ASSESSING THE IMPACT OF VULNERABILITY KNOWLEDGE ON NWS FORECASTERS AND TORNADO EMERGENCY ISSUANCE

KELSEY M. OTHLING

National Weather Center Research Experiences for Undergraduates Program
Norman, Oklahoma

MICHELLE E. SAUNDERS
OU/CASR
Norman, Oklahoma

JACK R. FRIEDMAN
OU/CASR
Norman, Oklahoma

ABSTRACT

The topic of tornado emergencies has not been studied extensively, especially regarding the deciding factors for issuance, perception by forecasters, and effectiveness in reducing tornado mortality compared to traditional warnings. Accessible knowledge of an area's hazard-specific vulnerabilities is critical to making accurate and efficient decisions during impactful severe weather events. This study assesses the Brief Vulnerability Overview Tool (BVOT) which has been shown to improve spatial situational awareness for weather forecasting offices (WFOs) and messaging to core partners. This paper is a novel exploration of the decision-making that goes behind forecasters issuing tornado emergencies, specifically looking at if access to the BVOT played a role. It also assesses the impact a forecaster's background may have on messaging and decision-making within a WFO. Data were collected using an online qualitative software to selectively code for patterns and themes found within transcripts of a severe weather event simulation. This study finds that NWS forecasters report that the BVOT increases the frequency and context of their messaging and improves spatial awareness to an area's associated vulnerabilities. During the test case—March 25, 2021—all forecasters, regardless of experimental condition, upgraded base warnings to a Particularly Dangerous Situation (PDS) while some forecaster teams that had BVOT issued a tornado emergency. However, many forecasters were hesitant to issue tornado emergencies due to lack of prior experience issuing them, uncertainty in issuance thresholds, and perceived negative public reaction.

1. INTRODUCTION

a. Tornado Emergency Decisions

Tornado emergencies have not been studied extensively and their definition or criteria for issuance originally were not well-defined or consistent. They also pose a major challenge for operational meteorologists because these warnings are rare, and they typically precede exceptionally destructive events that have great potential to cause massive loss of life and property. Tornado emergencies require forecasters to make immediate decisions regarding potential vulnerabilities on the ground, where they typically don't have the knowledge to make these decisions well. The first tornado emergency was issued May 3rd, 1999, as a destructive F5 tornado approached the Oklahoma City and Moore, OK areas (NWS Little Rock 2014). Forecasters at the NWS weather forecasting office (WFO) in Norman, OK had a tornado warning already in effect but felt they needed to enhance the wording in the warning in order to catch more of the public's attention to this disaster, thus a "tornado emergency" was issued (see Figure 1).

[1] *Corresponding author address:* Kelsey Othling, Manship School of Mass Communication - Louisiana State University, 8811 Southlawn Drive, Baton Rouge, LA 70810
E-mail: kothli1@lsu.edu

```
...TORNADO EMERGENCY IN SOUTH OKLAHOMA CITY METRO AREA...

AT 6:57 PM CDT...A LARGE TORNADO WAS MOVING ALONG INTERSTATE 44 WEST
OF NEWCASTLE. ON ITS PRESENT PATH...THIS LARGE DAMAGING TORNADO WILL
ENTER SOUTHWEST SECTIONS OF THE OKLAHOMA CITY METRO AREA BETWEEN
7:15 AND 7:30 PM. PERSONS IN MOORE AND SOUTH OKLAHOMA CITY SHOULD
TAKE IMMEDIATE TORNADO PRECAUTIONS!

THIS IS AN EXTREMELY DANGEROUS AND LIFE THREATENING SITUATION. IF
YOU ARE IN THE PATH OF THIS LARGE AND DESTRUCTIVE TORNADO...TAKE
COVER IMMEDIATELY.

DOPPLER RADAR HAS INDICATED THIS STORM MAY CONTAIN DESTRUCTIVE HAIL
TO THE SIZE OF BASEBALLS...OR LARGER.
```

Figure 1. *Warning text from the first tornado emergency issued by NWS Norman on May 3rd, 1999.*

At the time, forecasters had not followed any specific NWS protocol, and there was no national guidance for issuing the original tornado emergency. They issued this emergency primarily on "gut feeling". After the first tornado emergency, the NWS created guidance on the suggested wording for these products (Hawkins 2020). Currently, the NWS defines a tornado emergency as:

> *…an exceedingly rare tornado warning issued when there is a severe threat to human life and catastrophic damage from an imminent or ongoing tornado. This tornado warning is reserved for situations when a reliable source confirms a tornado, or there is clear radar evidence of the existence of a damaging tornado, such as the observation of debris. (NWS Glossary 2022).*

There is also now guidance to meteorologists in warning methodology through the Radar Applications Course (RAC). This course provides a suggested step-by-step process for decision-making when a severe hazard threatens a County Warning Area (CWA) including impact-based warnings guidance, tornado warning points of emphasis, and some criteria for tornado emergency issuance (NWS Warning Decision Training Division, 2022). This training states that, to issue a catastrophic tornado emergency tag, all three of these conditions must be met:

1. *Tornado confirmed (Tornado Debris Signature (TDS) or credible source)*
2. *Expected to impact populated area*
3. *Believed to be strong/violent (EF2+)*

Of central concern to this paper is the second required condition: that the Tornado Emergency category is reserved for tornadoes threatening damage to densely populated areas. While this is "generally" understood by operational meteorologists, what knowledge of vulnerabilities meteorologists have and how they draw on and reliably use this knowledge remains under-examined, so it is critical to understand what knowledge of "populated areas" shapes a forecaster's decision to issue such a rare warning product.

Although relatively little research has been published on tornado emergencies, there has been research on the decision-making process of forecasters issuing tornado warnings. Kim et al. (2022) found that, in addition to a dependence on radar velocity signatures, social factors, including communication, influence forecaster decision-making. Researchers have also found that newer meteorologists often issue tornado warnings more frequently than their more experienced colleagues (Boustead and Mayes 2014). Due to this research gap, this paper reports on how forecasters message and decide to issue these high-end warnings when faced with a significant weather event in an area of increased vulnerability. However, there's relatively little research on the specific ways in which meteorologists draw on vulnerability information to make decisions during high-impact impacts.

b. Vulnerability Assessment

Tornado mortality is highest in the southeastern region of the United States due to increased vulnerabilities, increased development, an elevated nocturnal tornado risk, and a greater number of mobile/manufactured homes, making this area more vulnerable to natural disaster impacts (Strader et al. 2019; Kis and Straka 2022). Several studies have assessed tornado risk in the Southeast using a variety of analytic and qualitative approaches (Ashley 2007; Schmidlin et al. 2009; Sutter and Simmons 2010; Emrich and Cutter 2011; Ashley and Strader 2016; Liu et al. 2019). There is, also, extensive research on how social vulnerabilities influence the impacts this region experiences from natural disasters (Cutter et al. 2003; Ashley et al. 2008; Schmidlin et al. 2009; Chaney and Weaver 2010; Ash 2017; Strader and Ashley 2018). Due to the heightened risks in the Southeast, forecasters find themselves considering both perceived and actual vulnerabilities — and the impact they have — on decision-making. This demands an increased spatial awareness of the vulnerabilities that exist in these areas.

Attempts at creating a tool to display vulnerabilities on a sharable geographic platform first arose in 2002 with the creation of the Community Vulnerability Assessment Tool (CVAT). This tool was developed by the National Oceanic & Atmospheric Administration (NOAA) Coastal Services Center to assist EMs and planners in their efforts to reduce hazard vulnerabilities through mitigation of these hazards, comprehensive land-use, and development planning (Flax et al. 2002). Its methodology assesses vulnerabilities of economic, societal, and environmental elements by creating maps of risk areas (e.g., floods, high winds, wildfires, etc.) using Geographic Information Systems (GIS) or other mapping technologies. Although the CVAT assessed hazard risk and social vulnerabilities, its purpose was more community-driven and less related to communicating weather vulnerabilities.

