The Crisis Informatics of Online Hurricane Risk Communication

by

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A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

Department of Computer Science

2019

This thesis entitled:
The Crisis Informatics of Online Hurricane Risk Communication
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IRB protocol #19-0077, 19-0109

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Thesis directed by Prof. Leysia Palen

Social media are increasingly used by both the public and emergency management in disasters. In disasters arising from weather-related hazards such as hurricanes, social media are especially used for communicating about risk in the pre-disaster period when the nature of the hazard is uncertain. This dissertation explores the sociotechnical aspects of hurricane risk communication, especially information diffusion, interpretation, and reaction, as it occurs on social media between members of the public and authoritative weather experts.

I first investigate the kinds of hurricane risk information that were shared by authoritative sources on social media during the 2017 Atlantic hurricane season and how different kinds of information diffuse temporally. This motivated a deeper qualitative analysis in a second study on the interactions between laypeople and experts around authoritative yet uncertain risk representations and how the mediation of the representations on social media impacts people's risk interpretations. Risk communication, however, is not only concerned with what authorities/experts see as the important message to get out and how people respond to those messages, but also about how people conceive of risk more independently. The issues that lay people are concerned about, as understood from their social media posts, are not necessarily the issues that authoritative sources are concerned about or would share in their risk messages. Thus, the third study takes this perspective and investigates what people do under highly constrained situations while preparing for and experiencing a multi-hazard hurricane, revealing the liminality of such experiences and the supportive role of social media. Throughout the research, social media is both a tool used by stakeholders for risk information sharing and communication purposes, but also a source of data that allows for analysis of these activities in situ, an affordance that not many other methods of data collection offer, especially in time- and safety-critical hazard events like hurricanes. Using social media to study these

issues contributes new ways of thinking about communicating hurricane risk and of measuring the effectiveness of such communication as well as novel findings that could benefit national weather agencies' operations.

Acknowledgements

This dissertation came together with the support of many people. I first want to thank my advisor, Leysia Palen. Thank you for guiding and motivating me through this journey. I aspire to both your expertise in research and effectiveness in mentoring.

To my committee members, Ken Anderson, Julie Demuth, Brian Keegan, and Clayton Lewis, thank you for your support and guidance. I appreciate the influence each of you has had in helping to shape this dissertation.

To my colleagues at NCAR, especially Rebecca Morss, Jen Henderson, Heather Lazrus, and Olga Wilhelmi, among many others I have met with over the years, thank you for welcoming me into your research community and helping to make my work meaningful at a practical level.

To the undergraduate research assistants who have worked with me on various parts of the research, Jamie Ackerson, Hande Batan, Jason Cummings, Marissa Kelley, Rohan Ramnani, Joy Weinberg, and Steven Yatko, thank you for your important contributions to this work. I know for many of you it meant reading tweets for hours on end, and I am so grateful for your time and hard efforts.

To my friends and colleagues, Jennings Anderson, Marina Kogan, and Robert Soden, I have so appreciated our friendship over the years. Our time working at the "big table" and using walkie talkies between our offices are some of my best memories at CU. I am also grateful to my colleagues and labmates Jim Dykes and Gerard Casas Saez for your collaborations.

To my former advisors at Santa Clara University, Silvia Figueira and Ruth Davis, thank you for being such wonderful mentors, for being the first professors to introduce me to computer science and engineering, and for encouraging me to pursue graduate school!

Finally, I want to thank my family and friends. To my parents, Ruth and Vito, especially, thank you for your unwavering support and encouragement through all the ups and downs. And to Jared, thank you for being with me and believing in me every step of the way.

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Introduction & Background

Chapter 1

Introduction

During disaster events, people are known to make use of information and communication technology for overcoming challenges and solving problems. Crisis informatics is the field of study that examines this use, combining social science knowledge of human behavior in disasters with big data and computing techniques to understand how people creatively use technology to cope with uncertainty during disasters (Palen & Anderson, 2016). Research in crisis informatics has been conducted to examine many behaviors and activities, including how people use information and communication technology to report about conditions from on-the-ground during crises (Liu, Palen, Sutton, Hughes, & Vieweg, 2008; Semaan & Mark, 2012), self-organize to create digital communities around information sharing and relief efforts (Palen, Hiltz, & Liu, 2007; Shklovski, Palen, & Sutton, 2008; Starbird & Palen, 2011; White, Palen, & Anderson, 2014), and engage in collective problem-solving and resource building (Palen, Vieweg, Liu, & Hughes, 2009; Qu, Wu, & Wang, 2009; Sarcevic et al., 2012; Soden & Palen, 2014). Crisis informatics research can be conducted in the context of any mass emergency, whether derived from natural hazards or from human-induced events (Olteanu, Vieweg, & Castillo, 2015). Much of the crisis informatics research to date involving disasters arising from natural hazards has focused on how people manage the uncertainty during or in the aftermath of the hazard, including the phases of impact, immediate response, and long-term recovery efforts. Comparatively, much less work has focused on how people use technology to manage uncertainty when a given hazard is *threatening* or, in other words, when there is a risk about whether and how the natural hazard may occur. Many types of natural hazards such as tornadoes, earthquakes, and wildfires have low predictability, and thus little to no warning during which to communicate risk before disaster strikes.

In contrast, extreme weather hazards can be predicted in terms of their occurrence, location, intensity, and impact, and thus are conducive to study as they pertain to the threat or risk of disaster. Moreover, weather forecasts are not perfect, and as such there is a ubiquitous element of uncertainty about extreme weather and the risks it poses. Thus, extreme weather—particularly the predictive phase of extreme weather—presents an interesting type of mass emergency that is understudied in crisis informatics. Extreme weather- and climate-related hazards are additionally important to study due to their potential for devastating social and economic impacts. The US regularly experiences disasters caused by such hazards, including hurricanes, severe storms, winter storms, drought, and wildfires. In 2018 alone, the National Oceanic and Atmospheric Administration (NOAA) reported that the US experienced 14 separate weather and climate disaster events that each exceeded $1 billion. The cumulative loss from these events caused more than $91 billion in damages (Smith, 2019). Dominating these disaster losses are hurricanes (Smith, 2019), which are extreme storms that can involve heavy rain, strong winds, and storm surge, and often strike highly populated coastal areas. Researchers across many fields are investigating ways to mitigate the death, damage, and distress that are associated with hurricane events. As a researcher with scholarly commitments to both human-centered computing and crisis informatics, I believe that one approach to dealing with these issues involves addressing the technologically-mediated relationship between people and information about hurricanes. Thus, this dissertation focuses on how people use available information to understand their risk and make protective decisions, such as how to prepare or whether to evacuate.

Though television has often been cited as the main source of hurricane information (Demuth, Morss, Morrow, & Lazo, 2012; Morss & Hayden, 2010), such information is increasingly communicated over social media among wide audiences, offering the opportunity to "see" and measure what happens on social media when hurricanes threaten, such as what kinds of authoritative information people pay attention to, what they do with that information, and how they think about risk more generally. Social media provides a place for authorities and experts to share the forecast and risk information they generate and analyze with broad audiences. In turn, it also provides a place for people to become aware of forecasts that may affect them, but also to interact with authorities about the information. As such, **this dissertation addresses multiple dynamics around how people communicate about and make sense of risk during hurricanes over social media.**

1.1 Communication of Hurricane Risk Information

To further motivate this research topic, I will first address the concept of risk in general. Though risk is defined and studied differently across disciplines, a simple definition of risk has been $Risk = Hazard \times Exposure \times Probability$ (National Research Council, 1989). This definition implies that "if decision-makers are provided with adequate information about the hazard itself (such as hurricanes), correct information on their level of exposure (such as whether they are located in a surge zone), and estimations of the probability of being impacted at that location (track probabilities and surge models), they can make reasonable estimations of personal risk" (Morrow, 2009, p. 3). Of course, a hazard like a hurricane becomes a risk, and potentially a disaster, when there are people to be threatened—in the absence of people, a hurricane is simply a meteorological event, not a disaster (Eiser et al., 2012). However, this simple definition does not account for the complexities of human behavior and response to hazards and risk information. One well-known model of how people respond to hazards known as the Protective Action Decision Model (PADM; Lindell & Perry, 2012). The model, shown in Figure 1.1, is based on the premise that people can vary in the extent to which they base their protective action decisions, such as evacuation or other preparations, upon thoughtful consideration of information about environmental and social cues, warning source and message characteristics, and channel access and preference. Thus, people will interpret and respond to similar information differently based on these factors. Effective risk communication research, then, must examine more than just the messages that are sent to those at risk.

The components of the PADM indicate some of the many different dimensions of the communication of hurricane risk information to be investigated. For one, risk and warnings can be

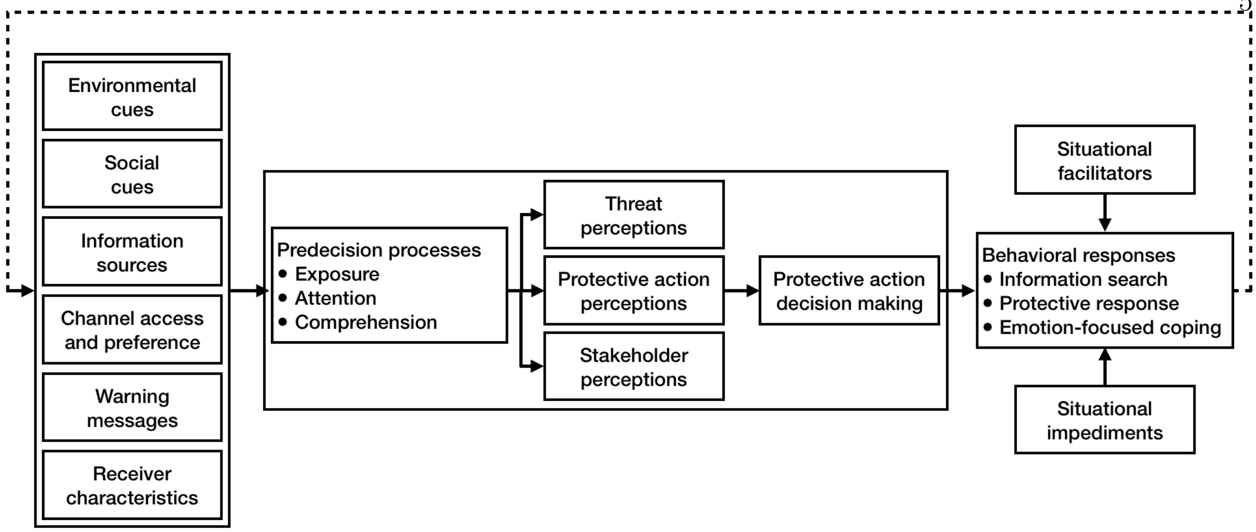


Figure 1.1: Protective Action Decision Model, adapted from (Lindell & Perry, 2012).

communicated by a wide range of authoritative sources, including government weather agencies like the NHC, other public officials, television meteorologists, news outlets, emergency response groups, and even less formal but still expert sources like stormchasers. Moreover, there is a variety of types of risk information for hurricanes that can be distributed on social media. Section 2.4 describes the range of products issued by the NHC, including textual products like tropical cyclone public advisories as well as graphical products like the Track Forecast Cone and storm surge watches and warnings. When considering graphical risk representations, which are generally better for effectively communicating risk (Lipkus & Hollands, 1999), there are several ways risk can be represented visually: as a **forecast**, or future state of the storm, such as the cone of uncertainty or spaghetti plots; as **observations**, or current states of the storm, such as radar and satellite imagery and reconnaissance data which inform risk assessment and forecasts; and as **preparatory information** such as that regarding evacuation. Visual risk graphics like these are becoming more widely shared by experts and laypeople alike on social media platforms during hurricanes, providing a way to study at scale the two-way communication and interactions that occur between the official sources who generate the information and the people who access it. This latter group, the recipients of risk information, similarly includes a variety of stakeholders and decision-makers, ranging from members of the public to businesses to other governmental and nongovernmental actors. Emergency managers act as translators of the scientific risk information for these groups (Demuth et al., 2012). Thus, this information is used for widely different purposes depending on who the recipient is and whether the information is received directly or indirectly. Many of these ways of understanding risk communication start with the risk information itself. However, as reflected in the PADM (Figure 1.1), people's behavioral responses are impacted by much more than just risk information. As such, risk information may be either at the foreground or in the background of risk communication research, depending on whether the research interest is around interpretation of specific types of information or behavioral responses to experiencing risk more broadly.

This high-level background on hurricane risk communication, of which many topics are covered in greater depth in Chapter 2, helps to motivate the research studies which I will introduce next.

1.2 Overview of Dissertation

This dissertation presents a compilation of published and under review manuscripts, each with introductory material to connect to the dissertation as a whole, as well as a concluding chapter which summarizes and discusses the research collectively. Here, I describe the evolution of the research across three empirical studies, beginning with the overarching research question:

How does social media support risk communication for hurricanes?

Each study developed findings which gave rise to a new set of questions that were addressed in the subsequent study. Given the visual nature of hurricanes and the growing prominence of risk communication on social media, the research began with the broad goal to investigate hurricane risk communication via imagery *in situ* as it occurs on social media. Study 1, an already published paper, mainly focuses on the diffusion of hurricane risk images—how they are engaged with and shared across social media—but also includes a qualitative analysis which gives brief insight into the context behind the diffusion of such information. This gave rise to Study 2 which builds on this insight with a more in-depth examination and qualitative analysis of how people discursively engage with others around risk imagery to as to make sense of it, scoped to just one type of image from the classification in Study 1. Findings from both these studies then provide insight into how people make use of authoritative visual risk information on social media.

Following Study 2, I intended to continue the thread of research around imagery in a more complex hurricane situation. Specifically, the phenomenon of overlapping tornadoes and flash floods (TORFFs) in a landfalling hurricane, such as was the case in Hurricane Florence in 2018, had been identified as an interesting meteorological phenomenon that also posed complex communication challenges, and thus warranted further social science research to understand whether new communication methods might be needed to address such challenges (Nielsen, Herman, Tournay, Peters, & Schumacher, 2015). I took this as an opportunity to understand people's behaviors around risk communication based on analysis of social media data collected during Florence. However, the data revealed that imagery communicating the overlapping threats was only a small part of authoritative communications and received little engagement by others. What was more salient in the data were the rich tweet narratives from members of the public who detailed their experiences throughout Florence, such as why they did not evacuate or what were their major concerns, as well as how the TORFFs impacted them. Study 3 then examines what people do under these more complex conditions that require ongoing sensemaking and how they conceive of risk that is not necessarily derived from or connected to specific pieces of authoritative risk information.

To tackle some of this ambitious work and mixed methods throughout the three studies, parts of this work were done in collaboration with multidisciplinary coauthors, including scholars with expertise in meteorology and atmospheric science, risk communication, statistics, and anthropology (an overview of the methods is provided in Section 1.5). Thus, the findings in each individual study are motivated by literature from a breadth of disciplines and also aim to contribute to these various disciplines. Next, I will describe the scholarly perspective with which I approach the research.

1.3 HCI/CSCW Perspective on Risk Communication

With training in HCI and CSCW (Computer-Supported Cooperative Work), I approach the study of risk communication (over social media) by examining what people do in real events involving risk—hurricanes, in this case. This is motivated by the central social theories that have dominated HCI research over the last several decades. Since computing has transitioned from a solo endeavor at a desktop computer to a networked experience involving computer-mediated interactions, HCI has recognized that what people do—action—and how they make sense of things—cognition—are not purely based on internal/mental or individual processes. Rather, they involve interactions with external representations—whether sticky notes we write to ourselves to remember to do things so as not to rely on our minds to remember for us, or diagrams that explain difficult concepts, such as risk, in ways that make it easier to come to solutions than words or sentences (Larkin & Simon, 1987; Rogers, 2008). Cognition also involves the context of one's situation and the other people involved, the latter of which is especially relevant when studying activities on social media platforms. Overall, theories of external cognition (Larkin & Simon, 1987; Rogers, 2008), distributed cognition (Hollan, Hutchins, & Kirsh, 2000), situated cognition (Robbins & Aydede, 2008), and situated action (Suchman, 1987, 1983) demonstrate the importance of studying human cognition and activity "in the wild" (Hutchins, 1995) or using ethnographic methods (Dourish, 2001; Suchman, 1987), as they occur in real-life settings and events. These approaches account for how components such as context, other people, and external representations influence how people process and make sense of information in the pursuit of some larger goal. As such, I use these approaches to study risk communication ethnographically as it occurs in near-real-time on social media during real hurricane events.

