent verbal probability statements and posed all questions and asked the participants to report their evacuation behavior in each scenario. Using the numerical format, 90.4% of the participants in the first scenario and 72.9% in the second scenario chose to evacuate the city in certain time into future. The authors found that the number of participants who chose an evacuation was significantly higher in scenario 1, which had a higher percentage but in a longer period, thus a less likely situation. The authors concluded that participants considered probability of the threat occurrence as the premier evacuation threshold for decision-making and failed to take the lead time into account for making an evacuation decision and understand that the scenario 2 was a more dangerous situation.

In the next section, we will explain the experiment that we designed and conducted to collect the data for addressing our research question. Besides, the data analysis part in the following section clarifies what statistical tools we used to obtain the knowledge from the obtained data.

3. Methodology

We designed an experiment in which a moving swath, consisting of five overlapping cones with different colors, was on a geographical map. The recipient's location was identified on the map and a reference bar, indicating different probabilities of the hypothetical tornado occurrence in different cones of the swath, existed on the bottom left of the map. The likelihood of the threat occurrence in areas outside the swath was zero. A digital clock was embedded on top left of the display showing the time into future (Fig. 1). We call the cones from the outermost level of the swath to the innermost as cones 1 through 5. The color scheme was determined based upon previous relevant research (Ash et al. 2014; Miran et al. 2017; Miran et al. 2018b), and the color information of different cones can be seen in Table 1. In this experiment, we considered five different weather scenarios and presented the dynamic information to the participants.

----- Insert Figure 1 about here ----

----- Insert Table 1 about here -----

In the first scenario, "*straight on-path hit*", the recipient was on the tornado path, a straight line that passes through cones' axis, and the tornado was moving toward the recipient. In this scenario, the direction of the tornado did not change. Figure 2a visualizes the trajectory of the tornado and the moments that the different cones touched the recipient's location. In the second scenario, "*off-path turning on-path hit*", the recipient was not initially on the tornado path but after a while, the tornado's direction changed and the recipient was on the path. Figure 2b shows the moments at which different cones of the PHI touched the recipient's location. The third scenario, "*straight off-path, off-path hit*", showed a situation in which the tornado was moving forward without changing its path. The recipient, however, was located below the path and the lower probability zone of the swath, cone 1, eventually touched the recipient. Figure 2c depicts the moments that the recipient entered cone 1 and left it. In the fourth scenario, "*on-path turning off-path hit*", the recipient was initially on the tornado path but after a while, the tornado changed its direction and hit the recipient through its lower probability zone, cone 1. Figure 2d shows the tornado path and the moments at which the tornado touched the recipient's location and left it. In the fifth scenario, "*on-path turning miss*", the recipient was initially on the tornado path but the tornado eventually changed its direction and missed the recipient (Fig. 2e).

---- Insert Figure 2 about here ----

a. Experimental design

We considered a crossover design in which all participants could see all five scenarios. This design enabled us to investigate the effect of two factors of proximity to the tornado, "proximity", and likelihood of the threat occurrence, "likelihood", on people's decision-making thresholds in a scenario in which a recipient could experience all likelihood levels of the PHI swath. The factor of "likelihood" had six levels as follows: "likelihood 0" corresponds to the area outside of the swath, "likelihood 1" corresponds to cone 1, "likelihood 2" to cone 2, "likelihood 3" to cone 3, "likelihood 4" to cone 4, and "likelihood 5" to cone 5. We were able to investigate the effect of being inside vs. outside of the swath on the decision-making.

b. Procedure

With real speed of a storm on a real geographical map, the total duration of each scenario should have been 2 hours. Due to experimental restrictions, however, we decided to present the dynamic displays in the fast mode and shorten the time of each scenario to 1 minute. The dynamic displays showed a preview of the predicted tornado trajectory in the next 120 minutes. In reality, however, each scenario lasted 1 minute. The dynamic weather information in format of videos was uploaded up on a surveying website, and the five scenarios were presented to the participants in a random fashion on their smart phones.

We instructed the participants to assume that they received the weather information in an ordinary day. There was a clock on the top left of the screen of each video. In the first frame of all five videos, the time was 4:30 p.m. and the weather information recipient was relatively far from the tornado, and eventually the threat moved toward it. The last frame of all five video was 6:30 p.m. After receiving the instruction, the participants were asked to open the URL of the survey on their smartphones, and considering the relative location of the weather information recipient to the swath, write down the time at which they would take any type of protective action, such as calling or trying to locate beloved ones, preparing home for the storm, or immediately taking shelter in a basement, in each scenario. The participants could see each scenario as many time as they wanted, move the videos forward or backward, and then report the time of their expected protective action (if any). At the end of the experiment, the participants were asked to choose one of the following choices that contributed more to make their decisions: the probability of the threat occurrence in their location, their proximity to the tornado, or both of these factors.