In the mid-2000s, the NWS called on the National Research Council (NRC) to recommend ways to more effectively estimate and communicate uncertainty in weather and climate forecasts (NRC 2006). With this research, a common theme was acknowledged that highlighted the need for probabilistic hazardous weather information. However, Galluppi et al (2015) noted challenges with deterministic and product-focused deliveries of decision information. For example, the time between watches and warnings creates information gaps where the public requires additional messaging and guidance. Forecasting a Continuum of Environmental Threats (FACETs) research explored the value of frequently updated, high resolution Probabilistic Hazard Information (PHI) to fill these data voids and communicate probabilistic hazard information more effectively (Rothfusz et al. 2018). This research highlighted the need for forecaster training on clearer threat information, how to convey improved uncertainty information, and updated data creation tools, along with introducing research into new experimental products that could better communicate vulnerabilities within a WFO. The Brief Vulnerability Overview Tool (BVOT) was developed to assist meteorologists in addressing many of these critical FACETs-related needs.

The BVOT is a GIS-based tool that forecasters can use within their existing Advanced Weather Internal Processing System (AWIPS) environment to display specific regional vulnerabilities. The goal of this tool is to provide additional spatial situational awareness to NWS meteorologists by allowing them to assess if a particular weather hazard might affect an area of heightened vulnerability in order to improve WFO messaging and decision-making efforts to their core partners (Friedman 2019). Vulnerability data is collected through a method designed by Friedman and LaDue, the Interactive Mapping of Vulnerability Exercise (IMoVE, previously the FIMoVE), that recorded forecasters and emergency managers navigating a map of their warning areas in order to identify challenges in communicating risks, probabilities, and preparedness to vulnerable communities in several WFOs (Friedman 2018).

The BVOT, thus far, has been shown to improve spatial situational awareness for WFOs and messaging to core partners. It also serves as a training and orientation tool for new meteorologists and improves connections with core partners by creating a "living document" of shared knowledge about vulnerabilities that is equally accessible to all offices (Friedman et al. 2022). Prior research has shown that although warning decisions are primarily based on forecasters' subjective judgements, decisions should be based on a consistent level of situational awareness (Alley et al. 2019; Andra et al. 2002; Scher 2018).

This study assesses how access to vulnerability knowledge as well as forecasters' backgrounds and prior experiences influences how forecasters communicate among themselves and to core partners. In addition, it will evaluate how this knowledge affects the decision-making processes before and during a severe weather event, focusing heavily on tornado emergency issuance.

Two research questions explored in this paper are (1) How does the BVOT influence messaging and decision-making in WFOs, specifically the issuance of tornado emergencies?, and (2) Does a forecaster's background lead to differences in communication and decision-making?

c. Messaging and Consistency

Traditionally, meteorologists rely on their experience with past severe weather events to know where vulnerabilities exist and whether to issue a severe warning (Bostrom et al. 2016; Heinselman et al. 2012; Hemingway and Robbins 2020). Research on how forecasters communicate with their core partners and to the public is extensive and there are often disconnects in the messaging within the weather enterprise.

To address this, Williams and Eosco (2021) looked at messaging and public interpretation of weather science knowledge and recommended a message consistency evaluation process for the weather enterprise. A few other studies have looked at messaging in the NWS (Burgeno and Joslyn 2020; Weyrich et al. 2019). These studies demonstrate that inaccuracy and inconsistency in messaging negatively affects public trust in weather forecasts and warnings. For example, Weyrich et al. (2019) found that the use of differing color schemes in hurricane forecasts were misunderstood by certain members of the public. This makes knowledge of an area's hazard-specific vulnerabilities critical to making accurate and efficient decisions during impactful severe weather events in a WFO.

d. Communication & Uncertainty in the NWS

One focus of this paper will be on how forecasters communicate confidence and uncertainty among themselves, to the public, and to emergency managers (EMs). Morss et al. (2008) investigated the public's perception of uncertainty in weather forecasts and found that communicating uncertainty effectively on a forecast-by-forecast basis may improve confidence and trust between the public and meteorologists. This theme of trust between forecasters and core partners is also assessed in research specific to relationships between meteorologists and EMs. Specifically, effective Decision Support Services (DSS) is positively correlated with commitment, trust, and satisfaction between EMs and forecasters, especially regarding the trustworthiness of reports from core partners in forecasters' warning decisions (Liu and Atwell Seate 2021). DSS communication highlights the importance of connecting with core partners instead of simply providing forecasts and helps to bridge the weather science knowledge gap between forecasters and EMs. This form of communication is critical for areas of the country where these differences in meteorological knowledge between forecasters and core partners are the greatest.

Although DSS mitigates some of the EM-forecaster knowledge gaps, it is important to recognize the regional differences in knowledge of weather forecasting and its involved uncertainties. League et al. (2010) found that EMs in Oklahoma tend to have more meteorological training and tailored weather knowledge and resources than the rest of the United States. This could create disparities among different regions and drastic differences in understanding and communication between forecasters and their core partners in certain regions less accustomed to particular weather hazards, thus impacting the efficiency of warning systems. Overall, the relationship between forecasters and EMs is important to disseminate uncertainties in forecasting complex severe weather events, and EMs typically report that outreach from NWS forecasters is beneficial in preparations in their CWA (Ernst et al. 2018).

In addition, certain aspects of messaging such as content and word usage impact public response to uncertainties and communication among forecasters. "Impact-based warnings" that are written to include more "scary" information and more detail on storm paths and recommended actions have been found to improve public actions in response to warnings and hazard communication from the NWS (Perreault et al. 2014). Research has shown that people make choices on how to better protect their lives and property during a weather disaster depending on the level of threat they perceive in messaging (Field et al. 2012). It is important, though, to not overwhelm the public and core partners with too much scientific jargon or irrelevant information that can inhibit the decision-making process. Forecasters should evaluate and communicate only the most necessary hazard information and communicate uncertainties relevant to specific decision needs and time frames (Doyle et al. 2019).

e. HWT Background & Experimental Design

In 2021, an experiment was conducted in the NOAA Hazardous Weather Testbed (HWT). The experiment was designed to assess two experimental products that could improve forecasters' warning decision-making and hazard communication. The purpose was not to analyze meteorologists' forecasting abilities (i.e., "skill"). The severe weather cases used in the experiment were each separated into three time periods during which teams of forecasters would issue products and communication to core partners and publics. The two experimental products tested were the BVOT and the Storm Prediction Center's (SPC) Experimental Timing Graphics. The SPC products focused on bridging the original outlook-watch-warning gaps by providing focused timing guidance for SPC risks in specific CWAs.

A total of eight real-world recorded severe weather cases were used (one of which is the focus of this paper). Not all cases were high impact since the goal was to test how the forecasters would respond to a variety of weather scenarios.

f. Participants

In this case study, 24 forecasters from 23 WFOs (and the Miami Center Weather Service Unit) across the continental United States were chosen to participate in this experiment (See Figure 2). Participants were selected from a variety of WFO locations with differing levels of experience as meteorologists and in the NWS. Forecasters from WFOs located geographically near the locations from which the case studies were drawn (i.e., Alabama and surrounding states in the Southeast) were excluded in order to avoid bias and previous knowledge of the actual weather event. In addition to the NWS participants, there were EMs from around the country that participated as core partners throughout the experiment.

