BAMS Article

Public Information Priorities across Weather Hazards and Time Scales

Makenzie J. Krocak, Joseph T. Ripberger, Sean Ernst, Carol Silva,
Hank Jenkins-Smith, and Abby Bitterman

ABSTRACT: As the abundance of weather forecast guidance continues to grow, communicators will have to prioritize what types of information to pass on to decision-makers. This work aims to evaluate how members of the public prioritize weather forecast attributes (including information about location, timing, chance, severity, impacts, and protective actions) on average and across event timelines in the severe, tropical, and winter weather domains. Data from three demographically representative surveys of U.S. adults indicate that members of the public generally prioritize information about event location, timing, and severity when evaluating the importance of forecast attributes. This pattern is largely consistent across hazard domains but varies across event timelines. In early stages of a forecast (such as the outlook time scale), people generally prioritize information about chance and location. In middle stages (watch time scale), event timing and severity become more important. In late stages (warning time scale), information about protective actions is a higher priority, especially for people with less exposure to a hazard.

KEYWORDS: Social Science; Forecasting; Communications/decision making

https://doi.org/10.1175/BAMS-D-22-0190.1
Corresponding author: Makenzie Krocak, mjkrocak@ou.edu
Supplemental material: https://doi.org/10.1175/BAMS-D-22-0190.2

In final form 3 February 2023

AFFILIATIONS: Krocak and Ernst—Institute for Public Policy Research and Analysis, University of Oklahoma, and Cooperative Institute for Severe and High-Impact Weather Research and Operations, and NWS Storm Prediction Center, Norman, Oklahoma; **Ripberger, Silva, Jenkins-Smith, and Bitterman**—Institute for Public Policy Research and Analysis, University of Oklahoma, Norman, Oklahoma

Forecasts of weather hazards are complex, often containing multiple pieces of information about the nature of the threat. Traditionally, research about weather forecasting capabilities has focused on what kinds of information meteorologists can realistically provide with reasonable accuracy at different points along the event timeline (e.g., Harrison et al. 2022; Wang et al. 2020; NSSL 2021). While this forecasting capability is critical to define the limits of what forecast information can be messaged to the public, it is also important to understand the kinds of information that people want, need, and find useful for their decision-making. This requires scientists and forecasters to know the types of information decision-makers *need*, instead of just the types of information they *can provide*.

The last decade of meteorological research has ushered in an unprecedented ability to provide new kinds of weather forecast information at longer time scales. Advancements in forecast model technology and data collection have given meteorologists new ways to identify when there will be extreme weather, where it will likely occur, how severe it is likely to be, the level of uncertainty in the forecast, and even to a degree what societal impacts a weather event may have, all with greater accuracy than ever before (e.g., Roberts et al. 2019; Benjamin et al. 2016; Gallo et al. 2022). The world is transitioning from a paradigm where information about the weather forecast was scarce or vague into an environment where there is almost too much information to provide in a single message. This transition has brought a series of important questions to the fore, including: What forecast information should be prioritized? What information do people most need and want when making protective action decisions? Do these information needs vary across hazards and/or time?

Previous work related to weather forecast message content generally focuses on how different content in messages can influence decision-making. Sutton et al. (2021) evaluated decision-making using tornado warning messages and found that the inclusion of protective action information increased people's understanding of the message, helped them decide how to respond, and increased both self-efficacy and response efficacy. Additionally, studies of message style find that warning messages should be clear and specific and emphasize the need for adequate detail to reduce recipients' response delay, all of which require *longer messages* (Wood et al. 2018). However, the ever-growing abundance of forecast information available to meteorologists will continue to force communicators to prioritize some information attributes over others when space and time become limited. This is especially true on social media, which is becoming an increasingly popular source for weather information—especially for those under age 35. In a 2021 survey of U.S. adults, 35% of respondents said they use social media (like Facebook and Twitter) at least once per week to get weather information (Krocak et al. 2021a).

Given the wealth of observations and model predictions available in real time, communicators can choose to provide a wide variety of forecast details to decision-makers. Examples include information about the location, severity, timing, chance, and impacts of weather phenomena, as well as recommended protective actions for those who may be impacted. These information attributes have been highlighted in prior work, and their importance has been established for decades (e.g., Mileti and Sorensen 1990; Lindell and Perry 2012; Sellnow et al. 2008).

As weather communicators look to craft more informative weather messages with new forecast information, knowledge about what information is most important to users is becoming increasingly essential. Forecast providers can craft more effective messages if they know which forecast attributes to highlight given the weather scenario and expected audience. To that end, this study evaluates how members of the public prioritize the six key weather forecast attributes mentioned previously across time (e.g., 5 days to 15 min) prior to the occurrence of severe, tropical, and winter weather events.

Data and methods

Data for this work come from three surveys in the Extreme Weather and Society Survey series, which is implemented and maintained by the University of Oklahoma's Institute for Public Policy Research and Analysis (IPPRA). Data on severe weather information priorities were collected using the 2021 Severe Weather and Society survey (WX survey), which was fielded between 8 and 17 June 2021 (Krocak et al. 2021a); data on tropical cyclone information priorities were collected using the 2021 Tropical Cyclone and Society survey (TC Survey), which was fielded between 22 June and 1 July 2021 (Krocak et al. 2021b); and data on winter weather information priorities were obtained using the 2022 Winter Weather and Society survey (WW Survey), which was fielded between 15 and 29 April 2022 (Bitterman et al. 2022). All three surveys were implemented online to U.S. adults (age 18+) who live in the continental United States. The WX and TC surveys had samples of approximately 1,550 U.S. adults and the WW survey had a sample of 1,423 U.S. adults. Survey quotas were used to ensure that the samples were demographically representative of the U.S. population as defined by U.S. Census estimates of gender, age, race, ethnicity, and NWS region. Table 1 demonstrates this representativeness by comparing population estimates from the U.S. Census to the characteristics of respondents for each of the surveys used in this work.