In this experiment, we recruited 109 participants with normal vision from some random classes at the engineering school of the University of Akron in Northeast Ohio. The average age of the participants was 20.18 years old (SD=1.49 yrs.) and majority of them were males (67%).

c. Data analysis

Since a recipient in scenario 1 could experience all levels of the "likelihood" factor, we can investigate the effect of the factor of "proximity" and the factor of "likelihood" of being impacted by the threat on the protective action decision using people's protective action choices in scenario 1.

We considered three zones on the outside of the swath and also on each cone associated with the nearness to the beginning of the PHI swath, and named them "proximity 1", "proximity 2", and “proximity 3”. For instance, in scenario 1, the recipient initially was located in “proximity 1” of “likelihood 0”, and as time passed, its location changed to ”proximity 2” of “likelihood 0”, and then “proximity 3” of “likelihood 0”. Afterward, the recipient entered “proximity 1” of “likelihood 1”, “proximity 2”, of “likelihood 2”, and so forth. There is equivalent distances between proximities for a given likelihood area.

We considered thirty fixed time intervals in the course of the scenario, with each interval of 4 minutes, and counted the number of event occurrence, the number of participants who asserted that they would take protective action, in each interval. The resulting count data can serve as dependent variable and the “proximity” and the “likelihood” as the independent variable for a Poisson regression.

Poisson regression is used when the response variable is a count. In this type of regression, we have Poisson random responses $Y_i \sim P(\mu_i)$ and we aim to model them in terms of explanatory variables x_i. Poisson regression is a generalized linear model with a link function of log as follows:

$$Log(\mu_i) = x_i'\beta \quad (1)$$

In this model, increasing x_i by one unit is associated with an increase of the corresponding coefficient in the log of the mean (Winkelmann 2008).

In order to investigate if being eventually inside vs. outside of the PHI swath has a significant effect on the protective action decision, we compared people’s responses to scenario 4 and that of scenario 5. The tornado trajectory in scenario 4 is similar to that of scenario 5, and the only difference is that the PHI swath in scenario 4 touches the recipient with its lower probability zone, but it completely misses the recipient in scenario 5. Given the fact that not all recipients decided to take protective action prior to end of the scenarios at 6:30 p.m. and the underlying distribution is skewed, using Cox proportional hazard regression can be an appropriate tool to address the research objective.

According to Cox proportional hazards regression, the hazard function is expressed as the chance of event occurrence at time t as follows:

$$h(t) = h_0(t)\exp(\beta' x) \quad (2)$$

where t is the time, $h_0(t)$ is the unspecified baseline hazard, and β is the coefficient of the x. In our study, which is a crossover study, we assumed that each participant has a separate underlying hazard. We stratify Cox proportional hazards regression on each subject, therefore the proportional hazards model holds separately for each subject (France et al. 1991). In our Cox regression, the covariate is "scenario" with two levels of "scenario 4" and "scenario 5", and the response is the event time, which is time of taking protective action.

The output of our experiment was the time of taking protective action. We aimed to understand what proportion of the people would take protective action at any time t. To achieve that goal, we plot the underlying Cumulative Distribution Function (CDF) of the event time for each scenario. If the distribution is unknown, the Empirical Cumulative Distribution Function (ECDF), which is a nonparametric unbiased estimator of the underlying Cumulative Density Function (CDF) (van der Vaart 1998), can be used in lieu of the CDF.

4. Results and discussion

Among 109 participants, 97 people responded to the questions of scenario 1 and scenario 2, and for each scenario, they chose a time at which they would take protective action. For scenario 3, 96 people responded to the question but only 51 of them, almost 53%, chose a time for taking the protective action. In scenario 4, 100 participants responded to the question but only 51 of them, reported that they plan to take protective action, and 49% of the participants replied that they would not take any protective action. In scenario 5, among 98 people who responded to the question, only 14 of them reported planning to take protective action.

