Hurricane Risk Communication: Visualization and Behavioral Science Concepts

BARBARA MILLET,^a ANDREW P. CARTER,^{b,f} KENNETH BROAD,^{b,c} ALBERTO CAIRO,^d
SCOTNEY D. EVANS,^e AND SHARANYA J. MAJUMDAR^c

^a *Department of Cinema and Interactive Media, School of Communication,
University of Miami, Coral Gables, Florida*

^b *Abess Center for Ecosystem Science, University of Miami, Coral Gables, Florida*

^c *Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida*

^d *Department of Journalism and Media Management, School of Communication,
University of Miami, Coral Gables, Florida*

^e *Department of Educational and Psychological Studies, School of Education and Human Development,
University of Miami, Coral Gables, Florida*

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ABSTRACT

Increasingly, the risk assessment community has recognized the social and cultural aspects of vulnerability to hurricanes and other hazards that impact planning and public communication. How individuals and communities understand and react to natural hazard risk communications can be driven by a number of different cognitive, cultural, economic, and political factors. The social sciences have seen an increased focus over the last decade on studying hurricane understanding and responses from a social, cognitive, or decision science perspective, which, broadly defined, includes a number of disparate fields. This paper is a cross-disciplinary and critical review of those efforts as they are relevant to hurricane risk communication development. We focus on two areas that, on the basis of a comprehensive literature review and discussions with experts in the field, have received comparatively little attention from the hazards community: 1) research concerning visual communications and the way in which individuals process, understand, and make decisions regarding them and 2) the way in which vulnerable communities understand and interact with hurricane warning communications. We go on to suggest areas that merit increased research and draw lessons or guidance from the broader hazards/social science research realm that has implications for hurricane planning and risk communication, particularly the development and dissemination of hurricane forecast products.

1. Introduction

Increasingly, the risk assessment community has recognized the social and cultural aspects of vulnerability to hurricanes and other hazards that impact planning and public communication. Improved forecast models and observational networks over the past several decades have given governmental entities an earlier and more accurate understanding of the risks posed by incoming hurricanes, but adequately communicating those risks in an actionable way to the general public has lagged behind. Traditional natural hazard risk communications

have frequently been based, at least implicitly, on “rational actor” assumptions, or the belief that more accurate information leads to more “rational” behavior in response (e.g., O’Sullivan et al. 2012; Owens 2000). However, experience has shown that even when given accurate and timely information about hurricane risks, some members of the public react in what appear to be “irrational” ways. By irrational, we mean responses that do not adequately align with experts’ assessment of appropriate risk behavior, based on calculations where risk equals probability multiplied by loss. For example, many people fail to evacuate even when there is a high probability of loss, or, alternately, evacuate when the cost of evacuation exceeds the risk-adjusted cost of damage.

This has led to increased focus over approximately the last decade on studying hurricane understanding and

^f Current affiliation: Center for Conservation Innovation, Defenders of Wildlife, Washington, D.C.

Corresponding author: Barbara Millet, bmillet@miami.edu

responses to forecast communications from a social, cognitive, or decision science perspective, through a broad array of social science perspectives and methods, from ethnographic studies to computer simulation experiments. A 2018 report by the National Academies of Sciences, Engineering, and Medicine, for example, acknowledges the “growing recognition that a host of social and behavioral factors affect how we prepare for, observe, predict, respond to, and are impacted by weather hazards” (National Academies of Sciences, Engineering, and Medicine 2018, p. 1). It lays out an “essential” interdisciplinary research agenda to develop greater understanding of “how people’s knowledge, experiences, perceptions, and attitudes shape their responses to weather risk” and even “affect the forecast process itself” (National Academies of Sciences, Engineering, and Medicine 2018, p. 1). Aligned with this broader agenda, our paper is a cross-disciplinary, critical review of hurricane forecast communications of those efforts in terms of their relevance to hurricane risk understanding. We focus on two areas that based on a comprehensive literature review and discussions with experts in the field have received comparatively little attention from the hazards community: 1) research concerning visual communications and the way in which individuals process, understand, and make decisions regarding them and 2) the way in which vulnerable communities understand and interact with hurricane warning communications.¹ We then identify areas that merit increased research and draw lessons or guidance from the broader hazards/social science research realm with relevance to hurricane planning and risk communication, particularly for those developing and disseminating hurricane forecast products.

2. Methods

The sources selected for this literature review were obtained through keyword searches, reviews of relevant articles’ bibliographies and reference lists, government reports, and media sources dealing with hurricane experiences, with a focus on research conducted with populations in the United States. References were selected for inclusion when they were foundational works that provided theoretical and methodological underpinnings of relevant social science research programs, or were studies of hurricane risk-related phenomena dealing with these fields. Additionally, we explored natural

hazards-related literature that could be similarly applied to the hurricane risk domain (e.g., attitudes toward shelters).

Throughout this article, we selected research that served as relevant demonstrations of the issues under discussion; they are not an exhaustive review of all relevant works, or even potentially relevant social scientific fields. Instead, they are intended to point the reader to lines of research that may provide actionable information to improve hurricane forecast and risk communication strategies. Our review was prepared to attempt to answer the questions set forth in Fig. 1.

a. Hurricane risk communication approaches

Those at risk from hurricane events tend to get their information about impending hurricanes from different sources (Broad et al. 2007; Dash and Gladwin 2007; Huang et al. 2012; Miller and Rivera 2010). Not only do those potentially at risk from hurricane strikes tend to rely on television, radio, Internet, and mobile applications (“apps”), but also frequently on informal social networks to evaluate their risk and the need to take actions such as evacuating. The format of the hurricane forecast or risk communications themselves take a variety of forms, both visual and nonvisual. Frequently, media sources will show the possible future path of the center of the hurricane. This is often accompanied by a “cone of uncertainty,” which in the Atlantic and eastern Pacific Ocean basins is created by the National Hurricane Center (NHC). However, other communications exist, including those that provide probabilistic information in textual form, those showing maps with areas under hurricane and tropical storm watches or warnings color coded, or those that simply give narrative descriptions (either spoken or textual) of the history of the storm and its possible paths. Because of the number of different governmental, media and other sources of such communications, they can take radically different forms, although in the United States the NHC tends to be the primary information source (Sherman-Morris et al. 2011) and the efficacy of its forecast graphics has been the subject of a number of studies (e.g., Boone et al. 2018; Broad et al. 2007; Ruginski et al. 2016). In recent years, the NHC has placed significant emphasis on a small number of “key messages” with accompanying graphics, focusing more on the impacts (such as flooding) and less on physical characteristics of the hurricane itself, such as its center.

b. Public reaction to hurricane information

Despite the costs of hurricanes in terms of both human life and the economy, and the fairly comprehensive and widely disseminated forecast information provided to

¹ For a comprehensive analysis of integrating social science into the weather enterprise generally, see National Academies of Sciences, Engineering, and Medicine (2018).

