An Analysis of Tornado Warning Reception and Response across Time: Leveraging Respondents' Confidence and a Nocturnal Tornado Climatology

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ABSTRACT: Nocturnal tornadoes are challenging to forecast and even more challenging to communicate. Numerous studies have evaluated the forecasting challenges, but fewer have investigated when and where these events pose the greatest communication challenges. This study seeks to evaluate variation in confidence among U.S. residents in receiving and responding to tornado warnings by hour of day. Survey experiment data come from the Severe Weather and Society Survey, an annual survey of U.S. adults. Results indicate that respondents are less confident about receiving warnings overnight, specifically in the early morning hours [from 12:00 AM to 4:00 AM local time (0000–0400 LT)]. We then use the survey results to inform an analysis of hourly tornado climatology data. We evaluate where nocturnal tornadoes are most likely to occur during the time frame when residents are least confident in their ability to receive tornado warnings. Results show that the Southeast experiences the highest number of nocturnal tornadoes during the time period of lowest confidence, as well as the largest proportion of tornadoes in that time frame. Finally, we estimate and assess two multiple linear regression models to identify individual characteristics that may influence a respondent's confidence in receiving a tornado between 12:00 AM and 4:00 AM. These results indicate that age, race, weather awareness, weather sources, and the proportion of nocturnal tornadoes in the local area relate to warning reception confidence. The results of this study should help inform policymakers and practitioners about the populations at greatest risk for challenges associated with nocturnal tornadoes. Discussion focuses on developing more effective communication strategies, particularly for diverse and vulnerable populations.

SIGNIFICANCE STATEMENT: We aimed to understand what time of the day members of the public were least confident that they would receive and respond to a tornado warning. Our results demonstrate that members of the public are not only less confident that they would receive warnings overnight, but they are least confident between midnight and 4:00 AM local time (0000–0400 LT). We then used a climatology of tornado reports to see where tornadoes occur during this time frame. Most of the tornadoes that occur between midnight and 4:00 AM occur in the Southeast, which is troubling because this area also has large numbers of people living in poverty or in less robust structures, like mobile homes. We also show that individual characteristics like age and the number of weather information sources someone accesses impact confidence in one's ability to receive warnings during this time frame. These results should help inform forecasters and emergency managers about the communities that need more time to respond to overnight tornado events.

KEYWORDS: Climatology, Operational forecasting; Social science; Communications/decision making

1. Introduction and background

Nocturnal tornadoes are difficult to forecast, difficult to see (and therefore confirm), and difficult to respond to because much of the population is asleep when they occur. As a result, nocturnal tornadoes are more than twice as likely to kill than their daytime counterparts (Ashley et al. 2008). Although most nocturnal tornadoes are not significant (i.e., less than EF2; Trapp et al. 2005), nocturnal environments can still be conducive for strong tornadoes (Kis and Straka 2010). Kis and Straka (2010) found that a majority of significant nocturnal tornadoes were associated with quasi-linear convective systems (QLCS, or more generally, a line of thunderstorms). These storms, and the associated tornadoes, are often more difficult to predict in real-time due to their rapid development and decay, giving forecasters little time to anticipate nocturnal QLCS tornado occurrence. Furthermore, parameters commonly used to forecast daytime supercell tornadoes (e.g., Thompson et al. 2003) are not as applicable in diagnosing nocturnal environments that may support significant tornadoes (Kis and Straka 2010). Similar work also showed that tornadoes that cause at least one death (nocturnal or otherwise) generally occur in environments that are less conducive for weak tornadoes (Anderson-Frey and Brooks 2019). Among these factors, a general lack of visual tornado confirmation makes tornado forecasting at night difficult and results in nocturnal tornadoes being more likely to go unwarned (Brotzge and Erickson 2010; Anderson-Frey and Brooks 2021).

Although nocturnal tornadoes can occur almost anywhere in the United States, the Southeast experiences a higher proportion of nocturnal tornadoes (Krocak and Brooks 2018). While tornado forecasting is very similar across the United

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States, the Southeast has some notable differences in the physical environments generally capable of producing these dangerous storms. For example, Anderson-Frey et al. (2019) found that tornadic environments in the Southeast tend to have higher wind shear values, but lower convective available potential energy than environments in the central United States. The Southeast also has unique socioeconomic characteristics, including a higher mobile home population and a higher proportion of people living below the poverty line (Ashley 2007). In fact, a study of particularly devastating tornadoes (i.e., tornadoes that cause more deaths than what should be expected) found that they tend to occur more frequently in the Southeast (Fricker and Elsner 2019). More specifically, an information seeking study of residents in Mississippi after the April 2011 tornado outbreak found that while most people responded to tornado warnings, many wanted to confirm the information from cues like hearing or seeing the tornado (Sherman-Morris and Brown 2012). While these actions are important, they can leave less time to shelter, which is particularly important for mobile home residents. These mobile homes are more susceptible to damage from weaker tornadoes, making them particularly dangerous during a tornadic event. There has been extensive work investigating the barriers that exist for mobile home residents to seek appropriate shelter. Survey work done by Ash et al. (2020) indicate that half of all mobile home residents in the Southeast would be comfortable sheltering in their home. One reason for this preference is residents believing that their mobile home can withstand higher winds than it can (e.g., Ash 2017; Ash et al. 2020). In addition to the general dangers of being in a mobile home during a tornado, studies have shown that mobile homes in the Southeast are particularly dangerous because of their more rural locations. Mobile homes in Alabama, for example, are less likely to be situated in neighborhoods and are generally farther away from shelters and emergency services (Strader and Ashley 2018; Strader et al. 2019). Taken all together, the Southeast is a particularly vulnerable population (Sutter and Simmons 2010).

