




The effect of providing probabilistic information about a tornado threat on people's protective actions

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Abstract

National Weather Service issues deterministic warnings in a tornado event. An alternative system is being researched at National Severe Storms Laboratory to issue Probabilistic Hazard Information (PHI). This study investigated how providing the uncertainty information about the tornado occurrence through PHI changes people's protective actions. In an experiment, visual displays of the probabilistic information and deterministic warnings were presented to fifty participants to report their expected protective actions in different scenarios. It was found that the percentage of people who expected to immediately take shelter right after receiving the weather information increased exponentially as their proximity to the threat decreased. When there was more chance that the information about occurrence of a particular tornado was false rather than true, in scenarios that the likelihood of the threat occurrence was less than 50%, providing it through PHI lowered the percentage of people who immediately took shelter. The ordinal logistic regression models showed that the probability of taking protective actions significantly changes by providing the uncertainty information when people have less than 20 min lead time before getting impacted by the threat. When the lead time is less than 10 min, the probability of immediately taking shelter increases to 94 from 71%, and when the lead time is more than 10 but less than 20 min, that probability increases from 53 to 70%, if they are provided with the probabilistic information. Presenting the likelihood of any tornado formation in the area did not have significant effect on the people's protective actions.

Keywords Probabilistic weather information · Weather uncertainty · Warnings · Warning polygons · Ordinal logistic regression

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1 Introduction

Tornadoes are among the most devastating natural disasters that put many Americans' lives and properties at risk, especially in some states, namely Texas, Oklahoma, Kansas, and Nebraska (Tornado Risks and Hazards in the Midwest United States 2007). In order to reduce fatalities due to this severe threat, it is crucial that people in the affected areas take appropriate protective actions (Mileti 1999). To achieve that goal, the public should be provided with accurate and trustworthy weather information that can elicit appropriate protective actions.

National Weather Service (NWS) has used different methods of issuing tornado warnings in the past 50 years, and many improvements have been made to enhance the effectiveness of the warnings (Coleman et al. 2011). In 2007, NWS adopted a storm-based method for issuing severe weather warnings using a tool called WarnGen. Although replacing the previously used county-based warnings by the storm-based ones improved effectiveness of the warnings (e.g., Sutter and Erickson 2010), still some problems exist with the current warnings (e.g., Lindell et al. 2016). To improve these warnings, scientists at National Severe Storm Laboratory (NSSL) are prototyping a new system to issue Probabilistic Hazard Information (PHI) in case of tornado events (Rothfus et al. 2014). It needs to be investigated how public's protective actions change if PHI is used in lieu of WarnGen's warnings.

In the next section, the challenges with the WarnGen's warnings are discussed and the idea of Probabilistic Hazard Information (PHI) is introduced. After that, the research objectives are presented. The first part of Sect. 3 describes an experiment in which participants saw graphical displays of the WarnGen's warnings and the probabilistic hazard information and reported their protective actions in different scenarios. The second part of Sect. 3 explains the data analysis method that was used to achieve the research goals. In Sect. 4, the results of the experiment are presented. Sections 5 and 6 discuss and conclude the results and explain the limitation of this study.

2 Background

Using WarnGen tool, forecasters draw polygons to encompass the areas at tornado risk. These storm-based warnings are binary and deterministic, meaning that people in all areas inside the polygon are under the same warning, without any difference in the likelihood of the threat occurrence. If people are inside the polygon, NWS expects them to take protective actions, and if they are outside the polygon, they are expected to ignore the warning (NWS 2007).

Ideally, a warning for a severe weather should be issued only if the threat will occur for certain. According to Lorenz (1963), however, the atmosphere should be viewed as a chaotic system, and weather forecasts must be considered as probabilistic. Therefore, any binary warning with two modes of danger or no-danger cannot be entirely accurate.

Many research studies have found that binary warnings, which lead to false alarms, can cause tremendous adverse effects for the public (Simmons and Sutter 2009). False alarms can result in economic costs, such as business closure, disruption of transportation systems, and unnecessary evacuation of people (Durage et al. 2015).

In addition to the above-mentioned problems with the binary deterministic polygons (warnings), it has been asserted that the public's understanding about deterministic polygons is at odds with the expectations of NWS (e.g., Montz 2012; Lindell et al. 2016).

Unlike the NWS's expectation, Sherman-Morris and Brown (2012), Ash et al. (2014), Lindell et al. (2016), Jon et al. (2018a, b) found a “centroid effect” meaning that people believed that polygons' centroid areas are more likely to get impacted by the threat and they expected to take stronger protective actions in those areas than the locations near the edges within the polygon.

The other problem with people's understanding of the deterministic polygons is that people cannot get the idea that the areas outside the polygon are almost risk free, and if the warning recipients are located there, they can ignore the threat. In another words, it is expected that there would be a significant difference in people's perceived risk when they are located just outside the edge of a polygon and when they are just inside its edge. In their study to investigate how people interpret the deterministic polygon, in addition to finding a centroid effect, Lindell et al. (2016) also found that there was a small difference between the people's judgment of the likelihood of the threat occurrence just inside edge of the polygon and that of just outside the edge.