FIG. 1. The literature review framework for understanding hurricane risk communications.

the public (at least in the United States), responses to such communications vary (e.g., [Dash and Gladwin 2007](#)). Even those at high risk for being impacted by a hurricane often do not act to reduce or minimize that risk (e.g., [Baker et al. 2012](#); [Ricchetti-Masterson and Horney 2013](#)). Mandatory evacuation orders are often not complied with by many people at risk ([Baker 2005](#); [Hasan et al. 2011](#); [Ricchetti-Masterson and Horney 2013](#)). Even when residents living in a high-risk area have hurricane shutters, they often do not put them up before the storm hits ([Baker et al. 2012](#)). Some researchers have found that few people living in evacuation zones plan to evacuate ([Milch et al. 2018](#)). Even those who plan to evacuate may not ultimately evacuate when the storm approaches ([Meyer et al. 2014](#)). Although perhaps counterintuitive, a number of researchers have found that individuals who have been affected by hurricanes in the past may be more likely to *underestimate* future hurricane risk ([Hasan et al. 2011](#); [Matyas et al. 2011](#); [Meyer et al. 2013](#)). Even where the public perceives a high risk of hurricane damage, their actions during hurricanes do not always appear to reflect that perception.

On the other hand, sometimes the public may *overestimate* hurricane risks, taking actions that go beyond what is necessary or believing themselves to be at risk even where they are not ([Dessaint and Matray 2017](#); [Dueñas-Osorio et al. 2012](#)). Residents may evacuate when they do not live in an evacuation zone ([Dueñas-Osorio et al. 2012](#)). [Meyer et al. \(2014\)](#) found that residents overestimated the likelihood they would experience hurricane-force winds by an average factor of 5, although only a small percentage thought they would experience personal harm. Commonly the public will simultaneously overestimate the possibility of, or damages

from, hurricane-force winds while underestimating the dangers posed by flooding ([Meyer et al. 2014](#); [Morss and Hayden 2010](#)).

3. Cognitive and cultural dimensions of risk

Although a comprehensive review of social science literature relevant to hurricane risk perception is not practical, below we attempt to provide a broad overview of different lines of social science research that may be of particular interest to hurricane forecast product developers, risk communicators, and emergency managers. Where other authors have provided more in-depth reviews of specific fields, we list those references. For areas that have not received significant treatment in the hurricane research literature, we provide particular detail.

Cognitive dimensions of hurricane risk perception

The second half of the twentieth century saw a cognitive revolution, heavily influenced by work in computer science, cybernetics, and communications, that supplanted simpler behaviorist approaches to thinking ([Gardner 1987](#)). Two lines of cognitive science research have become a critical part of risk and natural hazards research: 1) judgment and decision-making (JDM) and 2) mental models. Researchers in both areas attempt to capture the complex and often counterintuitive ways in which human beings reason and make decisions. Although a number of other approaches to the psychology of reasoning and decision-making exist, we examine those two areas here because the body of literature examining them is particularly useful to hurricane risk communication development.

4. JDM

JDM typically focuses on identifying specific heuristics, or the cognitive shortcuts people take when making decisions, usually about probabilities.² Although heuristics can sometimes be useful in avoiding expenditure of significant cognitive resources, in some cases they lead to recurrent biases whereby individuals may make suboptimal or apparently nonrational decisions in response to risk. By identifying consistent biases, researchers seek ultimately to present risk information in a way that results in behavior consistent with it. Although researchers have tended to identify discrete heuristics and biases that represent specific cognitive mechanisms, many may be different manifestations of the same or similar mental processes. For example, [Kahneman and Frederick \(2002\)](#) have proposed that many of the heuristics and biases that have been identified (many of the foundational ones by Kahneman and his colleague Amos Tversky) fall under a more general attribute substitution, or the tendency for individuals to reduce complex decision-making to simpler processes. Indeed, underlying much of the work on heuristics and biases in the JDM domain is the premise that human beings make decisions under two overall types of processes—system-1 thinking, which is fast, comparatively low effort, and often unconscious, and system-2 thinking, which is slow, conscious, and considered ([Kahneman 2011](#)). Because we do not have the time or mental resources to make all our decisions through system-2 thinking, we rely on system-1 thinking for much of our decision-making.

Because research into heuristics and biases tends to focus on identifying miscalculation of probabilities, it offers a useful body of knowledge for forecasters attempting to portray things like wind speed probabilities to the general public. Since heuristics and biases appear to lead to systematic and predictable errors across populations, communications about uncertainty—such as hurricane forecasts—might be better framed to reduce or eliminate such errors on the part of the public. By incorporating JDM principles into hurricane forecasts and risk communications, it therefore may be possible to improve risk decisions across entire populations all at once through tweaking how information is presented.

Although a comprehensive review of identified heuristics and biases, and their relevance to understanding hurricane risk decisions, is outside the scope of this paper, [Table 1](#) provides a summary of several heuristics

and biases we judge particularly relevant to the development and dissemination of hurricane risk communications and thus of possible interest to academics, forecasters, risk communicators, and emergency managers working in the field. Even though the judgment and decision-making paradigm is several decades old at this point, there is still substantial work that needs to be done. For example, for the purposes of hurricane (and other natural hazards) risk communications, connecting research into nonvisual cognitive mechanisms with those of visual cognitive mechanisms is critical (e.g., [Padilla et al. 2018](#)). Furthermore, significant additional research needs to be conducted into the complex interaction between the heuristics and biases tentatively identified by JDM research with the complex cultural and social factors influencing how different individuals and groups understand and act upon risk.

5. Mental models of risk

While JDM research tends to focus on identifying, typically in controlled laboratory settings, how people weigh and select alternate possible decisions ([Galotti 1989](#)), mental models research focuses more on how real-world experiences shape overall reasoning. Mental models are “beliefs about the networks of causes and effects that describe how a system operates, along with the boundary of the model ... and the time horizon considered relevant” ([Sterman and Sweeney 2007](#)). [Nersessian \(2002\)](#) theorizes they evolved as a flexible adaptation to move and interact through the physical environment. While JDM tends to focus on cognitive inputs and outputs—what decisions or choices result from specific ways in which information is presented—mental models researchers place more emphasis on holistic reasoning processes, or how human beings store, categorize, and manipulate information between input and output. Models develop through individual experiences, although many researchers assume that individuals in similar cultural contexts develop similar models, and the identification and description of such “group” mental models has become a popular approach in understanding risk evaluation and action (e.g., [Jones et al. 2011](#); [Wood et al. 2012](#)).