Research focused on the Southeast has investigated the complex relationships between forecasters, communicators, and residents in the Southeast. Work by Cross and LaDue (2020) investigated the relationship between emergency managers and forecasters, specifically with respect to the information emergency managers use when making decisions related to severe weather. One of the biggest challenges for emergency managers in the Southeast is the time spent waiting between scheduled weather products, only to then be expected to immediately make decisions when new information is made available (Cross and LaDue 2020). Similarly, Ernst et al. (2018) found that as events unfold, emergency managers prefer that forecasts become more frequent and detailed. Moreover, many emergency managers would prefer the expected likelihood of occurrence to be included in these forecasts.

People must receive information and then proceed through a complex decision process that includes understanding the risk, personalizing it, and then deciding if and how to respond to it (e.g., Drabek 1986; Mileti and Sorensen 1990; Lindell and Perry 2012; Brotzge and Donner 2013; Lindell 2018). However, none of the steps can proceed if people do not first receive the information about the threat (in this case, a tornado warning). One of the prevailing explanations as to why nocturnal tornadoes cause more deaths is centered around the perceived difficulty of receiving tornado warning information at night (e.g., Mason et al. 2018). If people are asleep, they are less likely to get a tornado warning (unless they have some kind of notification system, like a weather radio or phone notifications with sound). Since most people still get their weather information from television (e.g., Schmidlin et al. 2009; Chaney and Weaver 2010; Silva et al. 2019; Krocak et al. 2020), it is likely that many individuals would not receive tornado warning information at night.

With few exceptions, there has been little work to date that focuses on understanding the extent to which the general public receives tornado warning information at night (e.g., Simmons and Sutter 2005). While Lindell et al. (2013) synthesizes the literature around tornado reception and response, very little discussion is placed on the challenges of nocturnal tornadoes. Childs and Schumacher (2018) investigated the *perceived* ability of the general public to receive nocturnal tornado warnings, but this was done through surveys of National Weather Service (NWS) forecasters, broadcast meteorologists, and emergency managers, not through direct investigation of members of the public. Mason et al. (2018) directly surveyed Tennessee residents and found that those who were asked about daytime tornado warnings were more confident that they would have received a warning compared to those who received a nighttime tornado warning (83.7% of participants versus 48.3%). In addition to the likelihood of receiving a daytime warning, other factors like perceived risk to the area, years living in Tennessee, and race impacted the likelihood of receiving the nocturnal warning.

While warning reception is a necessary but insufficient condition for response, there is a similar lack of research on nocturnal warning *response* (e.g., protective action, behavioral intentions, etc.). There has been extensive research related to warning response during the day, including studies on sheltering behaviors after recent tornado events. For example, Miran et al. (2018) studied three tornadic events in the Oklahoma City metro and found that proximity to the tornado and weather information sources influenced respondents taking protective action. Other work has specifically looked at warning responses for mobile home residents and found that many people do not have adequate sheltering options outside of their mobile home (Schmidlin et al. 2009). Still, theoretical and applied advances suggest that people will not take action until they believe the probability of the tornado impacting them is sufficiently high (e.g., Jon et al. 2018; Lindell et al. 2016). Other studies have shown that even without probabilistic information, higher end warnings (like tornado warnings versus severe thunderstorm warnings) tend to elicit more response from participants (e.g., Casteel 2016; Casteel 2018; Ripberger et al. 2015). To combat this phenomenon, the National Weather Service recently began differentiating between lower end warnings and higher end warnings using impact-based statements. Still, it is important to note that challenges and barriers to warning response (e.g., needing confirmation of the tornado or having to go somewhere else for shelter) are likely heightened during the overnight hours

TABLE 1. Demographic representativeness of weather survey respondents. Population estimates were obtained from the U.S. census annual estimates of the resident population by sex, age, race, and Hispanic origin for the United States.

	U.S. adult population (%)	Participants (%)
Gender		
Female	51.3	51.3
Male	48.7	48.7
Age		
18–24	12.1	12.1
25–34	18.0	18.1
35–44	16.2	16.3
45–54	16.8	16.4
55–64	16.7	16.7
65 and up	20.2	20.4
Ethnicity		
Hispanic	16.1	16.3
Non-Hispanic	83.9	83.7
Race		
White	78.2	77.3
Black or African American	12.8	13.2
Asian	5.8	6.1
Other race	3.2	3.4
NWS region		
Eastern	31.7	32.0
Southern	27.0	26.8
Central	20.7	20.9
Western	20.6	20.3

because people are also less able to attend to developing tornado warning information.

This study seeks to build on work by Mason et al. (2018) by investigating tornado warning reception as a function of time of day, using a direct national survey of U.S. residents. We aim to address four primary research questions: 1) Does people's confidence in tornado warning reception and response decrease during the overnight hours? 2) If so, during what specific time frame do we see a marked reduction in this confidence? 3) Which areas of the United States see a higher frequency of nocturnal tornado occurrence? 4) What characteristics make individuals more or less confident in their ability to receive warnings overnight? We hope that this work adds to the current body of literature on nocturnal tornadoes by investigating a nationwide sample of respondents and by assessing specific time frames when respondents are least confident in their ability to receive and respond to warnings. This specification could support forecasters, broadcast meteorologists and emergency response personnel who are responsible for communicating threat information to the communities they serve.