Some researchers tried to revise the plain display of deterministic polygon to investigate how people's perception of the risk and their responses to the warnings change. They considered adding the radar image to the graphical displays of the warnings and changing the plain deterministic polygons to multiple-layer and color-coded polygons in which each color denoted a different level of likelihood of the threat occurrence in the respective level (region on the polygon).

Klockow (2013) conducted an experimental study using both deterministic and color-coded probabilistic polygons. Different colors of the probabilistic polygons denoted different levels of risk. In that research, different color-coding types, namely red-scale, which had single hue of red with different intensities for each level, multiple-hue, and diverging schemes, which centered on a neutral hue and had different intensities of two hues on the left and right to denote different levels of risk, were recruited. That study did not find any significant difference in people's interpretation of the likelihood of the threat occurrence not only between the deterministic polygons and color-coded probabilistic polygons but also among different color schemes of the probabilistic polygons.

In another study, Ash et al. (2014) changed shape of the polygon to a swath and examined the similar idea. In their experiment, they considered a deterministic swath and two probabilistic swaths with two different color-coding types of red-scale and multiple-hue. They found that the centroid effect still existed in the deterministic swaths but lessened in the probabilistic swaths. The researchers asserted that the probabilistic designs assisted the warnings recipients to discern their proximity to the threat, and this understanding had an effect on their responses to the tornado. The authors concluded that both design types could not inform people to consider the outer boundary of swaths as a threshold of the elevated level of risk.

Jon et al. (2018a) investigated effect of including radar images of storm cell to the deterministic polygon displays. Although the centroid effect was not completely eliminated by adding the radar images, the authors found that the radar images had an effect on the people's judgment of the risk in the locations inside the polygon. The participants of the research study found the likelihood of the tornado occurrence in the locations inside the polygon and close to the storm cell as high as the locations at polygon's centroid.

Jon et al. (2018b) also considered a red-scale polygon and a deterministic polygon in the presence and absence of the radar images and examined people's interpretation of the threat and their responses to them. The results of that study supported those of Klockow (2013) and Ash et al. (2014) that the color-coded probabilistic polygons did not fix the centroid effect problem.

2.1 Probabilistic Hazard Information (PHI)

It has been suggested that including likelihood of the threat occurrence in weather warnings can improve effectiveness of the warnings and people's decision-making process (Papastavrou and Lehto 1996). After conducting a survey in the USA, Morss et al. (2008) noted that majority of the participants had certain level of awareness about uncertainty in the weather information, and public can be provided with the uncertainty in the weather information.

Two types of uncertainty information about the tornado occurrence can be conveyed to the weather information recipients. The first one is the probability of impact of a specific tornado threat, and the second one is the background probability of formation of any tornadoes in the general area. In an atmosphere that is favorable in producing tornadoes, the background probability is enhanced.

In order to provide the public with clear hazardous weather information and fix the problems with polygon warnings, National Severe Storm Laboratory (NSSL) proposed a modern and flexible severe weather warning framework, called Forecasting a Continuum of Environmental Threats (FACETs). In particular, researchers and meteorologists at NSSL are investigating the idea of issuing Probabilistic Hazard Information (PHI) as the core idea to realize the FACETs (Rothfus et al. 2014).

With PHI, a multiple-level swath, which is color-coded (Karstens et al. 2015; Miran et al. 2016, 2017), is used to show likelihood of the area being impacted by a particular threat. Each color on the swath is associated with the likelihood of the threat occurrence within that level (See Fig. 1). Unlike the probabilistic warnings in Klockow (2013) and Jon et al. (2018b), PHI is enabled to show the threat's location at the moment at the beginning of the swath, and based on the past movement velocity, the threat is projected to move to the end of the swath in a specified duration, for example 50 min.

It can be expected that the knowledge of proximity to the tornado can contribute to eliminate the centroid effect. Jon et al. (2018b) concluded that the centroid effect can be mitigated if people know their proximity to the location of the "tornadic storm cell" outside the polygon. This finding also can be inferred from other research works as well. Wu et al. (2014) in a study investigated the effect of hurricane track on the judged likelihood of the threat occurrence and concluded that as the expected location of the threat gets closer, the perceived risk increases and vice versa. As some research showed that the perceived risk and protective actions are highly correlated (e.g., Ash et al. 2014; Miran et al. 2017; Lindell et al. 2016), the conclusion of the Wu et al. (2014) can be applied to the relationship between proximity to the tornado and the protective actions.

Using the PHI graphical displays and based on the relative location of a weather information recipient to the location of the threat, people are not only aware of the likelihood of the threat occurrence in their locations, but also know the lead time and their proximities to the threat. Therefore, we can expect that PHI could at least remedy centroid effect, which was a problem with the polygon warnings.