Each survey included two sets of questions to measure public priorities. The question sets were nearly identical except for mentions of hazard-specific information and slightly different time scales. In the first question, survey respondents were asked to rank the types of forecast information that are most important to them, *regardless of time frame*. The framing of this question was intended to induce a trade-off problem, where respondents had to prioritize what information was *more* or *less* important instead of being able to indicate that *everything* is important. Presentation of message characteristics (also called attributes) before ranking was randomized to prevent ordering effects. Question wording in the WX survey was as follows:

> Severe weather forecasts often include multiple pieces of information. We want to know how important each of the following pieces of information is to you. Please drag the boxes below to rank each piece of information from most important (top) to least important (bottom).

- Location: what area is the storm going to affect?
- Timing: when is the storm going to happen?
- Chance: how likely is the storm to occur?
- Severity: how intense is the storm going to be (for example: wind speed, hail size, amount of rain)?[1]

[1] TC survey: *Severity: how intense is the storm going to be (for example: wind speed, amount storm surge, amount of rain*)? WW survey: *Severity: how much snow or ice is the storm going to produce?*

Table 1. Demographic characteristics of the U.S. population according to the U.S. census (population estimates were obtained from the U.S. Census Annual Estimates of the Resident Population by Sex, Age, Race, and Hispanic Origin), the WX survey sample, TC survey sample, and WW survey sample. Values shown are unweighted percentages.

	U.S. adult population	WX survey	TC survey	WW survey
Gender				
Female	51.3	51.3	51.4	51.3
Male	48.7	48.7	48.6	48.7
Age				
18–24	12.0	12.0	12.0	12.8
25–34	18.0	18.0	17.9	17.7
35–44	16.3	16.3	16.4	16.7
45–54	16.4	16.4	16.4	17.7
55–64	16.7	16.7	16.7	16.4
65 and up	20.6	20.6	20.6	18.8
Ethnicity				
Hispanic	16.3	16.3	16.2	16.3
Non-Hispanic	83.7	83.7	83.8	83.7
Race				
White	77.9	77.9	77.8	77.9
Black or African American	13.0	13.0	13.0	13.0
Asian	5.9	5.9	5.9	5.9
Other Race	3.2	3.2	3.2	3.2
NWS Region				
Eastern	31.6	31.7	31.8	31.9
Southern	27.1	27.1	27.2	27.1
Central	20.7	20.7	20.6	20.7
Western	20.6	20.5	20.5	20.3

- Impacts: how might the storm impact you and surrounding areas? (for example: poor visibility, traffic delays, power outages, property damage)[2]
- Protective actions: how can you stay safe during the storm? (for example: slow down when driving, stay inside, seek shelter)[3]

To capture variation in the event timeline, the second set of survey questions asked respondents to identify the *most important* information attribute to them at multiple points before a hypothetical weather event. This consisted of four or five multiple choice questions asking respondents to pick the most important piece of information at each indicated point in the timeline. Respondents were allowed to select the same piece of information at multiple points if they chose to do so, but to force prioritization, they were *not* allowed to select more than one piece of information at a single point in the timeline. The points along the event timeline were chosen to be consistent with messaging time frames that roughly match the time scales when outlooks, watches, and warnings are issued before an event. Table 2 displays the points in time that were used on each survey. Question wording was as follows:

> Some people look for different kinds of information at different points in time. In the next few questions, we are going to give you a timeline and ask you to indicate the type of information that is most important at each point in time.

[2] TC survey: *Impacts: how might the storm impact you and surrounding areas? (for example: power outages, property damage).* WW survey: *Impacts: how might the storm impact you and surrounding areas? (for example: poor visibility, traffic delays, power outages, school or work closures, property damage).*

[3] TC survey: *Protective actions: how can you stay safe during the storm? (for example: stay inside, seek shelter, evacuate).* WW survey: *Protective actions: how can you stay safe during the storm? (for example: slow down when driving, stay inside).*

Aggregate responses to the first question were analyzed by calculating the mean ranking of each information attribute on a scale that ranged from 1 (most important) to 6 (least important) across the three hazard domains. Responses to the second question set were analyzed by calculating the proportion of respondents who chose each attribute at different points in time, again, across the three domains.

Table 2. The points along the event timeline (listed as "before the storm") survey respondents were asked to identify the most important piece of information. Response options included location, timing, chance, severity, impacts, and protective actions.

WX survey	TC survey	WW survey
3 days	5 days	5 days
1 day	3 days	3 days
4 h	2 days	2 days
60 min	1 day	1 day
15 min		Day of the storm

Despite significant differences in exposure, all three surveys were national in scope. This meant that respondents in California and Oklahoma, for example, were both asked to indicate information priorities in advance of severe weather events. Given significant differences in exposure (and experience), we might expect Californians to prioritize different types of information than Oklahomans. The same is true of tropical cyclone weather in Wyoming versus Florida, for example, or winter weather in Minnesota versus Texas. To account for these differences, respondents were stratified by the number of severe, tropical, and winter weather warnings their NWS Weather Forecast Office (WFO) issues in an average year. Data for the stratification came from the Iowa Environmental Mesonet's Archive of NWS Watch, Warnings, and Advisories (IEM 2022). Using these data, we grouped respondents into low or high exposure groups. For severe and winter weather, respondents at or below the 10th percentile in average warning frequency were assigned to the low exposure group; respondents at or above the 90th percentile were assigned to the high exposure group. For tropical cyclones, respondents from areas that received an average of one or more tropical warnings per year were assigned to the high exposure group; respondents with an average of zero warnings were assigned to the low exposure group.