2. Data and methods

a. Survey data

Survey data for this work come from the 2018, 2019, and 2020 iterations of the Severe Weather and Society Survey. These online surveys were fielded annually in late spring or early summer to U.S. residents aged 18 and older. The total number of survey respondents is 9006 (with 3000 in 2018, 3006 in 2019, and 3000 in 2020). The surveys generally consist of roughly 150 questions and take an average of 20–25 min to complete. Questions are designed to assess how U.S. residents receive, comprehend, and respond to severe weather information (Ripberger et al. 2019, Ripberger et al. 2020). For these surveys, Qualtrics (a research company that maintains a pool of Internet users who have agreed to take surveys) uses a dynamic sampling process to identify people in their panels and invite them to participate in the survey. To begin, invitations are sent to an anonymous group of panelists that match the demographic characteristics of the U.S. population. After people complete the survey, Qualtrics sends additional invitations to panelists based on demographic targets. If a given group is underrepresented (relative to U.S. census estimates), they send more invitations to that group; if the group is overrepresented, they send fewer invitations. This results in a diverse sample of survey participants that is generally representative of the U.S. adult population (Table 1).

This study asks respondents to think about how they receive and respond to tornado warnings. Each respondent was asked the following: If a tornado WARNING were issued for your area tomorrow at [randomized time], how confident are you that you would (i) receive the warning, and (ii) take protective action in response to the warning?

This set of questions was asked with three different times, randomized within each bin: one iteration between 1:00 AM and 9:00 AM (0100 and 0900 LT), another iteration between 10:00 AM and 5:00 PM (1000 and 1700 LT), and a final iteration between 6:00 PM and 12:00 AM (1800 and 0000 LT). These three bins of times were chosen to ensure that participants responded to reasonably different times of the day [e.g., instead of 8:00 AM (0800 LT), 9:00 AM, and 10:00 AM]. Respondents were instructed to rate their confidence for both items (receive and take action) for each of the three randomized times using a

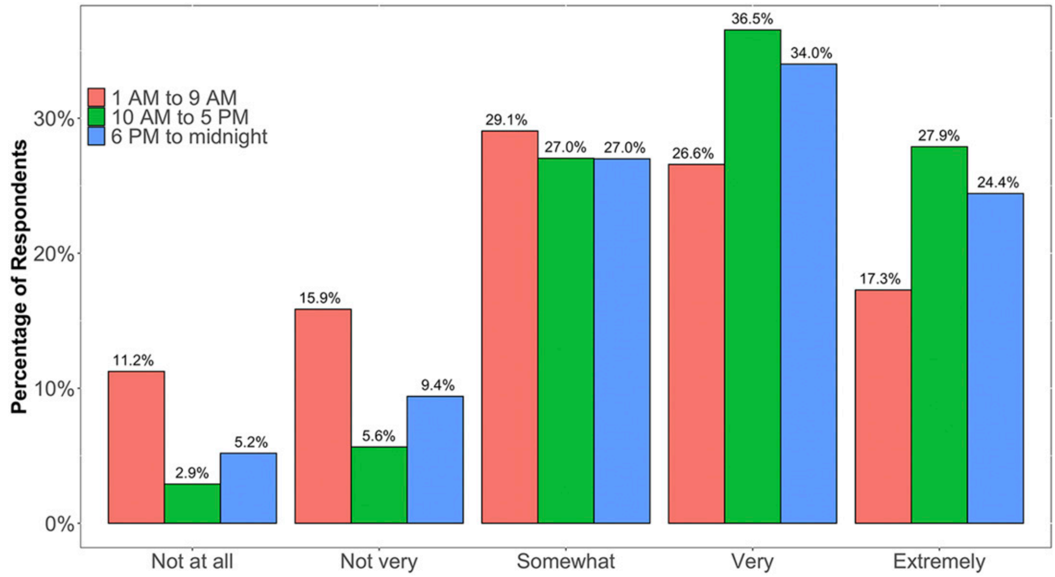

FIG. 1. Respondent reported confidence in receiving a tornado warning by different times of the day. For comparison, we combine responses in the ''very'' and ''extremely'' confident bins for the 10:00 AM–5:00 PM (65%), the 6:00 PM–12:00 AM group (nearly 60%), and for the 1:00 AM–9:00 AM group (43.9%). Similarly, we combine responses in the ''not at all'' and ''not very'' confident bins for the 10:00 AM–5:00 PM (8.5%), the 6:00 PM–12:00 AM group (14.6%), and for the 1:00 AM–9:00 AM group (27.1%).

five-point scale: with 1 indicating ''not at all confident'' and 5 indicating ''extremely confident.''

b. Tornado climatology data

An analysis of tornado occurrence by time of day was completed using the hourly climatology data developed by Krocak and Brooks (2018). Hourly tornado occurrence was calculated using the Storm Prediction Center's local storm report database for each point in the United States on an 80-km grid. Reports were gridded and then smoothed using a Gaussian kernel with a 120-km standard deviation. Finally, the mean value was calculated for each point over the 62-yr dataset. This hourly tornado climatology is then used to calculate the proportion of tornadoes that occur during specific overnight hours for each point.