When participants were asked to choose which of the factors of "likelihood of getting impacted by the threat" or "proximity to the tornado" contributed more to their decision-making, 85% of them responded that they considered a combination of both factors for making a decision.

a. Effect of the proximity and the likelihood on the protective action decisions

We used the data obtained from scenario 1 to build the Poisson regression model. The deviance goodness of fit test confirms that the model fits data appropriately ($\chi^2 = 30.05, \mathrm{df} = 22,\ p = 0.12$). Pearson Chi-Square of the goodness of fit test provided by SPSS statistical package shows that the assumption of equidispersion in the Poisson regression model is satisfied ($\mathrm{Value} = 26.72, \mathrm{df} = 22, \frac{\mathrm{Value}}{\mathrm{df}} = 1.21$). The likelihood ratio test showed that the overall effects of both factors of "likelihood level" and "proximity" were statistically significant (for the likelihood level factor: likelihood ratio $\chi^2 = 23.61$, $\mathrm{df} = 5,\ \mathrm{p} < 0.001$; for the proximityfactor: likelihood ratio $\chi^2 = 6.66$, $\mathrm{df} = 2,\ \mathrm{p} < 0.03$). Table 2 shows the exponentiated values of the coefficients.

----- Insert Table 2 about here----

For the "likelihood" factor, the reference level is "likelihood 5". Table 2 shows that there is a significant difference between the number of event occurrence, which is the number of people reporting to take protective action, in "likelihood 5" and those of "likelihood 1" and "likelihood

2” ($p < 0.001$ for both of them). The number of event occurrence within “likelihood 1” and within “likelihood 2” is 67.62 and 63.76 times greater than that of “likelihood 5”, respectively. There is no significant difference between the number of event occurrence in “likelihood 5” that of “likelihood 0”, “likelihood 3”, and “likelihood 4”.

For the “proximity” factor, the reference level is “proximity 3”. According to Table 2, there is a significant difference between the number of event occurrence in “proximity 2” and “proximity 3”. The number of event occurrence in “proximity 3” is 12.5 (1/0.08) times greater than that of “proximity 2”. The difference between number of event occurrence in “proximity 1” and that of “proximity 3” is not statistically significant.

b. Effect of the being inside vs. outside of the PHI swath on the protective action decisions

For this part, we considered the time of taking protective action (if any) in scenarios 4 and 5 as the dependent variable. The tornado trajectory in these two scenarios were similar but unlike in scenario 5, in scenario 4 the recipient was impacted by the lower probability area of the PHI swath. The underlying distributions were highly skewed, and some participants did not take any protective action by the end of the scenarios. In this situation, Cox proportional hazard regression is a useful tool for addressing the research goal.

After conducting Cox regression with the event time as the independent variable and the “likelihood”, with two levels of “scenario 4” and “scenario 5”, as the covariate, and stratified on the subject, it was revealed that the covariate was statistically significant ($\text{coeff} = 2.75, \text{Z score} = -4.62,\ p < 0.001$). This finding indicates that there is a significant scenario preference within the individuals. The hazard ratio of 2.75 shows that the chance of taking protective action for an individual in scenario 4 is 2.75 times that of the scenario 5. The results of test of the proportional hazard assumption based on weighted residuals (Grambsch and Therneau 1994) showed that the proportional assumption holds ($\chi^2 < 0.01, df = 1, \ p = 0.92$). The fact that our covariate, "likelihood" is categorical indicates that the linearity assumption holds as well.

This finding shows that being eventually inside the PHI swath (as in scenario 4) as compared to remaining outside of the PHI swath (as in scenario 5) significantly increases the likelihood of taking protective action by 2.75 times.

c. Investigating the underlying Cumulative Distribution Function

Since the vast majority of the participants did not expect to take protective action in the fifth scenario, plotting ECDF, Empirical Cumulative Distribution Function, with such a few observations might not be statistically appropriate. Therefore, we only plotted F_n values at different moments for the first four scenarios (Fig. 3). In Figure 3, *x*-axis in each scenario represents different moments in the experiment and the y-axis indicates the value of the empirical CDF, $F_n(t)$.

----- Insert Figure 3 about here----

1) SCENARIO 1, STRAIGHT ON-PATH HIT

It can be seen in Figure 3a that the percentage of people who would take protective action before being touched by the swath, at $t_{1,1}$, increases to around 15% as the swath becomes closer to them. After entering cone 1 at $t_{1,1}$, as the tornado gets closer to the recipient, the percentage of people who would take protective action significantly increases to 53% by $t_{1,2}$, the moment that cone 2 with 20%-40% chance of the tornado occurrence touches the recipient's location ($\chi^2 = 42.14, p \approx 0$).