Results

Mean overall attribute rankings were generally similar across the severe, tropical, and winter weather domains. Across all three hazards, respondents ranked location as the most important piece of information, with mean rankings of 2.38, 2.50, and 2.49 out of 6 in the severe, tropical, and winter domains, respectively (with a value of 1 suggesting a ranking of most important and 6 suggesting least important; Fig. 1). After location, timing, severity, and chance were ranked similarly to each other. In the severe and tropical domains, timing was ranked higher on average than chance or severity (the mean ranking for timing was 2.85 and 3.02 out of 6 in the severe and tropical domains, respectively), but severity and timing information were given nearly identical mean rankings in the winter weather domain (2.92 and 2.96; Fig. 1). Finally, impacts and protective action information were ranked similarly in the severe and tropical domains (around 4.5 out of 6), but impacts were rated higher (4.11) than protective actions (4.96) in the winter weather domain (Fig. 1).[4]

[4] While these results were similar across hazard domains, it is possible that different groups of people prioritize information in different ways. For example, people who regularly get winter storms may prioritize information differently than someone who has never seen snow before. To investigate these differences, we stratified the results in Fig. 1 by average annual warnings for the respondent's County Warning Area (CWA). We saw marginal differences across the high and low warning group. These results are shown in the supplemental material.

Severe weather hazards. As in the overall rankings, respondents' temporally specific priorities were generally consistent across the hazards, with a few notable exceptions. In the severe weather domain, chance and location information were chosen as the most important attributes for over 65% of respondents 3 days out from the event (Fig. 2). We theorize that this is related to participants trying to answer the question "Is it for me?" that emerges

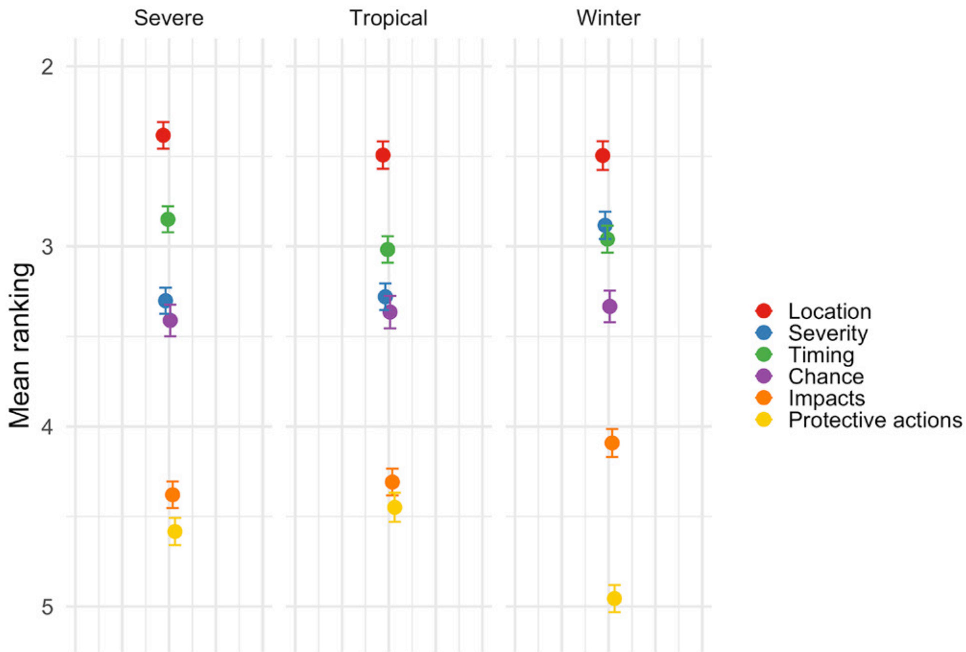

Fig. 1. Mean rankings of importance for different information attributes. A ranking of 1 indicates the most important piece of information, whereas a mean ranking of 6 indicates the least important piece of information. Error bars represent the 95% confidence interval. Note that these are overall rankings, not specific to any time frame.

when they are just starting to hear about a potential event during the outlook time frame. If the chance of an event happening is low, or if the event is not likely to impact a person's location, they are unlikely to continue seeking information about the event. However, this changed at 1 day out from the event, as location and timing information became the most often prioritized attributes. Severity and chance were also increasingly chosen at this time frame, suggesting an increasing interest in the details of the event at this point in the timeline (Fig. 2). At 4 h from the event (typically when a severe thunderstorm or tornado watch might be issued), severity, location, timing, and chance were the top four most chosen pieces of information, respectively. However, participants also began to more frequently choose impacts and protective action information at this time period (Fig. 2). These results suggest