The goal of risk communication is that it "raises the level of understanding of relevant issues or actions for those involved and satisfies them that they are adequately informed within the limits of available knowledge" (National Research Council, 1989, p. 2). For hurricanes, researchers and emergency management officials are often interested in people's decisions regarding evacuation, but also in other decisions regarding preparations and how people even comprehend risk information in the first place in order to then interpret and assess it for supporting such decisions. The challenge with hurricanes is that although technology has advanced greatly in recent years to improve forecasting, the risk information about them is still largely characterized by uncertainty, especially in the form of probability. Thus, when people are at risk of an oncoming hurricane and need to make decisions, they also must figure out how to deal with uncertainty. Since much of this information is now shared online, the theories in HCI that describe the ways that people interact with technology and with data through technology are valuable to understanding the ways that people use risk information shared over social media.

This dissertation presents a set of research designs that are set up so that we can understand behaviors around risk information and communication through this HCI and CSCW perspective. Seeking out risk information during or in anticipation of a disaster is a social experience—people do not just process such information alone, but in the context of being part of a family or community, for instance (Drabek, 1999). People also do not naively accept risk information and then immediately act on it, but engage with the information in a range of ways to make sense of it and apply it to their own situations (Mileti & Peek, 2000; Wood et al., 2018). This matches the two-way conception of risk communication that sees risk information not only as something transmitted by experts, but that is incorporated into a person's understanding of risk and decision-making (National Research Council, 1989). Additionally, the process of sensemaking to extract meaning from experiences of risk and uncertainty is an "ongoing accomplishment that emerges from efforts to create order and make retrospective sense of what occurs" (Weick, 1993, p. 635).

The combination of these issues applied within the context of technology and technology-mediated communication comprises the essence of crisis informatics research, which uses an HCI perspective to understand how people encounter data and information during a crisis event and how they align and adjust that information to the situations they encounter. Palen and colleagues have studied these issues in a wide range of mass emergency events since the advent of social media. Their work has shown how to maintain the interpretivist treatment of *why* things happen, as opposed to only *how much*, even with social media data that is so often treated quantitatively. The rich content of social media data, which sometimes includes textual, multimedia, geospatial, temporal, and other kinds of metadata, can be analyzed in many different ways. Treating such data ethnographically as traces of what people actually think or do during real disaster events enables research of the kind presented here, which aims to describe how and why people deal with risk and uncertainty in hurricanes.

As such, all three studies that follow in Chapters 3–5 examine how people engage in risk communication *in situ* during real hurricane events. We know first that people are exposed to a large number of risk images which represent the complex meteorological phenomena of hurricanes. The risk images themselves are often also complex and highly technical. Such images can be described as external representations which people use to make meaning out of complex situations (Larkin & Simon, 1987). I use these images in the research—particularly Studies 1 and 2—to look at information diffusion, or how information spreads on social media (Bakshy, Rosenn, Marlow, & Adamic, 2012; Goel, Anderson, Hofman, & Watts, 2016; Lerman & Ghosh, 2010). Diffusion not only entails exposure of others to information on social media, but also deeper forms of engagement through replying to images and their authoritative generators. In addition to studying the diffusion, the second study also looks at such engagement and interactions discursively to understand how people make sense of their situations. This reflects the social and external aspects of cognition related to this specific kind of risk information, and how people engage with the information and with others to ask questions and make meaningful representations that aid in their sensemaking and decision-making (Pirolli & Russell, 2011; Russell, Stefik, Pirolli, & Card, 1993). Additionally, even if people come to some understanding of risk, disasters are often characterized by constantly changing circumstances. In hurricanes, people may choose to evacuate based on the risk they see to their home, but find that the destination to which they choose to evacuate has become threatened as well. People may think that they can "weather" a Category 1 hurricane like they have in the past, only to find that the hurricane has suddenly intensified to a Category 4 with far greater impacts than they were warned about initially. The third study engages with the ongoing nature of sensemaking as theorized by Weick (Weick, 1993, 1995), in which people are constantly reevaluating their situations and making decisions in a liminal state of disaster.

The research designs for each study also make use of different levels of analysis with which to understand these varying issues of hurricane risk communication. The first study examines risk communication from a mass communication perspective because its analytical intention was to broadly describe the diffusion of hurricane risk imagery on social media. The second study examines the interactional and interpersonal aspects of risk communication by focusing on a smaller, scoped dataset and utilizing qualitative methods. The third study examines risk communication from the perspective of individual people experiencing a multi-hazard hurricane and sometimes seeking help from others. These are only some ways of studying hurricane risk communication and are not exhaustive, but are meant to cover a range of perspectives from broad to personal.

1.4 Overview of Research Studies

The first study is a broad investigation of authoritative hurricane risk images shared on social media during the 2017 Atlantic hurricane season. First, we categorize what kinds of images are shared by authoritative sources—people or organizations who are credible sources of information about hurricanes, such as public officials or meteorologists. This categorization of hurricane risk imagery shared on social media is itself a novel contribution that could inform future research. Then I define new temporal metrics of information diffusion on social media: **rate**, how quickly information diffuses, and **duration**, for how long information diffuses. Using these metrics, we compare how the different kinds of risk images diffuse and validate results using nonparametric statistical tests. This revealed interesting diffusion patterns, such as the longer diffusion duration for images of past hurricanes and the faster diffusion of NOAA-branded images. To examine why these patterns occurred, we further analyzed the content surrounding the diffusion to understand the context for the diffusion patterns. Methodologically, this study shows the kinds of detailed diffusion metrics that are possible to track with social media data which goes beyond simple retweet counts which are commonly used, as well as the value of combining quantitative and qualitative methods for understanding sociotechnical phenomena. This kind of engagement acts as a proxy for both exposure and attention, in that a person who diffuses content has necessarily both been exposed to that content and paid attention to it to the extent that they then redistributed it to others.

Study 2 follows on from the previous with a more focused, qualitative analysis of social media interactions around one risk image type, the spaghetti plot, derived from the same dataset. The spaghetti plot is a scientific visualization that was not originally intended for public use, but now gains a lot of attention when shared on social media. This study focuses on a more engaged kind of sensemaking in which people question the features of this particular graphic that aid in comprehension and also attempt to interpret it in highly localized ways, when really it depicts a macro view of a hurricane's potential track. Several difficulties arise in sharing these images on social media, and more specifically, microblogs. Although the images are meant to convey uncertainty, the microblog platform, Twitter, limits the extent to which an authority like a meteorologist can explain that uncertainty through a character limit for posts (now 280 characters). Additionally, the time-sensitive nature of a hurricane means people want to make sense of the images quickly. These and other factors often result in declarative interpretations that are inconsistent with the image's original intent. Through analyses of the interactions between public and authorities around these images, the paper describes these challenges and responsibilities of hurricane risk communication from both the public and authoritative perspectives. It also offers implications for the design of the specific image, the practice of hurricane risk communication on social media, and the public adoption of scientific knowledge.

Though risk communication can be understood from the point of view of the authorities who generate and share risk information as with the previous two studies, it can alternatively be understood from the point of view of people at risk. This brings me to the third study, which builds further on the overarching theme of sensemaking around hurricane risk by investigating what people do when under particularly highly constrained and uncertain situations that have less clearly defined protective measures. In particular, this study focuses on people who were threatened by multiple hazards—both tornadoes and flash floods—in Hurricane Florence. This combination can be dangerous because there is conflicting safety information advised for each hazard. In addition to the constraints posed by these co-occurring hazards, people's pre-existing vulnerabilities further constrained decision making in response to the threat, for instance when financial reasons prevented people from evacuating. Through careful data collection and analysis, we discovered that many people had detailed social media posts which, when read sequentially for any given person, served as unique personal narratives of their experiences during Florence. These narratives revealed the ambiguity of the situations people faced due to not knowing what to do or even what to ask for in some cases. Inductive analysis led to interpretation of these experiences as **liminal**, described in anthropology as rites of passage and the feeling of being "betwixt and between" states of normality (Turner, 1987; van Gennep, 1960). Social media served as a way for people to express their liminal experiences: sometimes these expressions of liminality were ways to get help or to improve their situation in some way, but sometimes they were made to ground their experiences so as to reduce feelings of ambiguity. This study provides implications that serve the meteorological community regarding public responses to multi-hazard warnings as well as the HCI community regarding the publicity of experience afforded by social media.

1.5 Overview of Methodology

This project utilizes a range of mixed methods to achieve a broad set of findings, which I will briefly overview here. All three studies primarily use data collected from Twitter during real hurricane events: Hurricanes Harvey, Irma, Maria, and Nate during the 2017 Atlantic hurricane season, and Hurricane Florence in the 2018 season. The data collection for the first two studies was done in a top-down manner, starting with the identification of authoritative sources and the collection of all their tweets throughout the 2017 season. We used content analysis methods to develop an original coding scheme and to iteratively code visual tweet content (i.e., attached imagery) according to types of risk information portrayed. To study the diffusion of this information, we also collected all replies, retweets, and quote tweets—representing three different forms of engagement on Twitter—related to those original authoritative tweets and developed novel metrics that describe the temporal diffusion of original tweets based on each form of engagement. We conducted statistical analyses to determine significant differences in diffusion according to these metrics between information categories. Finally, we conducted a targeted, exploratory qualitative analysis of the context of the diffusion—specifically, the replies and quote tweets, which include some additional text by the diffusing person and thus reflect higher engagement with content than retweets—to begin to understand why content diffused the way it did.

The methods for studying the interpretation of hurricane risk information built off of this and involved a more in-depth qualitative analysis focusing on one risk representation type, the spaghetti plot. In particular, we use discourse analysis to understand the conversations and interactions between authoritative sources and members of the public that occurred in relation to spaghetti plot tweets. To gain a more multidimensional understanding of the interactions, we also conducted interviews with a sample of the authoritative sources that supplemented the findings from the social media discourse analysis.

Finally, to study people's reactions to risk in a multi-hazard hurricane situation, we collected new tweet data during Hurricane Florence and conducted several rounds of user classification to identify people who had experienced both the tornado and flash flood hazards and produced collective narratives about their experiences. We qualitatively analyzed these narratives and applied social theory to understand these experiences as they were portrayed through social media.

This is a high level overview of the methods, and the full details for each study are available in each of the paper reprints that follow in the subsequent chapters of the dissertation.

1.6 Organization of Dissertation

The dissertation is organized into five parts. The following chapter in Part I consists of a review of the background literature that informs the research in the areas of disaster sociology, crisis informatics, risk communication, and hurricanes. Part II is comprised of a reprint of the first study which analyzes authoritative source hurricane risk imagery and its diffusion on social media which is a reprint of Bica, Demuth, Dykes, and Palen (2019). It also contains additional discussion connecting the study methods and findings to the larger framing of sensemaking, focusing on how the more straightforward way of engaging with risk information by spreading it is important to inform later processes of protective decision making and action. Part III is comprised of a reprint of the under review second study which uses discourse analysis to understand the social media interactions around hurricane risk imagery and how these interactions help people to make sense of the images, both in terms of comprehension and more personalized interpretation. Part IV is comprised of a reprint of the third study, also under review, which analyzes social media narratives of people under highly constrained conditions facing a multi-hazard hurricane event. Finally, Part V consists of a summary and discussion of findings across the studies, including implications of the research for the operational weather science community and for the field of HCI as well as future research directions.

Chapter 2

Background Literature

In this chapter, I review relevant background literature that informs the research in this dissertation. The literature review is organized into four topics: Disaster Sociology, Crisis Informatics, Risk Communication, and Hurricanes. Each of the research studies (Chapters 3–5) also includes its own background section which reviews literature specific to that study.

2.1 Disaster Sociology

2.1.1 Convergence in Disasters

In the aftermath of disaster events, it has been well-documented that people, as well as messages and volunteered supplies, converge to the disaster-struck area (Fritz & Mathewson, 1957). This phenomenon of human convergence can be problematic in that it attracts more people to the area than can be sustained or controlled in terms of transportation and communication. However, the problem is more complex than just an influx of "outsiders" or "strangers." Fritz and Mathewson emphasize the need to consider the differing needs and motivations of people converging on the area, some more legitimate than others, to determine the best solutions. Thus, they develop a terminology to describe five types of convergers to a disaster area based on their dominant motivations for converging: the returnees, people who previously evacuated and returned to the disaster area; the anxious, people who are indirectly affected by the disaster due to association with the victims; the helpers, people who offer informal assistance; the curious, people who are driven by the natural human tendency to investigate strange phenomena like disasters; and the exploiters, people who seek to gain through the misfortunes of others, though this motivation is less common in actual disaster events than commonly thought. This conceptualization is based on a spatial model of convergence behavior in which the disaster zones are clearly delineated and convergence is based on movement between zones. Kendra and Wachtendorf (2003) offered a different way of thinking of convergence not in spatial terms, but in terms of entering the response milieu. They also add two more motivations for convergence: fans and supporters who support emergency workers, and mourners and memorializers who express condolences for victims.

2.1.2 Temporality of Disasters

In emergency management, including within the US Federal Emergency Management Agency (FEMA), four disaster phases are generally used to describe macro-behavior: mitigation, preparedness, response, and recovery. Powell (1954) developed a theory of disaster stages that incorporated eight fine-grained stages, as outlined in Table 2.1. Depending on the type of disaster, some of these stages may be shortened or bypassed altogether; for instance, in the case of the September 11 ter-

Stage 0: Pre-Disaster State of social system preceding point of impact
Stage 1: Warning Precautionary activity includes consultation with members of own social network
Stage 2: Threat Perception of change of conditions that prompts survival action
Stage 3: Impact Stage of "holding on" where recognition shifts from individual to community affect and involvement
Stage 4: Inventory Individual takes stock, and begins to move into a collective inventory of what happened
Stage 5: Rescue Spontaneous, local, unorganized extrication and first aid; some preventive measures
Stage 6: Remedy Organized and professional relief arrive; medical care, preventive and security measures present
Stage 7: Recovery Individual rehabilitation and readjustment; community restoration of property; organizational preventative measures against recurrence; community evaluation

Table 2.1: The eight stages of disaster according to (Powell, 1954), as cited in (Palen & Liu, 2007).

rorist attacks which had no forewarning, there was no Stage 1 and shortened Stages 2 and 3 (Palen & Liu, 2007). On the other hand, hurricanes can be just the opposite, with lengthened warning and threat periods. As disasters are often breaking-news events, people's activities and information needs tend to be high tempo (Keegan, Gergle, & Contractor, 2012), so behaviors related to each stage may blur together.

2.2 Crisis Informatics

Social media and other information communication technologies have become an important part of crisis response. *Crisis informatics* is the field of research that studies the role of ICTs in crisis events, especially as used by citizens to respond to and cope with the event in conjunction with formal emergency response (Hagar & Haythornthwaite, 2005; Palen et al., 2009). Over time, the Internet and social media have enabled citizens to contribute to emergency response through sharing their own eyewitness accounts of crisis events, building online communities, and engaging in grassroots preparedness and response efforts, as well as for gathering information from both official and other informal sources.

2.2.1 Early Crisis Informatics Research

Several mass emergencies in the early 2000s were accompanied by activity and interaction on online forums which enabled people to self-organize and share information and resources about the disaster. Some of the earliest crisis informatics research investigated farmers' use of ICTs during the 2001 UK Foot and Mouth Disease crisis which led to farmers being quarantined and the entire countryside being placed on lockdown, limiting access to information regarding the disease (Hagar & Haythornthwaite, 2005). In response, farmers developed their own online community network called Pentalk, credited as one of the few positive initiatives to arise from the particularly devastating crisis and as a means of survival for many of the farmers. In the same year, citizens took to the web for a range of purposes in response to the September 11, 2001 attacks, including getting and sharing information, engaging in political advocacy, and memorializing victims (Foot, Warnick, &

Schneider, 2005; Foot & Schneider, 2004). Liu et al. (2008) analyzed public disaster-related activity on the image-sharing site Flickr, which evolved over its early years to support grassroots public efforts in disaster response through the sharing of eyewitness photography and the self-organization of information curation.

