Insights and Opportunities for HCI Research into Hurricane Risk Communication

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ABSTRACT

Communicating risk to the public in the lead-up to tropical storms has the potential to significantly reduce the impacts on both livelihood and property. While significant research has been conducted in the storm risk community on how people receive, seek, and utilize risk information, given the importance of computing technologies and social media in these activities, human-centered design stands to make important contributions to this area. Drawing on an extensive literature review and 48 interviews with hurricane experts and members of the public, this paper makes three contributions. First, we provide a broad overview of hurricane risk communication. We then offer a set of guiding insights to inform HCI research work in this domain. Finally, we identify 6 opportunities that future human centered design work might pursue. In sum, this paper offers an invitation and a starting point for HCI to take up the problem of hurricane risk communication.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); HCI theory, concepts and models.

KEYWORDS

Hurricane Risk Communication, Crisis Informatics

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1 INTRODUCTION

Helping the public make informed decisions about how to protect themselves, their families, and their communities during tropical storm events is a complex but lifesaving undertaking. Research in the field of weather risk communication has developed important insights to inform how storm experts can clearly and effectively convey guidance to the public around effective preparation, sheltering, evacuation, and other protective activities. These experts – weather forecasters, emergency managers, and meteorologists – rely on findings produced by this field to craft messaging to the public during what is known as the "predictive" or anticipatory phase of major storm events. We argue that human-centered design, as a body of literature and a collection of research methods, can significantly contribute to this field. At the same time, issues including socially relevant data and information, uncertainty, and safety-critical decision-making that arise in risk communication make the domain a rich site of study for HCI. In this paper we introduce the problem-space of tropical storm risk communication to an HCI audience, highlight important findings from prior research, and outline an emerging set of issues with which human-centered design may usefully engage.

Disasters triggered by tropical cyclones result in millions of dollars of damage and thousands of deaths every year [37]. Second to flooding, they are the most common type of disaster around the world [55]. Hurricanes, as they are called in the Atlantic and eastern Pacific Oceans, are cyclones which have sustained winds which reach 74 mph or greater. Though meteorologists classify the intensity of hurricanes according to their wind speed using the 1-5 categories of the Saffir-Simpson scale, they also can cause significant damage due to intense amounts of rainfall and wind-driven coastal flooding (called storm surge). These storms typically form in tropical latitudes and affect coastal areas of the Northern Hemisphere, where water temperatures are generally warmer and thus more conducive to cyclone development. The growth of urban areas in coastal regions, unsafe building practices, socioeconomic inequality, under-investment in preparedness and mitigation, and the impacts of climate change all contribute to an overall increase in hurricane risk around the globe [76].

The field of weather risk communication draws on disciplines including sociology, science and technology studies, psychology, and communication to understand and inform efforts to support effective decision-making related to hazardous storms. This paper focuses primarily on communicating expert understanding of storm risk to the public during periods of dangerous weather through computational mediums. It should be noted that other areas of weather risk communication have also looked at risk communication aimed at informing risk mitigation efforts before disasters or other modes of communication including expert-to-expert and public collaborations with experts to co-produce storm knowledge. The field has developed important theoretical and practical insights

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into the design of messaging strategies, information visualization techniques, and decision-making practices of the public under conditions of danger and deep uncertainty. Such insights offer valuable tools to societal efforts at reducing hurricane risk and impacts.

Despite significant progress, there are a number of persistent challenges in regard to effective communication of expert knowledge about storm risk to the public. For example, research has shown that graphics are more effective at communicating risk than text products, yet members of the public often have trouble interpreting commonly used graphics used to describe hurricane projections [26] [96] [105]. In addition, official information created and disseminated by hurricane experts at NOAA or local emergency management offices is increasingly competing for the public's attention with other sources of information including mainstream and social media and information received from neighbors, friends, and family-members. Another challenge is that many contextual factors, including prior experience with storms, socioeconomic status, and behaviors of an individual's social networks, influence people's decisions to prepare, evacuate, or take other protective actions prior to storms [15] [32]. Prior work in HCI has highlighted the importance of further in vivo studies through contextual inquiry or other methods in order to address the wide variety of contexts in which the public accesses and interprets risk information [11].

The central claim of this paper is that human-centered design (HCD) research can support improved efforts to communicate expert knowledge about risk to the general public in the "predictive phase" of tropical storms—that is, before they make landfall. HCD methods are well-suited to exploring the variety of information needs, communication pathways, and factors that influence decision-making that are relevant to hurricane risk. In addition, HCD approaches provide a range of options for evaluating technology choices and connecting findings of user research to practical design guidance. We will also argue that risk communication offers an important site of research for informing ongoing concerns in HCI related to uncertainty, supporting critical decision-making, and crisis informatics more generally. This paper thus fits into a genre of HCI contribution that seeks to apply the concepts and techniques of human-centered design to an external domain or problem space in ways that both enrich HCI as well as contribute to that particular domain [14] [50] [57] [98].

We begin by reviewing relevant literature in tropical storm risk communication, crisis informatics, and human centered design. Then, following a discussion of our research methods, we present the results of this work in two distinct sets of contributions. First, we discuss several "insights", drawn primarily from prior work in disaster studies and tropical storm risk communication intended to help HCI researchers new to risk communication orient themselves to this complex and evolving field of knowledge. These insights should serve as sensitizing ideas and help to design and frame research projects in this domain. Second, we offer a set of "opportunities", or areas of further work where human centered design may contribute to important or emerging problem areas in the domain. In sum, this paper offers an invitation for the HCI community to take up the problem of tropical storm risk communication and a fundamental set of concepts and research questions to orient initial HCI work in this area. In doing so, we contribute to the development of what an HCI approach to this complex and multi-faceted problem space might look like.