2.2 Research objectives

Previous studies concluded that conventional deterministic warnings could not eliminate the undesirable centroid effect (e.g., Klockow 2013; Jon et al. 2018b). From the other hand, Ash et al. (2014) asserted that color-coded probabilistic warnings assisted the people to discern their proximity to the tornado, and these warnings diminished of the centroid

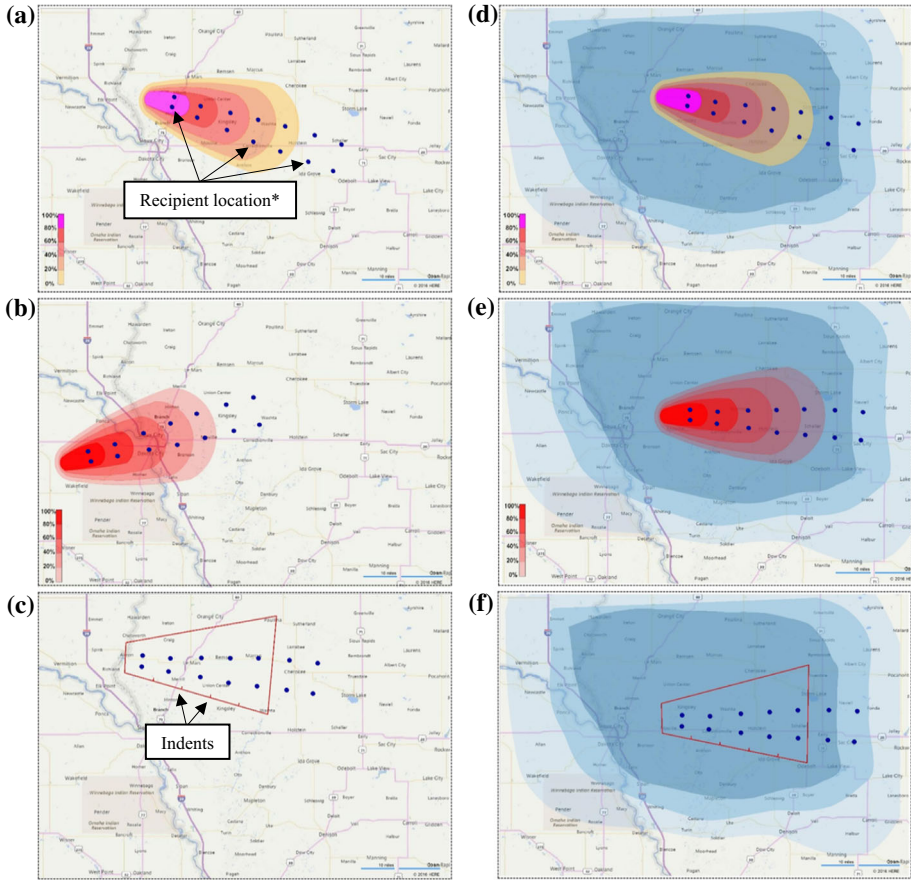


Fig. 1 The six different displays in the experiment. *Location of recipients on the seven threat proximity levels. In each scenario, the participants were presented with one of the six displays and with only one blue dot on it, and then asked to report their protective actions in that scenario

effect. The existing research gap that Ash et al. (2014) did not address is to know whether lessening the centroid effect in the probabilistic designs can be attributed to the effect of understanding the proximity to the tornado or it is the effect of color-coding on people’s decision-making. Therefore, the influence of providing information about the proximity to the tornado on the people’s protective actions, and also the effect of providing the probabilistic information per se on those actions, need to be investigated.

The objective of the current study in general is twofold. First, we want to model people’s taking shelter behavior as a function of their proximity to the center of the threat. Second, we want to understand how providing the uncertainty information about both a particular tornado occurrence through color-coded PHI swaths and the formation of any tornado in the area through color-coded background, in the presence of clear information about the proximity to the threat, changes people’s protective actions in a tornado event, as compared to deterministic polygons and the absence of the color-coded background.

3 Methodology and data

Fifty people, all US citizens with normal visions, were recruited from some public premises in Akron, Ohio. In a quiet experiment room, after receiving instructions, they were presented with displays of PHI swaths and deterministic polygons on a 15-inch laptop screen and asked to answer which of the following protective actions they would take in each scenario: no protective action, seeking out more weather information, or taking shelter immediately.

3.1 The experiment setup

Based on previous research studies (Ash et al. 2014; Miran et al. 2017), a color-coded swath consisting of five overlapping cones with different colors was considered. The color of each cone denoted likelihood of the threat occurrence in the associated area. Starting from the beginning of the swath, we call them cones 1 through 5.

The location of the threat at the moment is at the beginning of the swath, and the areas near to it are more likely to get impacted by the threat. Two color-coding types for the cones, namely “five-color” and “red-scale,” were chosen for this experiment. These designs can be seen in Fig. 1a, b. The color information of the cones and the probability of the threat occurrence at each cone can be seen in Table 1.

It was mentioned earlier that PHI swaths can convey not only the likelihood of the threat occurrence but also information about the recipients’ location and their proximity to the threat. For the experimental purpose, starting from the beginning of the swath to the end of it, we considered five proximity levels on the swath and called them threat proximity levels 1 through 5, respectively. By threat proximity level X, we mean the area that is confined between a tangent line at distal edges of cone X-1 perpendicular to the swath’s centerline and base of cone X. This idea enabled us to make sure that the distance between a recipient within threat proximity level X and the tornado was more than that of a recipient within threat proximity level (X-1). It is obvious that threat proximity level 1 consists of all area of cone 1.