Online forums have been particularly important in building and sustaining communities over the course of disaster events. Palen et al. (2007) investigated how the citizen-led online forums that emerged in relation to various crisis events allowed for public participation in emergency response by people both near and far, and both directly and indirectly affected by the event. They found that activity on these online forums made visible to a larger audience the role that local citizens have always played as the true first responders in emergency situations. Online forums played an important role in building and sustaining geographic community among those who had to evacuate in the aftermath of Hurricane Katrina (Shklovski, Burke, Kiesler, & Kraut, 2010), especially due to the affordances of web-based communications to activate both strong and weak ties in one's social network (Procopio & Procopio, 2007). Torrey et al. (2007) describe the coordination of donation activities among online communities. During the 2007 Southern California wildfires, emergent and innovative uses of ICTs supported community-relevant information exchange between dispersed evacuees that led to valuable community resources, particularly in a dearth of locally-relevant information from formal sources such as mainstream media (Shklovski et al., 2008; Sutton, Palen, & Shklovski, 2008).

Hughes, Palen, Sutton, Liu, and Vieweg (2008) draw on research across several disaster events as well as sociological theory about collective behavior in disaster (Fritz & Mathewson, 1957; Kendra & Wachtendorf, 2003) to frame disaster activity that occurs online as a matter of social convergence. They reinterpret in the online context seven types of social convergence used to describe on-the-ground disaster activities, showing examples of each in real disasters.

2.2.2 Social Media

Three main threads of social media and crisis informatics research have been identified by Palen and Hughes (Palen & Hughes, 2018): sociotechnical innovations afforded by social media, focusing on the public's uses of social media in emergencies; social media communications as data sources, focusing on how to manage and derive value from large amounts of social media data generated during emergencies; and applications to emergency management, focusing on how emergency response groups shift and adapt their policies and practices in response to such communicative changes. The following sections review relevant research within each of these high-level categories.

2.2.2.1 Information Sharing

One of the advantages of social media as a communication platform during disasters is that members of the public—particularly those affected—are able to contribute to the conversation, offering their on-the-ground accounts of what is happening, sometimes even before officials are able to respond. Studies of activity on online photo-sharing sites like Flickr have shown how citizens have taken on a new role of "citizen photojournalism," or alternatively as "mobile sensors," especially with the ability to capture and share photographs so easily with mobile phones and internet access (Fontugne, Cho, Won, & Fukuda, 2011; Liu et al., 2008, 2009). Such eyewitness photos are important to disaster response efforts and are even requested by formal disaster response agencies. Moreover, photos and images shared on social media sites during disaster can serve as more than just "sensing" on the part of the photographer, and can also communicate people's experiences, thoughts, and concerns about the event (Bica, Palen, & Bopp, 2017; Vis et al., 2013).

In addition to general reporting and accounting of events, people also use social media in contexts when there is a dearth of relevant or useful information from mainstream media or other official sources during a crisis event. During Hurricane Sandy in 2012, people in the Far Rockaway community, one that was both geographically and socioeconomically vulnerable, expressed on Twitter their feelings of being ignored by the media and the government (Anderson et al., 2016).

Twitter not only served as a way for people to express these feelings but to proactively reach out directly to official accounts and to gather information from their social networks. Similarly, people living in rural areas affected by the Southern California wildfires of 2007 developed "backchannel communications" via social media and community forums which arose from within the community itself precisely due to the lack of information provided via formal media sources (Shklovski et al., 2008; Sutton et al., 2008). A study of multiple online social forums found that citizens used the forums to share information regarding travel-related risks during the Zika virus crisis in the face of confusing, untimely, and inconsistent information from authoritative sources (Gui, Kou, Pine, & Chen, 2017).

2.2.2.2 Situational Awareness

As a data source, social media is valuable in contributing to or enhancing situational awareness in times of crisis. Situational or "situation awareness" is defined as "all knowledge that is accessible and can be integrated into a coherent picture, when required, to assess and cope with a situation" (Sarter & Woods, 1991, p. 55). For a crisis event, this is information that is both relevant to the event and able to help in understanding and responding to the event.

In the context of social media, identifying information that provides situational awareness during a crisis can be difficult given the noise of so much other irrelevant and unhelpful information that is also shared. In California's long-term drought crisis, official state government offices used social media for educating citizens about drought conditions and policies, finding that to achieve situational awareness information must be regularly updated and accurate (Tang, Zhang, Xu, & Vo, 2015). Specific features of social media posts that contribute to situational awareness features have also been studied. Vieweg, Hughes, Starbird, and Palen (2010) analyzed Twitter data from people "on the ground" in two disasters, the 2009 Oklahoma fires and the 2009 Red River Valley floods, to identify features of tweets that contribute to situational awareness such as geo-location information and retweeting. They also note the interesting phenomenon of "markedness" in which some information about a disaster over time becomes referred to not by proper names, like "the

Sheyenne River," but rather just "the river." This has consequences for how potential situational awareness information on Twitter can be found. Follow-up work developed an automated classifier for situational awareness to automatically identify tweets that contribute to situational awareness and to extract the relevant information (Corvey, Verma, Vieweg, Palmer, & Martin, 2012; Verma et al., 2011).

Machine learning techniques were similarly used by Alam, Ofli, Imran, and Aupetit (2018) for situational awareness classification. They applied sentiment analysis and infrastructural damage assessment techniques to textual and image-based Twitter data, respectively, collected during the 2017 Hurricanes Harvey, Irma, and Maria, in part to classify what they call "big picture" or "situational awareness" information for humanitarian organizations. Though findings such as the ability to automatically classify the damage level in social media images show promise, it is not clear how other findings presented might contribute to crisis management and emergency response, especially if not able to be computed in real-time. In general, automating the identification of information which is relevant and contributes to situational awareness in a crisis event remains a difficult task and a research area that many are continuing to pursue.

Other research in this area has developed ways of utilizing social media data for particular crisis and emergency management tasks, such as monitoring and forecasting epidemics (Aramaki, Maskawa, & Morita, 2011; Culotta, 2010; Paul, Dredze, & Broniatowski, 2014), detecting earthquakes (Sakaki, Okazaki, & Matsuo, 2010), surveying affected regions for disaster reconnaisance especially using photos shared by people on-the-ground (Dashti et al., 2014; Fontugne et al., 2011), and estimating the death toll after an earthquake (Yang, Wu, & Li, 2011). Another example combined people's evacuation behaviors as analyzed from social media data with other real-time data sources such as video cameras and traffic sensors in order to predict traffic to assist in the case of hurricane evacuation (Gottumukkala, Zachary, Kearfott, & Kolluru, 2012). Such examples show the value of social media as a real-time source of user-generated data by people affected by crises in aiding crisis management.

2.2.2.3 Information Credibility and Verification

False information can manifest in many ways and can be a critical problem during disasters when both emergency responders and affected citizens rely on accurate and timely information. Research has pointed to Twitter as a "social filter" (Castillo, Mendoza, & Poblete, 2011) in which much of the information posted is self-regulated or self-corrected by the crowd (Mendoza, Poblete, & Castillo, 2010; Palen et al., 2009; Simon, Goldberg, & Adini, 2015). Research has examined the characterization and identification of such information which can be digitally traced on social media. Mendoza et al. (2010) found through social network analysis of data after an earthquake that the propagation of tweets about rumors differs from tweets that spread confirmed news because rumor tweets are questioned more frequently than others. Castillo et al. (2011) also found measurable differences in the ways credible and non-credible information propagates on Twitter using machine learning classification methods. They found that credible information could in part be determined by the features of the propagating users. On the other hand, the propagation of rumors on social media is tied more to the contagious nature of rumors themselves rather than characteristics of who posts the rumor (Friggeri, Adamic, Eckles, & Cheng, 2014). Additionally, though some rumors and misinformation are intended to be malicious, this is not always the case. Messages from victims requesting help receive a great deal of attention on social media, yet when they continue to be propagated after the request has been dealt with, they can serve as misinformation because they are no longer relevant (Acar & Muraki, 2011). This demonstrates the importance of temporality regarding information verification on social media.

Starbird and colleagues have employed mixed-methods approaches to the characterization of rumors and rumor control on social media for crises (Andrews, Fichet, Ding, Spiro, & Starbird, 2016; Maddock et al., 2015; Starbird, Dailey, Mohamed, Lee, & Spiro, 2018; Starbird, Maddock, Orand, Achterman, & Mason, 2014; Starbird et al., 2016). They also found evidence of crowd-correction of false rumors, however the propagation of misinformation far outweighs that of the correction, which lags behind in both time and overall tweet volume (Starbird et al., 2014). They have identified features such as expressed uncertainty to help identify or predict rumoring (Starbird et al., 2018) and characterized the signatures of various rumors to show how they propagate online during crises (Maddock et al., 2015). Their work has also investigated the role of official sources in online rumoring, finding that they can impact both the propagation and resolution of online rumors (Andrews et al., 2016) and that journalists in particular engage earlier in both the spreading and correction of false rumors (Starbird et al., 2018).

In a different example of rumoring and rumor control, Tang et al. (2015) discuss how official agencies used social media to control rumors regarding California's multi-year drought, specifically that a storm with heavy rainfall would not cause the drought to end. The rumor control messages received high levels of engagement, demonstrating the robustness of social media for communicating with the public.

Information verification is particularly important, and more challening, when it comes to images shared on social media during disasters. Gupta, Lamba, Kumaraguru, and Joshi (2013) characterized tweets known to have contained fake imagery in Hurricane Sandy, such as the infamous photos of sharks swimming next to cars in floodwaters, showing that retweets and users' social networks corresponded to fake images. They developed classification algorithms to distinguish between tweets with fake and real images, achieving high accuracy. Boididou, Papadopoulos, Kompatsiaris, Schifferes, and Newman (2014) attempted to automatically classify tweets with unreliable media content as fake or real, but found it difficult to generalize a predictor among different kinds of disaster events, such as a hurricane and a terrorist attack. Another challenge to detecting fake versus real imagery is determining what is a "fake" image in the first place. Bica et al. (2017) discuss "appropriated imagery" that is shared on social media in relation to a crisis event, yet actually portrays another time, place, or event. These images are difficult to identify as appropriated because they are "real" photos in that they are not edited in blatantly deceptive ways (i.e., they may be cropped, but they have not been altered to add elements like sharks or to portray increased damage), and they are convincingly included in the social media narrative of the crisis in question, sometimes even included along with actual photos from the event. It is unclear whether to even classify appropriated photos as "fake," because even though they are not necessarily accurate portrayals of the crisis in question, they fulfill a different expectation of crisis imagery on social media of compelling a collective gaze to a region or population in need after a devastating event. In such cases, appropriated imagery may not be reasonably assumed to be malicious, and thus may serve some value in being included in the social media story around a crisis event.

2.2.2.4 Authoritative Uses of Social Media

Information exchange in disasters has traditionally been conceived as one-way, with information from officials being disseminated to members of the public (Hughes, St. Denis, Palen, & Anderson, 2014; Lindsay, 2016; Sutton et al., 2008). Yet, the role of ICT during crises and its use especially by publics has paved a new pathway for information exchange to go in both directions. Palen and Liu (2007) predicted that as ICTs have enabled increased public participation in disasters and thus new public streams of information, there would be a shift in formal emergency management and response to begin to incorporate relevant information from these streams. Other research has also pointed toward a future of increased use of public-generated data via ICT by formal emergency response institutions (Palen, Vieweg, & Anderson, 2011; Palen et al., 2009). Thus, for many organizational groups, however, social media use has shifted to become more participatory and interactive by incorporating data generated by citizens (Latonero & Shklovski, 2011; National Research Council, 2013; Palen & Liu, 2007; Simon et al., 2015; St. Denis, Palen, & Anderson, 2014; Tang et al., 2015)

Given the rise in the public's use of social media in crises, authorities are also increasingly using social media for *crisis communication*, particularly getting information to the public (Hughes & Palen, 2009). In a case study of social media communications during the 2014 Carlton Complex wildfire, Chauhan and Hughes (2017) categorized sources of official information into four types: Event Based Resources, Local Responders, Local News Media, and Cooperating Agencies, and traced the distribution of official information from each source type. They found that Event Based Resources, which arise during a specific crisis event and are thus dedicated to that event, post the highest proportion of on-topic information about a crisis event to social media, while Local News Media provide the timeliest information. However, some work has demonstrated the efforts of local responders in using social media for disaster communication and response as well. St. Denis et al. (2014) describe the social media communications and "integrated social media plan" of an Incident Management Team during the 2013 Colorado floods. The team used social media to get information out in the lack of mass media coverage, to solicit information from the public and send it back out as locally relevant storm coverage, and to monitor public communications for incidents in need of immediate response. Sometimes, when the support capacity of a formal emergency management group in a crisis event is exceeded, a team of trusted digital volunteers can help extend that capacity (St. Denis, Hughes, & Palen, 2012).

However, research indicates that social media crisis communication by authorities has not reached its full potential. In a case study of the public information officer at the Los Angeles Fire Department, it was found that an "information evangelist" was important to an organization's technological change and adoption of social media, yet this is not the case for many emergency management organizations which are skeptical of implementing social media (Latonero & Shklovski, 2011). One problem is that crisis and risk information can be communicated in an overly technical way as was the case in the Fukushima nuclear crisis (Ng & Lean, 2012). Though not necessarily sourced on social media, authoritative information regarding the Zika epidemic was found to be problematic in a number of ways for people making travel-related decisions, and as a result many turned to online social forums and shared information with each other and with locals of affected regions (Gui et al., 2017). Though this demonstrates the resourcefulness of members of the public when assessing risk in the face of unuseful authoritative information, it also demonstrates a missed opportunity for public health authorities themselves to participate on forums such as these with high public activity to help elucidate the ambiguities of the crisis situation.

2.3 Risk Communication

As with information exchange in disasters, communication of risk information was also thought to be one-directional in its early conception: the delivery of one-way messages from technical experts or other authorities to the general public. In this view, successful risk communication was only determined from the perspective of the senders of the messages and their ability to "get the message across" to enlighten or persuade an uninformed and passive public (National Research Council, 1989). However, there are several problems with conceptualizing risk communication in this way, particularly in a democratic society. It incorrectly assumes that people use costs-benefits analyses to assess risk, that costs and benefits are equally distributed across a society, that people share the same values, and that technical analysis is a substitute for political debate and citizen participation regarding controversial issues. Instead, the needs and values of citizens need to be considered along with expert technical knowledge when communicating about risk.

Risk communication has been defined as "an interactive process of exchange of information and opinion among individuals, groups, and institutions. It involves multiple messages about the nature of risk and other messages, not strictly about risk, that express concerns, opinions, or reactions to risk messages or to legal and institutional arrangements for risk management" (National Research Council, 1989, p. 21). It is distinct from risk messages, which are the declaratory messages that risk communicators send to recipients regarding risk around some hazard. Because they are often meant to inform nonexperts, the design of risk messages is particularly important so as to present clear and understandable information regarding complex and difficult concepts. The focus of research around risk messages is how to design them so as to change individual behavior. However, the process of risk communication involves more than risk messages alone and is multi-directional, considering messages that move from experts to nonexperts, nonexperts to each other, nonexperts to experts, and from citizens to public decision makers (National Research Council, 1989; Plough & Krimsky, 1987). While accurate messages about expert knowledge are necessary in risk communication, the overall aim of the process is to adequately inform people about risk, and thus the context of those receiving the risk information must be considered.

Risk interpretation is an important component of the risk communication process as people must be able to understand and interpret risks in order to make decisions (Eiser et al., 2012; Lindell & Perry, 2012). Risk arises from uncertainty and therefore requires one to make sense of uncertain information. Thus, studies of interpretation of uncertainty are also informative to risk communication more generally. Research about interpretations of weather forecasts and resulting decision-making has highlighted the important influence of uncertainty information. People tend to prefer uncertainty information to be included in such forecasts in part because they know that it must exist, regardless of whether it is portrayed in a forecast representation (Joslyn & LeClerc, 2012; Morss, Demuth, & Lazo, 2008). However, such uncertainty information should be presented in ways that the general public can relate to rather than meteorological interpretations of uncertainty that many do not understand (Joslyn, Nadav-Greenberg, & Nichols, 2009; Morss et al., 2008). Beyond more simplistic weather forecasts, one study found that the inclusion of uncertainty estimates made people trust climate change projections significantly more than when no uncertainty information was included (Joslyn & Leclerc, 2016). Their findings suggest that the common fear among scientists of appearing incompetent or uncredible by acknowledging uncertainty may actually be unfounded.