2 RELATED WORK

2.1 Weather risk communication

Weather risk communication is an interdisciplinary field of research and practice that focuses on the communication of information about hazardous weather before, during, and after an event. Broadly speaking, there are two types of weather risk communication: warning of immediate threats and communicating long-term risks to encourage preparation and mitigation. Both types of communication are important for saving lives in disasters. Research in this field draws on a range of qualitative and quantitative methods to understand decision-making behavior related to risk and develop effective means of communicating complex information about storm danger to select audiences. As both a field of basic research and an applied science, weather risk communication shares a similar relationship to relevant industry and practice as human-computer interaction.

Research in tropical storm risk communication has found that there are several components of effective public messaging. Communicating risk effectively requires consistent, clear, and concise messaging that is not fear-based [23] [31] [79] [82] [84]. Trust, whether in an organization, government agency, or spokesperson, is a major factor for risk reduction and protective action in weather-related hazards [81] [130]. This trusted authority should be working with a variety of institutions, scientists, and public officials to communicate accurate messages with 'one voice' [36]. Risk communication may be unidirectional, top-down communication from authorities to the public, which is often the case during a hazard event; however, there is growing evidence that two-way dialogue between the message creators and message receivers is more effective, in both crisis situations and in disaster mitigation [4] [35].

Weather risk communication practice is deemed effective if it supports informed decision-making regarding protective action [89]. Early warning systems, disaster mitigation, and disaster response messaging needs to reach every sector of the population, including those disconnected from traditional sources of communication [68] [80] [86] [115]. To meet these requirements, educational materials and risk messages should be targeted at specific audiences and employ multiple channels of communication, including social media, radio, print, internet, and telephone [11] [92] [111] [115]. As with HCI, successful weather risk communication also anticipates and designs for the specific needs, vulnerabilities, and cultural beliefs of the intended audience or users. Effective campaigns will be created with the participation and feedback of intended audiences and need to be dynamic and flexible enough to adapt to specific needs of various groups and changing circumstances.

2.2 Crisis informatics

Crisis informatics is an area of research and design within HCI that focuses on how digital technologies shape information seeking and sharing behavior related to disaster [99] [118]. Drawing upon classic scholarship in disaster studies, crisis informatics has highlighted the important ways in which members of the public play important roles in circulating and reinterpreting official disaster information [125]. This research has also discussed the public's use of technologies in coordinating informal, emergent citizen response to disasters [132]. As with risk communications, crisis informatics has documented the vital role of journalists in interpreting and broadcasting expert information about disaster [28]. While the field is best known for its contributions to understand the role of social media during moments of crisis [100] [107], other work in the area has looked at a wider range of technologies and temporalities relevant to hurricane risk including research into disaster risk models [116], post-disaster impact assessments [116], and the design of smartphone applications for creating and sharing disaster information [59].

Crisis informatics research has only recently begun to examine risk communication. With regards to tropical storm risk, crisis informatics and social computing research has utilized digital traces on social media as a means to understand people's online and offline behaviors during hurricane events. For example, by using social media data from people directly impacted by hurricanes, Metaxa-Kakavouli et al. [77] found that evacuation behavior is associated with social capital, i.e. the breadth of one's extended social network. In other work, Bica et al. [11] classified hurricane risk images shared by authorities on social media throughout the 2017 Atlantic hurricane season and described their prevalence, diffusion, and reception by the public. Their study supports prior risk communication research that suggests that emphasizing, rather than obscuring, uncertainty or alternative outcomes in visualizations may support better decision-making by viewers [45] [48].

HCI research has also examined online risk communication as it relates to public health crisis events. For example, Pine et al found that official risk communication about COVID-19 in the United States was too often contradictory, complex, or changing, so that the public often turned to their own social networks in the absence of clear signals from officials [103]. A study of online conversations during the Zika epidemic highlighted the challenges citizens faced with authoritative risk information and the countermeasures they took to find trustworthy guidance for their decision-making [46]. The extreme uncertainty of the Zika epidemic gave rise to multidimensional and speculative risk perceptions, highlighting the need for a more participatory approach to risk communication that engages laypeople/members of the public along with experts [47]. Such findings demonstrate the opportunity for HCI to contribute to the improvement of risk communication during hurricane events, both on- and offline.

2.3 Human-centered design

Human-centered design (HCD) is an area of research and practice that is being taken up in multiple domains as a means of understanding the distinct needs, capacities, and contexts of use for a range of technologies. For example, within the HCI community, health researchers use HCD to discover needs beyond curing diseases, such as empowering patients to "gain greater control over decisions and actions affecting their health" [74], helping patients support each other and learn from each other using online health communities [24], and using visualizations to better communicate risks to patients [112]. Other domains where human centered design approaches have made contributions include education [64], sustainability [65], personal informatics [38], mental health [34], and accessibility [8]. Through taking a broader perspective of problems and focusing on the experiences of people most impacted by the problem, HCD can open avenues for multiple kinds of insights and solutions into complex design challenges. In this paper we bring this lens to a similarly difficult set of questions, those raised by efforts to communicate information about tropical storm risk to the public.