By eliciting mental models in the risk or hazard domain, researchers seek to identify incorrect causal or relational model connections and take those into account when developing risk communications. This can be done by eliciting and comparing lay or general public mental models with decision models based on expert information, with the assumption that the expert decision models will lead to more optimal protective reasoning ([Morgan et al. 2002](#); [Bostrom 2008](#)).

² For a more thorough review of heuristics and biases related to hurricane risk communications, see [Milch et al. \(2018\)](#).

Once these are established, their ecological validity may be tested by constructing experiments in real-world situations. As Gladwin et al. (2009, p. 26) note, “[i]f risk communication is to be effective, the experiences, values and beliefs of intended audiences must be understood since social and cultural differences can influence access, perception, credibility, and actions.” Because of the comparatively broader reach of cultural and spatial influence of mental models research, which begins more through iterative research processes with subjects reacting to real-world phenomena, it may offer useful transcultural understanding of decision processes, and a better methodology for capturing group differences. Given the complex interaction between cognitive and social (and as discussed in the *visual risk communication* section) factors that impact things like forecast understanding, methodological pluralism can be critical for capturing those factors. Mental models research offers a particular strength here, as researchers have developed a wide variety of both direct and indirect methods to elicit mental models (Jones et al. 2011). Such methods include (and are often used in conjunction with each other in the same studies) interviews (e.g., Morgan et al. 2002), surveys (Wagner 2007), and even observations of participants engaged in games or simulations (e.g., Dray et al. 2006; Meyer et al. 2013).

Mental models research may inform decisions of what kind of risk communications should be conveyed to specific communities. There has been comparatively little research using mental models approaches into hurricane research specifically, although the general hazards mental model literature provides insights. Using a mental models framework, Bostrom et al. (2018) elicited mental models of the general public in Miami-Dade County (Florida) to explore public perception of hurricane impacts, exposure, and mitigation, and to examine, among other things, the decision processes that they engage in when exposed to hurricane risk information.

Cultural dimensions of risk

Hurricane risk communications that do not account for cultural, linguistic, and socioeconomic characteristics of their audience risk compounding the harm hurricanes cause to vulnerable populations, who often have economic and mobility barriers to both preparation and evacuation and thus can be more adversely impacted by hurricanes (e.g., University of Houston 2018). Although mental models research may capture some cultural differences between different group models, research informed by fields like anthropology, sociology, and cultural studies offers an expanded methodological and theoretical toolkit for understanding complex cultural

phenomena, particularly given that hurricanes, like many other environmental hazards, tend to disproportionately affect the most socially vulnerable (e.g., Pastor et al. 2006). How different groups approach risk and evaluate information sources can vary significantly based on cultural experiences. Similarly, linguistic barriers may complicate both providing forecast information and interactions between governmental staff and the public before and during evacuations.

Anthropologist Mary Douglas and political scientist Aaron Wildavsky developed “the cultural theory of risk” (Douglas and Wildavsky 1982), a conceptual framework and research approach potentially useful to forecast developers and emergency managers. Under this theory, conceptions of risk are shaped by social and cultural processes (Boholm 2003). Although cultural theorists do not deny the objective existence of risk, they hold that decisions about that risk are “inseparable from issues relating to power, justice and legitimacy” (Tansey and O’Riordan 1999, p. 72). As with mental models approaches to risk understanding, cultural theory assumes that members of groups tend to take similar approaches to understanding specific domains (Tansey and O’Riordan 1999). In evaluating how a target group might understand and act on a given hurricane forecast product, it is helpful to understand not just the group members’ beliefs about natural hazards, but also their experiences with, and attitudes toward, government (both local and national), the media, scientists, and law enforcement. This relates to the old adage of “communication is not what you say, it’s what people hear” and what they hear may be filtered by their perceptions of the provider of information (e.g., level of trust, competency, biases).

In many cases, for example, members of some communities may see evacuation risks that members of majority groups might not. Historically, many ethnic minorities and immigrant groups have been distrustful enough of authorities that they often avoid shelters for fear of arrest and deportation (Phillips 1993); anecdotal reports suggest this occurred following Katrina (Messias and Lacy 2007). While there were many other factors that impeded evacuation, shelter surveys found that among those who did understand the pre-Katrina warnings, many discounted or ignored them due to distrust of the authorities (Brodie et al. 2006; Eisenman et al. 2007; Elliott and Pais 2006). Fear of shelters does appear to be common—Farmer et al. (2018) found that 42% of public survey respondents from North Carolina stated they had safety concerns with respect to staying in a public shelter, and 25% stated they would not consider staying in a public shelter even if they could not reach their planned evacuation destination in time.

TABLE 1. Heuristics and biases.

Heuristics or biases	Description	Potential relevance to hurricane risk communication interpretation
Affect	Individuals often make a decision on the basis of conscious or unconscious feelings of “goodness” or “badness” (Slovic et al. 2007); affective modes of risk perception are more intuitive and faster than slower cognitive modes, but emotive responses often are based on factors that are irrelevant to the decision to be made	Severity of past experiences with hurricanes may influence the decision to evacuate (Trumbo et al. 2016), and areas that suffered severe damage from prior hurricanes may benefit from different communication strategies than areas that did not; communications may be more effective if they take into account different historical experiences of communities targeted or use (or refrain from using) emotive imagery that is based on actual risk to increase or reduce affect—too much affect could lead to overestimating risk, or even fatalism and lack of action
Anchoring and adjustment	Individuals often make predictions, estimates, or decisions by “anchoring” themselves to an initial value encountered and then adjust upward or downward in response to the additional information, even if they know or should know the “starting point” may be inaccurate (Kahneman and Tversky 1984)	Individuals may not pay as much attention to track deviations as they did to initial track forecasts (Baker 2005 ; Senkbeil et al. 2010), but Herdener et al. (2016) found that individuals able to quickly adjust in response to forecast track changes; more research is needed, but it is possible that initial communications may be more effective if they omit a forecast track and/or increase the cone to incorporate more potential areas of impact
Availability bias	Individuals tend to assess the frequency or likelihood of an event by how easily occurrences of that event come to mind (Tversky and Kahneman 1974)	Milch et al. (2018) attribute the tendency for individuals to have decreasing perception of the risks of hurricanes to the availability bias, and Shao et al. (2017) found, among other things, that coastal residents’ perceptions of multiyear trends in hurricane strength appeared to be influenced by the availability bias; communications about an imminent hurricane may be more effective if they take into account historical experiences of specific communities, such as explicitly warning about the historically unique characteristics of a hurricane
Confirmation bias	Seeking out information sources or interpreting evidence in ways that are consistent with preexisting beliefs (Nickerson 1998)	If several forecasts exist, individuals may put more weight on the forecast that has the potentially best (or most desirable) outcome for her/him; communications may be more effective if they limit the use of ensemble tracks or strongly convey that each model portrayed has misprojected forecasts in the past
Finite pool of worry	Individuals have “limited but renewable physiological, cognitive, and social resources for dealing with emotionally impactful events” (Linville and Fischer 1991); when faced with too many risks they tend to focus on one or a few of the risks and ignore others once they reach a threshold beyond which “worrying” about more risks just requires too much mental effort	Individuals that reach this threshold may ignore hurricane risk communications because they have too many other concerns regarding other risks, or they may ignore hurricane flooding risk because they are already thinking of hurricane wind risk; communications may be more effective if they prioritize the most severe risks