3. Results

Beginning with our first research question, we find that survey respondents were generally less confident in their ability to receive tornado warnings between 1:00 AM and 9:00 AM (Fig. 1). The modal confidence level from 10:00 AM to midnight is ''very confident,'' while the modal response for 1:00 AM–9:00 AM is only ''somewhat confident.'' Around 65% of respondents in the 10:00 AM–5:00 PM group and nearly 60% in the 6:00 PM–12:00 AM group reported being ''very'' or ''extremely'' confident. That proportion is only 43.9% for the 1:00 AM–9:00 AM group. Furthermore, there were almost twice as many respondents in the group who reported being ''not at all'' or ''not very'' confident between 1:00 AM and 9:00 AM (27.1%), versus the 10:00 AM–5:00 PM group (8.5%, $t = 13.6$ and $p < 0.01$) and the 6:00 PM–12:00 AM group (14.6%, $t = 9.4$ and $p < 0.01$).

While the results in Fig. 1 are illustrative, the time windows are relatively large, so it is difficult to pinpoint the precise window of time that is most concerning to respondents. To identify which specific time frame presents a marked reduction in confidence, we examine the proportion of respondents who report high levels of confidence (very confident and extremely confident) by hour of the day (see Fig. 2). Overall, the proportion of very confident and extremely confident respondents decreases between 11:00 PM and 5:00 AM (2300 and 0500 LT) for warning reception and response. During the other times [from 6:00 AM to 10:00 PM (from 0600 to 2200 LT)], more than 50% of respondents are highly confident they could receive and respond to a tornado warning. This proportion starts to decrease at 11:00 PM to a minimum of about 40% between midnight and 4:00 AM (0400 LT). This apparent reduction in confidence (as shown by the gray shading in Fig. 2) occurs for both reception and response confidence between 12:00 AM and 4:00 AM. During this period, the proportion of respondents who are ''very confident'' and ''extremely confident'' hovers around 40%. Then, the proportion of respondents who report high confidence for receiving and responding to warnings begins to increase again around 5:00 AM. Overall, there is a distinct difference between tornado warning reception confidence during daytime hours (10:00 AM–5:00 PM) and overnight hours (12:00 AM–4:00 AM).

While both reception and response decrease between midnight and 4:00 AM, tornado warning reception shows a greater difference between daylight confidence and overnight confidence. This is particularly concerning because warning reception is often the first step in the risk perception and response process

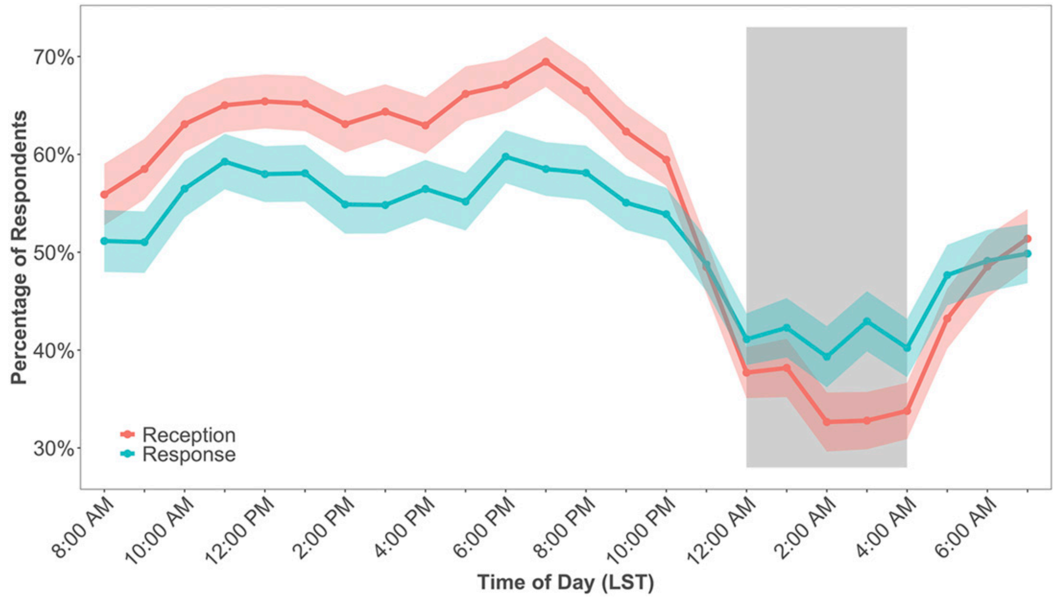

FIG. 2. The proportion of respondents who report being ''very'' or ''extremely'' confident in receiving and responding to a tornado warning by time of day. Shading indicates the 95% confidence interval.

(Lindell and Perry 2012). If vulnerable residents do not receive a warning, it is unlikely that they will take protective action.

Third, to assess which areas of the United States have a higher exposure to nocturnal tornado occurrence, we use the results shown in Fig. 2 to inform a climatology of nocturnal tornadoes. Specifically, we use the hourly climatology developed by Krocak and Brooks (2018) to calculate 1) the mean number of tornadoes that occur between 12:00 AM and 4:00 AM each year and 2) the proportion of the total number of annual tornadoes that occur between 12:00 AM and 4:00 AM across the United States. As shown in Fig. 3, we find that the maximum number of tornadoes that happen during this time frame occur in the Southeast, which is consistent with previous work (e.g., Ashley et al. 2008). This area is also where the highest proportion (up to almost 20%) of tornadoes occurs between 12:00 AM and 4:00 AM (Fig. 3). Given the societal vulnerabilities that also exist in these areas (e.g., Ashley et al. 2008; Strader et al. 2019; Fricker 2020), this result is concerning. Not only do these areas see the highest number of nocturnal tornadoes, but they see the highest number of tornadoes during the four hours when residents are least confident in their ability to receive warnings.