After entering cone 3, as the tornado becomes closer to the recipient within that cone, the percentage of people who would take protective action increases significantly from 53% to 92% prior to $t_{1,3}$ ($\chi^2 = 199.51, p \approx 0$). Almost 97% of the people would take protective action prior to entering cone 4 at $t_{1,4}$ with 60%– 80% chance of the threat occurrence, and 99% of the people would take protective action prior to entering cone 5 with more than 80% chance of the tornado occurrence.

The test of proportion showed that the percentage of people who would take protective action in cone 1 was not significantly different from that of cone 2 ($\chi^2 = 0.03, p = 0.86$), but the percentage of people who would take protective action within cone 2 is significantly different from that of cone 3 ($\chi^2 = 238.51, p \approx 0$), cones 4 ($\chi^2 = 683.95, p \approx 0$), and cone 5 ($\chi^2 = 1427.90, p \approx 0$).

The fact that different participants would take protective action in different probabilistic cones shows that different people had different probabilistic thresholds for taking protective action during the tornado threat. This difference is likely due to a combination of several factors including difference in people's risk tolerance for the weather-related risk and difference in perception of the weather information (Morss et al. 2010).

2) SCENARIO 2, OFF-PATH TURNING ON-PATH HIT

According to Figure 3b, the percentage of people who would take protective action before $t_{2,1}$, the moment at which the recipient is located on the tornado path, is only 2%, and it increases significantly to 10% prior to being touched by the outer border of the PHI swath at $t_{2,2}$ ($\chi^2 = 7.70, p = 0.01$). Like in scenario 1, as people become closer to the tornado within cone 1, with less than 20% chance of the tornado occurrence, the percentage of people who planned to take protective action increases significantly to 49% , prior to entering the second cone at $t_{2,3}$ with 20%-40% chance of the tornado occurrence ($\chi^2 = 59.67$, $p \approx 0$). Similar to the first scenario, around 40% of the people planned to take protective action when located within cone 1. Inside cone 2, as the people become closer to the tornado, the percentage of people increases significantly to 85%, prior to entering cone 3 at $t_{2,4}$ with 40%– 60% chance of the tornado occurrence ($\chi^2 = 93.20, p \approx 0$). This number reaches 99% prior to entering cone 4 at $t_{2,5}$ with 60%– 80% chance of the threat occurrence.

After conducting nonparametric test of proportion, with null hypothesis that the proportions in different groups are the same, between the percentages of people who would take protective action within cone 1 in scenario 1 and within cone 1 in scenario 2, it was revealed that there was no significant difference between the percentages in these two scenarios ($\chi^2 = 0.02, p = 0.88$). This test also showed that there was no significant difference prior to being touched by the swath, or within other cones as well ($\chi^2 = 1.33, p = 0.25$ for prior to entering the swath; $\chi^2 = 0.20, p = 0.66$ for cone 2; $\chi^2 = 3.15, p = 0.07$ for cone 3; $\chi^2 \approx 0$, $p \approx 1$ for cones 4 and 5).

3) SCENARIO 3, STRAIGHT OFF-PATH, OFF-PATH HIT

Contrary to the first two scenarios, in scenario 3, the participants only entered the areas with less than 20% chance of being impacted by the tornado. In this scenario, the percentage of the people who would take protective action prior to entering cone 1 at $t_{3,1}$ with less than 20% chance of the tornado is not statistically different from that of scenario 1 and scenario 2 ($\chi^2 = 0.04, df = 2$, $p = 0.98$). Around 40% of the people planned to take protective action while they are within cone 1. The test of proportion also showed that there was no significant difference between percentage of people who would take protective action prior to being touched by the swath in scenario 3 and that of scenario 1 and 2 ($\chi^2 = 1.2, df = 2,\ p = 0.54$).

Since the tornado trajectory in scenario 3 is similar to that of scenario 1, significantly higher percentage of participants who would take protective action in scenario 1 compared with scenario 3 ($\chi^2 = 56.70,\ df = 1,\ p \approx 0$) implies that being in areas with different probabilities of getting impacted by the threat significantly affected people's decision-making to take protective action.

4) SCENARIO 4, ON-PATH TURNING OFF-PATH HIT

In scenario 4, the recipient was initially on the tornado path and the tornado changed its direction right before touching the recipient at $t_{4,1}$, and only cone 1 impacted the recipient's location. By moment $t_{4,1}$, around 14% of the people would take protective action, and before leaving cone 1 at $t_{4,2}$, almost 42% of them reported planning to get involved into protective action.