3 METHODS

We draw our data from three sources. First, we conducted semi-structured interviews with 14 experts in the field of tropical storm modeling and risk communication. Interview participants were identified through convenience and snowball sampling and included headquarters and regional staff of the US National Weather Service, staff of the US National Hurricane Center, FEMA, regional offices of the National Ocean, and academic researchers with significant experience in the field of tropical storm risk communication. Interviews lasted between 45 and 90 minutes and were sought to understand the current state of practice in tropical storm forecasting as undertaken by experts, outstanding challenges in the field, and institutional responsibilities and constraints faced by government actors in communicating expert risk and forecast information to the public in the warning period for major storm events.

Second, we conducted an extensive literature review of hurricane risk communications literature. Our team reviewed 66 articles from peer-reviewed literature on the topic. Our article selection started from recommendations raised in expert interviews and our own team's prior research in the area. Other articles that were commonly cited in our initial set were also included through a snowball-style approach. For each article, we wrote a short 1-2 paragraph summary and also extracted key findings in relation to the following four questions that motivated the literature review. First, what are the specific decisions by the general public that government entities and other experts want to influence during the predictive phase of tropical storms? Second, what information and other factors do members of the public base these decisions upon? Third, what channels do members of the public rely upon to seek or receive information about storms? Finally, what does the literature tell us about how best to convey tropical storm risk information to the public?

Finally, we interviewed 36 members of the public from four hurricane-prone states in the United States: New York, Texas, Louisiana, and North Carolina. These states were chosen to reflect a range of storm type and frequency profiles. Participants were recruited through professional networks of our research team and social media channels. Though we did not formally screen participants, we note that a wide diversity of racial, gender, language, and personal experiences with disasters were represented across the interviews. The interviews lasted on average around 35 minutes and focused on detailed understanding of individuals' experiences with hurricanes over the last decade. We asked questions about where participants sought information, how they evaluated between competing forecasts, key decisions such as whether to evacuate or prepare in other ways, what factors influenced these decisions. Prior research in risk communication has conducted systematic, quantitative research into some of these questions [5] [18] [29] [52]. Here, drawing on design research practice, our priority was to gather detailed stories from the target audience of risk communications to understand the breadth and complexity of the design space.

To analyze the data collected from the interviews, we first performed a round of open, inductive coding across each interview transcript. We then organized existing codes into four categories describing: protective actions taken by respondents during or in advance of hurricane arrival; information seeking behavior and sources; prior experience with hurricanes; and impacts of the storm on the interviewee. The latter two categories were important for our analysis as they seemed to condition interview participants' assessment of information they received and how they interpreted it. Based on the interview coding and the literature review, we discussed as a team and developed first a set of "Guiding Insights", or important facets of hurricane risk communication that should help guide HCI research in the topic. We then created a list of "Research and Design Opportunities", or areas where HCI theory or methods may contribute to this problem space. For each insight and opportunity, we drafted a short memo using data from the interviews and the literature review. These memos were then discussed and edited by the authors and used to create the following sections of the paper.

4 GUIDING INSIGHTS

In this section we offer five guiding insights, drawn from our literature review and interviews, that we developed to assist HCI researchers who are new to disaster or risk communication research understand this complex problem space.

4.1 There's no such thing as a natural disaster

One of the fundamental arguments made by disaster researchers, regardless of disciplinary background, is that despite popular understanding and nomenclature, disasters are *social*, rather than natural in origin [13] [61]. During a disaster, hazardous phenomena like tropical storms interact with communities and the built environment in complex ways so that storms with similar characteristics may have markedly different impacts depending on where and when they strike. In the United States, population growth in hurricane-prone areas, anthropogenic climate change, destruction of wetland ecosystems, increased economic disparity, and changing patterns of infrastructure investments each play a role in shaping the growing damage of tropical storms [91] [104] [126]. In general, individuals and communities who are marginalized, whether as a result of race, class, gender, disability, or otherwise, are increasingly more likely to live in hurricane-prone areas, least able to cope with the impacts of disaster, and struggle the most to recover in the aftermath [27] [73] [117]. The social causes of disaster, and their disproportionate effects on vulnerable groups, are thus important starting points for human-centered design of tropical storm risk communication, which (by definition) will seek to account for how varied circumstances of different audiences will shape their information needs.

4.2 The Public's Mental Models of Risk Differ from Those of Experts

Many of the central challenges of tropical storm risk communication stem from the gulf of understanding between expert knowledge about storms and popular mental models surrounding risk and uncertainty [15]. Bridging that gulf requires, at minimum, greater understanding of the public's knowledge and beliefs about these topics and may require thinking differently about how risk models are currently constructed. A standard expert view about forecasts is the notion that a good or effective model is one that is a good predictor – where model outputs accurately match an empirical dataset [110]. However, the usefulness of a weather model for decision-making, is not guaranteed by a good empirical match [7] [66] [78] [95]. On this point Norton [93] argues that models used for decision support must help policymakers and the public to formulate and measure goals effectively, as well as propose and implement plans and policies to reach these goals. Even accurate model predictions may be miscommunicated or misused, resulting in undesirable outcomes [51]. Similarly, the output of a forecast can be effectively communicated, but may not be of a form useful to stakeholders within their specific decision context. The differences between expert understanding and the public's needs for hurricane risk information thus creates significant challenges for communicating storm risk.