Finally, to further investigate individual characteristics and geographic differences in nocturnal warning confidence, we provide a bivariate correlation matrix and estimate two multiple linear regression models. Both models take the following form:

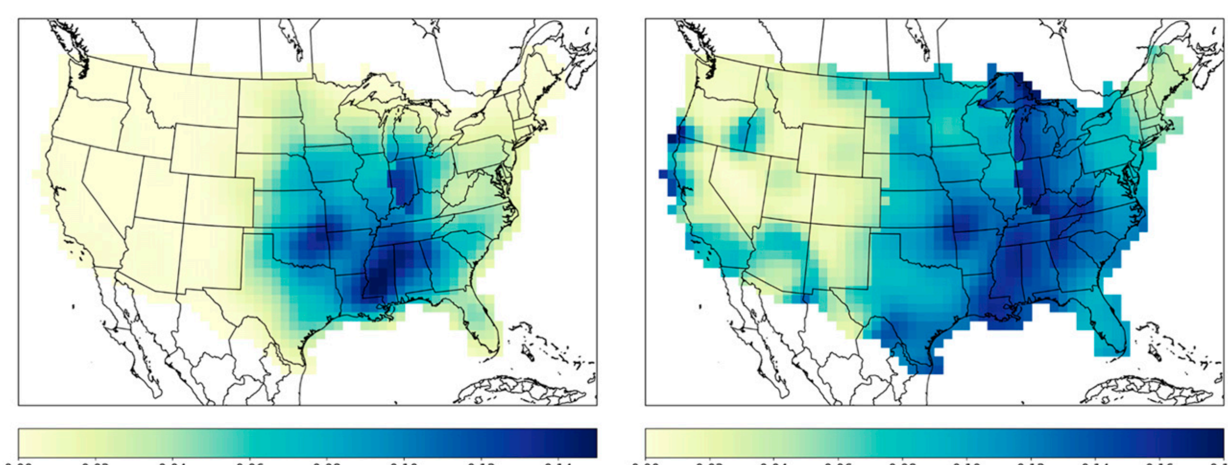

FIG. 3. (left) The mean number of tornadoes that occurred between 12:00 AM and 4:00 AM each year and (right) the proportion of the total number of annual tornadoes that have occurred between 12:00 AM and 4:00 AM.

TABLE 2. Input (explanatory) variables used in the multiple regression models.

Variable name	Description (survey question in *italics* when applicable)
Age	A numeric measure of age. *How old are you? [verbatim]*
Education	The highest level of education completed. This variable was reduced to two levels: "less than a college degree" and "college degree or higher." *What is the highest level of education you have COMPLETED?* *1—Less than high school* *2—High school/GED* *3—Vocational or Technical Training* *4—Some College; NO degree* *5—2-year College/Associate's degree* *6—Bachelor's Degree* *7—Master's Degree* *8—PhD/JD (Law)/MD*
Gender	A binary measure of gender. *Are you male or female?* *0—Female* *1—Male*
Race	A multiple-choice question measuring race. This measure was reduced to three levels: "White," "Black or African American," and "Some other race." *Which of the following best describes your race?* *1—White* *2—Black or African American* *3—American Indian or Alaska Native* *4—Asian* *5—Native Hawaiian or Pacific Islander* *6—Two or more races* *7—Some other race*
Hispanic	A binary measure of ethnicity. *Do you consider yourself to be Hispanic, Latino, or Spanish or to have Hispanic, Latino, or Spanish origins?* *0—No* *1—Yes*
Mobile home	A multiple-choice measure of home type. This measure was reduced to a binary measure: "Mobile home" and "Not a mobile home." *Which of the following categories best describes the nature of your current primary residence?* *1—Stand-alone (detached) permanent structure such as a house* *2—Condominium, town-house, or duplex that is attached to another structure* *3—Apartment or dormitory room that is part of a larger residential complex* *4—Mobile home (whether placed on a permanent foundation or not)* *5—Boat, boathouse, ship, dock, or other floating structure* *6—Other type*
Income	A multiple-choice measure of household income. *Was the estimated annual income for your household in [year]:* *1—Less than $50,000* *2—At least $50,000 but less than $100,000* *3—At least $100,000 but less than $150,000* *4—$150,000 or more*
Weather awareness	A subjective measure of personal weather awareness. *I follow the weather very closely.* *1—Strongly disagree* *2—Disagree* *3—Neither disagree nor agree* *4—Agree* *5—Strongly agree*
Warning history	A binary measure of previous tornado warning experience. *Do you recall having ever received a tornado WARNING for your area?* *0—No* *1—Yes*

TABLE 2. (*Continued*)

Variable name	Description (survey question in *italics* when applicable)
No. of sources	A composite measure of how many sources are used and how often each source is used. The sum of all eight answers was calculated for each respondent. *Broadcast radio* *1—Not much* *2—Little* *3—Somewhat* *4—Much* *5—A great deal* *Weather radio (National Weather Service radio)* *Television* *Internet web pages focused on weather forecasts, such as those provided by the National Weather Service* *Social media, such as Twitter or Facebook* *Word-of-mouth (including telephone calls or texts) from family, friends, neighbors, employers, coworkers, etc.* *Automated text or phone notifications* *Outdoor warning sirens*
Nocturnal tornado proportion	This value was calculated from the tornado climatology dataset for each respondent's location (see Fig. 3, right).