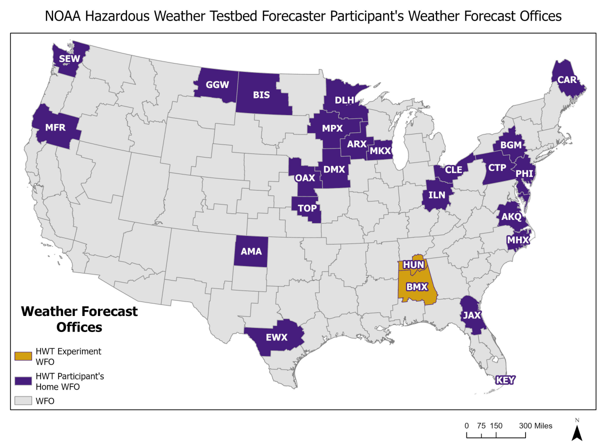

Figure 2. *Location of HWT experiment WFOs studied in this paper. Gold colors represent the WFOs used as the study area and purple colors represent participating forecasters' home WFOs.*

g. HWT Setup

NWS participants (working in teams of two) had access to one of three conditions for each case: Condition A was forecasters with access to both the BVOT and SPC products, Condition B was BVOT only, and Condition C only had access to the SPC graphics (see Table 1).

Table 1. *This table lists the experimental conditions for participants in the HWT experiment, indicating which teams had access to certain experimental products such as the BVOT and the SPC Timing Graphics. The gray boxes highlight groups that had access to the BVOT as part of their experimental conditions.*

	BVOT (experimental group)	**Non-BVOT (control group)**
SPC Exp. Timing Graphics	**GROUP A:** Assesses high temporal resolution product AND increased awareness of spatially-specific vulnerabilities on WFO and EM behavior	**GROUP C:** Assess high temporal resolution product on WFO and EM behavior w/o accounting for local vulnerability knowledge
Traditional SPC Outlook Product	**GROUP B**: Assesses increased awareness of spatially-specific vulnerabilities on WFO and EM behavior	

There were three time periods for each case, with three hours dedicated to each case. Each period, researchers recorded and examined sources of guidance for the meteorologists and their goals for communicating the severe weather event to EMs.

Period 1 was 24-36 hours prior to the severe weather event in which teams were provided with DSS templates specific to that particular case's WFO, which they could modify in terms of wording, graphics used, and style of presentation. There was an optional Google Meet briefing meant to simulate an NWS webinar-style briefing that forecasters had the discretion to use to communicate with their corresponding EMs.

Period 2 focused on the 4-12 hours prior to the event, again examining the messaging/DSS produced during the period, the needs of EMs, and what changed between the first and second periods. There was an additional optional Google Meet briefing, along with updated hazard graphics that were sent to core partners via Slack (used to simulate NWSChat, a communication tool used by the NWS and its partners, as well as simulating social media). Some teams had access to the new SPC timing graphics for this period.

In period 3, forecasters were placed into storm-on-the-ground conditions. They had to make decisions regarding issuing warnings and communication with core partners. The focus was on issuing formal NWS products, messaging via Slack, and optimal Google Meet "break-ins" to communicate with EMs. After each period, debriefing interviews were conducted that examined uncertainties prior to, during, and after the event; perspectives on vulnerability; expectations of the severe weather event; how communication unfolded with EMs; and whether the SPC timing graphics and/or BVOT was used and affected decision-making during the case period.

This paper will focus exclusively on one case out of the eight that occurred in the Birmingham WFO on March 25, 2021. This severe weather event involved 10 tornadoes, including ones that were strong and long tracked (NWS Birmingham 2021). This case highlights one EF-3 tornado that impacted the southern Birmingham metropolitan area. It is important to note that during the actual event, NWS Birmingham issued a tornado emergency for this storm.

2. DATA & METHODS

Google Meet recordings from the 2021-2022 HWT experiments were used as the primary source of data to qualitatively assess the communication and decision-making patterns of forecasters involved in the experiment. The videos allowed more context of the forecasters' tones of communication and visual interactions with the other forecasters and core partners. The videos were transcribed, and the primary investigators developed a codebook of 45 codes that was used to analyze the transcripts. Taguette, an opensource qualitative data analysis tool, was used for coding transcripts. For the purposes of this paper, a qualitative analysis was performed for themes of decision-making, uncertainty, and positive and negative feelings around how the BVOT may have impacted decisions or messaging related to tornado emergencies. Transcripts of briefings conducted with participants at the end of each week during the HWT experiment were used to assess overall themes and feelings of forecasters and EMs in response to the experimental tools provided and communication and decision-making process in the testbed.

For the purposes of this paper, several codes were chosen as areas of focus surrounding themes of BVOT usage and warning decision-making. These codes were also assessed for how often they were double coded for other relevant patterns to answer the research questions. The data identified in the codes were then coded thematically using an inductive approach similar to a categorical style of coding described by Saldana (2021). Memos were used extensively during the coding process to bin the codes into general related themes that will be addressed in this study's final analysis. This paper will focus on the most saturated themes found through this data analysis. These themes address the two research questions referenced earlier.

A comprehensive spreadsheet of forecasters' contacts, personal background information, and experimental conditions was used to connect themes found in the transcripts to forecaster backgrounds in order to help answer the research questions.

Screen recordings of forecasters' interactions with AWIPS were also used to assess how they issued warnings and interacted with the BVOT during Period 3. Slack records (in the experiment, used as a proxy for NWSChat and social media communication) were also reviewed to analyze communication between forecasters and EMs.

Overall emphasis of these data focused on differences in communication and decision-making among forecasters, changes in vulnerability awareness with or without the BVOT, and how this tool ultimately affected discussions about tornado emergencies and the trigger to issue them.

3. ANALYSIS

From the thematic analysis, several themes were identified from the codes and patterns found in the transcripts. These themes were: how the BVOT affected decision-making, how the BVOT affected messaging, and the effects of not having access to the BVOT on forecasters' decisions and messaging. In addition, forecaster backgrounds were taken into consideration while assessing these patterns for any implications this may have (including years of experience in the NWS, prior experience with tornadoes and related weather conditions, and whether they had issued these types of warnings/tornado emergencies before). These themes were repeatedly emphasized by the participants and related to the central research questions addressed in this paper.

a. The BVOT's Impact on Decision-Making

The BVOT played a role in some aspects of decision-making among the HWT participants, primarily during Period 3. One forecaster referenced extending a warning timeframe (i.e., reissuing and extending a polygon) because of BVOT, saying, "…I think I am going to issue one [tornado warning]. A little earlier than I normally would…that kind of pushed me over the edge to do a 60-minute tornado warning vs. the more typical 30 or 45-minute tornado warning" (SJ).

All teams, regardless of BVOT access, decided to upgrade their warnings from the original base warning to a Particularly Dangerous Situation (PDS), while three teams that had BVOT upgraded to a tornado emergency (see Table 2).

A forecaster who upgraded the warning to a PDS, but did not issue a tornado emergency, describes this decision:

> F11: So, I'm shrinking it [warning polygon] now. Don't want to shrink it too much, in case it becomes right moving, but. I think…I'm going to take this up to considerable tornado tag, just because we know it is going into a populated area? Vulnerable area. And, you know, it's had a pretty good TDS…

Three teams decided to issue a tornado emergency during the simulation; however, only one team specifically stated that the BVOT was their primary trigger for issuing the emergency. The forecasters from this team said:

> F10: And now I'm wondering, do you think we go tornado emergency with that cluster there?
> F9: Yeah, because, I mean, it's going into quite a…like you said, quite a lot of stuff there. I mean, it's heading right into basically the southern suburbs of Birmingham, or even the city itself, so…
> F10: All right, well, let's go ahead and upgrade that, I guess.