In the context of disasters, some work has focused on risk messages in the form of warnings and the public perception of and response to warnings. Warnings are messages about threat information communicated by local authorities to an affected population, including information about risk and potential courses of action to minimize the negative consequences of the impact, depending on the level of specificity (Lindell & Perry, 1987). Public response to warnings is a complex, social, and ongoing process, and is more than a simple assessment of whether one is at risk or not (Drabek 1999). In order to respond, people must hear, understand, believe in, and personalize the risk information, then decide what to do and finally perform the behavior (Mileti & Peek, 2000). Moreover, people's responses are influenced by a large number of factors regarding the nature and content of warnings, including attributes of the warning source, the message itself, the population receiving the warning response, and the disaster event for which the warning is sent (Drabek, 1999; Mileti &

Sorensen, 1990; Mileti & Peek, 2000). One myth of disaster warnings is that people immediately take protective action after the first warning message they receive (Mileti & Peek, 2000). In fact, a common phenomenon with disaster warnings known as "milling" describes how people "seek and confirm first and act later," spending time confirming and seeking additional information before acting on it, though this delay can be reduced with longer, more informative warning messages (Wood et al., 2018). Liu et al. (2017) investigated the effect of including maps in disaster warnings, finding that they may minimally increase message understanding or decision clarity. Interestingly, they found that the influence of emotion was much more significant on how people interpret warning information.

The processes explaining how people respond to warnings after the impact of a disaster are different from those explaining pre-impact warning response. Those who experience little or no loss in the impact of a disaster, or those who have no prior disaster experience, may be prone to a "normalization bias" in which they believe they will continue to avoid subsequent negative impacts (Mileti & O'Brien, 1992). This is particularly relevant to hurricanes, which are not only ongoing disasters that may continue to have more severe impacts after the initial landfall, but also affect coastal regions that attract many newcomers who may not have prior hurricane experience (Morrow, 2009).

2.3.1 Social Media Studies of Risk Communication

Social media as a data source is still nascent in the risk communication and weather/climate literature. As such, many of the studies that do incorporate social media tend to do so in simplistic ways, often using small datasets and/or basing analyses primarily on counts of keywords or retweets. Lachlan, Spence, Lin, and Del Greco (2014) examined the volume and content of tweets related to the 2012 Hurricane Sandy, focusing on the most commonly tweeted words and URLs leading up to landfall. However, in a more sophisticated content analysis, though on a subset of 1785 tweets, the authors investigated activity by government agencies and the prevalence of actionable versus emotive information which led to more insightful findings. For instance, they suggest the government's underutiliization of social media during a time when the public most needs information. They also suggested that Twitter may be a better source for emotional support as opposed to actionable information duriing disasters. In a separate study by the authors that analyzed 800 tweets during a winter storm (Lachlan, Spence, Lin, Najarian, & Del Greco, 2014), the authors found greater amounts of "usable" information in tweets with localized hashtags versus nonlocalized hashtags.

Ripberger, Jenkins-Smith, Silva, Carlson, and Henderson (2014) focused on the attention people pay to tornado communications as indicated by their social media posts. By modeling the relationships between tweets containing the word "tornado," the occurrences of watches, warnings, and actual tornadoes, and the number of people affected by each, they found that watches and warnings do produce a measurable increase in tornado-related tweet activity. Though this study addresses the important issue of attention to warning information, it begs for further research as to what people actually say or how they react to the information in their tweets.

Other work has incorporated content analysis. For instance, Silver and Andrey (2019) analyzed tornado-related tweets to uderstand information seeking, interpretation, and dissemination, and categorized the "actor groups" (like weather experts and media) as well as attributes of the content of the tweets themselves. They analyzed the various kinds of content shared by different actor groups throughout a tornado event. By only collecting tweets using two keywords, however, a great deal of relevant content that would also demonstrate the information behaviors the authors were interested in, such as replies and @mention tweets, was likely excluded.

Though not related to weather disasters, a study of risk communication around the Zika virus (Vos et al., 2018) also made use of content analysis to analyze tweets by public health agencies. They used a predictive model to determine tweet message features that led to greater message passing, or retweeting. They use results to suggest how to design messages about an emerging threat for diffusion on social media. As I will show in Studies 1 and 2 (Chapters 3 and 4), measuring diffusion based on retweet counts alone may not be entirely indicative of risk communication as one might think—without reading more into the context surrounding diffusion, one cannot know whether people are diffusing risk information because they find it useful, confusing, interesting, or something else altogether. The risk communication studies I have included here are valuable for their contributions to understanding more about what people do on Twitter regarding risk information. However, in general, social media risk communication studies are still maturing in terms of data collection and analysis.

2.3.2 Hurricane Risk Commuication

Risk communication research for hurricanes is particularly important given hurricanes' potential for catastrophic impacts. Demuth et al. (2012) describe how hurricane forecast, warning, and protective action information is created and communicated by three major groups that constitute the "hurricane warning system": NWS forecasters at the NHC and local weather forecast offices, local emergency managers, and local television and radio personnel. Through interviews and observational sessions with members of these groups, they find that the main challenges for hurricane risk communication are: the volume, complexity, and content of NWS products; the media's need for high quality and accessible information quickly; and emergency managers' use of scientific uncertainty information to plan for the worst case. One recommendation to address these challenges is to include regular meetings and increased coordination between members of these groups, a finding also echoed in other research of forecast and warning production and communication (Bostrom et al., 2016).

Research in this area has also considered how to improve the information communicated to the public and other end-users. Though improving forecast accuracy may seem to be an obvious way to improve forecast value, this is in fact not always the case. Providing reliable data about risk factors is only part of people's risk assessment processes (Morrow, 2009). Instead, to improve forecast and warning products, it is recommended to conduce user-oriented research and product development and to formally incorporate feedback from users, including the public and other members of the hurricane warning system, to better understand the social and behavioral contexts of warning uses (Bostrom et al., 2016; Demuth et al., 2012). Additionally, as discussed above, acknowledging and incorporating uncertainty information is important and helps to build credibility (Morrow, 2009).

Much hurricane risk communication research has utilized surveys to describe coastal residents' short-term risk perceptions and preparation decisions, particularly involving evacuation (Baker, 1991; Dash & Gladwin, 2007; Dow & Cutter, 1998, 2002; Huang, Lindell, & Prater, 2016; Morss & Hayden, 2010; Zhang et al., 2007). These studies have been limited to capturing people's risk perceptions and reflections on preparations only after the fact, often weeks or even months or years after the hurricane has passed. Other research has also examined how hurricane risk perceptions evolve over the course of the event. Meyer, Baker, Broad, Czajkowski, and Orlove (2014) conducted telephone surveys with at-risk coastal residents at regular intervals leading up to two hurricanes' landfalls. They found that despite high awareness among participants of the threat posed by hurricanes, people inadequately prepared, e.g. by not putting up storm shutters or not making evacuation plans. The primary reason for people not intending to evacuate, a topic also discussed in Study 3 (Chapter 5), despite being in evacuation areas was that they believed they were safe where they were, not because they felt barriers or constraints. This was also partially due to a common misperception of wind posing the primary threat as opposed to water. Though this seems to directly imply a lesser focus on wind and greater focus on specific impacts, particularly flooding, better maps and increased education about evacuation cannot be assumed to lead to better decisions and preparations among residents. It is difficult to change people's risk perceptions because they are often based on intuitive judgments (Slovic, 1987). A second study of people's evolving hurricane risk perceptions and behaviors used social media as a lens to investigate these issues as they occurred in real time during the course of a hurricane event (Demuth et al., 2018). This study found evidence of the nuanced ways in which people personalize risk information to themselves and their contexts, such as the geographical or structural characteristics of where they live. In this way, social media data can be valuable for authorities to understand people's risk perceptions to be able to create risk messages that encourage appropriate protective action for people at risk.

2.4 Hurricanes

I now turn to the topic of hurricanes, the hazard focus of this dissertation. This section provides background information on several aspects of hurricanes. First, I provide an overview which includes definitions of basic terminology, hurricane classification based on storm intensity, and impacts. Next, I describe some of the images used to portray risk and forecasts, namely the cone of uncertainty and spaghetti plots, and research that has examined perceptions of these various representations. Finally, I review literature regarding people's evacuation decisions and behaviors for hurricanes and how these are influenced by various factors.

2.4.1 Overview of Hurricanes and their Impact in the US

Hurricanes are among the costliest natural hazards to impact the US. Since 1980, there have been 42 hurricanes to affect the US that have caused at least one billion dollars of damages each and together have claimed more than 6000 lives (Smith, 2019). This dissertation focuses primarily on Hurricanes Harvey, Irma, Maria, and Nate in 2017 and Hurricane Florence in 2018. The word "hurricane" is used to describe tropical cyclones in the North Atlantic (they are also called "typhoons" and "cyclones" in other parts of the world). The US National Weather Service (NWS) defines a tropical cyclone as "a weather system that derives its energy from warm ocean waters and is characterized by a closed counterclockwise circulation in the Northern Hemisphere" (National Weather Service Houston/Galveston, 2019). Tropical cyclones are categorized into the following categories by the NHC:

- Tropical depression: tropical cyclone with maximum sustained winds of 38 mph or less
- Tropical storm: tropical cyclone with maximum sustained winds between 39 and 73 mph
- Hurricane: tropical cyclone with maximum sustained winds of 74 mph or higher
- Major hurricane: tropical cyclone with maximum sustained winds of 111 mph or higher, corresponding to a Category 3, 4, or 5 storm on the Saffir-Simpson scale

The official Atlantic hurricane season, which includes storms in the Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico, is from June 1–November 30. The peak activity of a season tends to occur from mid-August through late October, but deadly hurricanes can occur anytime in the season, and it is even possible for storms to occur outside this timeframe altogether. Tropical cyclones appear to be increasing in frequency and intensity in the North Atlantic (Nordhaus, 2006). Effects of climate change, especially rising sea surface temperatures from greenhouse warming (Knutson et al., 2010; Lim, Schubert, Kovach, Molod, & Pawson, 2018), are likely to lead to stronger hurricanes, though it is not clear what impact this might have on hurricane frequency.

The Saffir-Simpson Hurricane Wind Scale is a classification of hurricanes from Category 1 to 5 based on their intensity, or wind speed (Schott et al., 2019). It also provides examples of the types of damage that can be expected with a storm of each category, such as some damage to people or property by flying debris for a Category 1 hurricane to complete destruction of all mobile homes and extensive damage to roofs and windows for a Category 5. Damage caused by winds depends on factors such as local building codes and wind direction, and thus may not solely be accounted for based on the categorization. In general, damage rises by about a factor of four for every category increase. While the Saffir-Simpson scale provides a concise way to alert the public of potential impacts of various intensity hurricanes, it does not address the potential for other hurricane-related impacts not related to wind, such as storm surge, rainfall-induced floods, or tornadoes. This has been the source of much contention within the meteorology community in recent years over the value of the scale, as low intensity hurricanes may mislead people to think that damages will be minor.

There are many hazards associated with hurricanes. Storm surge flooding, the abnormal rise of sea water generated by a storm, is known to be the greatest threat to life and property. Flooding is not only a concern for coastal areas, but can also be induced by heavy rainfall in inland areas. This sort of flooding is known to be problematic for slow-moving hurricanes and tropical storms, such as occurred in Texas during Harvey. Strong winds and tornadoes are also a major hazard in hurricanes, and are especially of concern for people living in mobile or manufactured homes which often cannot withstand such winds. Tornadoes can occur within the outer rain bands on the right hand side of the track or in the eyewall. Two of the hurricanes studied in this dissertation, Harvey and Florence, had 52 and 44 documented tornadoes, respectively (Murphy, 2018; Stewart & Berg, 2019). The overlapping of multiple hazards in a hurricane can be particularly catastrophic. Study 3 (Chapter 5) examines the case of co-occurring tornadoes and flash floods in the landfall of Hurricane Florence. This combination of hazards is accompanied by conflicting safety information to get to higher ground for the flooding but lower ground for the tornadoes, and led to hundreds of people requiring water rescues by emergency management in the town of New Bern, North Carolina.

The mission of the NHC is “to save lives, mitigate property loss, and improve economic efficiency by issuing the best watches, warnings, forecasts and analyses of hazardous tropical weather, and by increasing understanding of these hazards.” The NHC issues a number of textual and graphical products. Textual tropical cyclone public advisory products are issued at least every six hours when there is a tropical cyclone in the Atlantic Ocean. When there is also a tropical storm or hurricane watch or warning issued, these products are issued every three hours. A tropical storm watch or warning means that tropical storm force winds are possible or expected in the specified area within 48 or 36 hours, respectively. Similarly, a hurricane watch or warning means that hurricane force winds are possible or expected within the specified area within 48 or 36 hours, respectively. There are also many graphical products issued by the NHC for tropical cyclones, such as the well known Track Forecast Cone, or cone of uncertainty. Studies 1 and 2 focus on visual hurricane information representations, including these official NHC graphical products. I review several of these graphics in the following section.

2.4.2 Forecast and Risk Images

The NHC Track Forecast Cone, also known informally as the *cone of uncertainty* or simply the *cone* (Figure 2.1), represents the probable track of the center of a tropical cyclone, sometimes with a black line running through the center that depicts the exact (probable) track. The white outlined cone itself is formed by connecting imaginary circles drawn around the forecast track at

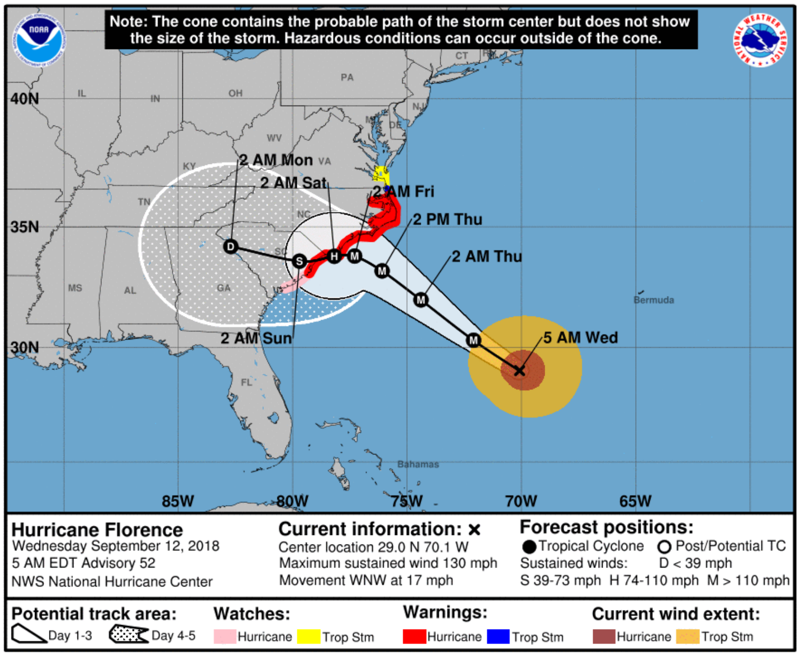


Figure 2.1: NHC Track Forecast Cone for Hurricane Florence in 2018.

12 hour intervals. The size of each circle, which determines the extent of the boundary of the cone, is set so that two-thirds of historical official forecast errors over the previous five years (e.g., for the 2019 season this is based on the errors from 2014–2018) fall within the circle. In addition, the graphic displays areas that are under hurricane and tropical storm watches and warnings as well as the extent of hurricane and tropical storm-force wind field. The watches and warnings occur over land and are denoted by various colors. The wind fields shows the extent of winds from the current center of the storm outward, often extending beyond the cone boundaries which, again, denote the errors from previous season as a way of estimating the most likely track area of the storm's center.