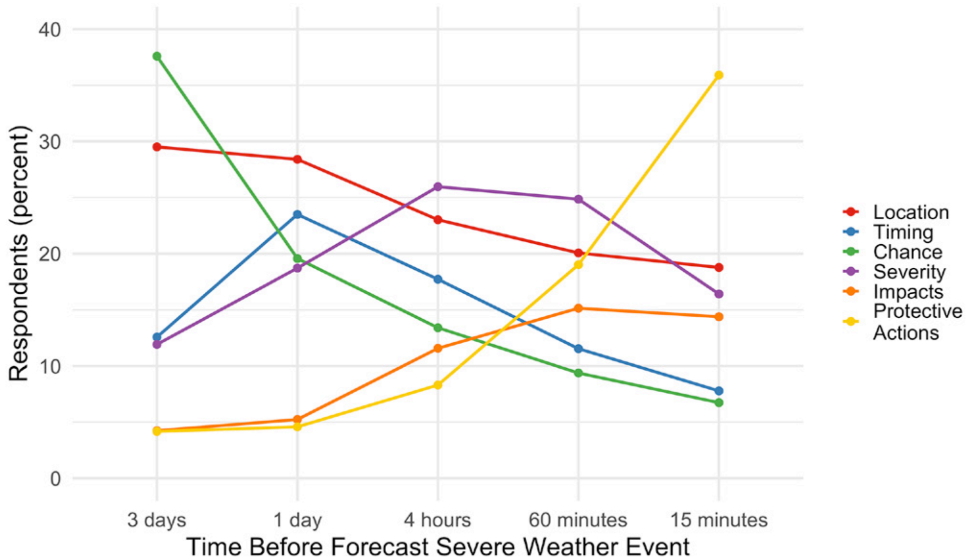

Fig. 2. The percentage of survey respondents that chose each information attribute as the most important at different points in time for severe weather events. See Table ES1 of the supplemental material for point estimates and standard errors.

that the details of the event are more important before warnings are issued because they dictate what preparations people may need to make in advance of the event. For example, if a severe weather event is forecast to hit during a large or outdoor gathering, an individual receiving that forecast may choose to cancel their plans to attend that event. If the severe weather is forecast to hit during a commute, a recipient may choose to leave early or stay late.

The survey results show a noteworthy shift in information priorities at 60 min out from a severe weather event, when the proportion of people who chose protective action information increased significantly from the 8.3% at 4 h to 19.1% at 60 min ($p < 0.001$; Fig. 2). Impacts were also chosen more frequently than previous time frames, while chance and timing information were chosen less frequently. This could be because an event is almost ongoing at this point. People do not need to know *if* it is going to happen or *when* it will happen if storms are already ongoing and are potentially an imminent local threat. At 15 min before the event (when a warning might be issued), protective action information became the most frequently chosen attribute, with over 35% (the modal response) of respondents choosing it. The next most frequently chosen information type was location, with just below 20% of respondents choosing it (Fig. 2).

The overall trends in information attribute prioritization across the severe weather event timeline tell an important story. Chance is most important further out from the event but decreases quickly as the event draws near. Conversely, protective action information has the opposite effect. This information is least important further out from the event, then increases in importance right before the event takes place. In addition to analyzing relative information preferences, it is interesting to note the evolution of agreement on which pieces of information are most important. In the severe weather domain, consensus decreased as the event approached, indicating increasing heterogeneity in information preferences at short time scales.[5]

[5] Shannon's entropy is a common statistic that analysts use to measure diversity of preferences. In this work, the entropy value was 2.17 at 3 days from the event and 2.35 at 15 min before the event. This increase in entropy is indicative of a decrease in consensus among respondents.

Tropical cyclone hazards. Information priorities across time before a tropical cyclone event showed very similar patterns to those in the severe weather domain. At 5 days before the event, location and chance were the most important details for the majority of participants, with nearly 65% of respondents choosing one or the other (Fig. 3). At 3 days before the

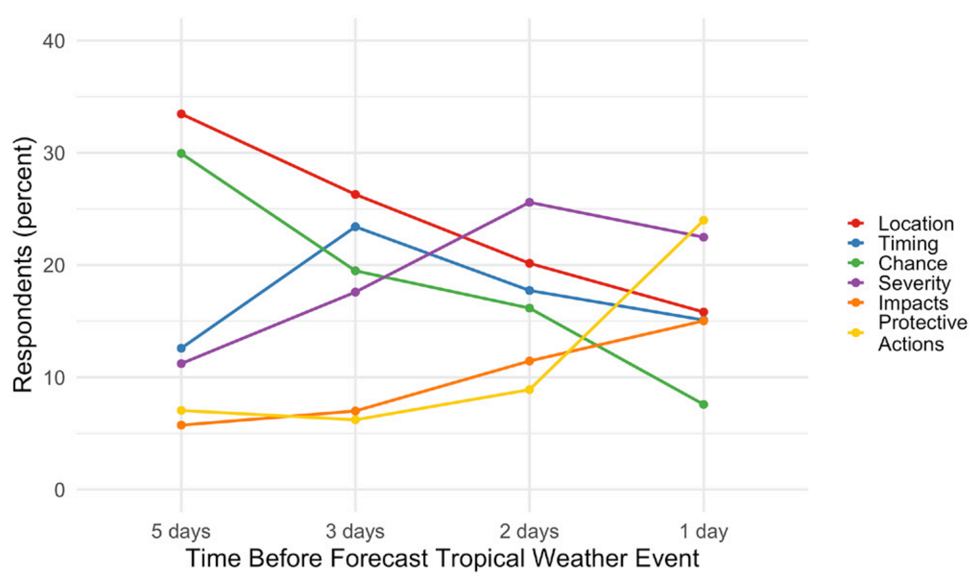

Fig. 3. The percentage of survey respondents that chose each information attribute as the most important at different points in time for tropical cyclone events. See Table ES2 of the supplemental material for point estimates and standard errors.

event, location remained the most important information type while timing became the second most chosen attribute, although chance and severity were close in third and fourth places, respectively. Fewer participants chose chance and location information as most important with each time step closer to the event, while severity was the most chosen attribute at 2 days before the event (Fig. 3).

At 1 day before the event, protective action and severity information had nearly identical proportions (24% and 22.5%, respectively). The large proportion of participants selecting severity information as most important so close to the event is not surprising given that the severity of the tropical cyclone greatly impacts what actions respondents take. For example, a stronger hurricane may mean people in homes well inland need to evacuate, while a weaker tropical storm may only require those same people to prepare their property and gather some supplies. Otherwise, the overall pattern of information preferences across time was similar to that for severe weather events (as shown in Fig. 2). Location and chance were most important further out from the event, while details like severity and timing were rated as more important as a tropical weather event approached, with protective action information becoming more important when the event became imminent. Like the severe weather domain, preferences were more diverse at 1 day before the event than they were at 5 days before the event, suggesting, again, that preferences diversify as tropical cyclone events become more imminent.[6]

[6] The Shannon entropy value was 2.28 at 5 days from the event and 2.50 at 1 day before the event.