Table 2. *This table shows each team of forecasters and their associated experimental condition as well as whether they chose to issue a tornado emergency. "Y" indicates that the team issued a tornado emergency and "N – PDS" means that the team did not issue a tornado emergency but did upgrade the original base warning to PDS.*

Team #	Exp. Condition	Tornado Emergency Issued?
Week 1		
Team 1	C	N - PDS
Team 2	A	N - PDS
Team 3	B	Y
Week 2		
Team 1	C	N - PDS
Team 2	A	Y
Team 3	B	N - PDS
Week 3		
Team 1	C	N - PDS
Team 2	A	N - PDS
Team 3	B	N - PDS
Week 4		
Team 1	C	N - PDS
Team 2	A	Y
Team 3	B	N - PDS

During the debriefing after the simulation, this same team was asked how the BVOT impacted their decision to issue the tornado emergency. One of the forecasters stated:

> F10: And then, while looking at the BVOT tool, we noticed a high concentration of

> vulnerable areas along the I-65 corridor south of Birmingham. Prompted us to issue a tornado emergency…So, the BVOT actually helped increase confidence for us to issue a tornado emergency, just given the concentration of the BVOT dots in that I-65 corridor south of Birmingham. So, we knew there was a lot that the tornado, which was already on the ground, was going to impact. So that helped increase confidence.

The other two teams that eventually issued a tornado emergency were actively using the BVOT at the time of tornado emergency issuance, although it is not conclusive that the BVOT was the direct cause for this decision. One of these forecasters who was asked about the BVOT's helpfulness in the event said that it didn't shape how they issued their products and emphasized the importance of vulnerability knowledge more so in planning stages:

> F6: I don't think so…you tend to put the warning out for where the weather threat is, and then, you know, kind of work from there. Kind of figure out what the most vulnerable things are on the path…if something's truly a vulnerable population that, you know, you're in the heat of the moment, is, you know, when you're in warning mode really the time to be working out who to call for that?...some of these campgrounds are going to need, like, hours of lead time. So it's good to be aware of that. But also, I think some of this should be done in the planning stages.

Despite stating that the tool did not shape their warning decision, this team still had the BVOT pulled up while issuing their tornado emergency.

Interestingly, a few of the other teams that had access to the BVOT said that they contemplated issuing a tornado emergency but did not due to hesitancies including a lack of prior experience issuing those products, perceived negative public impression of issuing a tornado emergency, and confusion about the required conditions for issuing them. Another forecaster referenced a fear of being too bullish with any warnings due to recent severe weather fatigue in the public.

> F20: …You try not to be death and destruction. You know, everyone's going to die. And provide, you know, because these aren't going to hit every area. You know, they're isolated…

Even a forecaster from a team who issued a tornado emergency expressed a similar sentiment of perceived severe weather fatigue or lack of action-taking:

> F19: I would also add that…[we] try to get the public to try to take it as seriously as we hoped they would. And you have all kinds of people in this broad range of population. Some of them say, well, I've never been hit by a tornado. It's not going to hit me today. Or, I survived the tornado outbreak of 1972 or whatever. You can never predict a future outcome just based on a previous outcome. There's some people that just won't listen to that. And so you worry. You worry about that segment of the population. And so, in the back of your mind, you just hope that enough people listen and avoid…you can avoid the bad that might come from this.

Many forecasters said that the BVOT tool would be less helpful for metropolitan areas due to the sheer amount of BVOT points densely packed into one area. One forecaster said,

> F24: I think if you're in a little bit larger metro area or a city or something like that, those…I mean, a specific mobile home park or something like that can actually be too exclusive of the area around it that's also under the gun.

Another team agreed, noting that they avoided using the BVOT because of its specificity, and they wanted to make sure an entire area was warned without focusing on individual sites.

Finally, there was discussion among the forecasters and EMs regarding the communicative value of PDS tags and tornado emergencies. In reference to PDS warnings, one forecaster said:

> F1: When we put in that there was…oh, about the PDS stuff. They [EMs] were wanting to know what the qualifications were to make PDS on there. We kind of had to look that up because, like, it's second nature to know what that means, but not know enough to explain it

> up easily without just doing a quick Google search, so…

This highlights the uncertainty, particularly for EMs, in what made these enhanced tags necessary, since while these warnings mean one thing to the NWS meteorologists, they don't necessary carry the same meaning for their interlocutors. PDS warnings are often issued when there is high confidence of violent (EF2+ tornadoes) and have specific guidelines for issuance, similar to tornado emergencies (Dean and Schaefer 2006).

Another trend seen in warning decision-making from the teams was a reliance on storm reports. Despite not having many reports to work from during this case, reports were cited by most teams as one of the primary factors for not only tornado emergency issuance, but general decision-making and messaging during Period 3. One forecaster stated:

> F15: I think we saw, it [the storm] was coming up on quite a bit of vulnerable areas. It only confirmed our fears when we started getting reports of some structure damage and stuff like that. I think the BVOT even confirmed those were real reports of what was damaged. So, yeah. That was really scary.

Getting notifications of reports such as tornado confirmation, structural damage, or injuries was highly correlated with tornado emergency issuance. One forecaster referenced that they would have issued a tornado emergency due to reports if they could re-do the experiment saying,

> F3: But then after I got done and, you know, we're hearing the damage reports coming in and I'm remembering the event, I'm thinking, it probably should have been an [tornado] emergency.

In addition to tornado emergencies, a few teams cited reports as the main factor in upgrading warning tags to PDS or considerable. One forecaster working the radar said to their team member,

> F23: Let me know if we get any other reports of confirmation there. I'm going to go considerable there.

After this forecaster upgraded the warning, the other forecaster on their team asked about the potential option for a tornado emergency upgrade:

> F24: Yeah. Did you have option for a tornado emergency?
>
> F23: Yup. I just decided not to do it. I'm waiting for, like, at least, it's always, like, I need a confirmation of tornado on the ground heading for a population center…
>
> F24: We have not gotten any reports in…

A common sentiment among the forecasters was that the BVOT made hearing the reports more personal, evoking emotion and reminiscence of past vulnerability experiences. The BVOT combined with damage report knowledge made it more difficult psychologically to see a storm move through an area deemed vulnerable. One forecaster said:

> F16: So having an emotional connection, I think, was a little bit enhanced. But the rotation was basically play-by-playing what the BVOT was showing and putting it in the slack chat. But definitely knowing, I think, did add a little bit of a human element to it.

This belief was expressed by another forecaster who said,

> F23: I think the BVOT makes you more, like, it's a little more stressful as a forecaster…You're given the vulnerabilities, so mentally it's a little bit more daunting, I guess.

One forecaster even elaborates on this feeling and how impactful vulnerability knowledge is combined with personal experience:

> F17: Because you're as aware of that urgency as the person on radar, seeing the TDS, seeing, you know, what the radar person is seeing. So it was as stressful to do my job…All I can do is say, hey, media person, please say this on air. Please pass this along. Hey, emergency manager, this is happening…But, you know, I can even say personally, knowing where my fiancée lives or my parents live in my neck of the woods, in my CWA, if I see something in those areas, I'm, like, okay, I've got to pay extra attention to this. Because it makes it personal…there are relevant things there. There are people in mobile homes that you know are likely still in mobile homes,

> unfortunately, or whatever. So it makes it a lot more personal of a decision.

It appears many other forecasters, even those who had access to increased vulnerability knowledge with the BVOT, still wanted confirmation of a tornado before issuing an emergency, and many had an emotional response to hearing impacts within the areas displayed as vulnerabilities.

b. The BVOT's Impact on Messaging

For teams with access to the BVOT, messaging was a dominant theme that changed the most throughout the HWT experiment. This included an increased frequency of messaging in the form of Slack messages to EMs during Period 3 and more frequent social media posts. The BVOT also affected warning text and the tag of warnings issued. In addition, three forecasters attributed storm reports to a change in their messaging.