The cone of uncertainty, one of the more common hurricane information products [15], exemplifies some of the challenges of risk communication. Pictured in Figure 1, the cone graphic shows the probable path of the storm center over time. The cone in the image delineates the boundaries enclosing two-thirds of modeled tracks based on historical data; thus, there is estimated a 66% chance that the center for the storm will be within the cone during the projected time frame [87]. The cone shape depicts a narrow range of possible storm track boundaries in the more immediate forecast, which expands into a greater range due to increased uncertainty of the track forecast further into the future. Prior work in risk communications has found that the public frequently misinterprets these images in a number of ways, including believing the size of the cone to represent hurricane intensity or that areas outside of the cone were out of the danger area [19] [109]. An alternative to the cone, the so-called "spaghetti plot", or ensemble graphic (Figure 2), shows individual tracks of selected models, but also struggles to effectively communicate uncertainty. The distinct tracks tend to be read as overly deterministic, especially when they coincide with significant landmarks [96]. Interpreting spaghetti plots can also be more cognitively taxing than for other visual hurricane forecast representations [26]. We return to the question of the cone in Section 5.1.

4.3 Protective action can be difficult or expensive; trust is therefore essential

Activities such as evacuation, boarding up storefronts and windows, and others that risk communication experts refer to as protective decision-making can be difficult or expensive undertakings, thus

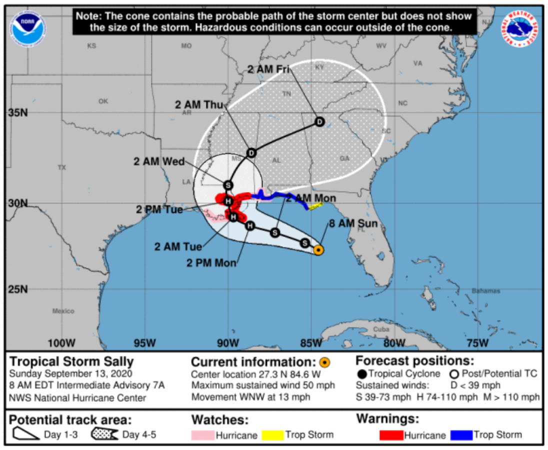

Figure 1: Example Cone of Uncertainty Graphic Source: National Hurricane Center

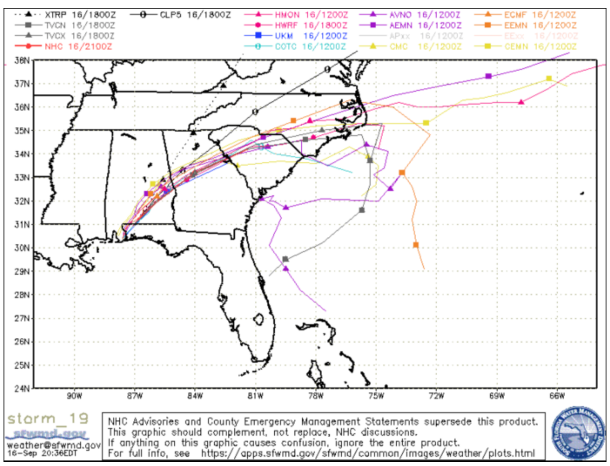

Figure 2: Example Spaghetti Plot Graphic Source: South Florida Water Management District

it is crucial that the public trust the information they are receiving. Many of our interviewees described situations such as lacking funds for gas or hotel-rooms, not owning a car, or having family members that weren't physically able to evacuate that made evacuation challenging. This research finds that "before deciding to take a disruptive and often expensive action such as evacuation, people must understand the forecast; believe it applies to them; and, most important, feel that they and/or their loved ones are at risk" [81] [6] [127]. Best practices in risk communication thus emphasize that risk warnings need to be clear and come from a trusted source [88]. While it is necessary to convey the serious nature of storm threat, it is critical to not *overstate* risks. Multiple interviewees told us that their trust in information sources had been negatively affected based on their perception, whether true or not, that the risk of previous hurricanes had been exaggerated. For example, one told us:

> *People are like evacuating, it was like a stage three zone where we were at blah, blah, blah, whatever. And then, like nothing happened, literally. And then when Sandy came along, people hesitated evacuating because of how the media hyped up that other hurricane that was supposedly going to come in September, and nobody ended up evacuating.*

While the public generally has high levels of trust in the National Hurricane Center, local media, and other important actors in the tropical storm risk communication ecosystem [16] [82], not all recipients share this trust, as shown in the example above. Trust must also be maintained over time [88]. Other factors that increase the public's trust in information sources include perceptions of knowledge and expertise; perceptions of openness and honesty; and perceptions of concern and care [102]. Designers of risk communication strategies should thus look for opportunities to cultivate audiences' trust in the source while effectively conveying information.

4.4 Information seeking and use practices are contextual and personal

Another aspect to keep in mind when designing or evaluating tropical storm risk communication products and strategies is the diverse and highly situated character of people's information seeking and needs. An example of this would be the difference between a resident of an area potentially within the storm's path versus their friend or family member living out of harm's way. Each has a stake in gaining information about the storm, but quite different needs in terms of spatial and temporal resolution of forecast, contexts in which they will be accessing the information, and decisions to make based upon it. In practice, the situation is significantly more complicated as numerous other factors influence individuals' information needs and usage. Thus, risk communication needs to be based on in-depth understanding of the multiple and complex audiences and the contexts in which they will be accessing information.