TABLE 1. (*Continued*)

Heuristics or biases	Description	Potential relevance to hurricane risk communication interpretation
Gambler's fallacy	The tendency to think that phenomena that come more easily to mind are more frequent (Tversky and Kahneman 1974)	Residents who have recently experienced a rare hurricane impact may mistakenly believe that it is less likely that they would experience another one (Arlakatti et al. 2006), but evidence for the impact of prior hurricane experience on evacuation decisions is mixed (e.g., Baker 1991); communications may be more effective if they reiterate that multiple hurricanes may strike in quick succession or that the fact that there has not been a hurricane strike for several years does not mean one is now more probable
Loss aversion	Weighing losses more heavily than gains when making decisions, even if economically "irrational" (Kahneman and Tversky 1979; Tversky and Kahneman 1981); loss aversion can come into play even when the choices of "loss" or "gain" are mathematically identical	Framing desired risk responses as avoiding loss may be more effective than as achieving gain in encouraging specific actions—for example, when deciding whether to frame forecast data as a strike probability or a miss probability (Wu et al. 2014); communications might frame risk to emphasize possible losses (e.g., in dollar terms)
Single action bias	Individuals who are faced with problems that may require multiple protective steps stop preparing after completing just one of those steps (Weber 1997)	When faced with a hurricane threat, individuals may take a single preparatory step to "relieve the psychological burden of inaction" and then stop (Mileh et al. 2018); communications might be designed to emphasize that multiple actions are needed for communities in the hurricane's path
Temporal/spatial myopia	Individuals tend to underestimate the costs of phenomena that are farther away in space and time	Respondents may resist putting up storm shutters because it is "too soon" (Mileh et al. 2018) or may delay "effort-intensive actions" until perceived storm risk reaches higher levels (Meyer et al. 2013, 2014); communications may be more effective if they list "deadlines" for actions like evacuation or shutter installation or if they emphasize that preparations frequently take longer than expected

This has been observed in other natural disaster contexts; for example, examining the Loma Prieta earthquake in California, [Bolin \(1990\)](#) found that some Hispanic victims of the earthquake were reluctant to enter shelters because of a fear of their residency status being challenged or because of the presence of armed National Guard troops that they associated (negatively) with the internal security apparatuses of their country of origin.

Different cultural, historical, and economic backgrounds have been shown to lead to different responses to forecast products and evacuation orders. In contrast to the above Katrina example, [Demuth et al. \(2016\)](#) found increased evacuation intentions were associated with older, female, Spanish-speaking, and Hispanic members of the public. Examining behavior during Hurricane Ike (2008), [Huang et al. \(2012\)](#) found that evacuation rates declined with distance from the coast. [Hasan et al. \(2011\)](#) found that hearing about an evacuation notice from a friend or relative resulted in a higher probability of evacuation than hearing about it from television or radio. Although the rationale behind differences in hurricane risk perception may not always be clear, where those differences have been empirically supported, they should be taken into account when crafting hurricane communication strategies. However, there are significant gaps and inconsistencies in this literature (e.g., [Baker 1991](#); [Huang et al. 2016](#); [Smith and McCarty 2009](#)). For example, [Smith and McCarty \(2009\)](#) found no significant relationship between race and evacuation in four multicounty regions of Florida studied, but did find such a relationship in a fifth region. In a metareview of 38 studies on hurricane evacuation decisions (both hypothetical and actual), [Huang et al. \(2016\)](#) found, among other things, little support for the hypotheses that female gender, hearing information from peers, or experience with hurricanes predicted evacuation, although the authors caution that their findings were limited by things like the fact that few studies reported the entire matrix of correlations among the independent and dependent variables studied, or explored mediation effects between different demographic variables ([Huang et al. 2016](#)). Relatedly, cultural and ethnic identity is often constructed in complex and intersectional ways; many individuals studied may fall into multiple categories, or have different identities interact, in ways that are not easily captured by broad-based categories like “white” or “Hispanic.”

Furthermore, as [Gladwin et al. \(2009\)](#) note, individuals do not make decisions in isolation but research into decision-making typically focuses on individuals as if they do. [Burnside et al. \(2007\)](#) found that as reliance on friends and family as an information source increased, the likelihood of evacuating did as well. [Phillips and](#)

[Morrow \(2007\)](#) note that minority families are more likely to be multigenerational, and thus may take longer to gather together family members to evacuate. Family structure is often determined not only by cultural expectations, but also by economics, with poorer individuals often more likely to live in larger family groups out of financial necessity. Even within similar cultural and economic contexts, residents of different areas may develop different responses to future hurricane risk. Using survey data collected during evacuations from Hurricane Gustav (2008), [Senkbeil et al. \(2010\)](#) found significant differences between evacuees from different areas in predicting landfall based on track information.