To be able to compare the effect of uncertainty information on the protective actions, we assumed five proximity levels on the deterministic polygon as well. These levels were

Table 1 Detailed information about the color-coded designs

Cone	Probability (%)	Design type					
		Five-color			Red-scale		
		Color	RGB	Transparency	Color	RGB	Transparency
1*	81–100	Fuchsia	225, 0, 225	10	Red	255,0,0	10
2	61–80	Dark red	245, 0, 0	40	Red	255,0,0	30
3	41–60	Light red	246, 141, 138	50	Red	255,0,0	50
4	21–40	Orange	244, 123, 62	50	Red	255,0,0	65
5**	0–20	Yellow	254, 204, 102	45	Red	255,0,0	80

*Innermost level of the swath

**Outermost level of the swath

identified by four indents (Fig. 1c). To be consistent with the PHI swaths, starting from the narrow edge of the polygon to its wide edge, these proximity levels are called as proximity levels 1 through 5.

In half of the scenarios, the background probability of any tornado formation in the area was presented as three shades of blue background under the polygons or the swaths. The darkest shade (RGB: 129, 174, 205) is referred to as threat proximity level B1 and is associated with the highest background probability, and the lightest one (RGB: 215, 228, 236) is referred to as threat proximity level B3 and is associated with the lowest background probability. The middle level (RGB: 174, 208, 226) is referred to as threat proximity level B2. Figure 1d–f shows different designs with three levels of the blue background.

Two threat proximity levels were considered outside of swaths and polygons, after threat proximity level 5. These levels are called threat proximity levels B1 and B2. In displays with tornado formation probability background (“WB”), these threat proximity levels were located in areas having the two darkest shades of blue, and these levels are plain in displays without tornado formation probability background (“WOB”).

We randomly located each of the three design types, “five-color,” “red-scale,” and “polygon,” on a geographical map and created different displays. Considering three design types and two options of WB and WOB displays, totally we had six different displays in our experiment. These six displays can be seen in Fig. 1.

Two locations for weather information recipients were selected within seven proximity levels, namely threat proximity levels 1 through 5, threat proximity level B1, and threat proximity level B2. We had no location for the recipients within proximity level B3. The location of a recipient was indicated with a blue dot on the display. Considering seven threat proximity levels, two recipients’ locations, and two types of background, “WOB” and “WB,” we had 28 different scenarios for each design type. The participants were presented each of these 84 different scenarios in a random fashion, and were asked to report their expected protective actions in each scenario. Figure 1 illustrates how locations of these blue dots on the displays looked like. Each time, participants were presented with one of the six displays including only one blue dot on it.

Considering our assumptions, both PHI swaths and polygons could provide information about the proximity to the threat, but only PHI swaths could convey additional probabilistic information about the threat occurrence. Therefore, effect of probabilistic information per se through color-coding can be understood by investigating any difference between the people’s protective actions using the swaths and using the deterministic polygons.

3.1.1 Instructions for the participants

Regarding the displays with PHI, the participants were instructed that the location of the threat at the moment is at the beginning of the swath, and it moves forward with a constant speed, and it takes 50 min to reach the end of the swath. They were told that the probability of the threat occurrence in each color-coded area can be seen in a reference bar in the bottom left of the displays. Regarding the displays with polygons, the participants were instructed to assume that polygons could inform the warning recipients about their proximity to the tornado and the lead time. They were told to assume that the location of the threat at the moment is within threat proximity level 1, close to the narrow edge and inside the polygon, and it takes 50 min to reach threat proximity level 5, and it moves forward with a constant speed.

3.1.2 Dependent and independent variables

There were three independent variables in this study, namely “design,” “background,” and “threat proximity level.” Two different types of PHI swath, “five-color” and “red-scale,” along with the deterministic “polygon” were three levels of “design” independent variable. The presence and absence of the blue background were two levels of the “background”, and “threat proximity level” independent variable had seven levels. All these explanatory variables were within-subject factors.

The dependent variable was people’s expected protective actions, which had three levels of “no action,” “seeking out more information,” and “immediately taking shelter.”

3.2 Data analysis

To investigate how providing the uncertainty information through color-coding changes the probability of taking protective actions, ordinal logistic regression models were used. In our experiment, X_1 = “background,” X_2 = “design” and X_3 = “threat proximity level”. Y had three levels, a = “no protective action,” b = “seeking out more information,” and c = “immediately taking shelter,” with associated probabilities of $P_a(x)$, $P_b(x)$, $P_c(x)$. Our interest was to investigate the effect of the independent variables on the probability of taking each level of the protective actions.