The tests of proportions showed that there was no significant difference between percentage of people who planned to take protective action either prior to being touched by the swath or within cone 1 in scenario 4 and those of previous scenarios ($\chi^2 = 2.03, df = 3,\ p = 0.57$ for prior to entering the swath; $\chi^2 = 3.92, df = 3,\ p = 0.27$ for cone 1). These findings suggest that people's protective action is independent of the swath trajectory or the people's initial location.

5) SCENARIO 5, ON-PATH TURNING MISS

More than 85% of the participants did not expect to take protective action in this scenario, and this is why we do not have an ECDF plot for scenario 5. This finding suggests that people rightly considered being inside the PHI swath a crucial point to take protective action, and again the probability of the threat occurrence had a significant effect on people's decision-making.

5. Summary

In the current research, our objectives were to study people's thresholds for taking protective action after receiving dynamic probabilistic information about a tornado occurrence and investigate how proximity to the tornado and likelihood of the threat occurrence in the recipient's location influence people's decision-making.

After running a Cox proportional hazard regression, it was revealed that both proximity to the tornado and the likelihood of the threat occurrence played a significant role in people's decision-making to take protective action against the tornado. This finding is in line with Ash et al. (2014) that the both mentioned factors have a significant effect on the protective action. The result of the model is corroborated by reports of overwhelming majority of the participants (85%) that both proximity to the tornado and the likelihood of being impacted by the threat affected their decision-making to take protective actions. However, this finding is different from that of Doyle et al. (2014) in which majority of the people considered only the likelihood of the threat occurrence for making evacuation decision in a volcanic event. The inconsistency might be attributed to the difference in the context of the events, and to the effect that the severity of the negative consequence of a hazard can have on people's perception of the risk and their decision-making (Slovic et al. 1979; Lowrance, 1980; Patt and Dessai, 2005).

The result of our study supports findings of Balluz et al. (2000) and Miran et al. (2018a) that being closer to a tornado increases the chance of taking protective action. Klockow (2013) also noted that distance to a hazard biases people's understanding of the risk. Our Cox regression model revealed that compared with the areas in the center of a certain cone, the people tend to take protective action either just prior to entering a cone with higher probability or just after entering it. In Lindell et al. (2016) that people were presented with deterministic warnings, which is a forecast of certainty about occurrence of a tornado in all points inside a warning area, higher level protective actions were observed in the center of the warning area. The authors call this undesirable phenomenon as “centroid effect”. Comparing the result of the current study and that of Lindell et al. (2016) highlights the effect of providing the information about people’s proximity to a tornado and the likelihood of the tornado occurrence in the area on people’s protective action. The fact that there is a significant difference in the people’s protective decisions between “proximity 2” and “proximity 3” implies that people respond to a tornado based on the probabilities more than the proximity. The number of event occurrence in “proximity 3” area, which is closer to an area with higher-level likelihood of being impacted by the threat, is 12.5 times more than that of “proximity 2” area.

Although all participants did not consider the areas outside of the swath as a risk-free zone, result of the Poisson regression showed that being inside the probabilistic PHI swath significantly affected people’s protective action. The fact that around 12% of people on average would take protective action prior to being touched by the swath’s outer boundary shows that they did not consider the boundary as the threshold for taking protective action. This was also observed in the previous research on people’s reaction to deterministic polygons as well, where some people did not consider the outer boundary of the polygon as the threshold for taking protective action (e.g. Lindell et al. 2016; Jon et al. 2018).

Our study showed that people’s expected protective action was independent of the tornado trajectory. If the probabilistic swath touches the recipient’s location, around 12% of people on average would take protective action prior to entering the areas with more than 0% likelihood of being impacted by the threat and almost half of them would take protective action before entering the areas with more than 20% chance of the tornado occurrence. Around 88% of the people would take protective action before entering the areas with more than 40% chance of the threat occurrence. Although these numbers of percentages are different from those of Morss et al. (2010), the numbers confirm their conclusion that the context of the hazard plays a significant role in people’s probabilistic thresholds for taking protective action. Morss et al. (2010) investigated people’s protective action against rain or frost, which is very different from a tornado threat. Our finding is close to that of Miran et al. (2018b). In that study, the percentage of people who would get involved in any kind of protective actions right after receiving the weather information was around 94%. The authors of that study, however, have noted in their paper that their results should not be compared with another research that is based upon people’s dynamic decision-making in which the weather information recipients have time to see the forecasted tornado’s movement in future and then make decisions accordingly.

d. Study limitations

The main limitation of this study is about its sampling. Only college students from a northeast Ohio campus participated in the experiment. In future studies, a bigger sample should be drawn from all groups of people with different sociodemographic characteristics, especially in areas that are more prone to the tornado occurrence, such as Oklahoma and Texas, where more people have experienced the tornadoes before. Besides, the effect of people’s demographic characteristics and tornado experience on people’s thresholds of taking protective action should be studied. In addition, future works need to address other natural hazards, like thunderstorms, to study how the findings of this study might be different (or similar) for other natural threats.