6. Visual risk communication

Visual communication involves conveying messages in combination with images. Visuals have desirable properties for revealing patterns and attracting visual attention that can enhance the understanding of risk ([Lipkus and Hollands 1999](#)) and are often used to communicate complex information, such as the information contained in hurricane forecasts. Graphical depictions of hurricane movement and areas of potential impact are widely used to communicate hurricane risk.

a. Graphical forecast products

For any active hurricane, the NHC issues a suite of hurricane forecast graphical products. This suite of graphical products includes newer products, such as the tropical storm and hurricane-force surface wind speed probabilities graphic, the tropical-storm-force wind time of arrival graphic, and the cumulative wind history (or wind field) graphic, in addition to the traditional track forecast cone of uncertainty graphic ([NHC 2017b](#)). The wind speed probabilities graphic presents the probability that sustained winds meet or surpass predefined thresholds at specific locations over certain intervals of time. The time of arrival graphics depict the most likely arrival and earliest reasonable times of sustained tropical-storm-force winds at specific locations. The wind history graphic shows the size of the storm and areas that may be affected by sustained tropical-storm-force and hurricane-force winds. The cone of uncertainty graphic provides the track forecast of the center of the storm together with an estimate of its uncertainty, and it also depicts areas under watch or warning ([Fig. 2](#)).

b. Current standards in graphic forecast products design and evaluation

The NHC first presented the cone of uncertainty graphic in 2002 ([Eosco 2008](#)). Technically, it represents

FIG. 2. An example of a hurricane forecast cone typically presented to end users by the National Hurricane Center (NHC 2017a; (https://www.nhc.noaa.gov/archive/2017/IRMA_graphics.php?product=5day_cone_with_line)).

the area within which the center of the hurricane has a 67% (two-thirds) chance of appearing, based on a 5-yr mean average track error. From a risk messaging perspective, the cone of uncertainty was meant to communicate uncertainty and emphasize the risks and impacts (Eosco 2008). Although the newer products may be more directly relevant to the hazards (e.g., winds, storm surge), the cone of uncertainty remains the most widely used graphic by the media and the general public. In fact, during the five days prior to Hurricane Irma's closest approach to Miami, over 70% of the NHC website's independent page views from Miami-Dade County were on the cone (D. Zelinsky 2018, personal communication).

Despite its widespread use, the cone of uncertainty graphic has several shortcomings. Most significantly, the cone of uncertainty is often criticized for not conveying all the needed information (Demuth et al. 2012). While the focus for the graphic is to provide a forecast for the center of the storm together with its uncertainty, this information may not be as relevant to public as the size of the storm, the wind and rain distribution, or the storm surge, none of which are presented in the graphic. Moreover, the graphic is overloaded with many different types of information, often providing the projected track line, as well as the cone depicting forecast uncertainty, areas under hurricane and tropical storm watch and warning, classification of the tropical cyclone (e.g., tropical storm, hurricane, major hurricane), and a detailed map legend (Broad et al. 2007). The map also employs seemingly arbitrary categorical color schemes—different hues—to represent watches, warnings, and current wind extent, which could be better depicted with

continuous color scales—different shades of the same colors (Slocum 1998). The vast data presented and graphic features used may contribute to visual clutter and information overload (e.g., Eppler and Mengis 2004).

While these criticisms regarding the amount and type of information are valid, research has shown that how the information is presented also leads to misinterpretation. For example, evidence has shown that some people feel safer in locations outside of the cone limits (Broad et al. 2007; Cox et al. 2013; Wu et al. 2014). Many readers believe that there is no imminent risk beyond the cone, although by design there is in fact a one-third chance that the center of the storm will not be within the cone at all. This misperception may be a consequence of the black border surrounding the cone shape, communicating a physical boundary for storm risk (Liu et al. 2015; Ruginski et al. 2016). The public's misperception that the cone serves as an impact area is likely exacerbated by the forecast track line. Evidence suggests that people believe that areas along the central black line are “higher in danger while ignoring both the size and severity of the storm impact extending beyond the track” (Gedminas 2011, p. 9).

Moreover, the shape of the cone is often misinterpreted to communicate information about the size of the storm. For example, instead of construing the widening shape of the cone as representing more uncertainty as the forecast moves further into the future, users misread the shape as indicating that the hurricane grows larger over time (Liu et al. 2015; Ruginski et al. 2016; Padilla et al. 2017; Boone et al. 2018). Furthermore, research indicates that people may use a heuristic relating the cone size to storm intensity (Ruginski et al. 2016; Padilla et al. 2017).

To address some of the shortcomings with the cone of uncertainty, the NHC now includes a message on the graphic explaining that the cone contains the probable path of the storm center but not the size of the storm, and that significant hazards can occur over a hundred miles from the center. The NHC also provides the cone of uncertainty graphic with and without the forecast track line. Additionally, the NHC has expanded its repertoire of forecast products to include more relevant information about the hazards of hurricanes. The goal of such efforts is to reduce the misinterpretations associated with the cone of uncertainty.

c. Graphic comprehension and mental models

Such misinterpretations of the cone of uncertainty and other forecast products are likely related to mental models. Kosslyn (1989, 2007) explained that graphic comprehension does not depend just on how well a graphic is built, but mostly on the knowledge readers

have about the topic it represents, the meaning of the symbols it contains, and the way they are arranged. In discussing the principle of “appropriate knowledge,” Kosslyn claims that “if you assume that the members of the audience know more than they actually do and you use unfamiliar language, displays, or concepts, you will not connect with them” (Kosslyn 2007, p. 5). When readers have an appropriate mental model of a graph or map, they can use it as a referent to interpret graphs or maps of the same kind (Canham and Hegarty 2010).

However, if readers lack a mental model, they will need to develop it before they can interpret any graphic they have never seen before (Lee et al. 2016). Upon encountering an unfamiliar graphic, readers first construct a frame based on reading titles, legends, and annotations, and on exploring the content of the graphic itself recalling domain knowledge—if any—and personal experience. They use analogy to interpret the graphic, comparing it to other types of graphics seen in the past. This very often leads to mistakes, as a shaded area on one type of map may signify an area under threat, but on a graphic like the cone of uncertainty it represents a range of possible paths of the center of the storm. Readers also tend to read abstract graphics as if they were pictorial representations, sometimes interpreting icons and symbols as literal depictions of physical objects of phenomena (Arcia et al. 2016).

The level of expertise and experience of readers, then, is crucial to develop mental models that match the content of a visualization. It is easier to interpret specific types of graphs, charts, or maps if readers have seen those same types of graphics before. Domain-specific knowledge plays a substantial role, as well: readers with expertise in meteorology, for instance, may be more likely to correctly read graphics pertaining to their area. Familiarity and domain-specific knowledge may also influence interpretations of uncertainty in graphical displays, but according to a large review of literature in geospatial uncertainty visualization (Kinkeldey et al. 2014), some methods of representing uncertainty are more generally intuitive and, therefore, may help build correct mental models regardless of preexisting knowledge. For example, fuzziness—blurring the boundaries of objects—and transparency were considered superior to other techniques such as color saturation or sketchiness (making objects look like they were hand drawn instead of computer generated). The authors hypothesized that “fog and blur are metaphors for lack of clarity or focus (as in a camera) and thus directly signify uncertainty” (Kinkeldey et al. 2014, p. 383). They explain that these intrinsic methods of representing uncertainty—altering properties such as blur or value of objects already present on the visualization—indicate the existence

of uncertainty per se, but do not allow readers to accurately assess the degree of uncertainty. For detailed assessment of probability and uncertainty, extrinsic methods—glyphs such as error bars, which are not part of the representation of the information itself, but added to it—may be more useful (Slocum et al. 2003).