Despite many forecasters not issuing tornado emergencies, many said that the BVOT allowed them to update warnings during this period more often, specifically adding context and specific vulnerabilities into the warning message, along with more specific timing information. Related to the theme of timing, one forecaster said,

> F18: … I think the BVOT tool kind of helped highlight those other individual sites that we probably would not have known of before. So the multiple mobile home parks. We were able to get some time of arrival on that.

Some other participants added more information that helped to provide spatial context to the warnings. One forecaster said,

> F18: But also having extra detail that you can put in the tornado warning. Text is important, too.

Another forecaster agreed with the BVOT's helpfulness in general spatial awareness stating,

> F23: I think as a radar operator, it just made me more situationally aware of what was out there as targets.

The forecasters who attributed the BVOT to affecting their messaging primarily used it to communicate more with core partners on Slack. One forecaster said:

> F15: Yeah, it was mostly putting stuff in the Slack chat. We did a few…I did a few social media posts with just radar screen grabs and then saying, seek shelter. And then more detail through, like, an NWS chat, where I'd use the BVOT to reference where it was.

Another forecaster decided to include specific vulnerability locations in their messaging:

> F18: Let's see what else there is. There's also Green Park South Mobile Home Park. Both of those ETAs are about 15 minutes. Here, here. Nope. I don't see anything else of main concern right now…I can put that in the Slack if you want me to, actually.

One team even decided to communicate directly with the EM during the storm-on-ground conditions:

> F15: Well, let's see what's right…looks like across the interstate. So I could probably send you that. Indian Springs Village. Okay, it's kind of headed toward a state park, a veteran's park, and more community living. Paul [the NWS team's EM partner in the experiment]. Do you have an end time? Possibly done by phone vs. chat/e-mail. Do you have time to take call? Should I invite Paul in here?

Overall, most participants had a positive view of the BVOT in regard to messaging, saying that it was useful and a "good messaging point".

Social media was another messaging platform that was highly utilized to communicate vulnerability knowledge. Many used social media in combination with Slack to communicate vulnerabilities to EMs in coordination with the public:

> F9: Yeah. I would say it was pretty rapid-fire in the Slack, as well, and trying to convey, obviously, areas that are being impacted, as well as some of the things we noticed in the tool, as well. Trying to convey that to the EM and convey that to chat and get that all on social media…

Another forecaster referenced the severity of the event as reasoning for making a post on social media.

Despite the BVOT changing messaging for most of the teams, four out of the 24 forecasters insisted that it didn't change how they messaged, or they had to be more careful with the specifics in their messaging. One forecaster said that the BVOT's usefulness in messaging came down to its' helpfulness to message context:

> F17: Yeah. I would say from my end, it didn't necessarily change, you know, how I would have done the message…But again, it added context to it. Instead of just a roadway, it's just passing over I-65. No, it's over I-65 and these are the things in the area.

Regarding message specificity, one forecaster who did end up issuing a tornado emergency said:

> F22: So, I ended up not putting specific BVOT locations on my social media messaging because I didn't want people adjacent to a BVOT location to say, "well, they didn't say my neighborhood, so I'm not going to seek shelter," even though they're most definitely in danger.

This forecaster cited a fear of negative public perception in response to messaging content. Another forecaster expressed a similar sentiment of perceived negative public perception, but more as a response to the possibility of over-messaging:

> F20: You know, I'll take a one supercell tornado chewing things up versus, you know, several along the line. I mean, you're able to pay attention. And [my NWS team partner] even at one point said, well, what else should we put out right now? Because there's only so much in WarnGen that you can do. But I think the key is, you know, the social media aspect and that's kind of a delicate balance, too, trying to figure out how busy is your EM? You're throwing all this information to them. I'm sure that, you know, they're getting a flux of information in.

c. Decision-Making and Messaging Without BVOT

One of the focuses of this data analysis was analyzing how teams messaged and made decisions without access to BVOT in order to see if there was a noticeable difference in this decision-making as compared to the teams with access to the BVOT. It is important to emphasize that all teams warning for the March 25, 2021 severe weather case upgraded their warnings to a PDS/considerable tag and only a few of the teams with access to the BVOT issued a tornado emergency. In addition, there was no team without BVOT that issued a tornado emergency.

One forecaster, who did not have access to the BVOT, hinted at the BVOT's potential value, even for an experienced forecaster. Despite three decades of experience, this forecaster struggled with hesitancy in issuing a tornado emergency. Although they did not end up issuing a tornado emergency, this forecaster contemplated it and referenced their lack of experience issuing emergencies:

> F8: So, there's five injured. Strong tornado. Dang. Oh, yeah. It's going to go…so, most likely you're probably going to have to make a call to the EM as soon as the thing begins…It's headed to the biggest population center. Oh, my God. Yeah, that's classic. So, they already issued a warning. So, what am I going to be doing? Oh, I know what I'm doing. And I've never done one before, is a tornado emergency. I've never done one…Oh, crap. I have no idea what I'm doing. Huh. That's interesting. Oh, man, that's a long-track one, there. Jesus. This one…It's already entering Shelby County, where our EM is.

This particular forecaster later stated in the debriefing that they would have liked to have access in order to assess the vulnerabilities. When asked why they did not issue a tornado emergency, this forecaster said,

> F8: I did not do an emergency, because it wasn't in the Birmingham area, but I did do considerable, which said large and damaging tornado.

Interestingly, this forecaster references his lack of tornado emergency issuance because of the storm not heading toward the Birmingham area; however, it is important to consider that this city has loose boundaries, and technically the storm did go into the Birmingham region and its associated vulnerability points. This, then, begs the question that if this forecaster had access to the BVOT, would the decision to issue a tornado emergency have been easier?

Since teams without the BVOT had less spatial awareness of vulnerabilities, these teams tended to rely much more on reports and confirmations of tornadoes in their warning decision-making. One forecaster was asked in the debriefing about questioning whether they were doubting if there was an actual tornado on the ground. Their response was:

> F14: I don't think I…not really. It just would have been nice for absolute, 1,000% confirmation.

This perceived absence of spatial awareness was the sentiment of another team that did not end up issuing a tornado emergency. One of the forecasters described the feeling of missing out without the BVOT:

> F13: It's going to be weird not looking at BVOT. Now I've been spoiled. I feel like I should…
> F14: It's in your head.
> F13: Now it's going to be, like, what am I missing? You know, what vulnerable areas should I be, like, discussing with you that I'm not anymore? I'm going to feel negligent. It's kind of a weird feeling.

One additional pattern to point out with this forecaster interaction is that this team had been exposed to the BVOT in other cases, so they had familiarity with the tool and its abilities to display an area's vulnerabilities. By mentioning it in this particular case, this may indicate that lack of access to the BVOT was a downside and that this team saw the tool as beneficial in certain aspects of their previous decision-making and messaging.

d. Forecaster Background and Communication/Decision-Making

Forecasters' backgrounds played some in how they issued warnings or messaged within the experiment, but it was not the primary factor. This study cannot conclusively say that years of experience in the NWS played a role in decision-making and messaging since the teams were mixed when it came to years of experience; however, we did find that previous experience with similar weather conditions such as tornadoes and high-impact quasi-linear convective system (QLCS) events correlated with increased confidence in warning decision-making and messaging during this case study.

The forecasters who cited previous experience working with storms similar to this event said that it made it easier to handle decisions and messaging during the experimental simulation. One forecaster from one of the Northeast WFOs said,

> F16: …this actually reminds me of something that I went through a few years ago, where a very strong radar signature similar to this one hit a metro area.