For example, several of our interview participants lost power during the hurricanes they experienced, disrupting their access to many communication channels and information sources. As another example, many of our interviewees recounted feeling anxious or scared in the run-up to and during storms, emotional states which shape people's evaluation of risk information. In addition to contextual factors, people's social networks and worldviews also condition their reading of risk information [32] [71] [83]. Our interview participants reported that their decisions to take protective action during storms was influenced by what their friends, family, and neighbors were doing. Research in risk communications has found that events such as school or business closings, road closings, and suspended public transportation are other types of social cues that heighten people's perception of risk [1] [33]. When asked about their experience in Hurricane Sandy, one Manhattan resident reported not really taking the storm seriously until they went out shopping and discovered:

> *you couldn't get food in the markets... It's just that when I was with everyone else when I felt everyone else's anxiety I started feeling the same thing. Before that I was sort of following it honestly like some sort of*

> *weird excitement in a way just to see what was gonna happen.*

Other factors, such as an individual's past experience during storms or perspectives on climate change also impacts decision-making [71] [83]. Ultimately, taking protective action in a hurricane is an act of individual agency. Many protective actions that risk communication seeks to inform during the predictive phase of tropical storms occur at the individual level, such as tidying up objects, moving cars, boarding windows, etc. [68]. Risk communication products and strategies must therefore attempt to take into account the many different needs, dispositions, and contexts of the intended audience and ultimately, support users to make informed decisions that best respond to their own circumstances.

4.5 Effective risk communication requires many forms of knowledge and expertise

The significant amount of expertise that is utilized by forecasters to model and project hurricane threat and impacts can create the impression that the information they produce is somehow neutral or merely technical in nature. Indeed, prior work has demonstrated that risk information can "hide the basic normative questions essential to ... decision-making in the mystique of statistics" [39]. One effect of this is to create a counterproductive hierarchy between experts and the local knowledge and lived experiences of at-risk communities [2] [58] [75]. However, any effort to quantify complex phenomena such as the potential impact of storms on local communities will necessarily involve judgment calls and value-laden decisions [118]. These concerns align with work in HCI and critical data studies that seek to unpack and mitigate the various ways in which data standards, algorithms, and other socio-technical processes contain biases and assumptions that reflect the interest and worldviews of those who create them, simultaneously excluding and marginalizing other perspectives [9] [43] [62] [63] [94].

Risk communication is often conceived of as a process whereby experts, such as forecasters and meteorologists, transfer knowledge about potential threats to the public for their response [4] [30]. This one-way communication, referred to variously as the broadcast, deficit, or transmission model, has come under scrutiny from various directions, but is still largely characteristic of many risk communication processes [30] [114]. Critiques of these approaches argue that science and risk-intensive protective action design problems are inherently interdisciplinary and require more knowledge than any single person or discipline possesses [3] and that knowledge relevant to hurricane risk is distributed among residents of affected areas as much as scientists and other experts. New insights, ideas, and methods for communicating and activating hurricane risk information will arise by bringing different, even contested, points of view together to create a shared or at least collective understanding among those participants of a hurricane decision-making process. Risk-informed decision-making should be conceived of as a series of personal interactions with information tools and artifacts mediated by familiar groups of people and knowledge communities [3]. New technologies, artifacts, workflows, and participatory processes should afford those exposed to hurricane risk to contribute to the framing and resolving the complex problem of risk communication and protective action.

5 RESEARCH & DESIGN OPPORTUNITIES

In this section, we draw further on our interviews and literature review, as well as our experience as HCI scholars, to map out six opportunities for HCI research and design to contribute research and practice in hurricane risk communication. Where possible, we draw on HCI methods or findings in adjacent domains to illustrate this potential and provide grounding for our arguments. As a collection (summarized in Table 1), these opportunities draw on a range of subfields and research areas within HCI to improve upon or reimagine current approaches to hurricane risk communication. They also stand to enrich the field of HCI through engagement with this complex and challenging problem space.

5.1 Beyond the cone

5.1.1 Background. Our research suggested that the cone of uncertainty, introduced above, may play an outsized role in the public understanding of risk. The cone graphics are prominent in most discussions of hurricane risk in the media and are widely shared on social media [11] and were the only information product mentioned by participants in our interviews with the public. During our interviews at the US National Hurricane Center, one staff member noted that according to web-traffic data, many visitors to the website only view the cone graphic and then leave. They found this concerning for two reasons. First, as discussed above, these graphics are frequently misinterpreted. Second, even when accurately understood by the public, cone graphics only convey some of the information that the public may need to make decisions around protective action. Depending on the storm, forecast information not provided by this graphic, such as potential storm-surge, inland rainfall quantities, or flash-flood potential, may also be important for supporting public decision-making.

5.1.2 Future work. We see two opportunities for human-centered design research to go "beyond the cone" in supporting effective tropical storm risk communication to the public. First, contextual recommendations can be provided around cone graphics to help people better understand and interpret the information presented in the cone. Here, HCI research on context-aware recommender systems, so often used in the e-commerce space [21], may contribute to understanding how to deliver personalized risk information over web or mobile applications based on reliably available data such as user location or storm characteristics. Such recommendations could be further personalized if users were willing to share further information about themselves or their residences.

Second, HCI scholars have developed an active area of research in the areas of visualizing uncertainty. This work may be relevant to developing alternative ways of accomplishing the risk communication goals of the cone graphic and spaghetti models [44] [54] [60]. One study has even explored how certain forms of graphical interaction may support science education goals by helping users learn to improve their ability to evaluate uncertainty in other contexts [53]. Research in the field of risk communication has argued for almost two decades that providing users with information about the degree and source of uncertainty in forecast models improves their trust in information sources and supports decision-making [88]. Yet more work remains to be done to develop approaches to doing so that inform rather than confuse users.