d. Graphic comprehension and visual saliency

Over the past few decades, neuroscientists investigating the biological processes that underlie vision have developed visual attention models that predict what part of images human beings focus on, both unconsciously when the eye first sees the image and consciously after the brain has time to interpret the image (Koch and Ullman 1987; Pieters and Wedel 2004). Visual attention processes can be investigated through two computer-based methods: 1) eye tracking, which investigates where subjects’ eyes land and how long they stay there (Orquin and Loose 2013), and 2) visual saliency algorithms, which computationally provide the same information without the need of a human subject (e.g., Harel 2006). This can give further insight into design elements of hurricane forecast graphics and allow researchers and risk communicators to ensure that attention is drawn to the most important elements of the graphic. The results of an algorithmic analysis of a cone of uncertainty graphic created by the authors using the visual saliency algorithm developed by Harel (2006) are shown in Fig. 3; the original image is on the left, with the visual saliency map superimposed on the right. Red areas represent areas of the graphic that would likely be paid the most attention by a human observer. The results of this analysis suggest that the most salient feature of the cone of uncertainty is the center line.

It is clear that how forecast graphics are presented is important to adequately informing the public of hurricane threat (Sherman-Morris 2005). The ways that people misinterpret the graphic suggest a complex relationship between visual communication design and message objectives (Eosco 2008). Because misinterpretations of hurricane forecast graphics may have detrimental consequences (Eosco 2008), it is important to understand how end users interpret this visual and assess hurricane risk.

e. Alternative graphic forecast products design and evaluation

To improve interpretations of graphic forecast products, some researchers have proposed modifications to the cone and alternative visualizations to communicate hurricane risk. Initial efforts included Steed et al.’s visualization method that displayed a hurricane’s previous track and wind swath area by processing all of the advisories over the life of a hurricane and using brush

FIG. 3. An example of the GBVS visual saliency algorithm of Harel (2006) applied by the authors to a hurricane forecast graphic. (left) The original image of a National Hurricane forecast graphic for Hurricane Irma. (right) The same image with a visual saliency heat map overlaid; the darker red parts of the heat map predict higher visual saliency, or the tendency of the human eye to be attracted to that part of the image.

stroke methods (Steed et al. 2009). However, their efforts did not include visualization of the uncertainty associated with a hurricane prediction, nor did they conduct user studies comparing their method against the standard. In an unpublished master's thesis, Gedminas (2011) explored how varying color and opacity of the hurricane forecast visualization may reveal uncertainty. The study relied on eye tracking and psychophysiological measures to evaluate if novices using such graphic attributes results in any significant differences in viewer response. Findings did not support the improvements and therefore suggest the problems are inherent in the display type.

Cox et al. (2013) later explored alternative ensemble path visualization focused on showing the uncertainty associated with hurricane predictions (Fig. 4). They conducted a study, with nonexperts, to examine estimates of spatial distribution of hurricane impact probability when using their alternative visualization compared to the NHC cone of uncertainty. Their visualization approach relied on direct visualization of an ensemble of possible hurricane tracks generated from historical data and current advisory information. In comparing the cone of uncertainty against their alternative visualization, this study demonstrated that their method was more informative about the uncertainty in the trajectory but also more cognitively difficult to interpret.

Following Cox et al.'s efforts, Liu et al. (2015) developed a time-varying ensemble display to provide users with information regarding the predicted state of a storm at a specific time. The researchers estimated the likelihood of hurricane risk by interpolated simplicial

depth values in the path ensemble. In doing so, they developed a time-varying display presenting potential hurricane paths associated with a storm for a specific time period and location, including representation of the prediction uncertainty and storm characteristics. Although they did not formally evaluate user performance using their visualization, they revealed that their visualization approach also suffered the misperception that the storm increases in size as the risk region increases, although they note that such a result is inherent in any approach that uses spatial extent as an uncertainty measure.

Other research efforts have explored the impact of visualization type on participants' judgements of potential storm damage. These comparisons have been

FIG. 4. Adapted figure showing an example of the alternative visualization tested in Cox et al. (2013).

FIG. 5. Adapted figure showing an example of the stimuli tested in [Ruginski et al. \(2016\)](#).

focused on whether summary displays result in greater misinterpretations than ensemble displays ([Ruginski et al. 2016](#)). [Ruginski et al. \(2016\)](#) compared five different encodings of ensemble data (three summary displays, one display of the mean, and one ensemble display) of hurricane forecast tracks ([Fig. 5](#)). The three summary displays included the NHC's cone of uncertainty (with a centerline), a cone without the centerline, and a cone with a soft or "fuzzy" boundary. The other two conditions included a visualization with only the centerline and Cox et al.'s ensemble display. In the comparative evaluation, nonexperts were tasked to predict the storm damage for a given location using one of the five visualization types. Results indicated that when using summary displays participants believed that locations at the center of the hurricane would receive more damage at a later time. In contrast, when using the ensemble display participants rated that the damage

will be less at the later time. They also found that participants were significantly more likely to report the hurricane growing in size over time when viewing the summary displays relative to the ensemble display.

Building on these findings, [Padilla et al. \(2017\)](#) explored the effects of summary and ensemble displays on interpretations of hurricane uncertainty data. This study focused on understanding how salient information in a visualization draws attention and influences judgment. They found that novice users interpreted hurricane size and intensity differently when viewing the cone of uncertainty and an ensemble display. Consistent with previous work, their findings support that viewers of the cone of uncertainty are more likely to perceive the storm is increasing in size over time. Further, they found that viewers of the ensemble display assessed the uncertainty of hurricane paths more effectively than with the cone of uncertainty. However, the ensemble display

also biased viewers' point-based judgments. The researchers concluded that viewers of both summary and ensemble visualizations were negatively biased by the salient features for specific tasks (Padilla et al. 2017). Additionally, ensemble displays have been criticized for excessive visual clutter and interpretation difficulty when presenting large ensemble data (Liu et al. 2017).

The varied attempts at creating alternative hurricane visualizations have been focused on improving visualization of the uncertainty surrounding hurricane paths. However, these attempts do not address the potential mismatch between the type of information the forecast products provide and the information that general public needs to make decisions. In agreement with Milch et al. (2018), a personalized presentation of hurricane hazards may improve communications for storm risk. A system approach providing warnings and recommended actions based on the user's specified location and other user specified characteristics is recommended. This approach would provide the user with tailored information and may reduce some of the confusion surrounding interpretation of hurricane forecast products and the subjective probability assessments of hurricane risk.