This forecaster did not end up issuing a tornado emergency, however. Another forecaster, who happened to be the only one in this case study to add specific BVOT points to their warning message text, said that their fellow team member's level of experience in forecasting allowed additional important context to their warning:

> F18: …And I thank [my fellow NWS team member] for some of his help. You know, some of his expertise here. Putting some additional detail into the warning box, text that you might not be able to do on other events when there's a lot going on, and kind of taking that next step.

With forecasters' home WFOs located in areas of across a wide spectrum of weather/climate conditions, this paper looked at whether severe weather and tornadoes encountered in the experiment played a role in how the participants messaged or issued warnings. One forecaster cited his experience working in fire weather as beneficial for messaging and social media output, stating:

> F1: Yeah. That's more of what we do here, honestly, is just reminding people, like, for fire weather. It's such…like our warnings don't necessarily mean there's fires, but it's the preparation for them. So, I find myself doing more safety stuff and awareness than I do necessarily like, hey, there's a warning or, hey, there's the updated forecast.

This same forecaster also mentioned that they had specialized schooling for tornadogenesis, which helped them understand more about the tornado's structure to help make decisions during the experiment, despite not having access to the BVOT.

A few other forecasters were also familiar with the weather conditions they would encounter in the HWT experiment such as squall lines, tornadoes, and severe weather events involving supercells. A lead forecaster from the Northeast region said,

> F11: I mean, a lot of times in our home CWA…and I'll speak for [my fellow NWS team member], too, because I know it doesn't differ too much from me, but a lot of our severe events can be squall line QLCS events…

Another forecaster was familiar with dealing with radar holes in their home WFO, which is often common in the Southeast.

A few forecasters expressed their lack of experience as being a downside to working an event in Central Alabama. One NWS meteorologist from the Northeast region with relatively few years of experience said,

> F12: I've never had to forecast for a high risk. Only practice in school. Never real-world simulation, so. This is stressful.

Another forecaster from the Southern region said that they were more used to flash flooding events and not as experienced with tornadic storms. This forecaster, during this particular severe weather case, was also the only one to issue a flash flood warning, which shows prior experience in weather conditions impacting decision-making. Another forecaster mentioned that his lack of experience in the case study's weather conditions allowed them to put more confidence in the EM, stating:

> F14: There's a lot of factors there… I have a lot more confidence in our EMs here, because they're experienced, they've seen this kind of weather, they've dealt with high risk. You don't deal with this in certain parts of the country.

Finally, despite having two decades of forecasting experience, one forecaster from a northeast WFO who stated they were more familiar with colder weather conditions said they had not worked with QLCSs much and never had seen a tornado. In contrast, their team member had experienced at least 20 tornadoes working in areas of the country such as the Midwest and Great Plains. This is what made previous experience in similar weather conditions a factor in tornado emergency issuance and decision-making; however, it is difficult to make a conclusion that this was a considerable factor since teams were comprised of forecasters from a variety of geographical backgrounds.

Despite differences in experience with weather conditions, most forecasters in the debriefing interviews still said the BVOT would be beneficial for back-up WFOs and newer forecasters. One forecaster stated:

> F17: I don't know what special areas there are. I don't know where their mobile home parks are, where their vulnerable populations are, you know, anything like that. So I think this is invaluable for backup offices to have that context.

Adding to the argument that the BVOT could be critical for backup WFOs, the forecaster who ended up using BVOT points in their messaging said:

> F18: …I'm not from the severe weather area, but, you know, when we didn't have a BVOT [for other cases during the experiment] compared to when we did have a BVOT in these cases, you know, I think it was helpful…to highlight those areas of higher concern. You know, when you're not familiar with what's going on or a certain geographic area…

e. A Resulting Theme: Tornado Emergency Hesitancy, Warning Uncertainty, and Awareness of Public Perception/Trust

Frequent false alarms and higher perception of tornado warning inaccuracy in the NWS tends to decrease public trust and consequently protective action in response to future tornado warnings (Ripberger et al. 2015). The forecasters in this study were hesitant to issue tornado emergencies because of this, in addition to lack of experience issuing them and uncertainty regarding the exact qualifications of issuance. Although the BVOT may have provided more spatial vulnerability awareness and increased detailed messaging during a high-impact event, its usefulness for tornado emergencies may have been clouded by these outside psychological factors. Research has shown that individuals perceiving greater levels of uncertainty will experience greater levels of stress during decision-making, and this perceived stress is negatively associated with decision quality (Phillips-Wren and Adya 2020). Information overload, time pressure, and event complexity also contribute to this degraded decision quality. One forecaster even mentioned the false alarm concern stating:

> F23: …I was waiting to hear what kind of a confirmation I could get on the ground heading into that more populous area, and I would have probably done an emergency if I had some kind of confirmation of that on the ground. I think that's typically the policy, is zero false alarm.

Lots of uncertainty surrounding the qualifications for upgrading warnings to PDS or to an emergency was seen in most participants. For a few NWS meteorologists, having the BVOT increased psychological stress because of the high awareness of vulnerabilities combined with damage reports that may have further exacerbated the mental toll of these high-impact decisions. Meteorologists have many different decisions to make at once during a severe weather outbreak, so certain decisions and messaging must be prioritized. Often during this HWT experiment, forecasters said that after the event, they probably would have made different decisions in retrospect.

A theme of high awareness of public perception and trust in the NWS is seen in the sentiments from many forecasters as to why they did not issue a tornado emergency despite increased vulnerability knowledge.

Some prior experience in public severe weather fatigue translated into forecasters having increased awareness of the public's perception of weather warning and outlook products, which one forecaster explained could be a factor when choosing how to message and warn. They stated:

> F16: I think part of it too, especially where I'm at, up in the northeast, you get a couple of events in a row, and people start getting cranky about it. But that's probably one other thing that would be going on, too, would be if there would be some cranky people out there who are kind of done with it.

This public severe weather fatigue was noted in other parts of the experiment as a limiting factor for tornado emergency issuance, as cited by a few other forecasters who did not issue a tornado emergency for this reason.

4. CONCLUSION

This paper reports on the analysis of vulnerability knowledge using the BVOT and its effects on messaging and decision-making, specifically in the case of issuing tornado emergencies. It also analyzes factors in forecasters' previous experiences and backgrounds that may affect these decisions. This study concludes that the BVOT did increase the frequency of messaging in NWSChat and to core partners, along with an increase in social media posts. It allowed for more specificity and context in warnings for some forecasters. All teams, regardless of condition, upgraded warnings to a PDS, while some teams with BVOT upgraded a step further to a tornado emergency; however, the upgrade to a tornado emergency was less common due to a lack of experience in issuance, perceived lack of clear guidelines, or hesitancy due to possible negative public perception.

Teams that had the BVOT often communicated BVOT locations in Slack and increased their frequency of messages. Some also added additional context and details of vulnerabilities in the warning text.

For forecasters without access to the BVOT, there seemed to be less spatial awareness of vulnerabilities and there were no upgrades to tornado emergencies. Despite forecasters from all conditions citing storm reports as a major factor for issuing tornado emergencies, PDS warnings, or increased messaging, those without BVOT relied more heavily on reports for confirmation. This could indicate that the BVOT may have been a factor, in addition to storm reports, for issuing tornado emergencies.

Forecaster backgrounds were not a major factor in decision-making or messaging when it came to years of experience as a forecaster or working in the NWS due to the randomized nature of the teams in the experiment; however, prior experience with related weather conditions similar to the experimental case examined, such as tornadoes or supercell events, was correlated with increased confidence and spatial awareness while issuing warnings or messaging, with some forecasters citing lack of experience with similar weather conditions as a negative factor.