Table 1: Research & Design Opportunities

1. Beyond the cone	
The cone of uncertainty is a widely viewed and shared graphic during hurricanes, but it is problematic for two reasons: 1) It is frequently misinterpreted. 2) It does not convey all the information to support public decision making (potential storm-surge, inland rainfall quantities, or flash-flood potential).	• **Provide contextualized recommendations** around cone graphics to help people better understand and interpret the information presented in the cone • In graphics, **show the degree and source of uncertainty in forecast models** to improve trust in information sources and supports decision-making
2. Communicating impacts and vulnerabilities	
Providing the public with the potential impacts of storms is likely to support decision-making	• **Provide impact statements** alongside other indicators of storm hazard • **Use photographs or video** to convey the impacts of storms is the use of photographs or video that can be shared on social media. • **Contextualize information** to one's local area
3. Signal to noise on social media	
During storms, people in at-risk areas are frequently inundated with competing information from social media, news, government, and friends and family-members. Community-based networks are a vehicle for sharing important information that wasn't available through official sources.	• **Support top-down messaging:** Craft or amplify messaging from official sources in ways that ensure reliable information is more visible or resonant with target audiences than other sources. • **Support bottom-up messaging:** Understand the development and activities of local information sharing practices to support their work to share credible information, combat misinformation, and assist one another during disasters.
4. Embracing uncertainty	
Risk communication often treats uncertainty as a challenge to be overcome. However, the purposeful inclusion of ambiguity can support deeper appropriation of complex technologies by users.	• Study effective methods for **visualizing uncertainty** for hurricane forecasts. • Graphic risk representations are typically mediated by experts on TV, print or digital news, and even social media. Study **how mediators can highlight uncertainty** via other platforms or for other types of hurricane risk visualization.
5. Participatory design of risk information products	
The public's mental models of risk differ from those of experts. Broadening participation in the design of hurricane risk information products to include more diverse communities can ensure that the various forms of expertise, knowledge, and lived experiences are incorporated into the design of risk communication approaches.	• **Engage "leading users"** in participatory processes around the evaluation and improvement of risk information tools could lead to novel insights and improved design. • Participatory design processes may help shift design processes away from technical feasibility that experts focus on, and **shift toward more practical information needs of the public** during storms.
6. Designing for different audiences	
People's information needs as well as how they seek out and interpret storm information vary widely. Effective risk communication requires many forms of knowledge and expertise.	• **Persona development and user-journey tracking** may assist in determining how to meaningfully segment "the public" into user groups to inform the effective design of hurricane risk information for diverse audiences. • Engage in collaboration with people with a variety of abilities to achieve **inclusive design**.

5.2 Communicating impacts and vulnerabilities

5.2.1 Background. Research and best practices in weather risk communication suggests that providing the public with the potential impacts of storms is likely to support decision-making [88]. Many information products focus on measures of storm intensity, such as the Saffir-Simpson Wind Scale that categorizes hurricanes from 1-5 according to wind speed, or other information such as estimated time of arrival or forecasted levels of inland rainfall or storm surge. This is no doubt important information, but recent work has investigated approaches for helping users understand for example, how sustained 70mph winds or two feet of storm surge might impact their communities [22].

5.2.2 Future work. One approach, currently used on a number of U.S. National Weather Service sites, is to provide impact statements alongside other indicators of storm hazard. An example impact statement, referring to 58-73mph winds, includes guidance such as "some damage to roofing and siding" and "unsecured lightweight objects become dangerous projectiles" in these conditions [90]. This added information helps audiences understand what can otherwise be abstract scientific classifications in terms that assist their decision-making.

Another approach to conveying the impacts of storms is the use of photographs or video. Prior work in risk communications suggests that these forms of communication may be more effective than maps or other forms of data visualization in helping convey the potential consequences of hurricanes [108]. In support of these findings, many of our interview respondents mentioned that seeing photographs or livestream videos of friends and neighbors on social media gave them important insights into what was happening during storms. For some, these images and videos were needed to convey the gravity of the situation and motivated them to take protective action where official forecast information had not.

HCI has already contributed important findings to understanding how people share visual imagery of storm impacts on social media, including the importance of contextualization to one's local area and of representing uncertainty [11]. These findings may be built upon further through augmented or virtual reality techniques that have been experimented with in science education and visualizations about climate change and disaster [10]. The Weather Channel has also used these tools to communicate disaster risk to the public [56]. AR/VR tools have also been used by HCI research into science education [106]. Such approaches offer the potential to deliver contextualized risk information to the public in ways that includes familiar local landmarks and settings, which is thought to improve user understanding and trust. Finally, including information about vulnerable communities or public resources is another tactic that may be useful. Communication of vulnerability ahead of storm arrival could provide additional information to users about potential impacts of the storm in ways that support decision-making or improved understanding of hurricane risk.