$$y_i = \beta_0 + \beta_1 A_i + \beta_2 E_i + \beta_3 G_i + \beta_4 R_i + \beta_5 H_i + \beta_6 I_i + \beta_7 M_i + \beta_8 W_i + \beta_9 S_i + \beta_{10} F_i + \beta_{11} N_i + \epsilon_i,$$

where, y is the outcome variable (confidence and confidence deficit) we predict for each survey respondent, i; A, S, F, and N are continuous measures that indicate a given respondent's age, the number of warning sources they rely on, how closely they follow the weather, and the percentage of tornadoes that happen between 12:00 AM and 4:00 AM at the respondent's location; E, G, H, M, and W are binary measures that indicate the respondent's education, gender, ethnicity, home type, and previous warning history; R and I are multicategory variables that indicate the respondents race and income; and ϵ is the error term. See Table 2 for a description of each independent variable. We use ordinary least squares (OLS) regression to estimate the coefficients (β) in the models. The outcome variable for the first model is the respondent's confidence in receiving a tornado warning between 12:00 AM and 4:00 AM, the window of lowest confidence from the analysis above. The outcome variable for the second model is the respondent's "confidence deficit," which we calculate by subtracting the respondent's confidence between 12:00 AM and 4:00 AM from their confidence between 10:00 AM and 5:00 PM. For most respondents, the deficit is positive; they have more confidence in warning reception between 10:00 AM and 5:00 PM than between 12:00 AM and 4:00 AM.

The bivariate correlation matrix (Table 3) reveals a variety of significant relationships in the data. For example, it shows that there is a strong negative relationship between the two outcome variables. On average, respondents who are more confident that they will receive a tornado warning between 12:00 AM and 4:00 AM have a smaller confidence deficit than respondents who are less confident that they will receive a warning during that time window. Likewise, the correlations indicate a relationship between a variety of demographic characteristics and confidence in warning reception. Among these, the correlation is highest for age. On average, older respondents have less confidence in warning reception and a larger confidence deficit than younger respondents. In addition to demographics, the correlations indicate significant relationships between weather specific characteristics of respondents and the outcomes of interest. Most notably, respondents who get weather information from a wide variety of sources have more confidence that they will receive tornado warnings 12:00 AM and 4:00 AM and a smaller confidence deficit that respondents who get information from relatively few sources. While these correlations provide important information about bivariate relationships, they do not indicate the relative ("partial") effect of each variable on the outcomes of interest after accounting for the effect of the other variables in the models. The regression models we estimate provide this information.

Estimates from the first model (Table 4) indicate that age and race are the only demographic variables that relate to confidence in warning reception when accounting for all the covariates at once. Older respondents are less confident that they will receive tornado warnings between 12:00 AM and 4:00 AM than younger respondents, but the difference between the two groups is fairly modest. Each unit increase in age corresponds with a 0.01 decrease on the 5-point confidence scale, so the difference between respondents who are 20 and respondents who are 65 is less than half a point on the scale. Likewise, African American respondents are more confident than white respondents, but, as with age, the difference between the groups is fairly modest (0.17).

The remaining variables that significantly predict confidence relate to experience, information sources, weather awareness, and exposure to nocturnal tornadoes. Respondents who have been in a past tornado warning indicate a little more confidence than people who have not (0.13). Respondents who frequently get information from multiple sources also have more confidence that they will receive warnings between 12:00 AM and 4:00 AM than people who rely on few sources. Consistent with

TABLE 3. Pearson correlation matrix showing the relationship between the variables in this analysis; * indicates $p < 0.1$; ** for $p < 0.05$; *** for $p < 0.01$; SD is the standard deviation.

Variable	Mean	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. Confidence	2.94	1.27	—																	
2. Confidence deficit	0.87	1.24	−0.68***	—																
3. Age (years)	47.15	17.46	−0.15***	0.15***	—															
4. Education (<college = 1)	0.40	0.49	0.03	−0.05**	−0.05***	—														
5. Gender (male = 1)	0.48	0.50	−0.02	<0.01	0.11***	−0.11***	—													
6. Race (White = 1)	0.77	0.42	−0.05**	0.11***	0.13***	−0.05**	0.04**	—												
7. Race (Black or African American = 1)	0.14	0.34	0.09***	−0.11***	−0.11***	0.10***	−0.03	−0.73***	—											
8. Race (Other race = 1)	0.09	0.29	−0.04*	−0.03*	−0.06***	−0.05**	−0.03	−0.59***	−0.13***	—										
9. Hispanic (Hispanic = 1)	0.16	0.37	0.04*	−0.08***	−0.14***	<0.01	−0.08***	−0.04*	−0.04*	0.10***	—									
10. Income (< $50k = 1)	0.39	0.49	<0.01	−0.01	0.04*	0.32***	−0.14***	−0.07***	0.09***	−0.01	0	—								
11. Income ($50k–$100k = 1)	0.34	0.47	−0.01	0.02	−0.01	−0.07***	−0.01	0.02	−0.03	0.01	0.02	−0.57***	—							
12. Income ($100k–$150k = 1)	0.17	0.37	<0.01	<0.01	−0.03	−0.18***	0.09***	0.03*	−0.04*	<0.01	0.02	−0.36***	−0.32***	—						
13. Income (> $150k = 1)	0.11	0.31	0.01	<0.01	<0.01	−0.18***	0.12***	0.04*	−0.05**	<0.01	−0.04*	−0.28***	−0.25***	−0.15***	—					
14. Home (mobile home = 1)	0.05	0.22	−0.01	−0.01	−0.02	0.09***	−0.03*	−0.03	0.04**	−0.01	<0.01	0.09***	−0.04**	−0.02	−0.05**	—				
15. Warning history (Yes = 1)	0.63	0.48	0.14***	−0.01	−0.02	−0.01	−0.01	0.05**	0.04*	−0.12***	−0.04**	<0.01	0.02	0.01	−0.03	0.01	—			
16. No. of sources	25.83	6.71	0.40***	−0.14***	−0.11***	0.01	−0.05**	−0.07***	0.07***	0.02	0.07***	−0.03	<0.01	0.02	0.02	−0.02	0.12***	—		
17. Weather awareness	3.81	1.00	0.19***	0.04*	0.11***	−0.06***	<0.01	0.06***	−0.05**	−0.02	0.01	−0.04*	0.03	−0.01	0.02	−0.05**	0.11***	0.28***	—	—
18. Nocturnal tornado perception	9.26	3.63	0.13***	−0.06***	−0.05**	0.07***	−0.05**	−0.04**	0.12***	−0.08***	−0.03	0.08***	<0.01	−0.05**	−0.05***	0.04*	0.34***	0.04*	0.02	—