For situations in which the response variable has more than two categories, a logistic regression model can be viewed as an extension of an ordinary logistic regression with dichotomous response variable. The ordinal logistic regression dichotomizes the outcome while still using the order of the response category through partitioning the data into successive dichotomous groups that form cumulative splits to the data. In other words, when the response has m ordinal levels, the logit model in an ordinary logistic regression changes to cumulative logit models for $m - 1$ scenarios. This method is called “Proportional Odds” (Agresti 1996; O’Connell 2006). In our study, we can dichotomize the response variable and consider two ordinary logistic regression models. The dichotomous response variable for the first model is {if the response is “a” = 0, if response is either “b” or “c” = 1}, and the dichotomous response variable for the second logistic regression is {if the response is either “a” or “b” = 0, if the response is “c” = 1}. To find a parsimonious model that simultaneously considers effects of the explanatory variables in both ordinary logistic regressions, it must be assumed that the explanatory variables have the same effect on the odds of the response variables in each of the two models. This assumption is called “assumption of proportional” (Agresti 1996), which can be checked by a “score test.” The score test is very conservative and it is acceptable to consider $\alpha = 0.01$ (O’Connell 2006).

We already know that the effect of explanatory variable “threat proximity level” cannot be the same on the response variables of both ordinary logistic regression models. The responses at closer proximity levels to the tornado probably will be higher and vice versa (Miran et al. 2017). If the score test confirms our prior knowledge, to be able to study the cumulative probability of taking protective actions at each proximity level for each design type, an ordinal logistic regression should be run for each proximity level of each design type.

4 Results

Table 2 shows the percentage of people who expected to take each level of protective actions at different proximity levels of each design type right after receiving the weather information. In all three design types, when the recipients were in closer locations to the

Table 2 Percentage of people who expected to take different levels of protective actions in different scenarios

Threat proximity level	Protective action	Design type		
		Five-color	Red-scale	Polygon
1 (LT < 10 min)	No action	1.83	1.22	4.27
	Seeking out more info.	4.27	1.83	18.90
	Taking shelter immediately	93.90	96.95	76.83
2 (10 < LT < 20 min)	No action	3.05	1.83	3.05
	Seeking out more info.	26.22	25.00	43.29
	Taking shelter immediately	70.73	73.17	53.66
3 (20 < LT < 30 min)	No action	3.61	3.22	4.27
	Seeking out more info.	66.51	66.30	65.24
	Taking shelter immediately	29.88	30.48	30.49
4 (30 < LT < 40 min)	No action	4.27	3.05	5.49
	Seeking out more info.	85.98	83.54	72.56
	Taking shelter immediately	9.76	13.41	21.95
5 (40 < LT < 50 min)	No action	17.07	15.24	16.46
	Seeking out more info.	76.83	75.00	65.24
	Taking shelter immediately	6.10	9.76	18.29
B1 (50 < LT < 60 min)	No action	54.88	50.00	43.90
	Seeking out more info.	41.46	46.34	48.78
	Taking shelter immediately	3.66	3.66	7.32
B2 (60 < LT < 70 min)	No action	72.27	71.95	67.07
	Seeking out more info.	26.29	26.22	31.10
	Taking shelter immediately	1.44	1.83	1.83

LT lead time

threat, the percentage of times that they preferred to chose “immediately taking shelter” option increased, and the percentage of times that they did picked “not protective action” decreased. Regarding the second level of protective actions, seeking out more weather information, the percentage of times that participants chose these actions increased until threat proximity level 4 and then decreased.

4.1 A model for the effect of the information about proximity to the threat

We found that in both cases of using polygon and PHI’s swath, the percentage of people who expected to immediately take shelter right after receiving the visual information increased exponentially as they were presented with scenarios with closer recipient’s location to the threat. Figure 2 depicts the fitted exponential curve for the PHI’s data, and Fig. 3 depicts it for the polygon’s data. The R-square for the fitted curve of PHI data is 98.46% and for the fitted curve of polygon data is 92.78%, meaning that the exponential curve can be a good fit for the percentage of people who immediately took protective actions for both PHI’s data and polygon’s data. The equations for the PHI’s fitted curve and the polygon’s fitted curve are as follows, respectively:

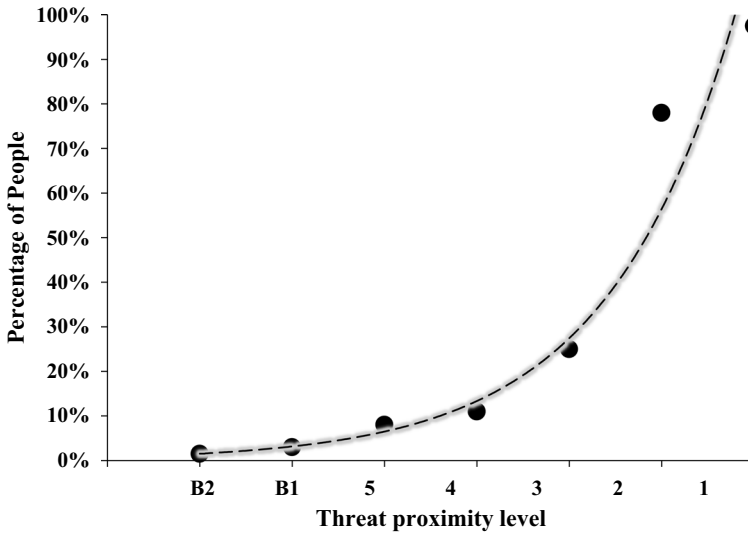


Fig. 2 Percentage of people who expected to immediately take shelter at each proximity level using PHI