Winter weather hazards. Respondents' information priorities across time before a winter event followed a similar trajectory as the tropical cyclone timeline. Participants chose severity information as most important more frequently as a winter weather event approached in time. Beginning at 5 days before the event occurs, chance and location were the two most chosen attributes (Fig. 4). Although chance and location information were less frequently chosen as most important, this pattern held at 3 days before a winter weather event, with timing and severity information more frequently chosen.

Notably, in all three hazard contexts studied in this work, chance and location were the most frequently chosen information types for the longest-range time frame. This highlights the need for individuals to understand if an event is going to impact them before they are concerned with other details like timing and severity.

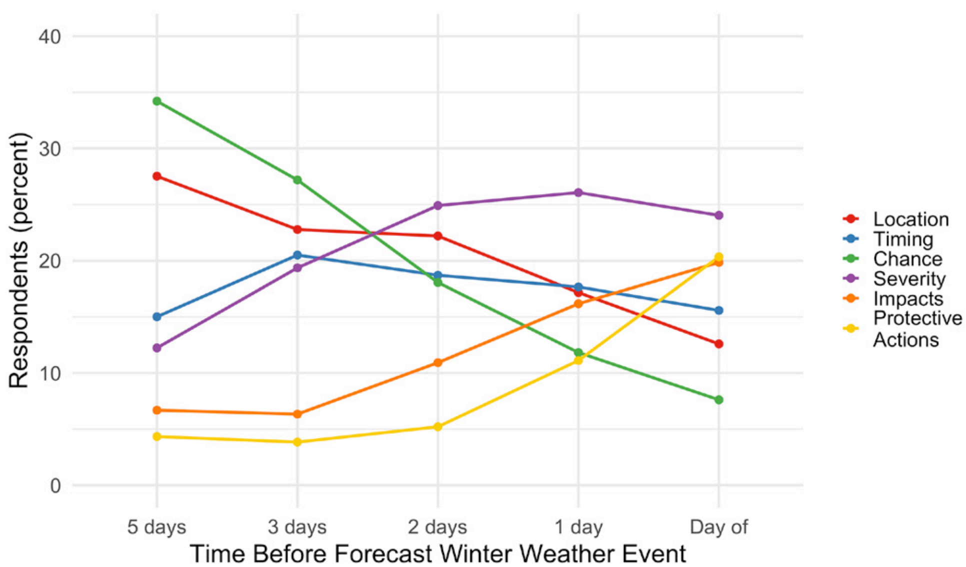

Fig. 4. The percentage of survey respondents that chose each information attribute as the most important at different points in time for winter weather events. See Table ES3 of the supplemental material for point estimates and standard errors.

At 2 days before a winter weather event, 25% of respondents chose severity as the most important information attribute. Location remained the second most frequently chosen information type, while chance fell to fourth most chosen below timing information (Fig. 4). Severity remained the most important piece of information for most participants for both the day-before and day-of time frames, while the proportion of respondents who chose chance, location, and timing information as most important decreased across the same time period. Finally, the proportion of respondents who chose impacts and protective action information increased as the event approached, with both being chosen by about 20% of participants by the day of the event. Thus, participants highlighted severity, protective action, and impact information as the top three most important pieces of information on the day of a winter weather event, respectively. Finally, in addition to looking at relative preferences, we also assessed overall consensus among respondents. Similar to severe and tropical domains, consensus decreased as the event drew near.[7]

[7] The Shannon entropy value was 2.27 at 5 days from the event and 2.49 on the day of the event.

Previous hazard experience. Another notable pattern consistently seen across all three hazard domains was the increase in respondents prioritizing protective action information as the event became imminent. Protective action information was the most chosen attribute right before the event in the severe and tropical domains, and it was in the top three most chosen attributes in the winter weather domain. While this trend was present in all three hazard domains, we expect that different populations may prioritize information differently. For example, people with less experience with hazardous weather events may know they are in danger but might be unaware of what they can do to protect themselves. Therefore, we might expect people in Florida to prioritize protective actions less often than people in Wyoming given a tropical cyclone event. To investigate differences across exposure to the three hazard domains (as a proxy for previous experience) we use mean annual warning counts in respondents' NWS County Warning Area (CWA) to stratify the prioritization of protective action information (Fig. 5).[8] As a reminder, we defined the "low" and "high" warning groups

[8] We chose to specifically focus on the differences in protective action prioritizations because they showed consistent differences across exposure groups. The supplemental material shows the results for all six information attributes. We also analyzed information prioritizations across demographic groups, which showed marginal differences. See the supplemental material for these results.