5.3 Signal to noise on social media

5.3.1 Background. During storms, people in at-risk areas are frequently inundated with competing information from social media, news, government, and friends and family-members. Indeed, recent work in crisis informatics has argued that social media is a vital source of the social and environmental cues that the public rely on to interpret and contextualize official forecast information [11] [33]. The volume and diversity of this information, which includes speculation, rumors, out of date forecasts, or misinformation, can reduce individuals' exposure to, or trust in, authoritative risk communication from expert sources. The overwhelming amount of content produced during disasters, and the challenges of distinguishing fact from noise in such conditions, has been noted in other types of emergencies. In February 2020, World Health Organization director-general, Tedros Adhanom Ghebreyesus, used the word "infodemic" to describe the rapid spread of fake news about COVID-19, and how this could endanger communities by spreading misinformation. Nicola Bruno studied the online coverage of the Haiti Earthquake where "micro-posts on Twitter, pictures on Flickr and amateur videos on YouTube were used by big news organizations in the immediate aftermath of the quake" [20], often without necessary context or careful fact-checking associated with journalistic standards. HCI research that supports risk communicators and the public to identify reliable and relevant information could be approached from either the top-down: storm experts and other reliable sources working filter separates signal from noise on social media and other channels, or bottom-up: supporting community-level information sharing efforts.

5.3.2 Future work. Top-down approaches to addressing this issue include working to craft or amplify messaging from official sources in ways that ensure reliable information is more visible or resonant with target audiences than other sources. For example, work in crisis informatics has recommended useful practices for sharing official information over social media, in particular how the inclusion of details such as geo-location, location-referencing information, and situational update categories may, if judiciously employed, help affected communities to establish situational awareness [121] [122] [134]. An example of a conscientiously constructed tweet that applies a combination of geo-location and situational update information: "Fire Warning for Love Co. People east of Oswalt rd near/ Mariette to evacuate to the east" [121]. Journalists, and in particular broadcast meteorologists, also play an important role in coping with the volume of information, in providing context and explanation for official information. They also engage with information on social media and can help to combat misinformation and rumors [123]. Further work in applying these insights to the hurricane risk communication space could substantially help ensure lifesaving information reaches the public during storms.

Bottom-up solutions draw on local social or community networks that have already been established for trusted and dependable sources of risk information during storms. For example, an interviewee who experienced Hurricane Sandy noted that he often referenced a "website that showed some buoy miles out from land." He used the buoy as a reference point for measuring water height, warning his neighbors through a local Facebook group when he noticed something alarming. He told the interviewer:

> *I think the water was 14 feet above normal height and cross referenced that with the previous hurricane and*

> *it was a lot worse, so I knew we were going to get more water than we've ever had before.*

Here, community-based networks acted as a vehicle for sharing important information that wasn't available through official sources but helped to clarify the gravity of the impending storm. HCI researchers could look to further understand the development and activities of local information sharing practices in order to support their work to share credible information, combat misinformation, and assist one another during disasters.

5.4 Embracing uncertainty

5.4.1 Background. Much of the discussion about uncertainty in science and risk communication treats uncertainty as problematic, or as a challenge to be overcome [119]. Hence there is intense focus on identifying and reducing sources of uncertainty in risk models and developing effective means of communicating the remainder. While such efforts are no doubt essential, there are several strands of work in HCI that explore the benefits of engaging with uncertainty. Research in the area of ambiguous design, for example, has argued that purposeful inclusion of ambiguity can support deeper appropriation of complex technologies by users [42]. Game design rests on careful use of uncertainty to create tension, challenge, and engagement from participants [25]. Prior crisis informatics research in flood risk visualization has explored the role of serious games and deliberative risk communication strategies to support deeper understanding of complex information about disaster [116]. Such approaches also show promise in the context of tropical storm risk communication [12].

5.4.2 Future work. When considering uncertainty in the context of hurricane risk communication, several approaches can be adopted from HCI. First, many hurricane risk graphics tend to highlight the certainty of forecasts rather than the uncertainty. For example the cone and spaghetti plots are among the most common visualizations of hurricane track forecasts. Yet the representations of uncertainty they provide, if any, are often difficulty to assess. The official NHC track forecast cone graphics (typically) include a text disclaimer at the top that reads: "Note: The cone contains the probable path of the storm center but does not show the size of the storm. Hazardous conditions can occur outside of the cone." Yet, most other depictions of the cone by news and media organizations do not include the disclaimer, nor any alternative. Spaghetti plots are non-standardized and unregulated by government organizations, and in many media representations do not even offer the model names corresponding to each forecast track, much less associated probabilities or uncertainties. Thus, there is much opportunity for HCI and information visualization research to continue studying effective methods for uncertainty visualization approaches for hurricane forecasts [20] [105] [109] [113] [133].

In addition, hurricane risk communication is rarely only graphic in nature. Graphic risk representations are typically mediated by their creators or other experts by way of television broadcast, print or digital news, and even social media. Thus, the responsibility of communicating hurricane risk uncertainty belongs not only to the visual depictions, but also to those who show and describe them to the public. In a study of the communication of hurricane risk on social media, Bica et al. [12] suggest the need for "re-ambiguation of risk" to accurately convey risk in spaghetti plots, which can suffer from an over-deterministic portrayal of forecasted tracks. Mediators such as broadcast meteorologists do so by offering longer, more detailed blog posts in addition to their short-form text accompanying the images in social media posts, as well as engaging heavily with their audiences to answer questions, correct misinterpretations, and guide decision-making when possible. Additional HCI research can investigate how mediators can highlight uncertainty via other platforms or for other types of hurricane risk visualization.