6. Conclusion

This study tried to shed some lights on prediction of people's protective behavior in case of a hypothetical tornado event. Understanding people's behaviors in such disastrous events helps the forecasters to issue the weather information in accordance with people's understanding of it.

The present study confirms findings of previous research (e.g. Morss et al. 2010; Ash et al. 2014) that both proximity to the tornado and the likelihood of the threat occurrence significantly influence the people's decision-making, and it showed that the people's thresholds for taking protective action is independent of the tornado trajectory.

Our result that being inside the risk area, PHI swath, significantly influences people's decision-making shows that most of the people were able to understand the boundary of the risk area, and PHI could help people to make informed decisions.

The participants of this study had different thresholds for taking protective action. This finding is in line with previous research (e.g. Joslyn and Savelli 2010; Morss et al. 2010) that the probabilistic weather information should be provided to the public in a way that they can make decisions on taking protective action based upon their own thresholds rather than defining thresholds by the officials and recommending people to take protective action at certain thresholds. Further research, however, is needed to investigate people's thresholds for taking different types of protective actions. The finding of this research underscores potential contribution of PHI that enables people to make personalized decisions, and in turn, enhances the effectiveness of the weather information in a tornado event.

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Tables

Table 1: Color-information of different cones of PHI

Cone	Probability	RGB	Color
1*	0%-20%	254,204,102	Yellow
2	21%-40%	244, 123, 62	Orange
3	41%-60%	246,141,138	Light red
4	61%-80%	245, 0, 0	Dark red
5**	81%-100%	225, 0,225	Fuchsia

* outermost level of the swath
** innermost level of the swath

Table 2: Parameter Estimates

Parameter	Exp (Coefficient)	Wald χ^2	p-value
Intercept	2.01	2.31	0.13
Likelihood 0	8.21	3.10	0.08
Likelihood 1	67.62	16.51	< 0.001
Likelihood 2	63.76	14.35	< 0.001
Likelihood 3	2.71	0.16	0.68
Likelihood 4	1.95	0.07	0.79
Likelihood 5	1	-	-
Proximity 1	0.04	3.70	0.06
Proximity 2	0.08	6.16	0.01
Proximity 3	1	-	-