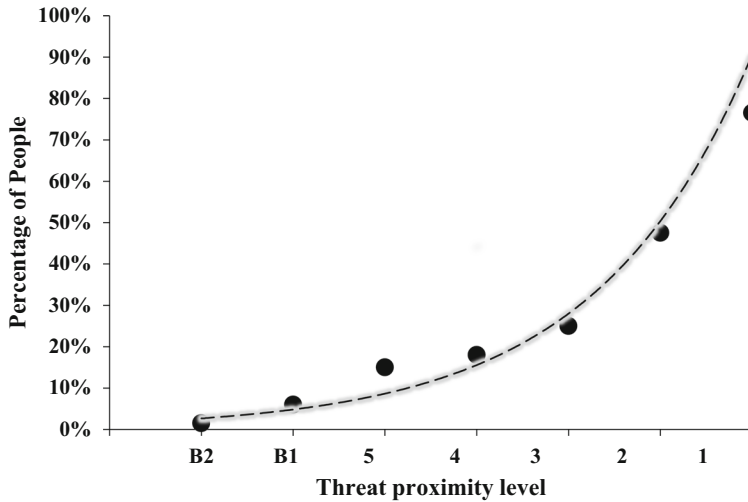


Fig. 3 Percentage of people who expected to immediately take shelter at each proximity level using deterministic polygon

$$Y = 0.007e^{0.720x} \tag{1}$$

$$Y = 0.014e^{0.587x} \tag{2}$$

In the next step, we considered percentage of people who reported that they would immediately take shelter as a random variable (considering the order of the values with respect to the recipient’s proximity level) and did a formal statistical test to ensure that an

exponential distribution is an appropriate fit for the values of percentages with respect to the proximity to the tornado in both PHI and polygon cases. The null hypothesis for these goodness-of-fit tests, which were conducted using R Statistical Package, is that the data follow an exponential distribution and the alternative hypothesis is that the data do not follow an exponential distribution.

The goodness-of-fit tests showed that the p value for the test with PHI's data is $0.20 > \alpha = 0.05$, meaning that we cannot reject the null hypothesis and conclude that the distribution is not exponential. The maximum likelihood estimate of the distribution's parameter is 0.32. The p value for the test with polygon's data is $0.98 > \alpha = 0.05$, and the same conclusion can be made here as well. The maximum likelihood estimate in this case is 0.27.

4.2 Ordinal regression models for analysis of the effect of the probabilistic information

Initially, an ordinal regression model using all three independent variables, “background,” “design,” and “threat proximity level,” was run. As mentioned in the data analysis section, alpha of 0.01 should be chosen for the score test. The results, however, showed $p < 0.00$ (Chi-sq = 389.39, $df = 7$). Therefore, as expected, the proportional assumption is not met and we cannot use the ordinal logistic regression with these three independent variables.

To tackle this issue, we run an ordinal regression model, with “design” and “background” as the explanatory variables, for each of seven proximity levels.

According to Table 3, results of tests for the overall model fit, and only fitted models 1 and 2 are statistically significant. It means that only these two models improve prediction of the probability of taking protective actions at the respective proximity levels over the models that include only intercepts. The p values of the other models are greater than $\alpha = 0.05$. Hence, it cannot be claimed that the other five models improve the predictions over the models that only include intercepts.

Results of the score tests for seven ordinal regression models showed that the proportional assumption is upheld for all seven models (p value greater than 0.2 for all seven models). It means that the effect of “design” and “background” are not statistically different across the two cumulative splits of the data for all models. In other words, for each model, if two separate ordinary logistic models are fit, the slopes for “background” and “design” factors are similar. Thus, for each of these models, one parsimonious model can be used to estimate the odds ratios for both independent variables. In these models,

Table 3 Model fitting information

Model	Chi-sq.	df	Sig.
1	42.22	3	0.00*
2	15.88	3	0.00*
3	2.19	3	0.53
4	6.50	3	0.09
5	4.77	3	0.19
B1	1.87	3	0.60
B2	1.15	3	0.76