7. Communicating hurricane risks to diverse audiences

Even when visual information is presented similarly, studies over the past decades have shown risk may be interpreted differently by people with different cultural, ethnic, or economic backgrounds. Often such interpretations are linked with questions of trust, power, and historical experience. Frequently, those who are at most risk from hazards are often also least able to recover from them. The costs of things like evacuation—costs of which members of vulnerable communities are often very aware—can differ significantly between audiences, and two individuals who face the same physical risks from a hurricane may face dramatically different overall risks when social and economic factors are incorporated into their personal analysis. For example, Wang and Yarnal (2012) found that elderly people living on barrier islands were less socially vulnerable to hurricanes despite facing higher physical risk than poorer elderly residents living in physically “safer” areas inland.

From a practitioner standpoint, issues of “meteorological justice” can be informed by the related but larger and better-established literature on environmental justice. As articulated by this environmental justice literature, environmental disparities often work synergistically to cause damage on multiple fronts. Those who are at most risk from hazards are often also least able to recover from them (e.g., Haney et al. 2010).

In developing and disseminating hurricane forecast products or risk communications, understanding these different types of cultural frames may help forecasters, media staff, and emergency managers understand that such products or communications will be interpreted in different ways by different audiences (Elliott and Pais 2006; Rosenkoetter et al. 2007). One potentially effective way to ensure that risk communications are disseminated efficiently to vulnerable communities is for emergency managers to involve members of those communities in planning and strategy processes, as well as recruiting members of those communities into the disaster professions and research community (Morrow 1999; Pastor et al. 2006, p. 39). The growing body of literature analyzing risk understanding at the community level also offers tools for the practitioner to strategize for communities they may be personally less familiar with (e.g., Eisenman et al. 2007). Community-based shared strategizing may also leverage Broad et al.'s (2007) suggestion for individually tailored communications approaches, where risk communicators and managers can work with both physical data and local knowledge to craft carefully tailored communications that take into account both physical risk and cultural factors to improve risk behavior. Such approaches have long been applied in other domains such as health risk communication (e.g., Campbell and Quintiliani 2006; Kreuter et al. 1999).

Social and environmental justice

Since questions of meteorological justice implicate not just scientific or technical decision-making on the part of forecast developers or risk communicators, but also questions of ethics and sometimes politics, some researchers may feel hesitant about addressing them. While the larger philosophical debate regarding the normative dimensions of risk communication are outside the scope of this review, if one accepts the foundational premise that hurricane forecast products and communications should be designed to reach the widest possible audience, it is necessary to engage with existing inequities in order to fulfill that goal. Effective meteorological justice must therefore ensure epistemic justice, or the equitable distribution of information regardless of the listeners' place in society (Fricker 2013).

Effective hurricane risk communication cannot lie solely in developing effective visual communications. Just because the same forecast product is provided to everyone does not mean that information has been distributed equitably; individuals in vulnerable communities may not have the same capabilities to react to natural hazards. Furthermore, as noted above, trust can become an issue. Just because a risk communication is received does not mean it is understood; just because it is

understood does not mean it is believed. How forecast and other risk communication developers can take this into account when designing the substance of communications remains largely unexplored, although each subsequent natural disaster tends to reinforce the need for such inquiry (e.g., [Morss et al. 2017](#)).

Hurricane Katrina especially “opened a window on a world of hurt often ignored by media, policymakers and the public ... residents of the poorest and blackest neighborhoods of New Orleans quickly educated America that disasters are not equal opportunity affairs” ([Pastor et al. 2006](#)). Disadvantages persisted well after the storm had passed; white residents were more likely to successfully return and pick up their lives than black residents ([Haney et al. 2010](#), p. 102).

Many of these complexities recurred when Hurricane Maria (2017) hit Puerto Rico. Lack of trust in the government influenced hurricane risk decisions, with some Puerto Ricans seeing evacuation as a pretext that would lead to a “massive land grab” as poorer residents would lack the resources necessary to return ([Klein 2018](#)). Rumors of poor conditions at the government shelters also led many residents to stay at home instead, despite living in at-risk flood zones in flimsy homes ([Venes 2017](#)). Building trust between forecasters, emergency managers, and vulnerable communities is complicated in these situations; for one thing, in many cases the lack of trust may be historically justified. Although they happened during similar time periods, media reports suggest that the federal government’s reaction to Hurricane Harvey (2017) in Texas was significantly more comprehensive and efficient than its reaction to Hurricane Maria in Puerto Rico ([Vinik 2018](#)). Certainly, governmental employees are in many cases legally required to evaluate and refine forecast products and communications to ensure they are adequately informing the public as a whole regarding hurricane risk. The U.S. Code (U.S.C.), for example, requires some National Weather Service employees to “liaise with users of products and services of the National Weather Service, such as the public, media outlets ... to evaluate the adequacy and usefulness of the products and services of the [NWS]” (15 U.S.C. section 8545). Similarly, the National Oceanic and Atmospheric Administration through the U.S. Weather Research Program is mandated to “conduct outreach and education activities for local meteorologists and the public regarding the dangers and risks associated with inland flooding” (15 U.S.C. section 313c).

Accounting for environmental inequities when developing risk communications strategies is difficult, given the different geographical, social and procedural forms such inequities take ([Bullard 1994](#)). Furthermore, vulnerability is often not static but related to changing

social and economic processes ([Bankoff et al. 2004](#), p. 2). As [Bankoff et al. \(2004, p. 5\)](#) note, “vulnerability ... is embedded in complex social relations and processes ... def[ining] the possibility of reading vulnerability from a general chart, and points to the need for more local (or regional) and more dynamic analyses of what makes certain people vulnerable to risk.”

Still, ethnographic and qualitative research into the social and cultural dynamics of communities at risk can offer insight to practitioners seeking to refine how risk communications are developed and distributed ([Brodie et al. 2006](#); [Eisenman et al. 2007](#); [Elliott and Pais 2006](#); [Pastor et al. 2006](#); [Perry 1979](#)). For example, [Eisenman et al. \(2007\)](#) conducted extensive qualitative interviews with Katrina evacuees, and found that extended family relationships played a large part in evacuation decisions, but those relationships were not necessarily suitable for distributing new information, and that nonfamily but in-network organizations like churches might be. [Brodie et al. \(2006\)](#) interviewed evacuees and found that residents of low-income areas could be better served by concrete information on how and where to evacuate if they lacked transportation or resources to find housing, and that the credibility of officials providing that information could be important in determining whether such information is acted upon.