TABLE 4. Estimates from OLS regression model of confidence.

	Unstandardized coefficient	Standard error	Standardized coefficient	P value
Age (years)	−0.01	0.001	−0.11	<0.001
Education (<college vs college+)	0.05	0.04	—	0.19
Gender (male vs female)	0.04	0.04	—	0.26
Race (Black or African American vs White)	0.17	0.06	—	0.002
Race (Other race vs White)	−0.11	0.07	—	0.10
Hispanic (Hispanic vs Non-Hispanic)	−0.05	0.05	—	0.38
Income ($50k–$100k vs <$50k)	−0.02	0.05	—	0.66
Income ($100k–$150k vs <$50k)	0.01	0.06	—	0.92
Income (>$150k vs <$50k)	0.06	0.07	—	0.40
Home (mobile home vs not mobile home)	0.05	0.09	—	0.60
Warning history (yes vs no)	0.13	0.04	—	0.002
No. of sources	0.07	0.003	0.35	<0.001
Weather awareness	0.13	0.02	0.10	<0.001
Nocturnal tornado perception	0.03	0.01	0.09	<0.001
Intercept	0.68	0.15	0.00	<0.001
Observations		3720		
Adjusted R^2		0.19		
Residual std error		1.14		
F statistic		65.15 (df = 14; 3705) $p < 0.001$		

the correlation analysis above, this is the largest effect we observe in the regression analysis. The difference between respondents who get information from relatively few sources ($x = 8$) and many sources ($x = 40$) is more than 2 points on the 5-point confidence scale. As with experience and reliance on multiple sources, we see that respondents who indicate high levels of weather awareness generally have more confidence than people who indicate low awareness, but the effect is fairly modest in comparison to the effect of source totals. Finally, the regression estimates indicate that respondents with more exposure to tornadoes that happen between 12:00 AM and 4:00 AM are more confident that they will receive warnings during those hours than people with less exposure, but again, the effect is relatively modest in size.

Estimates from the second model (Table 5) indicate that many of the same variables that predict average confidence in tornado warning reception between 12:00 AM and 4:00 AM also correlate with the deficit in confidence that many respondents report. Consistent with the results above, older respondents indicate more of a deficit than younger respondents, and African American respondents indicate less of a deficit than white respondents. In addition, the estimates suggest statistically significant differences between male and female respondents and between Hispanic and non-Hispanic respondents.

TABLE 5. Estimates from OLS regression model of confidence deficit.

	Unstandardized coefficient	Standard error	Standardized coefficient	P value
Age (years)	0.01	0.001	0.11	<0.001
Education (<college vs college+)	−0.06	0.04	—	0.19
Gender (male vs female)	−0.08	0.04	—	0.04
Race (Black or African American vs White)	−0.31	0.06	—	<0.001
Race (Other race vs White)	−0.14	0.07	—	0.04
Hispanic (Hispanic vs Non-Hispanic)	0.19	0.06	—	0.001
Income ($50k–$100k vs <$50k)	0.04	0.09	—	0.70
Income ($100k–$150k vs <$50k)	0.03	0.05	—	0.48
Income (>$150k vs <$50k)	−0.01	0.06	—	0.81
Home (mobile home vs not mobile home)	−0.04	0.07	—	0.60
Warning history (yes vs no)	0.05	0.04	—	0.25
No. of sources	−0.03	0.003	−0.15	<0.001
Weather awareness	0.07	0.02	0.06	0.001
Nocturnal tornado perception	−0.02	0.01	−0.05	0.003
Intercept	0.98	0.16	0.00	<0.001
Observations		3679		
Adjusted R^2		0.06		
Residual std error		1.21		
F statistic		16.42 (df = 14; 3664) $p < 0.001$		

Males indicate less of a deficit than females, and non-Hispanic respondents display more of a deficit in confidence than Hispanic respondents. Finally, the deficit is a bit smaller among respondents who identify with "other" races than it is among respondents who identify as white. In terms of magnitude, it appears that age and race have the strongest effect on the confidence deficit.

In addition to these demographic differences, the estimates indicate that information sources, general weather awareness, and frequent exposure to tornadoes between 12:00 AM and 4:00 AM relate to the deficit in confidence that many people have during this time of day. Consistent with the findings above, multiple information sources and relatively high exposure seem to reduce the size of the confidence deficit that respondents express. In contrast, weather awareness seems to increase the size of the deficit, suggesting that these respondents may be more cognizant and worried about the difficulties of receiving warnings between 12:00 AM and 4:00 AM. Finally, in terms of magnitude, we again see that information sources exert the strongest effect on the deficit.