The NHC updated their Track Forecast Cone product in 2017 to make it consistent with other forecast products, to improve upon the fonts and colors, and to add the extent of hurricane- and tropical storm-force winds.[1] Figure 2.1 shows the current version of the product.

Another way of representing hurricane track forecasts is through the use of *ensemble forecasts*. Ensemble methods are used across scientific domains but have gained much traction in weather fore-

[1] https://www.nhc.noaa.gov/news/20170309_pa_2017SeasonChanges.pdf

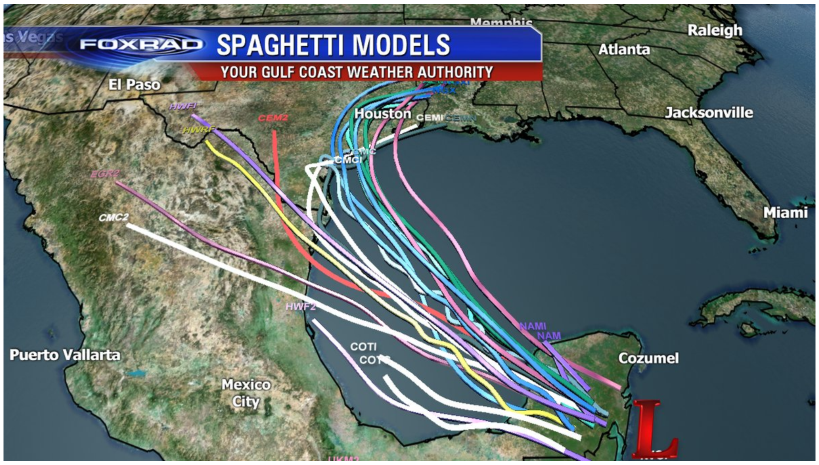


Figure 2.2: Ensemble model of various track forecasts (spaghetti plot) for Hurricane Nate in 2017.

casting in recent years with the advancement of numerical weather prediction (Gneiting & Raftery, 2005). One common hurricane forecast visualization using ensemble methods is the spaghetti plot, as shown in Figure 2.2. This image portrays explicit probable forecast tracks based on different numerical weather precition models. Unlike the NHC Track Forecast Cone, spaghetti plots are not officially produced by the NHC, nor are they standardized among the forecasters and scientists who do use the graphic. These issues, along with further technical detail related to the graphic, are further explored in Study 2 (Chapter 4), for which the spaghetti plot is the focus of the data used to study interactional hurricane risk communication.

Much research has been done on how people perceive and interpret visual forecast images around hurricanes and weather in general, primarily via laboratory studies and surveys. People are known to misinterpret forecast information in particular ways, such as making deterministic conclusions from probabilistic estimates (Morss, Lazo, & Demuth, 2010; Tak, Toet, & Van Erp, 2015). Additionally, the type of graphic used to represent a hurricane forecast largely impacts people's interpretations of it. Two commonly used methods for displaying visual-spatial uncertainty, such as for hurricane forecasts, are summary displays, which summarize uncertainty statistics and are meant to be easier to understand, and ensemble displays, which show multiple data values from which statistical information may be derived (Padilla, Ruginski, & Creem-Regehr, 2017). For hurricane forecasts, summary displays like the cone of uncertainty are commonly misinterpreted as showing a hurricane's size or intensity (Broad, Leiserowitz, Weinkle, & Steketee, 2007), while ensemble displays such as "spaghetti plots" are misused for point-based judgments rather than identification of larger patterns (Padilla et al., 2017; Ruginski et al., 2016). Research by Rickard, Schuldt, Eosco, Scherer, and Daziano (2017) has also examined the different influences in hurricane risk messaging of two types of visual information: "iconic" images, which are representations of something in the real world, and "indexical" images, which show some physical connection to what is being depicted (Messaris, 1997). Indexical hurricane images, such as a photograph showing a house inundated with storm surge, may cause greater risk perception and evacuation intention than iconic images, such as a regional map depicting storm surge projections, because the former provide "proof" of the risk (Rickard et al., 2017). Despite this research, it has also been recognized that further behavioral research is needed to better understand which graphics and visualization techniques promote appropriate public response, including how to communicate probabilities and uncertainty information (Gladwin, Lazo, Morrow, Peacock, & Willoughby, 2007).

2.4.3 Evacuation

Given the potentially catastrophic impacts of hurricanes, there is much focus on evacuation as the primary protective behavior that people can take to keep themselves safe. Research on hurricane evacuation behavior has investigated both expected responses to hypothetical hurricane scenarios, often via laboratory-based experiments or surveys, as well as actual decisions as studied in poststorm research, often via surveys or interviews. Huang et al. (2016) note advantages and drawbacks of each. While studies of actual evacuation behaviors correspond best to what people do in real-world settings, they often rely on recollections of decisions months after the storm has passed when the research is conducted and provide no way of testing novel conditions like new message formats or rare hurricane situations. Experimental studies that create hypothetical hurricane scenarios overcome these drawbacks, but people's decisions may not resemble those in real-world conditions.

Many factors influence evacuation behavior, including household- and individual-level variables. Individual factors include age, though with varying results (Gladwin, Gladwin, & Peacock, 2001; Lazo, Bostrom, Morss, Demuth, & Lazrus, 2015; Sadri, Ukkusuri, & Gladwin, 2017; Sankar, Doshi, & Goodie, 2019), cultural worldviews (Lazo et al., 2015; Morss et al., 2016), and gender (Dash & Gladwin, 2007; Lazo et al., 2015; Morss et al., 2016). However, the predictive value overall of demographic variables in general on evacuation behaviors and intentions has been inconclusive (Bowser & Cutter, 2015; Huang et al., 2016; Yongsatianchot & Marsella, 2019). Variables associated with individuals' risk perception, particularly perceived risk of flooding and living in a mobile home, have also been found as positive indicators of evacuation (Burnside, Miller, & Rivera, 2007; Sadri et al., 2017; Smith & Mccarty, 2009). At the household level, factors corresponding to evacuation include number of children (Hasan, Ukkusuri, Gladwin, & Murray-Tuite, 2011; Sankar et al., 2019; Solís, Thomas, & Letson, 2009), household or geographic location (Hasan et al., 2011; Sadri et al., 2017; Solís et al., 2009; Stein, Dueñas-Osorio, & Subramanian, 2010), type of evacuation notice, i.e. mandatory or voluntary (Hasan et al., 2011; Sadri et al., 2017), and having pets, though this is a negative indicator of evacuation (Lazo et al., 2015; Solís et al., 2009).

Research examining the influence of past hurricane experience has produced varying results. Some work has found past experience not to be predictive of evacuation behavior (Morss et al., 2016; Sankar et al., 2019), while other work has found it to be a positive predictor (Lazo et al., 2015; Sadri et al., 2017; Yongsatianchot & Marsella, 2019). Noting the problem with treating past hurricane experience as a binary variable, Demuth, Morss, Lazo, and Trumbo (2016) showed that it is a much more complex variable encompassing many different aspects itself; treating it as a binary variable misses the nuances of and distinctions between people's different experiences, such as whether they evacuated or experienced tangible effects such as damage or property loss. Additionally, when one's past experience involves repeated, false evacuation orders, this may result in their turning more to the media for risk information (Dow & Cutter, 1998).

Social ties and networks are also indicators of evacuation behavior. Several studies have found that family and friends have a stronger influence on one's evacuation behaviors than the media, particularly as a source of risk or evacuation information (Burnside et al., 2007; Hasan et al., 2011). On the other hand, others have found that the source of forecast information is not a significant factor in the evacuation decision (Solís et al., 2009). Those with larger social networks and those with social networks that are broader-reaching with weaker social ties are more likely to evacuate (Metaxa-Kakavouli, Maas, & Aldrich, 2018; Sadri et al., 2017).

Several reviews of the hurricane evacuation literature have summarized and synthesized findings from individual studies like those above. Baker (1991) was one of the earliest, summarizing findings from hurricane evacuation studies from 1961 through 1989, and is the basis for much of the work reviewed here. Baker found some of the most important variables affecting evacuation behavior to be risk area, actions by public officials, home type, ability to personalize the risk. Dash and Gladwin (2007) highlight the importance of warning message interpretation and risk assessment in people's evacuation decision-making processes. Bowser and Cutter (2015) review the significant predictors of evacuation intent and response based on prior work—personal risk perception, official warnings, warning dissemination channels, sheltering options, use of private auto, housing type, and storm factors—and also note the areas where more needs to be known regarding evacuation decision making and behavior. Huang et al. (2016) conducted a statistical meta-analysis of both "actual" and "hypothetical" hurricane studies in which they summarize the main variables affecting evacuation. They find that laboratory and online experiments reveal similar responses to those during actual hurricanes.

Most of this work has modeled evacuation behavior as a dependent variable based on a predetermined set of vulnerabilities (i.e., variables asked about in surveys and interviews). Though this kind of research is effective at systematically determining the differing influences of particular variables on evacuation, it is not ideal for understanding the complexities and dynamic nature of individuals encountering the uncertainties of disasters (Dash & Gladwin, 2007; Eiser et al., 2012). The research presented in this dissertation utilizes *in situ* data produced by people as they anticipated and experienced a hurricane, allowing a more nuanced perspective of their situations.

Part II

Hurricane Risk Imagery Diffusion

Chapter 3 Prologue

Chapter 3 is a reprint of:

Melissa Bica, Julie L. Demuth, James E. Dykes, and Leysia Palen. (2019). Communicating Hurricane Risks: Multi-Method Examination of Risk Imagery Diffusion. *Proceedings of the CHI Conference on Human Factors in Computing Systems* (CHI '19, Glasgow, UK)

It is included in this dissertation with the permission of my co-authors. The paper was published in 2019, with the research occurring from the end of the 2017 Atlantic hurricane season in November 2017 through mid-2018. The 2017 season saw a number of catastrophic hurricanes impact the U.S. and Caribbean, including Hurricanes Harvey, Irma, Maria, and Nate. We conducted quick response research (Palen et al., 2009) to capture social media activity quickly after the events occurred due to the high-intensity and rapid nature of information production during these events. As part of this, we hired five undergraduate student researchers to help with the ambitious tweet data classification task (Round 1 coding, described in greater detail in Section 3.4.1.3).

As the first study conducted as part of the dissertation, it presents a broad overview of how hurricane risk images diffuse on social media, focusing on risk images originally communicated by authoritative sources. Thus, this study investigates online hurricane risk communication at a mass communication level. Specifically, the paper addresses three research questions: 1) What kinds of hurricane forecast and other risk graphics are posted by authoritative sources? 2) How do different types of authoritative-source forecast and risk images diffuse for hurricane events, and how does diffusion differ based on the type of image, or the authoritative source user? 3) What does the content of replies and retweets/quote tweets reveal about how people relate to hurricane risk and forecast images?

Measuring the diffusion or spread of risk information on social media is important to the larger frame of sensemaking and hurricane risk communication because risk perception and decision-making do not happen automatically with the presence of risk information. Rather, as the Protective Action Decision Model (Lindell & Perry, 2012) outlines, before either of these can happen, people must undertake predecision processes with regard to information, including exposure, attention, and comprehension. The diffusion of such risk images over social media is a proxy for both exposure—that the information has been seen by people—but also attention, in that people must have paid enough attention to the information to pass it on to others. Thus, exposure and attention are important components of the risk communication and decision-making process.

Although many forms of information may influence risk perception and decision-making such as social and environmental cues and warnings, this study deals with one broad form of information, risk images shared by authoritative sources, though many different types of risk images are considered. I chose to focus on images in this study because of the inherent visual and spatial nature of hurricanes and hurricane risk which lend them to being portrayed via computer-generated graphics and often maps. These images are interesting from an HCI perspective because they can be complex in terms of conveying highly technical and scientific information, but also uncertain information, as is the nature of a forecast.

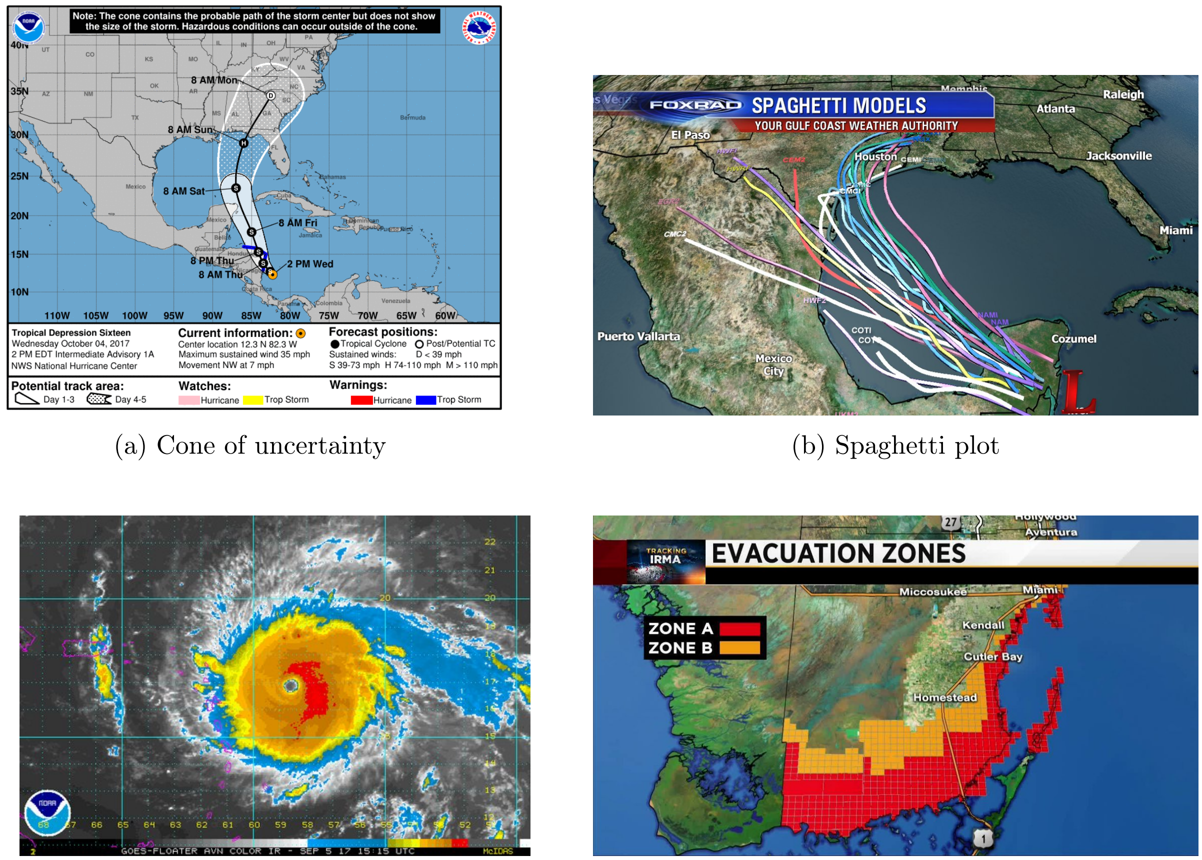
Chapter 3

Communicating Hurricane Risks:
Multi-Method Examination of Risk Imagery Diffusion

3.1 Introduction

Disaster events arising from natural hazards are characterized by uncertainty, such as who or where will be impacted, how and when to evacuate, or how much damage will be sustained. Risk communication therefore is critical, as its purpose is to provide information about a potential hazard and its impacts for people to use to protect themselves and mitigate destruction. However, communicating risk is itself challenging, as it often includes depicting probabilities or a range of scenarios in ways that people can understand and make decisions about. Communicating natural hazard risks has been and remains a central concern to emergency practitioners and weather scientists alike, no matter the mode of communication. Visualizations with maps and satellite imagery are typical forms of communication to reach populations in the broad swaths of geography that are threatened by hazards. Such images are "products" that are issued by formal organizations periodically and distributed to news stations and emergency management groups to use locally (Demuth et al., 2012).