It is important to note that investigative methodologies must be chosen particularly carefully when dealing with vulnerable populations, both to comply with ethical restrictions set by institutional review boards, as well as to ensure that sufficient data are collected. Some vulnerable populations are generally difficult to reach and may need careful outreach to ensure participation (e.g., [Pottick and Lerman 1991](#)). Furthermore, behavioral phenomena may be context dependent, and some communities may respond to risk communications in ways that are not reflected in other study populations.

Over the past two decades, researchers have also begun developing social vulnerability indices that attempt to quantify the impact of social factors on how individuals and communities withstand and recover from environmental hazards (e.g., [Bjarnadottir et al. 2011](#); [Burton 2010](#); [Chakraborty et al. 2005](#); [Cutter et al. 2003](#)). One of the most comprehensive and ambitious social vulnerability index databases has been developed by the Geospatial Research, Analysis, and Services Program (GRASP) at the Centers for Disease Control (CDC) and the Agency of Toxic Substances and Disease Registry. The GRASP index provides social vulnerability scores based on 15 different census variables to provide an overall social vulnerability measure at the census tract level, as well as individual vulnerability values under four different “themes”: Socioeconomic status,

TABLE 2. Article highlights.

Communicating hurricane risk to the public effectively is a complex process that requires interdisciplinary understanding of the cognitive, cultural, and visual aspects of risk understanding
Although there has been significant research conducted into how the public understands and acts upon hurricane risk, there remain significant gaps and inconsistencies that need to be addressed in future research
Such research should be both theoretically and methodologically pluralistic, and communication strategies that are based on such research should be constantly tested for ecological validity in real-world situations
Although the literature to date may not offer a perfect roadmap for the hurricane risk communicator or emergency manager to follow, it does offer insight into possible approaches and pitfalls when attempting to warn the public of hurricane risk
There have been several attempts to improve forecast graphics depicting the uncertainty surrounding hurricane paths, but these attempts have not always addressed the potential mismatch between the type of information the forecast products provide and the information that audiences need to make decisions
Satisfying information needs may require a movement toward a more personalized hurricane risk information system that takes into account the listener's cultural, geographical, linguistic, and economic circumstances

household composition/disability, race/ethnicity/language, and housing/transportation ([Centers for Disease Control 2018](#)). Particularly useful for practitioners is the fact that CDC data are fully accessible online ([Centers for Disease Control 2018](#)).

8. Conclusions

Over the past several decades, the size of the body of research on hurricane risk perception and behavior has increased significantly. Risk researchers have a far greater understanding and awareness of the complexities of how people, particularly the general public, interpret hurricane risk. In addition, the larger body of cognitive science, visual communication, and social research on risk understanding and behavior generally also offers insights into hurricane emergency management, and templates for further hurricane-specific research. In this section we briefly highlight some of the particular strengths and weaknesses of the extant literature and explore current research needs ([Table 2](#)).

In terms of strengths, increasing population and coastal development and a greater understanding of the need for quality social science research to inform the work of emergency managers has contributed to the significant amounts of research following in the wake of each major hurricane. As more people are impacted, we are able to gather larger amounts of data, for example, retrospective data of evacuation patterns. Similarly, additional data as to what information sources tend to be used by whom, incidences of evacuation, the role of information spread by word-of-mouth, social media, etc., can help ensure hurricane risk communication strategies are continually refined for local populations with varied sociocultural characteristics. However, given that past studies have found various demographic factors to be inconsistent predictors of hurricane decision-making, additional research is needed into how such factors can be used, and the potentially complex interaction

between them (e.g., [Huang et al. 2016](#)). Furthermore, the communications themselves can often help explain evolving understanding and response to hurricane risk information ([Morss et al. 2017](#)).

Additionally, Hurricane Katrina especially led to a burst of research into the impacts of hurricanes on more vulnerable communities, including more qualitative and ethnographic studies (e.g., [Eisenman et al. 2007](#); [Farmer et al. 2018](#)) that examine in more granular detail how individuals on the ground understand hurricane risk and make their decisions. This research has provided important insights into the role of social groups in communicating hurricane risk information, the importance of issues of trust in determining responses to things like evacuation orders, and the oftentimes contentious politics involved in managing storm events, factors that are often outside the comfort zone of typically technocratic emergency managers, hurricane researchers, and engineers.

There are still numerous gaps in the existing literature. For example, although our understanding of decision-making and risk evaluation has increased through the larger bodies of judgment and decision-making and other cognitive psychology research, there has been comparatively little research applying these methodological and theoretical approaches to hurricane-related behavior specifically, although at least some researchers are attempting to extrapolate insights from those fields into understanding hurricane behavior (e.g., [Bostrom et al. 2018](#); [Milch et al. 2018](#)). Linking specific hurricane-related behavior to identified cognitive biases or heuristics seems a fruitful line of inquiry, given that JDM literature has focused largely on how members of the public make decisions based on probabilistic information.

Similarly, research on hurricanes and vulnerable populations is hindered by the fact that so much of it studies Katrina and its specific cultural and political context. While there are certainly lessons to be drawn

from Katrina, similar research into other hurricane events and the communities impacted may provide a fuller picture of the special risk faced by many vulnerable communities. Hurricane Maria in Puerto Rico will likely have significant lessons for environmental managers and hurricane risk communicators, once they have been worked out, although Puerto Rico itself still bears the scars and dysfunction caused by the storm.

In terms of visual communications, the current practice has been on the development of visualization approaches focused on improvement recommendations and alternative visualizations for displaying uncertainty in hurricane forecasts. Notable efforts have been made in exploring alternative visualizations for hurricane track and track uncertainty (Cox et al. 2013; Liu et al. 2015, 2019).

Despite the efforts to improve hurricane forecast graphics, the strong focus on track uncertainty fails to serve diverse audiences (i.e., emergency management, first responders, and the general public). A particular problem with this approach is that the same hurricane visuals are being used to satisfy different information needs. Research has indicated that the visualization approach should align with user tasks (Padilla et al. 2017), suggesting that different risk communication approaches may better suited across the user groups. Additionally, while visualizations are valuable, visual communication alone does not provide enough information for accurate decision-making (Eosco 2008).

Effective, science-based hurricane forecast communication strategies need to draw on both theoretically and methodologically pluralistic approaches that adequately capture the diverse ways in which different people understand and act on forecast products, and be rigorously tested for ecological validity. Forecast products must not only be clear and accurate but also need to account for the often unintuitive cognitive biases that can lead to misinterpretation. Forecasters, emergency managers, and researchers should attempt to develop strategies that increase equitable access to hurricane risk information to those communities that are more vulnerable to hurricane risks.

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