The hesitancy of many participants to issue tornado emergencies highlights the need for more research on the definition and criteria for tornado emergency issuance, as this type of warning is rarely used. Because of this, there may be some scrutiny of tornado emergencies as being "off the cuff" decisions. As Ernst et al. 2021 noted, certain wording in messaging could lead to a false alarm effect and loss of trust in the public. These misunderstandings could increase the vulnerability of people in harm's way, especially if they are already severe weather fatigued. In addition, if a tornado emergency is issued and reports do not back up its issuance, public trust can be negatively impacted which was the case for a storm that passed through Jonesboro, Arkansas on April 15, 2022. Despite forecasters in NWS Little Rock issuing a tornado emergency based on observations and storm reports, no tornado or damage was confirmed after the event which made some meteorologists claim that the bar needs to be raised for declaring tornado emergencies in order to protect against false alarms and a subsequent undermining of public trust in the NWS and future warnings (Cappucci 2022).

Most forecasters agreed that the BVOT would be a beneficial tool for back-up WFOs or newer forecasters to gain more spatial awareness of vulnerabilities in an area, but fewer believed that it is helpful in making high-impact warning decisions.

Future studies are needed to assess the psychology behind hesitancy in issuing high-impact warnings, what triggers certain people to issue them, and how tornado emergency definitions can be improved to be clearer. It is also critical to study the efficacy of tornado emergencies compared to traditional warnings or PDS warnings in public action-taking in the face of hazards. As Perreault et al. 2014 concluded, more "scary" warnings were not seen as credible as traditional warnings, thus less public action was taken.

Finally, it is important to highlight the limitations in this study: only one case out of eight was analyzed, and it was the only case involving a potential tornado emergency within the broader HWT experiment. Thus, for the study of tornado emergencies, a larger sample size is required before making definite conclusions. The research questions in this study are complex and context-dependent so much so that they cannot be fully answered in a single paper. However, the findings presented here provide a baseline of understanding for future research on tornado emergencies and the effectiveness of vulnerability assessment tools on forecaster decision-making.

5. ACKNOWLEDGMENTS

We thank the forecasters and EMs who participated in the 2021 HWT experiment which provided critical data for this paper's findings. This work builds upon the work of Drs. Jack Friedman and Daphne LaDue in developing the BVOT tool and additionally Dr. Michelle Saunders and Alex Marmo studying the BVOT's initial effects un the HWT. Special thanks are also given to study mentors Dr. Michelle Saunders and Dr. Jack Friedman for revising and providing constructive feedback on this analysis. We are also grateful for the National Weather Center and Research Experiences for Undergraduates (REU) program directors Alex Marmo and Dr. Daphne LaDue for developing and conducting activities and workshops beneficial to the quality of this paper. This paper was prepared by authors with funding from the National Science Foundation (NSF AGS-2050267). The statements, findings, conclusions and recommendations in this study do not necessarily reflect the views of the University of Oklahoma (OU) or the National Weather Center (NWC) or other NOAA affiliates.

6. REFERENCES

Alley, R. B., K. A. Emanuel, and F. Zhang, 2019: Advances in weather prediction. *Science*, **363**, 342–344, https://doi.org/10.1126/science.aav7274.

Andra, D. L., Jr., E. M. Quoetone, and W. F. Bunting, 2002: Warning decision making: The relative roles of conceptual models, technology, strategy, and forecaster expertise on 3 May 1999. *Wea. Forecasting*, **17**, 559–566, https://doi.org/10.1175/1520-0434(2002)017<0559:WDMTRR>2.0.CO;2.

Ash, K. D., 2017: A qualitative study of mobile home resident perspectives on tornadoes and tornado protective actions in South Carolina. USA. *GeoJournal,* **82(3)**, 533–552, https://doi.org/10.1007/s10708-016-9700-8.

Ashley, W., 2007: Spatial and temporal analysis of tornado fatalities in the United States: 1880-2005. *Wea. Forecasting*, **22**, 1214–1228, https://doi.org/10.1175/2007WAF2007004.1.

Ashley, W., A. Krmenec, and R. Schwantes, 2008: Vulnerability due to nocturnal tornadoes. *Wea. Forecasting*, **23**, 795–807, https://doi.org/10.1175/2008WAF2222132.1.

Ashley, W. S. and S. M. Strader, 2016: Recipe for disaster: how the dynamic ingredients of risk and exposure are changing the tornado disaster landscape. *Bull. Amer. Meteor. Soc*., **97(5)**, 480 767–786, https://doi.org/10.1175/BAMS-D-15-00150.1.

Bostrom, A., R. Morss, J. Lazo, J. Demuth, H. Lazrus, and R. Hudson, 2016: A mental models study of hurricane forecast and warning production, communication, and decision making. *Wea. Climate Soc.*, **8**, 111–129, https://doi.org/10.1175/WCAS-D-15-0033.1.

Boustead, J. M., and B. E. Mayes, 2014: The role of the human in issuing severe weather warnings. *27th Conf. on Severe Local Storms*, Madison, WI, Amer. Meteor. Soc., 4B.2, https://ams.confex.com/ams/27SLS/webprogram/Paper254547.html.

Burgeno, J. N., and S. L. Joslyn, 2020: The impact of weather forecast inconsistency on user trust. *Wea. Climate Soc.*, **12**, 679-694, https://doi.org/10.1175/WCAS-D-19-0074.1.

Cappucci, 2022: *No twister confirmed after dire 'tornado emergency' in Arkansas*. The Washington Post, https://www.washingtonpost.com/weather/2022/04/20/arkansas-tornado-emergency-nws-false/.

Chaney, P. L. and G. S. Weaver, 2010: The vulnerability of mobile home residents in tornado disasters: The 2008 Super Tuesday tornado in Macon County, Tennessee. *Wea. Clim. Soc*., **2(3)**, 190–199, https://doi.org/10.1175/2010WCAS1042.1.

Cutter, S. L., B. J. Boruff and W. L. Shirley, 2003: Social vulnerability to environmental hazards. *Social science quarterly*, **84(2)**, 242–261, https://doi.org/10.1111/1540-6237.8402002.

Dean, A. R., and J. T. Schaefer, 2006: PDS watches: how dangerous are these "particularly dangerous situations?"; *23rd Conference on Severe Local Storms*; St. Louis, MO; Amer. Meteor. Soc., 5.4, https://ams.confex.com/ams/23SLS/webprogram/Paper115252.html.

Doyle, E.E., D. M. Johnston, R. Smith, and D. Paton, 2019: Communicating model uncertainty for natural hazards: A qualitative systematic thematic review. *Int. J. Disaster Risk Reduction*, **33**, 449-476, https://doi.org/10.1016/j.ijdrr.2018.10.02.

Emrich, C. T. and S. L. Cutter, 2011: Social vulnerability to climate-sensitive hazards in the southern United States. *Wea. Climate Soc*., **3(3)**, 193–208, https://doi.org/10.1175/2011WCAS1092.1.

Ernst, S., D. LaDue, and A. Gerard, 2018: Understanding emergency manager forecast use in severe weather events. J. *Operational Meteor*., **6 (9)**, 95-105, doi: https://doi.org/10.15191/nwajom.2018.0609

Field, C. B., Barros, V., Stocker, T. F., Dahe, Q., Dokken, D. J., Ebi, K. L., . . . Midgley, P. M., 2012: *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the Intergovernmental Panel on Climate Change.* New York, NY: Cambridge University Press.

Flax, L.K., Jackson, R.W. and Stein, D.N., 2002: Community Vulnerability Assessment Tool Methodology. *Natural Hazards Review*, **3**, 163-176, https://doi.org/10.1061/(ASCE)1527-6988.

Friedman, J. R., 2019: Designing, Creating, and Testing the Brief Vulnerability Overview Tool (BVOT) for NWS Forecasters; *14th Symposium on Societal Applications: Policy, Research and Practice*; Phoenix, AZ; Amer. Meteor. Soc., TJ18.3, https://ams.confex.com/ams/2019Annual/meetingapp.cgi/Paper/351897.