*Statistically significant at $p < 0.05$

Table 4 Results of the two ordinal regression models in detail

			Coeff.	Std. Err.	Wald	df	Sig.	95% conf. Int.	
Ordinal regression model for threat proximity level 1	Design	$\beta_{10}\dagger$	-3.22	0.37	77.79	1	0.00*	-3.93	-2.50
		$\beta_{20}\S$	-1.56	0.26	35.34	1	0.00*	-2.07	-1.04
		Five-Color	1.53	0.38	16.62	1	0.00*	0.79	2.27
	Background	Red-Scale	2.27	0.49	21.28	1	0.00*	1.30	3.23
		Polygon	0	-	-	0	-	-	-
		WB	-0.64	0.31	4.20	1	0.06	-1.25	-0.03
		WOB	0	-	-	0	-	-	-
Ordinal regression model for threat proximity level 2	Design	β_{10}	-3.22	0.32	103.49	1	0.00*	-3.84	-2.6
		β_{20}	-0.22	0.18	18.48	1	0.02*	-1.24	-0.79
		Five-Color	0.70	0.23	9.35	1	0.00*	0.25	1.15
	Background	Red-Scale	0.84	0.23	12.85	1	0.00*	0.38	1.30
		Polygon	0	-	0	0	-	-	-
		WB	-0.11	0.19	0.36	1	0.55	-0.49	0.26
		WOB	0	-	-	0	-	-	-

* Statistically significant at $p < 0.05$
 † Intercept of the first ordinary logistic regression
 § Intercept of the second ordinary logistic regression

“polygon” is considered as the reference level of the independent variable of “design,” and “WOB” for that of “background.”

Goodness-of-fit tests were conducted for the seven models. The p values for these tests were greater than $\alpha = 0.05$, meaning that all models were adequately fit to the data, and the current models are good enough. Therefore, there is no need to change the models.

Since the research aim was to understand whether providing the uncertainty information about the threat occurrence significantly changes probability of people’s taking protective actions, and only models 1 and 2, models for proximity levels 1 and 2, were significant, we just considered these two models for further analysis.

Table 4 shows results of the two ordinal regression models in detail. In both models, the p values for the two levels of “design” are less than $\alpha = 0.05$, and it can be concluded that there is a significant relationship between “design” and the level of the protective actions. In another words, when the recipient’s location is within either proximity level 1 or 2, the probability of taking a stronger protective actions increases, if PHI is used instead of the deterministic polygon.

According to that table, p value for “background” in none of the models is greater than $\alpha = 0.05$. It means that the effect of providing formation probability of any tornado in the area, “background,” on the protective actions is not significant.

We used coefficients of the regression in Table 4 and calculated the predicted probabilities of taking different levels of protective actions. The similarity of the predicted results in Table 5 to the actual results in Table 2 shows that our predictive models provide a good fit to the data.

5 Discussion

Increasing the probability of people’s taking shelter at the right time in case of a tornado occurrence can improve the public safety. Probabilistic hazard information (PHI) is an idea that is being prototyped at NSSL to communicate clear and understandable weather

Table 5 The predicted probabilities of taking different levels of protective actions for different design types

Protective actions	The probability (%)					
	Threat proximity level 1			Threat proximity level 2		
	Five-color	Red-scale	Polygon	Five-color	Red-scale	Polygon
Not protective action	1.57	0.69	6.54	2.15	1.86	4.31
Seeking out more info....	6.35	3.25	21.96	28.40	26.84	47.08
Taking shelter immediately	92.08	96.06	71.50	69.45	71.30	52.91

information to the public. Using PHI, the weather information recipients not only could be aware of the likelihood the threat occurrence at their locations but also understand their proximity to the center of a tornado.

In this research, we intended to model people's taking shelter behavior right after receiving the weather information as a function of their distance to the center of the tornado, and also investigate how providing the uncertainty information about both a particular tornado occurrence through color-coded PHI swaths and the formation of any tornado in the area through color-coded background changes people's protective actions in a tornado event, as compared to deterministic polygons and absence of the color-coded background.

Two different color-coded probabilistic designs, "five-color" and "red-scale," representing the PHI, along with a non-color-coded "polygon" design, similar to those generated by the WarnGen tool, were studied. The effect of providing the background probability of formation of any tornado in the area was studied through color-coding of the background of the designs. In our study, we assumed that both PHI swaths and deterministic polygons could provide information about the proximity to the threat, but only PHI swaths could convey additional probabilistic information about the threat occurrence. Therefore, any difference between the people's protective actions using the swaths and using the deterministic polygons can be attributed to the effect of the probabilistic information.

5.1 Modeling people's protective actions in terms of their proximity to the threat

The results showed that in both cases of using PHI swaths or deterministic polygons, the percentage of people who expected to immediately take shelter right after receiving the weather information increased exponentially as they received the warnings in closer distances to the tornado threat. This finding should not be misinterpreted that in a dynamic presentation of the weather information to the people in which the threat gets gradually closer to the people, they will wait until the highest probability levels and then start taking shelter. Studying people's decision-making in a dynamic situation is beyond the scope of this paper.

Our finding is consistent with conclusion of a previous research study on three real tornado events, which occurred in Oklahoma in 2013, that people's knowledge of their proximity to the tornadoes has a significant effect on the probability of their taking shelter during a tornado event (Miran et al. 2018).

As it was mentioned in Sect. 2, other challenge with polygon warnings is that people, contrary to NWS's expectation, do not consider the polygon's outer boundary as a

threshold for escalating their perceived risk or actions. The presented model of this study replicates finding of previous studies (Ash et al. 2014; Jon et. 2018a) and shows that people's taking shelter behaviors, from the locations outside the wide edge of the polygons until locations inside its narrow edge, follow a specified trend line and people did not consider the boundary of the polygon as the threshold. This problem exists in case of using the swaths as well.