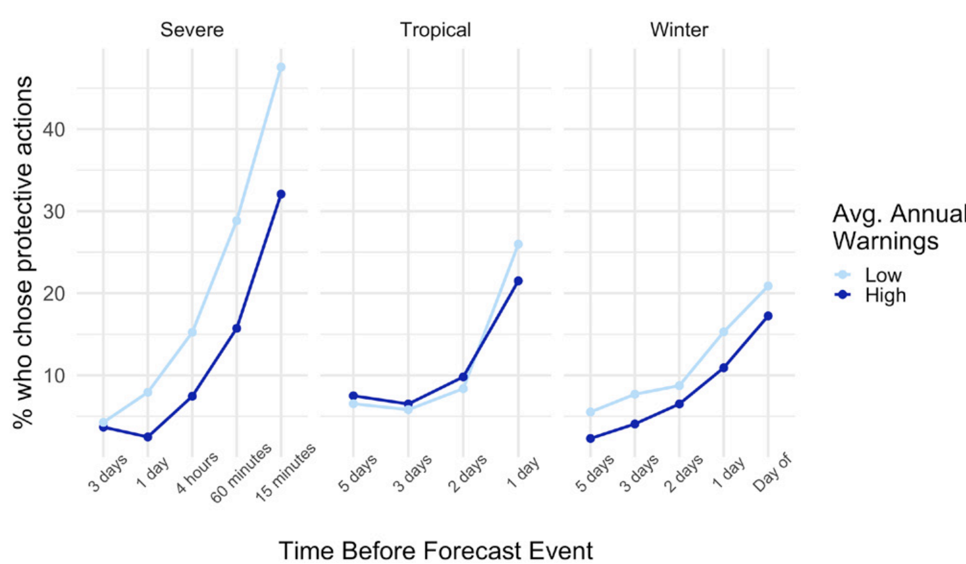

Fig. 5. The percentage of survey respondents that chose protective actions as the most important at different points in time for all three hazard domains. These results are stratified by mean annual warning count for the respondents NWS County Warning Area. See Table ES4 of the supplemental material for point estimates and standard errors.

as the 10th and 90th percentiles of mean number of warnings per year in a respondent's CWA. These results are robust to varying thresholds for the low and high warning groups (i.e., 20th and 80th or 25th and 75th percentiles).

Participants with low annual warning counts were more likely to prioritize protective action information at all points in the timeline for severe and winter weather events. This difference was largest during the warning time frame, where 47% of respondents with low numbers of annual severe weather warnings chose protective action information compared to 33% of respondents with high annual severe weather warnings ($p < 0.05$). For the winter weather event, nearly 22% of low warning count respondents prioritized protective action information, compared to 18% of high warning respondents. The tropical cyclone event differed slightly in that respondents with low warning counts were about equally likely to choose protective actions as high warning count respondents until 1 day before the event. At this point, 26% of low warning count respondents chose protective action information, compared to 22% of high warning count respondents. While these results are suggestive of a trend toward those with less experience prioritizing protective action information more often than those with more experience, the winter weather and tropical cyclone results were not statistically significant at the $\alpha = 0.05$ level.

Discussion

Although there are hazard-dependent details, the overall pattern of what information participants found most important across time was relatively consistent. For all three hazard domains, respondents first prioritized information to answer the question of whether an event will affect them (this is also known as the personalization of risk; Lindell and Perry 2012; Sellnow et al. 2008), which includes information about the chance the event will occur and the location that will be affected. Chance and location information may be conflated by survey respondents, as the location of the event inherently drives the likelihood that someone will experience the hazard. People are often looking for location-specific data because they need to understand if they should continue to worry about a weather hazard, or if they can continue to prioritize other problems in their lives over a potential weather threat. Once an event became more certain as it approached in time, individuals tended to prioritize details like timing and severity information. The timing of the event can have huge implications on what actions people take, such as rearranging schedules, seeking out potential shelter areas, finding better shelter for cars, or any other preparatory action related to work, school, and preexisting plans people have. Assuming that an approaching event remains relevant and severe enough to warrant protective action, then the impacts and action information became important for individuals to understand what to expect from a hazard and what to do to in response to it.

Impact and protective action information were generally most important to participants as an event drew near. However, some of the most notable hazard-specific differences in information preferences occurred as each hazard became imminent. Protective actions were by far the most important piece of information in the warning time frame (i.e., 15 min before the event) in the severe weather domain, but this pattern did not hold for tropical weather or winter weather. For tropical events, severity information remained important until the day before the event, when protective actions and severity were almost equally prioritized by participants. In the winter weather domain, severity remained the most often chosen piece of information but impacts and protective actions were the next most important. The importance of severity information in these contexts may reflect the relationship between the severity of a tropical cyclone or winter storm and the actions that people take to manage increasingly significant impacts. A more severe tropical cyclone may mean evacuating the area instead of gathering supplies and staying at home, while a more severe winter weather event may require staying home because schools and workplaces are closed versus taking extra precautions while driving to those locations. Alternatively, the protective actions suggested for tornadoes, severe hail, and wind are generally the same regardless of severity: get inside the lowest level of a well-constructed building away from windows, preferably in a basement or storm shelter.

In addition to analyzing the relative information preferences for each hazard type, we also explored the consensus in preferences among respondents across time. For all three hazard types, preferences became more diverse as the event became more imminent. This result may reflect the variety of experiences, expectations, and circumstances that individuals face as events approach. Different people expect and require different sorts of information. For some, protective action information is critical. For others, they know what to do in different situations, and are looking for more specific information to guide their actions (e.g., information about severity and impacts). This variety of preferences makes it especially challenging for forecasters at this time frame. Ideally, forecasters highlight as much information as they can given time and space constraints.

Along these lines, stratifying the results by mean annual warning count (as a proxy for exposure and experience) showed some differences in preferences for protective action information, especially at the warning time frame. Respondents with fewer average annual warnings were more likely to prioritize protective action information than respondents in areas where warnings are more common. These results coincide well with the findings of Sutton et al. (2021), who showed that protective action information helps people decide how to respond to a tornado warning and increases their belief that they can successfully protect themselves from the hazard. Jointly, these results highlight the benefits of including protective action information in weather hazard messaging, particularly for those less familiar with the hazard.