Figures

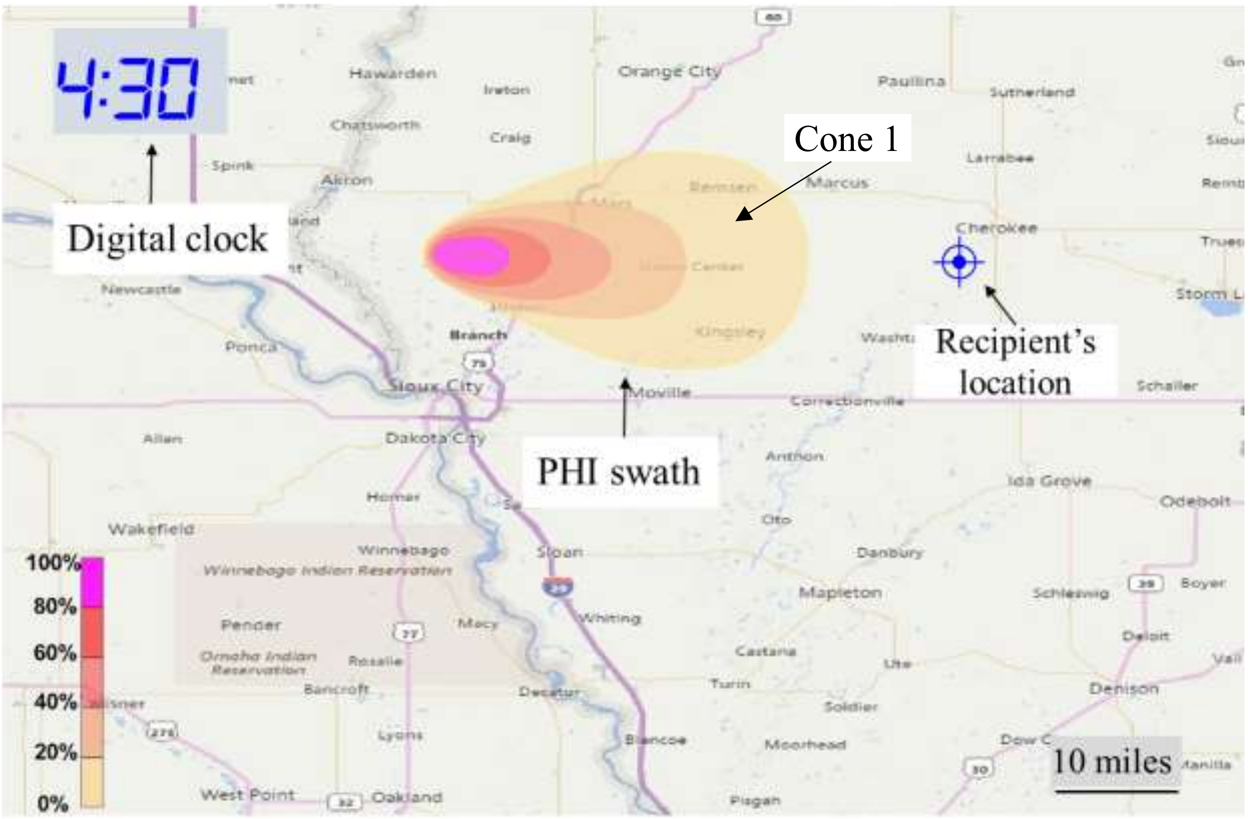
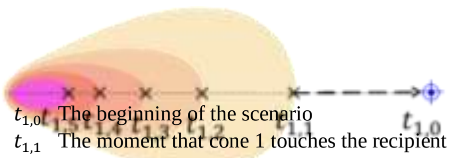
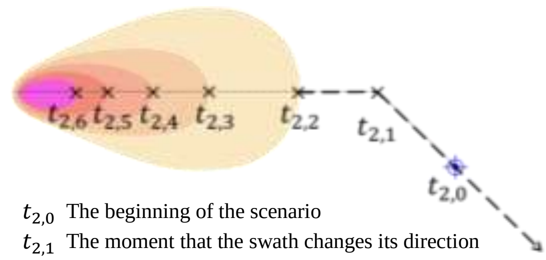


Figure 1 Screen shot from the experiment showing the PHI swath on the map along with the clock and the recipient's location



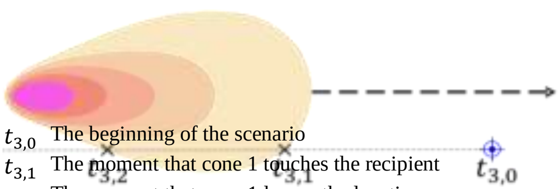
$t_{1,0}$ The beginning of the scenario
$t_{1,1}$ The moment that cone 1 touches the recipient
$t_{1,2}$ The moment that cone 2 touches the recipient
$t_{1,3}$ The moment that cone 3 touches the recipient
$t_{1,4}$ The moment that cone 4 touches the recipient
$t_{1,5}$ The moment that cone 5 touches the recipient

(a)



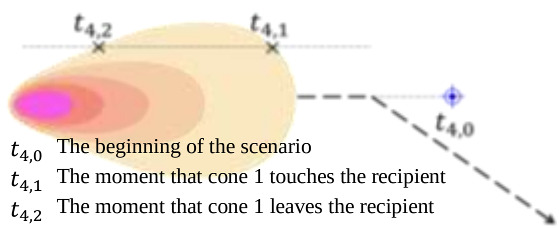
$t_{2,0}$ The beginning of the scenario
$t_{2,1}$ The moment that the swath changes its direction
$t_{2,2}$ The moment that cone 1 touches the recipient
$t_{2,3}$ The moment that cone 2 touches the recipient
$t_{2,4}$ The moment that cone 3 touches the recipient
$t_{2,5}$ The moment that cone 4 touches the recipient
$t_{2,6}$ The moment that cone 5 touches the recipient

(b)



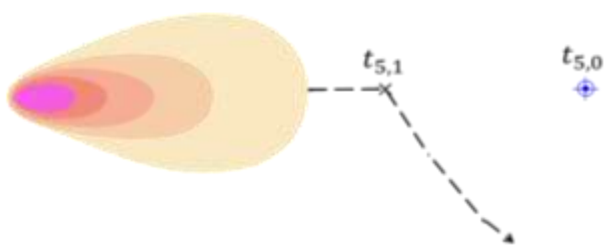
$t_{3,0}$ The beginning of the scenario
$t_{3,1}$ The moment that cone 1 touches the recipient
$t_{3,2}$ The moment that cone 1 leaves the location