5.2 Effect of providing the probabilistic information on people's protective actions

The present study is in line with results from Lindell et al. (2016) that the perceived likelihood of a tornado strike affects people's behavioral responses. The analysis of the results showed that in scenarios where there is less than 20 min lead time to get impacted by the threat, and the probability of the threat occurrence is more than 60%, providing the threat probabilistic information through color-coded PHI significantly increases the likelihood of people's taking shelter. In other words, when there is less than 20 min lead time, the color of fuchsia and red in the "five-color" design and two shades of red in the "red-scale" design contributed to a significant increase in the chance of people's taking shelter.

In scenarios that the lead time is less than 10 min, the effect of providing the likelihood of threat occurrence on the protective actions gets even more pronounced. In such a highly dangerous scenario, with more than 80% chance to get affected by the tornado threat, it is expected that the recipients immediately take shelter. Our results in Table 5 show that the predicted likelihood that a recipient immediately takes shelter is 23% more when he/she uses a PHI swath instead of a deterministic polygon. Therefore, we can conclude that the PHI was more effective than the deterministic polygons to elicit more appropriate protective behavior from the weather information recipients

In scenarios where there is 10–20 min lead time and is still dangerous, the likelihood that a layperson immediately takes shelter is almost 13% more when he/she uses the PHI, which is provided with the uncertainty of the threat occurrence, than that of the cases that he/she uses the deterministic polygon.

In scenarios where there is more than 20 min lead time and the chance of the threat occurrence is between 0 and 60%, providing the uncertainty information through PHI does not significantly change the probability of people's taking protective actions. This finding is aligned with results of other research that people do not respond to warnings when they understand that the probability of false alarms is more than the probability of true alarms (Simmons and Sutter 2009). According to Table 2, in scenarios where the probability that the tornado would not occur is more than the probability of the tornado occurrence, the percentage of people who used probabilistic hazard information and expected to immediately take shelter is less than percentage of people who used deterministic warnings of polygons and expected to immediately take shelter.

Regarding the effect of providing uncertainty about any threat occurrence in the area through different shades of the blue background, it did not change significantly the probability of taking protective actions.

This finding again supports previous works (Ash et al. 2014; Lindell et al. 2016; Jon et al. 2018a) that people do not consider the outer boundary of the graphical weather information, either probabilistic or deterministic displays, as a threshold for escalating their response to the tornado threat

As it was the case in Klockow (2013) and Ash et al. (2014), color-coding method, neither using a single hue of red with different intensities for each level of the swath nor using multiple-hue for different levels of the swath, played a significant role on the probability of taking protective actions.

6 Conclusion

This study concludes that as the distance between an information recipient and the tornado decreases, the expected protective actions get stronger, and vice versa. It also supports findings in Ash et al. (2014) that in probabilistic swaths, the strongest protective actions can be expected from the locations where likelihood of the threat occurrence is higher.

This study found that the probabilistic information per se has a significant effect on the people's protective actions in a tornado event and enhances the effectiveness of the weather information. This effect, however, is correlated with the proximity to the tornado. In scenarios in which the likelihood that the warning is a true alarm rather than a false alarm, providing the probabilistic information incited stronger protective actions.

Contrary to Ash et al. (2014), the strongest expected protective actions in both deterministic polygons and probabilistic swaths are in the same zone, and the intensity of the actions decreases outward. This finding shows that it is effect of information about the proximity to the tornado, and not the probabilistic information, that assisted people to have the same pattern for their protective actions. Unlike studies of Ash et al. (2014), Lindell et al. (2016), and Jon et al. (2018b), we instructed the participants to assume that the current location of the tornado is just inside the polygon near the narrow edge, and the tornado moves toward the wide edge of polygon with a constant speed.

It can be inferred that both PHI designs and deterministic polygons, which are assumed to inform the weather information recipients about their proximity to the tornado, eliminated the centroid effect and this issue can be attributed to the effect of being aware of the proximity to tornado. This finding is supported by Jon et al. (2018b) that knowledge of location of “tornadic storm cell” outside the polygon could diminish the centroid effect. PHI which provides that information could fix the centroid effect problem of the Warn-Gen's polygon.

The main limitation of this study, as it was the case in Lindell et al. (2016) and Ash et al. (2014) is that the static images of the deterministic warnings and PHI were presented to the participants. Future research works can consider a real dynamic and moving PHI to study the thought process that lead to different protective decisions, when people are exposed to the probabilistic information about a tornado occurrence. The other limitation that should be taken into account in future studies is that the participants used a 15-inch monitor to see the displays, and in reality people would be more convenient to use their smartphones to get updated about the weather information.

This study recruited participants from north east Ohio, where not many people have not experienced a severe tornado event in person. In a future study, this experiment can be conducted in areas that are more prone to tornado occurrence, like Texas and Oklahoma, to study the effects of tornado experience and people's sociodemographic characteristics on their interpretations of the PHI.

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