5.5 Participatory design of risk information products

5.5.1 Background. Broadening participation in the design of hurricane risk information products to include more diverse communities can ensure that the various forms of expertise, knowledge, and lived experiences are incorporated into the design of risk communication approaches. As a set of widely used methods in HCI and adjacent fields, participatory design enables "non-experts" to be informed participants within personally relevant decision processes that are meaningful to them. In addition, PD aligns with emerging recommendations around deliberative, or dialogic models of risk communication that highlight the value of two-way communication between experts and the public [4] [30] and provides opportunities to demonstrate that the public has situated and contextualized knowledge that can improve the design of technologies intended for their use. Done well, participatory design creates a "third space" [85] where designers and users can effectively collaborate around meaningful design challenges.

5.5.2 Future work. Some members of the public we spoke to about their information-seeking behavior described developing a range of intricate and intentional hurricane risk information processes specific for their decision needs, risk tolerance, and possible protective actions. This was particularly true for those who had lived in the same area for a significant period of time and experienced multiple major storm events. Indeed, despite stereotypes of the public being irrational, uninformed, or helpless victims during emergencies, decades of research have shown that people are likely to behave rationally, according to available information, during crises [40]. The complex approaches developed by some members of the public typically entailed networks of hyper-local knowledge communities, social cues, employer protocols, national and local news media, social media, weather apps, and government alert subscriptions. Engaging such "leading users" in participatory processes around the evaluation and improvement of risk information tools could lead to novel insights and improved design.

In addition, participatory design processes may help shift design processes away from scientific proof, technical feasibility, and institutional viability that experts focus on, and toward more practical information needs of the public during storms [97]. Participatory design of hurricane risk information products would allow participants to deliberate about issues of hurricane risk that directly affect them, their relations, or their sources of livelihood. Involving those considered "non-experts" in hurricane risk information design processes is therefore a strategy for ensuring that concern for the public good is placed ahead of the success and reputation of experts or their organizations [39]. Evidence from related fields suggest that this may further legitimize the development and implementation of hurricane risk information, tools, policies, and plans [66] [129]. The co-construction of knowledge that can occur when experts and at-risk communities collaborate around issues characterized by deep uncertainty has the potential to rebalance priorities and power relationships between these groups in favor of more productive partnerships and increased public safety [116] [131].

5.6 Designing for different audiences

5.6.1 Background. As discussed in Section 4.4, people's information needs as well as how they seek out and interpret storm information vary widely. Our interviews with people who had experienced hurricanes further reinforced the finding that "the public" is a diverse set of groups with distinct needs [82] [83]. These needs aren't often aligned with the original design goals of an existing information product or those of other users, particularly experts in the weather forecast community or emergency response. Our interviews with staff of the National Hurricane Center found that while some effort is made to provide specialized information to some groups, such as mariners, there is significant opportunity to further develop products that more specifically target particular user groups' needs. Such needs may be determined by residential or work location, economic status, technology use, and disability status. Further research into hurricane risk information, along with standard human-centered design techniques such as persona development and user-journey tracking, may assist in determining how to meaningfully segment "the public" into user groups to inform the effective design of hurricane risk information for diverse audiences. Here we demonstrate the potential through examination of two user groups.

5.6.2 Future work. First, research in disaster risk communication has identified important differences in information-seeking behavior needs between disabled and non-disabled user groups [120]. For example, one study has found that hearing-impaired persons rely most on friends and family for hurricane risk information, while non-hearing-impaired persons with disabilities rely on television sources more than internet sources [72]. At present, most risk information sources available to the public are not geared towards people with disabilities [101], which can result in a lack of targeted services and assistance to these users [128]. HCI has a strong tradition of research in the area of accessibility that stands to contribute to developing a more robust understanding of how hurricane risk information design can better meet the needs of people with disabilities. Recent work in this field suggests that such investigations would be best accomplished through extended and iterative collaboration with people with disabilities [8].

Second, hurricane risk has an inherently spatial character. Risk information is therefore most actionable when it is specific to users' locations [70]. Our interviews with both staff of the National Hurricane Center and members of the public raised the opportunity for hurricane risk information products to be further localized in order to assist the public in locating the hazards and potential impacts that are relevant to where they live and work [52] [71]. What is geographically relevant is influenced by user-specific factors, such as risk perception, the influence of neighbors, residence construction, access to transportation, awareness of evacuation zones, and media reference to local landmarks [124]. Many of our interviewees noted the difficulty in accessing localized forecasts and protective action recommendations from government information products and social media posts, highlighting that official hurricane risk maps are typically at the regional or national scale. HCI work in areas such as geo-visualization [41] [49] thus stands to support users by developing products and interfaces that deliver localized information.

6 CONCLUSION

Over the past five decades tropical cyclones have, on average, killed 10,000 people and caused $15 billion dollars in damage a year [37]. These impacts are only predicted to increase as a result of anthropogenic climate change and continued population growth and urban development in storm prone areas [55] [67]. Improving the ways in which science can help at-risk communities understand, prepare for, and mitigate the impacts of major storm events is thus a critical task, and one to which HCI can make important contributions. In this paper we provide an overview of an initial research agenda for HCI that focuses on communicating risk information to the public during the predictive phase of storms. As HCI research in this space continues to develop, we anticipate that further opportunities will develop and that we may also take on related questions, such as risk communications focused primarily in urban and regional planning decisions aimed at mitigating storm risk, rather than taking protective action in the lead-up period. Inasmuch as we argue that HCI can support this agenda, we also believe that our field would be enriched through focus on these issues. Questions of representation of uncertainty, trust in information, and the human relationship to the environment are critical areas of work across HCI that research into tropical storm risk communication may inform.

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