Impact information was never rated as the most important piece of forecast information in any of the three weather domains studied here, which may be partially due to survey design. The questions forced prioritization on respondents, meaning that the rankings displayed in the results are relative, not absolute. Although the impacts attribute was often near the bottom of the average rankings, that does not necessarily mean that impact information was not important, it simply means that other pieces of information were prioritized over impact details. Furthermore, respondents may be assuming impact information from severity information, especially if they have previous experience with the hazard.

In addition to these trade-offs in the experimental design, it is also important to recognize the limitations of online survey instruments. These surveys often do not serve vulnerable populations as well and favor data collection from those with a higher socioeconomic status (Jang and Vorderstrasse 2019). Additionally, there is a known self-selection bias with all surveys, and in particular younger populations tend to take online surveys more often than older people do (Jang and Vorderstrasse 2019). Survey quotas were used to mitigate these impacts, but further work should specifically study those who are less likely to be represented in surveys, through interviews, in person experiments, focus groups, and other methods to ensure that these findings reflect the needs of highly vulnerable groups.

Using the cumulative results of this work, we suggest a general framework for forecasters and communicators to use when building weather forecast communication products (Fig. 6). We reference the outlook time frame (used here to reference 1–5 days in advance of the event), watch time frame (used here to reference a few hours to 1 day in advance of the event), and warning time frame (a few hours to a few minutes before the event), but we recognize that these products are specific to the hazard domain. During the outlook time frame, respondents generally want to know the chance that an event is going to happen and the location that will most likely be impacted. Other details (like timing and severity information) can

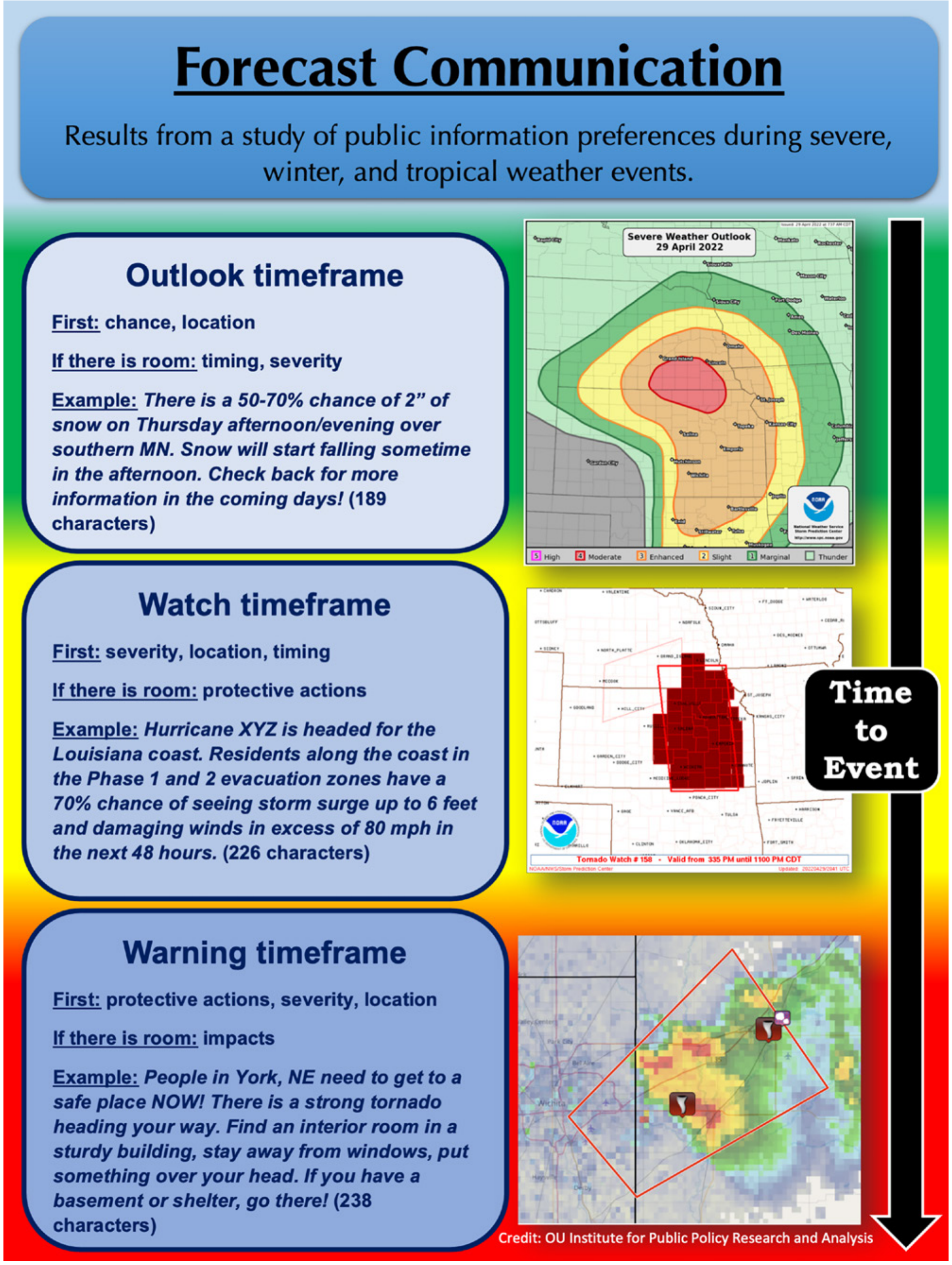

Fig. 6. **A framework of information to include at different points in the event timeline.**

also be useful if space in a message allows. During the watch time frame, messages should emphasize details on hazard severity and timing, as well as location if possible. Protective action suggestions also become increasingly important to discuss during this time frame. As the event draws near and enters the warning time frame, protective action and severity information (as well as location) become the most important details to include. Protective action information is particularly important for those who are not as familiar with the hazard, suggesting action information is especially important for anomalous events occurring outside their normal geographic range. Finally, information about the impacts of a hazard are important to include in the warning time frame if space allows. While this framework should not be thought of as defining the *only* information to include, it provides empirical guidance to forecasters and communicators in the weather enterprise who are working to create products and disseminate information that matches public priorities as extreme weather events unfold in time. One example of other information that was not tested in this work is pre-preparation actions (making an evacuation plan, cleaning out storm shelters, buying gas for generators, etc.). This information can be important to include seasonally and during shorter time frames (like the outlook phase) but was not included in this framework since it was not tested in this study. Future work should seek to include more types of information at longer time frames.