Hurricanes are the focus of this study because of the tremendous risk they pose to people's well-being. Moreover, hurricane attributes such as their size, motion, intensity, and associated risks are predictable to an extent, albeit with uncertainty, yet they all can rapidly change leading up to landfall. Thus, weather forecasts and related products are distilled representations of risk communication about evolving hurricane threats (Bostrom et al., 2016; Broad et al., 2007; Morss



(a) Cone of uncertainty

(b) Spaghetti plot

(c) Satellite image

(d) Evacuation map

Figure 3.1: Example hurricane risk images. Credit: NOAA, FOX 26 Houston, WPLG Local 10.

et al., 2017). Here we look at different types of visual hurricane risk information, as shown in Figure 3.1, including hurricane forecasts (e.g. the cone of uncertainty and ensemble or "spaghetti" models), observations of the hurricane (e.g. radar or satellite imagery) which inform risk assessment and forecasts, and evacuation information. We refer collectively to these as **hurricane risk images**.

People in hurricane-threatened regions are frequently exposed to these images, which have long been available via television stations, newspapers, and the National Hurricane Center (NHC) website. In recent years, social media has become another important means for distributing hurricane risk information, especially given that hurricanes typically form several days before landfall, offering much opportunity for people to discuss their risk and make meaning of these information products. Despite the prevalence and variety of hurricane risk images, the emergency management and weather science communities know little about the effectiveness of visual risk communication in supporting risk assessment and decision-making.

This multi-method investigation empirically examines the diffusion of visual risk communication products during the sequence of hurricane events during the 2017 Atlantic Hurricane season to understand which products diffuse and how. We investigate aspects of individual and collective human interaction with imagery that is generated and shared by authoritative sources, using Twitter as the platform for capturing this activity. As part of the research design, we collected tweets from these sources to focus on scientifically-informed representations. However, as we discuss in Section 3.7, the data collected *in response* to these posts were not restricted in any way. To begin, we inductively examined the images:

> **RQ1**: What kinds of hurricane forecast and other risk graphics are posted by authoritative sources?

Then, to understand human interaction with hurricane risk imagery, we first had to measure the diffusion of such images on Twitter. Because there are many different kinds of risks visualized for a hurricane, such as its potential track or current location, its impacts if/when it occurs, and protective and preparedness information provided to reduce one's harm from it, we also want to know how the response differs to images portraying different kinds of risk. Diffusion of risk imagery is likely to be driven by a number of factors, including but not limited to the type of risk depicted in the image and the type of authoritative source from which it comes, as there are differences in the function and mission of different groups who convey hurricane risk (Demuth et al., 2012). Thus, we ask a second set of research questions:

> **RQ2**: How do different types of authoritative-source forecast and risk images diffuse for hurricane events? How does diffusion differ based on the type of image, or the authoritative source user?

Finally, after characterizing *what* types of imagery were diffused by *whom* and *how* they diffused, we sought to understand more about *why* the images diffused as they did:

RQ3: What does the content of replies and retweets/quote tweets reveal about how people relate to hurricane risk and forecast images?

We conducted three studies to answer each of the research questions: a descriptive statistical analysis of a hand-coded dataset of authoritative hurricane risk images (RQ1, Section 3.4), a bivariate statistical analysis of the diffusion of these images using new diffusion metrics developed for this research (RQ2, Section 3.5), and targeted qualitative analyses of diffused content (RQ3, Section 3.6).

Findings contribute to multiple concerns in the expanding field of human-computer interaction, including that of information visualization and challenges with representing concepts like uncertainty, risk, and probability in consumable ways for a broad public (Greis, Ohler, Henze, & Schmidt, 2015; Ibrekk & Morgan, 1987); the relationship between formal and informal risk communication by computer-mediated means in disaster response (Gui et al., 2018; Palen et al., 2010); understanding the nature of information diffusion on widely adopted social platforms, and devising methods for that study (Goel et al., 2016; Romero, Meeder, & Kleinberg, 2011); and supporting needs of the weather scientific and practitioner communities to understand socio-behavioral phenomena around their information products (National Academies of Sciences Engineering and Medicine, 2018).

3.2 Background

We organize the background review section to first consider what the research reveals about the effectiveness of hurricane risk imagery in general. We then segue to studies in crisis informatics that attend to risk communication. Finally, because this research relies on methods for examining the complicated matter of social media information diffusion, we briefly review the most relevant literature in this area.

3.2.1 Perceptions about Hurricane Risk Images

Research on hurricane forecast image interpretation has been mostly conducted in the laboratory (Padilla et al., 2017; Rickard et al., 2017; Ruginski et al., 2016; Tak et al., 2015) and via surveys (Joslyn & Savelli, 2010; Morss et al., 2008; Morss et al., 2010). Research has shown that people confuse deterministic and probabilistic forecasts, but prefer forecasts that explicitly express uncertainty (Morss et al., 2010; Tak et al., 2015). For hurricanes, though, depictions of risk and uncertainty can be difficult to effectively communicate and interpret (Demuth et al., 2012; Eosco, 2008). The type of graphic used affects interpretation. Forecast uncertainty visualizations can display summarized uncertainty statistics or an ensemble of multiple data values or scenarios (Padilla et al., 2017). Summary displays like the cone of uncertainty are commonly misinterpreted as showing a hurricane's size or intensity (Broad et al., 2007), while ensemble displays such as spaghetti plots which show a range of probably hurricane tracks are misused for point-based judgments rather than identification of larger patterns (Padilla et al., 2017; Ruginski et al., 2016); even forecasting experts have made these errors (Pappenberger et al., 2013). "Indexical" images—photos of damage—may have more impact on risk perception than iconical images—evacuation maps and forecasts—because they are perceived to provide "proof" of risk (Rickard et al., 2017).

Missing from these studies is the ecological validity that comes from *in vivo* examination, which we hope to account for in part in this study. This is because in addition to cognitive perceptions of forecast visuals, context and social processes also affect interpretations of risk messaging and protective decision-making behavior (Lindell & Perry, 2012). Prior experience with a weather phenomenon plays a significant role (Demuth et al., 2016). Similarly, evacuation decisions are influenced not only by risk information, but also by other variables like information source, household location, and vulnerabilities (Hasan et al., 2011; MacEachren et al., 2005).

Visual representations are more effective for communicating risk and making risk information useful for decision making than numerical representations because they reveal data patterns, hold attention, and match the qualitative ways people judge probabilities (Lipkus & Hollands, 1999;

Roth, 2012).

3.2.2 Imagery & Risk Studies in Crisis Informatics

Though a majority of research on social media and disasters has focused on text communication as it supports self-organization and peer production (Keegan, Gergle, & Contractor, 2011; Starbird & Palen, 2011; Starbird, Palen, Hughes, & Vieweg, 2010; White et al., 2014), information verification and rumor detection (Maddock et al., 2015; Mendoza et al., 2010; Starbird et al., 2018), localized versus international social media conversations in disasters (Bruns & Burgess, 2012; Kogan, Palen, & Anderson, 2015), and natural language processing and machine learning techniques (Imran, Castillo, Diaz, & Vieweg, 2015; Imran, Mitra, & Castillo, 2016), a small but growing body of research examines the visual components of such communication (Mortensen, Hull, & Boling, 2017; Seo, 2014; Vis et al., 2013). We know that images not only receive more engagement on social media platforms than text-only posts (Rogers, 2014), but also communicate more—and more complex—information. Graphics are generally better than numerical or textual representations for communicating risk (Lipkus & Hollands, 1999). The photographs and other visual images shared by those closest to the disaster have a different quality and orientation toward accuracy than those by distant onlookers (Bica et al., 2017). Photos of damage can provide crucial information to humanitarian groups (Alam et al., 2018). These examinations inform how we collected data and sampled and interpreted the communications between formal and informal response as well as within the informal response.

In terms of risk information, research about the Zika virus showed that social media users desired specific, contextualized information, and that local knowledge was important to inform decision-making (Gui et al., 2017). Risk perception around the Zika epidemic was multidimensional and speculative, highlighting the need for greater engagement of the public in risk communication (Gui et al., 2018).

3.2.3 Diffusion via Social Media

Methods for studying the diffusion of forecast and risk imagery based on image content and source are themselves important to this work, as diffusion indicates how and to what extent images receive attention online. Information diffusion on social media is a well-studied area. Research has modeled information diffusion on online social networks like Twitter and Digg (Lerman & Ghosh, 2010), including the role of strong and weak ties (Bakshy et al., 2012), or determining whether "cascades" or virality can be predicted based on features of the network or content itself (Cheng, Adamic, Dow, Kleinberg, & Leskovec, 2014). Goel et al. (Goel et al., 2016) defined a diffusion measure, "structural virality," to distinguish between tweets that diffuse by broadcast versus virally; it uses follower networks to infer diffusion of tweets across users. In this research, we focus on *timing* rather than follower relationships because of the rapidly evolving nature of hurricanes. We are also interested in not just retweets, but also replies and quote tweets, as the latter can include context from the diffusing user such as emotional reactions, clarifying questions, and descriptions of how the information impacts them, all of which can be analyzed qualitatively for further understanding of the reasons for diffusion.

Research on crisis-related information diffusion includes how certain memes became viral during a political uprising (Starbird & Palen, 2012), how rumors around a crisis event propagate and the trustworthiness of information (Andrews et al., 2016; Friggeri et al., 2014; Mendoza et al., 2010), and differences in how "locals" and "globals" share information (Kogan et al., 2015; Starbird & Palen, 2010), all of which contribute to our method and interpretation.

3.3 2017 Atlantic Hurricane Season

The 2017 Atlantic hurricane season, which officially ran from June 1 to November 30,[1] was especially active and catastrophic: ten hurricanes formed, with six classified as "major," meaning Category 3 or stronger (i.e., winds greater than 110 mph) as measured by the Saffir-Simpson Hurricane Wind Scale. Extensive damage was sustained in the southeastern US, Mexico, Central

[1] https://www.nhc.noaa.gov/climo/

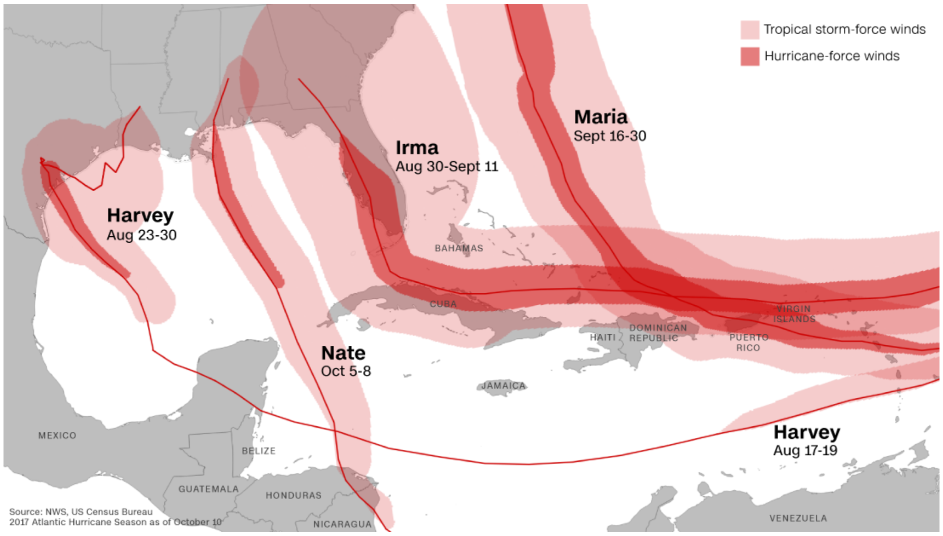


Figure 3.2: Tracks of Hurricanes Harvey, Irma, Maria, and Nate during the 2017 Atlantic season. Credit: CNN.

America, South America, and many island countries and territories in the Caribbean Sea. The most active portion of the season was a period of just over ten weeks and included seven hurricanes: Harvey, Irma, Jose, Katia, Lee, Maria, and Nate. This research focuses on four of these (see Figure 3.2): three which made landfall classified as major hurricanes—Harvey, Irma, and Maria—as well as Hurricane Nate, which was the costliest natural disaster ever in Costa Rica. (Jose and Lee didn't make landfall; Katia hit as a weak Category 1 with lesser damage than other events.) Thousands of fatalities occurred due to the season's hurricanes, including an estimated 2,975 alone in Puerto Rico after the massive destruction from Maria.[2]

3.4 Study 1: Image Collection & Coding

3.4.1 Data and Methods

We used a top-down approach to collect hurricane risk image tweets from accounts we identified as "authoritative sources" of information about hurricanes and their associated risks.

[2] https://www.bbc.com/news/world-us-canada-45338080

3.4.1.1 Identification of Authoritative Sources

Authoritative sources are people and organizations who provide authoritative and credible hurricane forecasts, observational information, and associated risks. Though others shared forecast and risk images on Twitter, we designed the scope of the investigation to examine the diffusion of and conversation around what originates as scientific communication. The primary groups who create and communicate hurricane risk and forecast information, known as the "hurricane warning system" (Demuth et al., 2012) consist of the National Weather Service (NWS) forecasters at the National Hurricane Center (NHC) and local weather forecast offices who characterize and convey hurricane threats, emergency managers and other government officials who take actions (e.g., issue evacuation orders) to protect citizens, and television and other media personnel who curate and communicate hurricane information (Bostrom et al., 2016; Morss et al., 2017).

We identified these sources in two ways: manually, employing the expertise of one of our authors and other collaborators who work in meteorology and weather risk communication at the National Center for Atmospheric Research (NCAR), and via user-created lists that compile Twitter accounts of official information. For manual identification, we created lists of users for each major and/or landfalling hurricane as it occurred (Harvey, Irma, Maria, and Nate), as well as kept a running list of "general" sources that applied to all events (e.g. NWS). Though we did not identify sources specifically for the minor and/or non-landfalling hurricanes that occurred in between (Jose, Katia, and Lee), these hurricanes were included in the tweet data of many of the sources we identified. For the Twitter lists, we found two public lists each for Harvey and Irma,[3] created by twitterers @mattdpearce, a national correspondent for the Los Angeles Times, and @FEMAlive, the official FEMA account for live chats and events, which is only active during specific events.

In total, the research identified 796 Twitter accounts, classified into one of five categories: **Weather-News/Media**: TV meteorologists; websites or TV channels devoted to weather, or the weather division of broadcast news channels; **Weather-Government**: weather-related government

[3] Hurricanes Maria and Nate did not have similar Twitter lists, and so we manually identified local sources of risk information for these.

agencies like NOAA, NASA; meteorologists/scientists at NWS, including NHC; **Weather-Other**: independent weather experts, researchers, and stormchasers; **News** (non-weather-specific): local through international news and media agencies, reporters, journalists, and photographers; TV and/or online; or **Government** (non-weather-specific): public officials; emergency management; government agencies and departments; military; city, county, and state accounts. Counts of accounts and tweets that constituted the final data set for each of these authoritative source user categories are shown in Table 3.1.

3.4.1.2 Tweet Data Collection

For each authoritative source, we next collected: all tweets *from* the user, all tweets *in reply to* the user, and all *retweets* and *quote tweets* (similar to retweets, but including extra comments from the reposter) of the user's tweets—what we collectively refer to as a user's *contextual-plus tweet stream*. The "plus" refers to the extension of the data collection method for "contextual tweet streams," which entails collecting all tweets posted *from* the set of identified users over some window of time (Anderson et al., 2016). By additionally collecting the replies to and retweets of these authoritative users' tweets, we can study their diffusion quantitatively and qualitatively, including the conversations that form around users' original tweets. Contextual-plus and simple contextual tweet streams identify a far larger proportion of event-related tweets than relying on keywords and hashtags alone (Weller, Bruns, Burgess, Mahrt, & Puschmann, 2014), and they

Table 3.1: Counts of Twitter accounts and risk image tweets for each authoritative source user category.

User Category	Accounts		Original Tweets	
Weather-News	188	38.4%	9433	57.1%
Weather-Gov't	41	8.4%	2890	17.5%
Weather-Other	14	2.9%	472	2.9%
News/Media	142	29.0%	3067	18.6%
Government	98	20.0%	657	4.0%
Other	6	1.2%	12	0.1%
Total	489	100%	16531	100%

typically contain more contextual information about a user's experience with the event (Anderson, Casas Saez, Anderson, Palen, & Morss, 2019).