Friedman, J. R., D. S. LaDue, M. E. Saunders, A. N. Marmo, 2022: Does Awareness of Vulnerabilities Impact the Product Issuance or Messaging of WFOs?: Testing the Operational Use of the Brief Vulnerability Overview Tool (BVOT); *17th Symposium on Societal Applications: Policy, Research and Practice*; Remote; Amer. Meteor. Soc., 7A.5, https://ams.confex.com/ams/102ANNUAL/meetingapp.cgi/Paper/398829.

Friedman, J. R., and M. J. Wagner, 2018: Using the Forecaster Interactive Mapping of Vulnerability Exercise (FIMoVE) Tool to Identify Strengths and Gaps in the Continuum of High Impact Weather Communication: Assessing the Knowledge−Communication−Community Network During VORTEX-SE 2015-2017; *13th Symposium on Societal Applications: Policy, Research and Practice*; Austin, TX; Amer. Meteor. Soc., 7.5, https://ams.confex.com/ams/98Annual/webprogram/Paper328223.html.

Galluppi, K., S. F. Piltz, K. Nuckles, B. Montz, J. Correia, and R. Riley, 2015: Improving weather and emergency management messaging: The Tulsa Weather Message Experiment. *10th Symp. On Societal Applications: Policy, Research and Practic*e, Phoenix, AZ, Amer. Meteor. Soc., 3, https://ams.confex.com/ams/95Annual/webprogram/Paper270086.html.

Hawkins, M., 2020: National Weather Service Instruction 10-511, 64 pp, http://www.nws.noaa.gov/directives/.

Heinselman, P. L., D. S. LaDue, and H. Lazrus, 2012: Exploring impacts of rapid-scan radar data on NWS warning decisions. *Wea. Forecasting*, **27**, 1031–1044, https://doi.org/10.1175/WAF-D-11-00145.1.

Hemingway, R., and J. Robbins, 2020: Developing a hazard-impact model to support impact-based forecasts and warnings: The Vehicle Over Turning (VOT) model. *Meteor. Appl.*, **27**, e1819, https://doi.org/10.1002/met.1819.

Kim, J., A. A. Seate, B. F. Liu, D. Hawblitzel, and T. Funk, 2022: To Warn or Not to Warn: Factors Influencing National Weather Service Warning Meteorologists' Tornado Warning Decisions. Weather, Climate, and Society, **14** (3), 697-708, https://doi.org/10.1175/WCAS-D-20-0115.1.

Kis, A.K., and J.M. Straka, 2022: Nocturnal Tornado Climatology. *Weather and Forecasting*, **25**, 2, 545-561. https://doi.org/10.1175/2009WAF2222294.1.

League, C. E., W. Diaz, B. Philips, E. J. Bass, K. Kloesel, E. Gruntfest, and A. Gessner, 2010: Emergency manager decision-making and tornado warning communication, *Meteorol. Appl*., **17 (2)**, 163–172, https://doi.org/10.1002/met.201.

Liu, B. F., and A. Atwell Seate, 2021: The evolving weather service: Forecasters' perceptions of their relationships with core partners. *Wea. Climate Soc.*, **13**, 437–448, https://doi.org/10.1175/WCAS-D-20-0097.1.

Liu, B. F., M. Egnoto, and J. R. Lim, 2019: How mobile home residents understand and respond to tornado warnings. *Weather, Climate, and Society*, https://doi.org/10.1175/WCAS-D-17-0080.1

Morss, R. E., J. L. Demuth, and J. K. Lazo, 2008: Communicating uncertainty in weather forecasts: A survey of the U.S. public. *Wea. Forecasting*, **23**, 974–991, https://doi.org/10.1175/2008WAF2007088.1.

NRC, 2006: *Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts*. National Academies Press, 122 pp., https://doi.org/10.17226/11699.

NWS, 2022: Glossary: Tornado Emergency, https://w1.weather.gov/glossary/index.php?word=tornado+emergency.

NWS Birmingham, 2021: Long-Track Tornadoes of March 25, 2021, https://www.weather.gov/bmx/event_03252021.

NWS Little Rock, 2014: What is a tornado emergency?, https://www.weather.gov/lzk/toremer0514.htm

NWS Warning Decision Training Division, 2022: Warning Methodology- Screen, Rank Analyze, Decide, 10 pp, https://training.weather.gov/wdtd/courses/rac/documentation/rac22-warn-method.pdf.

Perreault, M. F., J. B. Houston, and L. Wilkins, 2014: Does Scary Matter?: Testing the Effectiveness of New National Weather Service Tornado Warning Messages, *Communication Studies*, **65:5**, 484-499, DOI: 10.1080/10510974.2014.956942

Phillips-Wren, G. and M. Adya, 2020: Decision making under stress: The role of information overload, time pressure, complexity, and uncertainty. *Journal of Decision Systems*, **29**, 1–13. https://doi.org/10.1080/12460125.2020.1768680.

Ripberger, J. T., C. L. Silva, H. C. Jenkins-Smith, D. E. Carlson, M. James, and K. G. Herron, 2015: False alarms and missed events: The impact and origins of perceived inaccuracy in tornado warning systems. *Risk Anal.,* **35**, 44–56, https://doi.org/10.1111/risa.12262.

Rothfusz, L. P., R. Schneider, D. Novak, K. Klockow-McClain, A. E. Gerard, C. Karstens, G. J. Stumpf, and T. M. Martin, 2018: FACETs: A proposed next-generation paradigm for high-impact weather forecasting. *Bull. Amer. Meteor. Soc.*, **99**, 2025–2043, https://doi.org/10.1175/BAMS-D-16-0100.1.

Saldana, J. 2021: *The Coding Manual for Qualitative Researchers.* Sage Publishing, 440 pp.

Scher, S., 2018: Toward data-driven weather and climate forecasting: Approximating a simple general circulation model with deep learning. *Geophys. Res. Lett.*, **45**, 12 616–12 622, https://doi.org/10.1029/2018GL080704.

Schmidlin, T. W., B. O. Hammer, Y. Ono, and P. S. King, 2009: Tornado shelter-seeking behavior and tornado shelter options among mobile home residents in the United 592 States. *Nat. Haz.*, **48(2)**, 191–201, https://doi.org/10.1007/s11069-008-9257-z.

Strader, S. M., K. Ash, E. Wagner, and C. Sherrod, 2019: Mobile home resident evacuation vulnerability and emergency medical service access during tornado events in the southeast United States. *Int. J. Disaster Risk Reduct.*, **38**, 101210, https://doi.org/10.1016/j.ijdrr.2019.101210

Strader, S. M. and W. S. Ashley, 2018: Fine-scale assessment of mobile-home tornado vulnerability in the Central and Southeast U.S. *Wea. Clim. Soc*., https://doi.org/10.1175/WCAS-D-18-0060.1.

Sutter, D. and K. M. Simmons, 2010: Tornado fatalities and mobile homes in the United States. *Nat. Haz*., **53(1)**, 125–137, https://doi.org/10.1007/s11069-009-9416-x.

Weyrich, P., A. Scolobig, and A. Patt, 2019: Dealing with inconsistent weather warnings: Effects on warning quality and intended actions. *Meteor. Appl*., **26**, 569–583, https://doi.org/10.1002/met.1785.

Williams, C. A. and G. M. Eosco, 2021. Is a Consistent Message Achievable?: Defining “Message Consistency” for Weather Enterprise Researchers and Practitioners. *Bull. Amer. Meteorol. S.*, **102**, E279-E295. https://doi.org/10.1175/BAMS-D-18-0250.1