4. Discussion

Severe thunderstorm and tornado warnings are often a trigger for people's decision-making processes for response during high impact weather events (Lindell and Perry 2012; Mileti and Sorensen 1990). Therefore, reception of these products is vitally important for decision making. Given the numerous challenges with nocturnal tornadoes and their associated warnings, we sought to understand *if* there was a difference in how confident people are that they will receive tornado warnings overnight, *when* that deficit occurs, *where* that confidence deficit is most concerning, and *what* characteristics may influence people's reception confidence.

Our data show that there is a substantial difference in tornado warning reception confidence between warnings issued from 10:00 AM to 10:00 PM and warnings issued from 12:00 AM to 4:00 AM. Roughly 27% of respondents are *not* confident in their ability to receive a warning between 1:00 AM and 9:00 AM, compared to only 9% between 10:00 AM and 5:00 PM and 15% between 6:00 PM and midnight. This finding aligns well with forecasters' perceptions of warning reception and implies that while tornado warnings can be issued at any time of the day, the barriers to receiving them vary significantly by time of day (e.g., particularly when people are asleep). These results are consistent with previous findings from Mason et al. (2018), which found lower levels of warning reception overnight for Tennessee residents.

Next, when we evaluate where most of these events occur, we find that the Southeast receives more events during the main time period of concern (12:00 AM–4:00 AM) than other parts of the United States. These results are similar to previous studies (e.g., Ashley et al. 2008) that also show the Southeast as a hotspot for nocturnal tornado activity. What is particularly concerning is the higher levels of mobile home residents and others who may need more time to respond to tornadic events by moving to sturdier buildings (Ashley 2007; Strader and Ashley 2018; Strader et al. 2019). The juxtaposition of more events occurring during times when residents are least confident in their ability to receive warnings and many of those residents needing extra time to take shelter makes the Southeast particularly vulnerable to tragic outcomes during nocturnal tornado events.

Regression models indicate that a few demographic variables and the weather awareness and preparedness variables influence people's confidence in receiving warnings between 12:00 AM and 4:00 AM. We believe this is promising because while it may not be possible to change demographic characteristics, communication strategies directed at specific populations and individual adaptations in weather awareness and preparedness levels may help improve nocturnal tornado warning reception. In particular, the *number* of weather sources was shown to be the most significant variable in both models. Residents that access multiple weather sources were not only more confident they would receive a warning between 12:00 AM and 4:00 AM, but they also had a smaller confidence deficit between their 10:00 AM–5:00 PM rating and their 12:00 AM–4:00 AM rating. Increasing the number and types of weather sources may be one relatively straightforward way to increase self-efficacy related to tornado warnings. Forecasters and communicators should continue to emphasize the use of weather radios, cell phone apps, Wireless Emergency Alerts, and other forms of passive notification systems. Increased use of these tools will ultimately increase the likelihood of someone receiving warning information while they are asleep or otherwise occupied.

There are important nuances to consider when using online survey data. Although the data comes from a representative sample of the U.S. population with regards to age, race, ethnicity, gender, and NWS region, there may be some bias toward those with access to Internet, especially at lower income levels and in rural areas. Therefore, it would be a worthwhile endeavor to study particularly vulnerable populations (e.g., the elderly, lower income populations, and mobile home residents) to understand how their perceptions and needs differ from others. Additionally, the climatology data comes from the most comprehensive storm report database, but that database has been shown to have numerous reporting issues, including a population bias (e.g., Verbout et al. 2006; Anderson et al. 2007). This bias may lead to areas with higher populations producing more reports, artificially inflating the extent rate of tornadoes in more populated areas, particularly in the earlier years of the reporting database (Elsner et al. 2013).

These findings highlight a need for increased research on the challenges that nocturnal warning reception pose and the urgency to find solutions for those that are most vulnerable. Forecasters and emergency managers in particular could benefit from knowing when warning reception confidence begins to decrease (our results show this is around 10:00 PM) to help decisions related to forecast product scheduling and emergency notification timing. For example, priming residents to be prepared for tornado warnings ahead of time may help ease concern about warning reception while people are asleep. As severe weather forecasting technologies and practices improve, allowing meteorologists to feel confident in the occurrence of severe weather hours in advance, forecasters and communicators should work together to communicate this threat during periods when residents are more likely to receive information (i.e., between 10:00 AM and 10:00 PM), even if the threat is hours away. Additionally, forecasters and communicators should continue to promote having multiple ways to receive warning information, including devices like weather radios and phone apps or alerts, which would alert people even when they are asleep or not paying attention, to ultimately help increase people's confidence in receiving warnings.

Although this is already happening in many areas, advanced forecasting and communication of severe events will require multiple members of the weather enterprise to engage in effective communication efforts on multiple platforms before the storms form. This is particularly important in the Southeast given the higher potential for nocturnal tornadoes between 12:00 AM and 4:00 AM. The research on rural mobile housing and socioeconomic vulnerabilities (e.g., Ash et al. 2020; Strader et al. 2019) in this area compounds the need for more response time than what a warning can provide. Ultimately, informing residents of the potential for nocturnal tornadoes hours in advance may help convince those most vulnerable (like mobile home residents) to find alternative shelter prior to warnings being issued. While there are many challenges with nocturnal tornadoes (both physical and societal), most of them cannot be addressed if residents do not receive forecasts or warnings in the first place.

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Data availability statement. The survey data are available at: https://dataverse.harvard.edu/dataverse/wxsurvey. The tornado climatology data are available at: https://www.spc.noaa.gov/wcm/.

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