We collected the contextual-plus tweet streams of each of the 796 authoritative starting when Harvey first formed to when Nate dissipated (Aug. 17–Oct. 10, 2017), totaling 9,866,351 tweets. We are interested in risk information and responses pertaining to the forecast phase of a hurricane—i.e., when the hurricane is threatening and occurring—rather than the post-disaster response and recovery phases. So, though the impacts of each hurricane continued long after the final date chosen for this research, the content informing risk assessment and preparatory decision-making was produced in the time leading up to landfall.

3.4.1.3 Coding Images for Hurricane Forecast/Risk Information

The first round of coding identified all tweets posted by authoritative sources containing hurricane risk imagery (either as still images, videos, or animated GIFs). Of the 9.87M contextual-plus tweets, 85308 were original tweets with imagery posted by an authoritative source account. Coding was done by the first author and five trained paid coding assistants. The task was binary: an image tweet was coded as either containing a hurricane risk image or not. The coders had a detailed training document with the coding scheme which included 14 types of risk information to be coded as well as example non-hurricane risk images. These categories were developed iteratively across the initial coding task, and then reapplied across the set once the list was stable.

All coding by the assistants was in the presence of the first author. The inter-rater reliability among all six coders was measured with Krippendorff's alpha at three points throughout the five weeks of coding and increased from beginning (α=0.84), to middle (α=0.88), to end (α=0.95); all are considered acceptable for agreement (Neuendorf, 2016). From this round of coding, we identified 16,789 (19.7% of the original 10M) tweets containing hurricane risk imagery from 500 (62.8% of the original 796) authoritative source accounts.

A second round of coding was conducted by the first author to classify the specific type of each of the identified risk image tweets. The coding scheme was expanded from the 14 categories

Table 3.2: Description of categorized data set of authoritative-source hurricane risk image tweets and their diffusion. Because image categories are non-mutually exclusive and any number of categories can be applied to an image tweet, the columns add up to more than 16,531 (the total number of tweets), or more than 100% for percentages.

Risk Image Category *Non-Mutually Exclusive*	Tweets in Category	% of All Tweets	Replied To	Total Replies	Retweeted	Total Retweets	Quoted	Total Quote Tweets	Not Diffused
Cone of Uncertainty	5103	30.9%	40.9% (2086)	7477	82.7% (4218)	112,503	7.6% (389)	1246	14.9% (761)
Spaghetti	478	2.9%	61.5% (294)	1434	92.3% (441)	8365	5.0% (24)	38	6.9% (33)
Uncertainty	6736	40.8%	42.2% (2844)	10,517	83.2% (5605)	151,209	7.5% (505)	1528	14.5% (978)
Tropical Forecast Advisories	2113	12.8%	38.0% (802)	3372	84.7% (1789)	76,721	9.9% (209)	831	13.7% (289)
Radar/Satellite	6229	37.7%	43.5% (2712)	18,553	85.2% (5310)	283,555	6.1% (377)	1014	13.1% (813)
Evacuation	141	0.9%	44.0% (62)	191	87.9% (124)	3350	6.4% (9)	12	10.6% (15)
NWS/NOAA	3767	22.8%	34.5% (1299)	7250	90.5% (3409)	156,943	9.9% (373)	1119	9.0% (339)
Past	131	0.8%	56.5% (74)	2612	92.4% (121)	34,316	14.5% (19)	94	6.1% (8)

outlined in Round 1 coding to 22 categories which included greater detail. Any number of the 22 low-level categories could be applied to an image tweet. 258 tweets were removed in this round of coding due to the tweet or account being deleted by the service provider or the user.

In this paper, we selectively scope the analysis for **eight exemplary risk image categories** which are prominent visual hurricane representations spanning multiple types of risks. The Round 2 coding results for these categories are in the first three columns of Table 3.2. A total of **16,531** (19.4% of all tweets from authoritative sources) original tweets from **489** (61.4% of the initial 796) sources were identified as containing risk imagery. By qualitatively coding these tweets in this iterative manner, we were able to answer **RQ1**.

3.4.2 Hurricane Risk Images: What Does (Not) Diffuse

Using the full contextual-plus data of the 9.87M image tweets, we next identified all users who engaged with the 16K original risk image tweets, by either replying directly to them (depth) or retweeting/quote tweeting them, thus creating a new thread around the risk image on their own Twitter timelines (breadth). While reply diffusion reveals a variety of conversations among likely strangers on an authoritative-source image, retweet diffusion can reveal more personalized reactions to images when retweeted on a user's own timeline.

In total, 259649 unique users (not already included in the 489 authoritative sources) diffused the 16531 authoritative-source risk image tweets. Of these tweets, 14184, or 86%, were retweeted a total of 523509 times by 240795 users, and 6561 tweets, or 40%, were replied to 36154 times by 26692 users. A much smaller proportion (3000, or 7%) were quote-tweeted ("quoted"), while 13% were not diffused at all, meaning they were not replied to, retweeted, nor quoted.

Different hurricane risk image categories diffused differently, shown in Table 3.2. The most common category is *uncertainty* at 41% of all tweets in the data set; this category comprises mainly *cone of uncertainty* images, which account for 31% of tweets. *Radar/satellite* image tweets, which represent the **current state** (observations) of a storm, were the next most common at 38%. Tweets with a *spaghetti plot*, another representation of the hurricane itself, were uncommon at only 3% of the data; however, this category had the highest percentage of tweets that were replied to at 62% and nearly the highest that were retweeted at 92%, compared to 44% replied to and 85% retweeted for *radar/satellite* and 41% replied to and 83% retweeted for *cone of uncertainty*. Note that cone and spaghetti plot graphics both represent potential **future states** (forecasts) of a storm.

The **past** category consists of imagery conveying information about risks from past hurricanes, whether from days or years ago. Though there were only 131 *past* risk image tweets (0.8% of the data set), these had relatively high rates of replies (56%), retweets (92%), and quote tweets (15%) compared to other categories. This suggests that these images were engaging, and were useful, in some way, to convey risk about the current hurricane threats. We return to this phenomenon of *past* risk imagery in the subsequent studies.

3.5 Study 2: Defining & Measuring Diffusion

This study addresses *how* different risk image categories of tweets diffused (**RQ2**). We examine the diffusion patterns of a given tweet or class of tweets relative to image content (the type of risk imagery) and the authoritative sources.

In hurricane events, which require frequent updates as storms evolve, temporal diffusion reveals insights about uptake in relation to physical events. The research therefore considers the period for which risk information stays relevant by investigating how quickly it diffuses, for how long, how many users are reached, and how these diffusion metrics differ across different kinds and sources of risk information.

3.5.1 Method

This study focuses on retweet and reply diffusions. Retweets are often used as a way of constructing networks to understand diffusion (De Choudhury, 2014; Goel et al., 2016; Hale, 2014; Lerman & Ghosh, 2010), and they capture the *breadth* of diffusion of a tweet, in that many users who may or may not follow the original twitterer repost to their own timelines, potentially exposing it to a new set of people. Replies, on the other hand, represent the *depth* of diffusion of a tweet, because they form a discussion thread or threads attached to the original tweet itself.

To measure the diffusion of hurricane risk image tweets based on their retweets and replies, we graphed diffusion "cumulative adoption curves" (Goel et al., 2016) for individual tweets in the data set, which show cumulative count of retweets or replies across time. These can be thought of as "diffusion signatures" for each tweet. From these signatures, we identified three primary characteristics which contribute to diffusion: total count, duration, and rate. (See examples in Figure 3.3.) Because of the long tail of tweet diffusion (77.8% of tweets are diffused once or not at all), diffusion analyses using the **count** turned out to be insignificant. Thus we focus on the other two characteristics.

The **duration** represents how long a tweet was diffused, and is measured from the time a tweet was first posted to when it received its final retweet or reply; it represents the "life span" of the tweet. The **rate** is calculated as the gradient of the count of tweets over time, starting from the original tweet. The duration and rate metrics are calculated for retweet-, quote tweet-, and reply-based diffusion. Rate is measured using the first 95% of a tweet's diffusion (i.e. its replies, retweets, or quote tweets), an empirically-determined value which accounts for the steady, initial

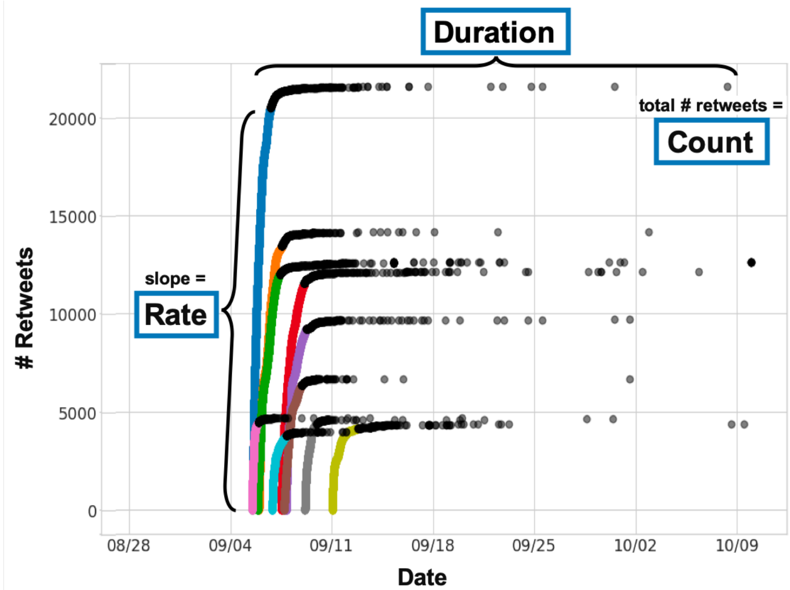


Figure 3.3: Diffusion adoption curves for top retweeted tweets, as an example to demonstrate metrics. Black portions represent the final 5% of diffusion (e.g., the last 5% of retweets). Rate is calculated for the first 95% of diffusion per tweet; duration and count are calculated for the entire curve.

wave of diffusion and ignores the tail-end where people reply or retweet long after the tweet was first posted, as depicted in Figure 3.3 in black. The first 95% of the diffusion signature tends to have the steepest slope or, more precisely, the fastest rate of diffusion.

3.5.2 Diffusion by Risk Image Category

For a given risk image category, we conducted statistical analyses (Kruskal-Wallis tests[4]) to compare diffusion of tweets coded with that category to diffusion of all others (i.e., tweets not coded with that category). These tests were performed for each diffusion mechanism (reply, retweet, and quote tweet) and metric (duration and rate). Though we calculated these values for quote tweet diffusion, few differences in quote tweet diffusion metrics were statistically significant, given how infrequently the original 16K tweets were quoted. Additionally, all quote tweet findings that *were* significant were directionally the same as for retweets, i.e., for both retweet and quote tweet diffusion, tweets for a given image category had a longer (shorter) duration, and/or a faster (slower) rate.

[4] For the Kruskal-Wallis test, we compared medians of diffusion distributions.

Thus, only significant results for reply and retweet diffusion are presented in Figure 3.4, for eight risk image categories.

The **Duration** column of Figure 3.4 shows for each risk image category the median duration of tweets in that category compared to that of tweets in all other categories, separately for replies and retweets. All significant results reveal longer diffusion durations for tweets with a given risk image category than without.[5] For example, *cone of uncertainty* image tweets are replied to for a significantly longer time (1:14 vs. 0:51) and retweeted for a significantly longer time (2:44 vs. 2:14)

[5] This is possible because we only show 8 of the total 22 risk image categories; other categories exhibit the opposite trend, balancing these results.

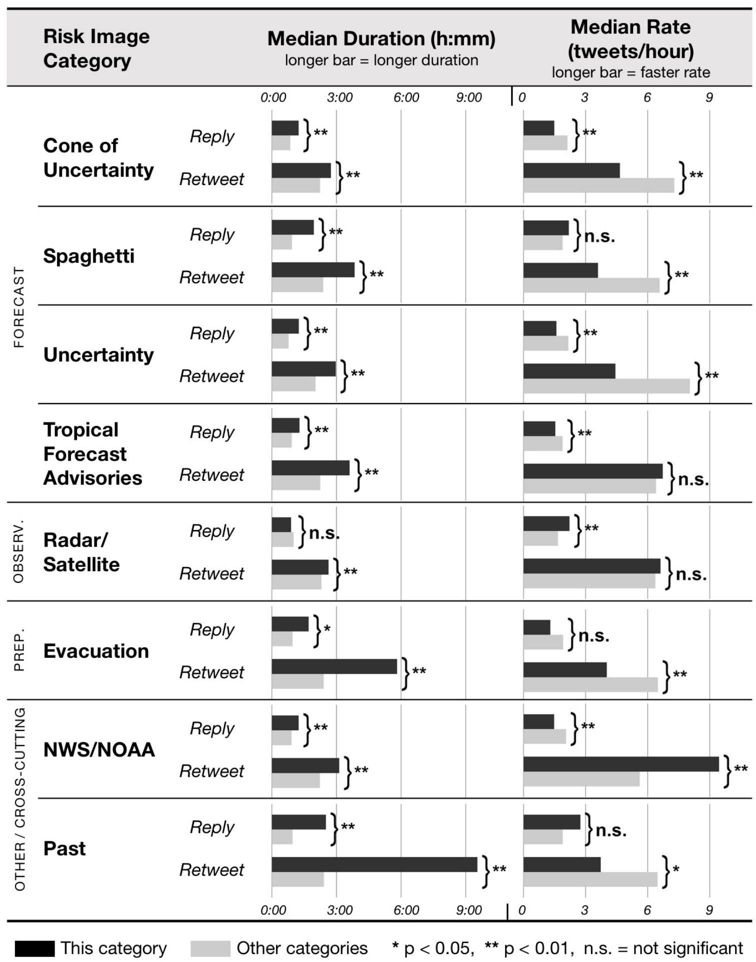


Figure 3.4: Diffusion measurements (*duration*, the lifespan of a tweet, and *rate*, the speed at which a tweet diffuses) for replies to and retweets of risk image categories.

than other risk image tweets, as seen by comparing the black bars to the gray bars in the *cone of uncertainty* graph for **Duration**. In fact, all four *forecast* image categories exhibit similar duration patterns of ~1–3 hours for replies and retweets; this mirrors the temporal frequency with which new hurricane forecast information is provided, including by NHC, which updates the cone and other products every three hours when a coastal watch/warning is in effect. The category with the longest duration signature is *past* with a median retweet duration of greater than nine hours, suggesting that the information in these risk images has longer temporal relevance; we explore this further in Study 3.

The **Rate** column of Figure 3.4 shows for each risk image category the median rate of replies to and retweets of tweets in that category compared to that in all other categories. *Radar/satellite* images had faster reply diffusion than others (2.2 vs. 1.6 tweets per hour). As a type of *observational* risk image, this category portrays current conditions and very near-term risk in a way that is different from other risk image categories. *Radar/satellite* imagery plausibly has a high rate of diffusion because it conveys what is currently happening in a visually compelling way (e.g. Figure 3.1c) that people can make meaning out of even if they do not understand the technical details of the image. *NWS/NOAA* tweets—authoritative risk image products stamped with a logo from one of these organizations, regardless of the source user—are retweeted faster (9.4 vs. 5.6 tweets per hour) than other categories and have the fastest retweet rate among the eight presented here. The stamp of a government weather organization on a hurricane risk image likely garners trust from people, prompting them to disseminate these images more quickly than other risk images, at a median rate of one retweet per six minutes.

These findings motivated further qualitative content analysis on how people textually and conversationally respond to different categories to make sense of these sometimes surprising results. This analysis is presented in Section 3.6.

3.5.3 Diffusion by Authoritative Source Category

As with the risk image categories, we conducted Kruskal-Wallis tests to compare diffusion across source user categories. We additionally implemented a non-parametric pairwise multiple comparisons procedure (Dunn's test) to identify significant differences *among* source user categories, rather than differences based on the presence or absence of a source category. All results have $p < .01$; durations are reported as hh:mm.

3.5.3.1 Diffusion duration

Risk image tweets from Government accounts have a *longer reply duration* (01:56) than News (00:44) and Weather-News (00:58) tweets. Government tweets and Weather-Other tweets have *longer retweet durations* (05:15 and 04:27, respectively) than all other source categories (News: 02:40, Weather-Government: 02:25, Weather-News: 02:08). This suggests that risk information from government sources might have more long-term relevance for affected people, or more long-term interest for people in general, than risk information shared by news sources.