(c)



$t_{4,0}$ The beginning of the scenario
$t_{4,1}$ The moment that cone 1 touches the recipient
$t_{4,2}$ The moment that cone 1 leaves the recipient

(d)



$t_{5,0}$ The beginning of the scenario
$t_{5,1}$ The moment that the PHI's direction changes

(e)

— — The tornado path
.... The location of the recipient at different moments relative to the swath

Figure 2: Tornado path and the location of the weather information recipient at different moments relative to the swath

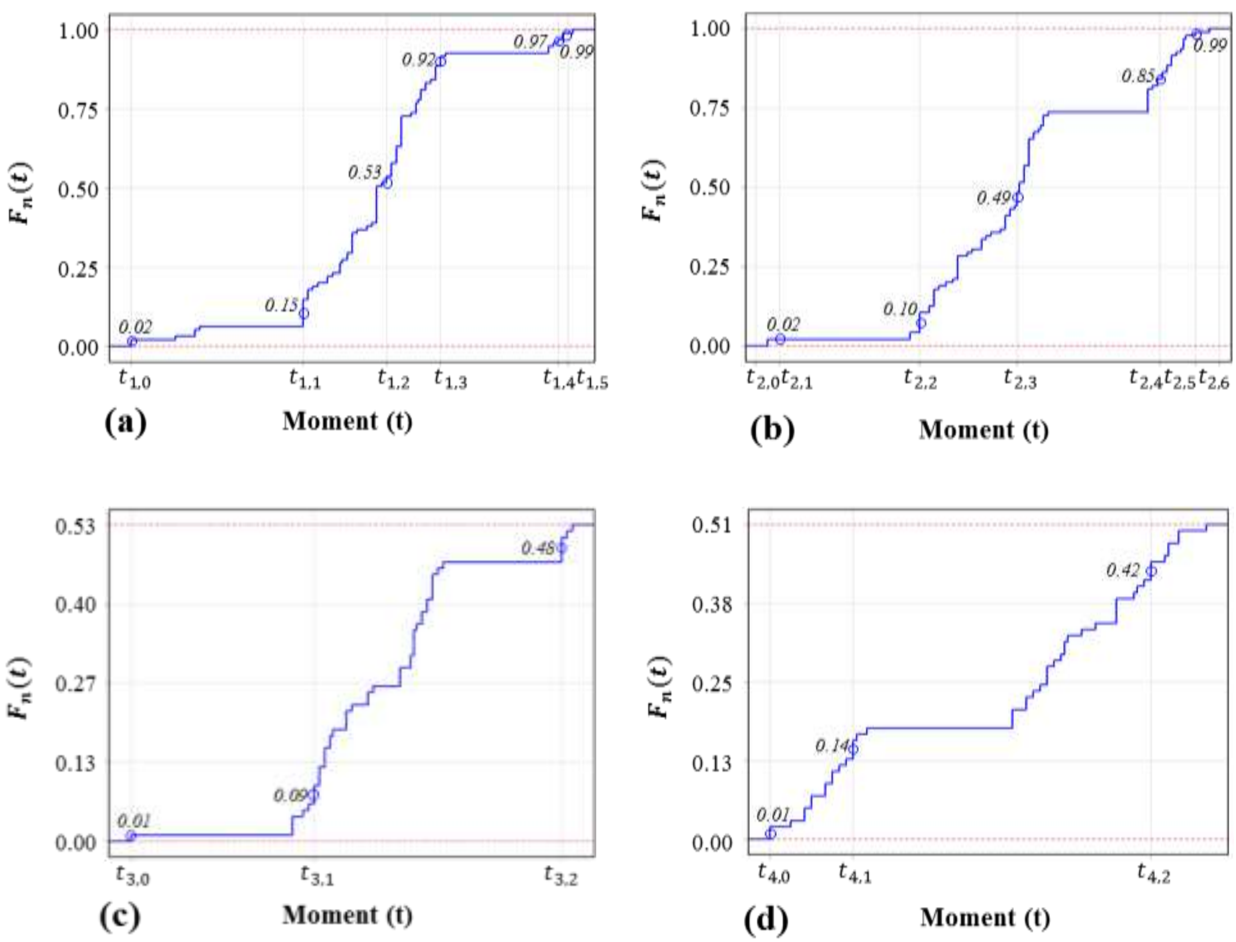


Figure 3: ECDF of different scenarios. **a** Scenario 1. **b** Scenario 2. **c** Scenario 3. **d** Scenario 4