Acknowledgments. Data collection for this project was funded by the OU Office of the Vice President for Research and Partnerships. Data analysis was funded by the NOAA Weather Program Office under Grants NA18OAR4590376, NA20OAR4590345, NA16OAR4320115, and NA22OAR4590519.

Data availability statement. Data from the Extreme Weather and Society Survey can be found at https://dataverse.harvard.edu/dataverse/wxsurvey. Mean annual warning counts can be calculated using data from the IEM at https://mesonet.agron.iastate.edu/request/gis/watchwarn.phtml. R code to reproduce the results in this manuscript can be found on the OU Institute for Public Policy Research and Analysis GitHub: https://github.com/oucrcm/wxsurvey.

References

Benjamin, S. G., and Coauthors, 2016: A North American hourly assimilation and model forecast cycle: The Rapid Refresh. *Mon. Wea. Rev.*, **144**, 1669–1694, https://doi.org/10.1175/MWR-D-15-0242.1.

Bitterman, A., and Coauthors, 2022: Refining the baseline: Public reception, understanding, and responses to winter weather forecasts and warnings in the contiguous United States. Harvard Dataverse, accessed 2 June 2022, https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/OXT3K8.

Gallo, B. T., and Coauthors, 2022: Exploring the watch-to-warning space: Experimental outlook performance during the 2019 spring forecasting experiment in NOAA's Hazardous Weather Testbed. *Wea. Forecasting*, **37**, 617–637, https://doi.org/10.1175/WAF-D-21-0171.1.

Harrison, D. R., M. S. Elliott, I. L. Jirak, and P. T. Marsh, 2022: Utilizing the high-resolution ensemble forecast system to produce calibrated probabilistic thunderstorm guidance. *Wea. Forecasting*, **37**, 1103–1115, https://doi.org/10.1175/WAF-D-22-0001.1.

IEM, 2022: Archived NWS watch, warnings, advisories. Iowa Environmental Mesonet, accessed 24 June 2022, https://mesonet.agron.iastate.edu/request/gis/watchwarn.phtml.

Jang, M., and A. Vorderstrasse, 2019: Socioeconomic status and racial or ethnic differences in participation: Web-based survey. *JMIR Res. Protoc.*, **8**, e11865, https://doi.org/10.2196/11865.

Krocak, M. J., J. T. Ripberger, C. Silva, H. Jenkins-Smith, A. Gaviria-Pabón, A. Forney, and A. Bitterman, 2021a: Continuing the series: Public reception, understanding, and responses to severe weather forecasts and warnings in the contiguous United States. Harvard Dataverse, accessed 2 June 2022, https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/QYZLSO.

——, ——, ——, ——, S. Ernst, A. Gaviria-Pabón, A. Forney, and A. Bitterman, 2021b: Continuing the baseline: Public reception, understanding, and responses to tropical cyclone forecasts and warnings in the contiguous United States. Harvard Dataverse, accessed 2 June 2022, https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/Q2S7OJ.

Lindell, M. K., and R. W. Perry, 2012: The protective action decision model: Theoretical modifications and additional evidence. *Risk Anal.*, **32**, 616–632, https://doi.org/10.1111/j.1539-6924.2011.01647.x.

Mileti, D. S., and J. H. Sorensen, 1990: Communication of emergency public warnings: A social science perspective and state-of-the art assessment. Oak Ridge National Laboratory Rep. ORNL-6609, 162 pp., https://www.osti.gov/servlets/purl/6137387.

NSSL, 2021: Spring forecasting experiment 2021 preliminary findings and results. NOAA/NSSL, 86 pp., https://hwt.nssl.noaa.gov/sfe/2021/docs/HWT_SFE_2021_Prelim_Findings_FINAL.pdf.

Roberts, B., I. L. Jirak, A. J. Clark, S. J. Weiss, and J. S. Kain, 2019: Postprocessing and visualization techniques for convection-allowing ensembles. *Bull. Amer. Meteor. Soc.*, **100**, 1245–1258, https://doi.org/10.1175/BAMS-D-18-0041.1.

Sellnow, T. L., R. R. Ulmer, M. Seeger, and R. S. Littlefield, 2008: *Effective Risk Communication: A Message-Centered Approach.* Springer, 197 pp.

Sutton, J., L. Fischer, and M. M. Wood, 2021: Tornado warning guidance and graphics: Implications of the inclusion of protective action information on perceptions and efficacy. *Wea. Climate Soc.*, https://doi.org/10.1175/WCAS-D-21-0097.1.

Wang, C., P. Wang, D. Wang, J. Hou, and B. Xue, 2020: Nowcasting multicell short-term intense precipitation using graph models and random forests. *Mon. Wea. Rev.*, **148**, 4453–4466, https://doi.org/10.1175/MWR-D-20-0050.1.

Wood, M. M., D. S. Mileti, H. Bean, B. F. Liu, J. Sutton, and S. Madden, 2018: Milling and public warnings. *Environ. Behav.*, **50**, 535–566, https://doi.org/10.1177/0013916517709561.