3.5.3.2 Diffusion rate

Weather-Other risk image tweets (from independent meteorologists, researchers, and storm-chasers) have a *faster reply rate* (3.7 replies per hour) than Weather-News (1.9), Weather-Government (1.3), and Government (1.3) tweets. News tweets have a *faster reply rate* (2.4) than Weather-Government tweets. Weather-Government tweets have the *fastest retweet rate*, (16.2 retweets per hour), while Government tweets have the *slowest retweet rate* (4.1). Though hurricane risk image tweets from government sources diffuse for a longer time than tweets from other sources, they also diffuse more slowly, with news sources and independent weather experts receiving the fastest reply rates, suggesting that the independents have a broader reach when diffusing similar types of information. They may be valuable mediators between the product creators and the general public. Interestingly, though general government tweets are retweeted the slowest, tweets from weather-specific government organizations like the NWS and NHC are retweeted the fastest.

3.6 Study 3: Qualitative Analysis

To understand the meaning behind these differences in diffusion patterns for different risk visuals (e.g. *why* are tweets with the cone of uncertainty replied to for a longer amount of time than other risk image tweets?), and to address **RQ3**, we conducted a targeted qualitative analysis of the textual and conversational aspects of replies and quote tweets.

3.6.1 Method

We analyzed the content of replies to and quote tweets of a sample of the original 16K forecast and risk image tweets. Retweets are not a part of this analysis, as they are simply references to other tweets that do not contain new textual content. We selected one image category per type of visual risk image to get a full representation of the dataset while also scoping the analysis: *cone of uncertainty* for hurricane forecast, *radar/satellite* for observational information, and *evacuation* for preparedness information, as well as *past* as a category that cuts across all the others and was shown in Study 2 to have the longest median duration time. For each category, we sampled up to 50 original tweets that had more than three replies or quote tweets (for some categories, there are fewer than 50 original tweets meeting this criterion). For instance, if tweets in a given category have a longer reply duration than tweets in other categories, then we selected the top 50 tweets with more than three replies in that category with the longest reply durations, then qualitatively analyzed the content of all replies to these 50 tweets. We extracted common high-level themes in relation to diffusion topics, and also remarks that were perhaps not common but noteworthy, in that they suggest alternative insights that englighten this research interpretation, and are noted as such.

Here we report findings from analysis of the textual features of 9291 replies and quote tweets that contributed to diffusion of 253 original, authoritative source risk tweets.

3.6.2 Forecast Risks: Cone of Uncertainty

Cone of uncertainty tweets have longer reply and quote tweet durations and slower reply rates than other categories of hurricane risk images. There is a stark difference in the content of the longest-duration replies compared to that of the longest-duration quote tweets. The replies are primarily grounded in managing uncertainty about risk, i.e. questions about the track *("The million dollar question, where does it turn?")*, requests for more localized information *("@hurricanetrack chances this moves up to US East Coast?")*, and even expert opinions on travel-related risks *("Hey NHC if you had a trip schedule for the BVIs from 9/2-9/8 would you cancel?")*. Quote tweets, on the other hand, are more informal and reactive, especially regarding the onset of Nate after several other hurricanes: *"Break out your bumbershoots and wellies next week!"*, *"Well that's just flippin' fantastic. Ugh."*, *"LEAVE US ALONE! This has been the worst hurricane season!"*.

These differences reflect the mechanics of each type of diffusion: **replies** are attached to the original risk image tweet itself, and thus are potentially exposed to others similarly affected by the hurricane and/or others paying attention to the same tweet, while **quote tweets** are posted only to the quoting user's timeline, and thus are exposed only to the quoting user's friends, family, and followers.

The cone tweets with the slowest reply rates include replies days later that revisit the tweeted forecast information, particularly for Irma (*"So weird to look back at this projection."*), comparing the Irma track to 2016 Hurricane Matthew's (*"This is hurricane Matthew all over again. Everyone is hysterical but nothing will happen yet again"*), and expressing discontent and distrust in the information conveyed in the cone forecast (*"This cone is deceiving. The hurricane force winds are only 50 miles across. This looks like it is 360 miles large"*).

One person replied to a cone tweet 22 hours later saying: *"TRACK HAS GREATLY CHANGED AND IS STILL CHANGING. TAKE THIS TWEET DOWN. It is misleading."* There are several interesting points to note with this reply tweet. First, the speaker is implying that they believe content should be updated in real time even after a postdate, and that any outdated information or information that has since evolved should be taken down, which indicates their misunderstanding about the features of microblog platforms. Second, the speaker is continuing to propagate the tweet by replying to it 22 hours later, meaning others would have seen it appear in their feeds again despite the fact that it was no longer up-to-date. Third, the tweet represents a misunderstanding of the track portrayed by the cone graphic, and that though it is *always* "changing" at any given moment, the static graphics are only released by the NHC at regular intervals (every three hours) and are not updated in real time.

3.6.3 Observational Risks: Radar/Satellite

Radar and satellite image tweets had a faster reply rate than other categories. As mentioned previously, the visually compelling nature of these images likely influences their quick diffusion, and this is supported by many replies such as *"She's beautiful. In a graphic way."*, *"Lovely/terrifying"*, *"Magnificent."* These kinds of comments are not found on any other kind of hurricane risk graphics, thus emphasizing the unique ability of this category of risk imagery to captivate audiences.

People responded to more than the appearance of the graphics, as well. Similar to the cone, people wanted more contextualized information to aid their evacuation decisions (*"Thoughts on if you live in Bradenton??'*) and about the threat to specific areas (*"Where is Irma at right now? I have friends in the USVI."*). Also common were reflections on past hurricanes resembling the current ones (*"Looks like hurricane andrew in 1992, check it out"*) and questions about how to interpret the imagery (*"Maybe you could explain to us laymen what the various colors mean so we can understand better?"*, *"Baseline? What does a normal hurricane look like? Asking for those of us with no expertise on the subject."*).

3.6.4 Preparedness Information: Evacuation

Risk can also be communicated through preparedness and response recommendations, such as evacuation information. Tweets portraying evacuation graphics (typically maps) were replied to for a longer time than other risk image tweets. The replies to such evacuation tweets reveal a strong need for additional and more specific information regarding evacuation orders: people wanted to know whether they should evacuate ("*If I live just north of 6, should I leave?*"), whether evacuations were mandatory ("*Wait, is all of Zone A now mandatory evacuation?*"), where to evacuate to ("*Where are we suppose to go if we are in the evacuation area?!*"), and how to evacuate ("*What is the route that is even open out of new territ. Tell residents where to go*"). Additionally, users expressed that the evacuation maps in tweets lacked timestamps to indicate how up-to-date the information was.

3.6.5 Past Hurricane Graphics

Tweets regarding past hurricanes, whether from years ago or days ago, were both replied to and quote tweeted significantly longer than tweets in other categories. We found this particularly interesting because these tweets do not directly portray current threats in the way other hurricane risk images do. Some of the longest-duration replies and quote tweets compare the past forecast pictured to the current hurricanes at the time to emphasize the latter's threat: *"Andrew was always a small storm. A powerful little buzz saw. Irma, she's husky."* However, the vast majority of diffusion of past forecast tweets is political in nature. Many of these original tweets make reference to climate change, which because of its politicized nature seems to invite this type of response. However, many others were only politicized *by* people's responses in the replies and quote tweets.

The past forecast tweet with both the longest reply and quote tweet durations (12+ days and 2+ days, respectively) compares radar imagery of three hurricanes from 2010 to three in 2017, showing the hurricanes nearly matching in size and location, with the text: *"Absolutely uncanny copy-paste from 7 years ago. Very bizarre. #Irma #Jose #Katia #Igor #Julia #Karl."* The replies are mainly around climate change controversies (*"Not bizarre. They script this shit."*, *"But but but global warming tho"*). Other tweets, such as one from @CNN stating *"Yes, climate change made Harvey and Irma worse,"* clearly invite such politicized responses. The surprising diffusion of past hurricane image tweets is thus attributed more to people's desire to discuss politics than to anything having to do with the hurricanes or their risks per se.

3.6.6 Political and Off-Topic Diffusion

These qualitative analyses uncovered many replies and quote tweets that were not related to hurricanes, but rather about fake climate change, there not being an appointed FEMA administrator at the time, and more, and were intended to make political statements. The tweet with the most replies (2825) and third most retweets (13,988) was an urgent, yet non-controversial hurricane risk message regarding Hurricane Harvey: *"NOTICE: The levee at Columbia Lakes has been breached!! GET OUT NOW!!"* The reason for its vast diffusion was that it had been retweeted by @realDonaldTrump, the official Twitter handle for the current US President, thus exposing it to his 3.7M followers. More than 75% of replies to this tweet were unrelated to hurricanes, and were instead commentary on Trump and US politics. This was the only one of the 16,531 tweets in the dataset diffused by Trump.

To determine whether these political tweets were a large percentage of replies overall, we randomly sampled and read $n = 100$ tweets from the 36K total replies to risk images to classify each as purely political (off-topic) or having anything to do with hurricanes or forecasting. We found 25 off-topic tweets. Keywords derived from the data helped in identifying other off-topic tweets: "trump", "climate", "climate change", "global", "warming", "heating", "obama", "antichrist", "fema", "donald", "drumpf", "white", "suprem", "fake", "bush." These terms were used only as a starting point, as not all off-topic tweets contain one, and not all tweets containing one were off-topic. Based on this, a sample of $n = 500$ ensured no more than a $\pm 2.5\%$ error in our off-topic prevalence estimate for the entire dataset; in this sample, we found 105 off-topic tweets for an estimated prevalence of 21%. Excluding from this sample the off-topic replies to the tweet above that was retweeted by Trump, this decreases to 17.3%.

3.7 Discussion and Implications

This multi-method investigation uses social media as the platform for examination of 1) what risk images are shared for hurricanes, 2) how these images differently diffuse based on type of risk portrayed and type of authoritative source user, and 3) why these images diffuse the way they do based on recipients' responses and questions. In this section, we discuss how the findings contribute to HCI, highlighting implications for design, policy, and methodology.

3.7.1 Design Implications

We might think of current risk imagery as boundary objects that sit between the scientific, practitioner, and lay communities—and therefore bear a great deal of burden. Because risk communication must be directed to often millions of people under threat, the implications of risk interpretation are many: they must be put in relation to both the assessment of danger felt by any one person as well as the various costs associated with mass response. The scientific representations present authoritative assessment, but cannot on their own resolve what people consequently do. This depends on further translational work downstream, which is where there are opportunities for the innovation of new information products to support risk communication.

Thus, an important implication from this work is how to reduce the burden on risk imagery for communicating critical, yet often uncertain, information to various stakeholders. Study 3 showed that with all hurricane risk visualizations, laypeople/the public request information that is localized to their particular situation, whether it pertains to where they live, where they might travel, or where their friends or family are located. **Risk information visualizations should be designed such that people may contextualize risks to their own situations and utilize the information more effectively**, rather than interpret risks only as they apply broadly to an entire state or geographic region. Media platforms could enable the use of interactive images that allow users to zoom and pan to more granular levels. Authoritative sources who generate and share these images could additionally outline forecasted impacts at the city- or neighborhood-level to be visually incorporated into the risk image or included in the associated text post. Further still, distilled, localized information for various locations could be presented in *new* risk representations meant specifically for public use, rather than combining public risk information with complex, scientific representations.

Such visualizations of uncertainty, risk, and probability that are consumed by the public are notoriously difficult to both render and interpret (Greis et al., 2015; Ibrekk & Morgan, 1987). However, uncertainty in visualizations can help people to make better estimates (Greis et al., 2018), suggesting that uncertainty should be made *more* obvious in hurricane risk images. The NHC track forecast cone is updated annually, but graphics like spaghetti plots are not standardized and often elicit confusion from the public. **Risk representations should convey uncertainty as appropriate in understandable, meaningful ways so that people can make best use of the information in interpreting risk.**

3.7.2 Methodological Contributions

This research demonstrates the complexities of studying the diffusion of large-scale phenomena—in this case hurricane risk—on widely adopted social network platforms. As hurricanes rapidly evolve and information about them is regularly updated, people must regularly (re)orient to the changing risk. This rapidly changing information delivery and consumption environment that we see in this case, but exists in others too, thus requires specialized methods to describe diffusion.

As an HCI contribution, we empirically determined in Study 2 that the diffusion of tweets could be quantified by two characteristics—duration and rate—in terms of three different mechanisms—retweets, quote tweets, and replies—to identify those image tweets that possess distinctive diffusion signatures. This quantitative analysis in turn inspired qualitative analysis to obtain further insight about why certain images and image categories diffuse. By examining replies back to authoritative sources as well as quote tweets to friends and followers, we gain insight on how people interpret risk imagery through their questions and comments, as well as the different uses of replies and quote tweets for interacting with risk images. We see reactions that are contextualized relative to people's own hazards risk situations as well as to their worldviews about other matters that disasters encompass, such as reactions to climate change arguments and political disputes around emergency response activities. **This research considers risk image diffusion as more than just risk assessment in a strictly rationalized, information retrieval sense, and thus assesses rea-**

sons why certain threads endure as part of a complex information environment, building upon and contributing to the field of crisis informatics research by deepening the questions we pose and the approaches we take.

3.7.3 Policy Implications

A final aim of this research is to support the needs of the weather scientific and practitioner communities to understand socio-behavioral phenomena around their information products. To highlight a few points: As evolving atmospheric phenomena, hurricanes can strengthen, weaken, shift course, slow down or stall. Accordingly, the risks posed by them evolve as well, and this evolution is represented in the risk information produced. Updated observations and forecasts of the hurricanes are then provided on a regular basis, and evacuation orders are issued or rescinded. The diffusion signature patterns reveal a correspondence between the duration and the temporal "relevance" of the information produced about evolving risks. This suggests that **people are broadly attuned to the temporal "cadence" of different types of hurricane risk information**—i.e., that forecasts and observations turn over on the order of 1 to 3 hours, evacuation information is more static, and that past hurricane information can be indefinitely "relevant" as an indicator of potential risks of a current hurricane. The inclusion of timestamps on all risk imagery would further support this.

An important exception arose for the critical category of evacuation, which provides actionable risk information for the public. The median duration for retweets of evacuation orders is about 6 hours, even though orders are issued further in advance of landfall and not usually updated. This suggests that **evacuation information should be regularly reintroduced into the social media sphere for it to receive timely attention.**

Additionally, this research suggests potential changes to practices around sharing hurricane risk imagery on social media, particularly by authoritative sources, supporting related HCI work on rioting behavior (Denef, Bayerl, & Kaptein, 2013) and emergency communication from police and fire (Hughes et al., 2014). Studies 1 and 2 identified and quantified diffusion of several types of hurricane risk images, but Study 3 showed that such diffusion metrics may not tell the full story, as diffusion is an indicator of many different reactions and responses. Thus, in addition to using quantifiable diffusion statistics offered by social media platforms, such as “reach” and “impressions” from Twitter and Facebook, **authoritative sources who produce and share risk information should be heavily engaged in the resulting conversations** to answer questions, clear confusion, and gauge and shape the public’s understanding of risk.

Part III

Interpretation of Risk and Uncertainty Information

Chapter 4 Prologue

Chapter 4 is a pre-print of work currently under review. It is included in this dissertation with the permission of my co-authors, Leysia Palen and Joy Weinberg.

Risks associated with natural hazards events such as hurricanes are increasingly communicated on social media between authoritative sources and the general public, and, as such, they must be conveyed effectively in ways that many audiences can understand. For hurricane risk communication, visual information products generated by meteorologists and scientists at national weather agencies portray forecasts and atmospheric conditions at varying levels of technicality. This study examines issues about communicability of uncertainty in these risk images, with a focus on a popular hurricane risk image type that tackles the portrayal of uncertainty using multiple, discrete lines of a storm's possible trajectories: the "spaghetti plot."

It directly builds upon methods and findings from Study 1, especially the qualitative analysis portion, but also utilizes new methods to examine these issues in greater qualitative depth. Study 1 was concerned primarily with measuring and characterizing the diffusion of risk imagery on social media and offered a glimpse of what insights could be gained through qualitative analysis of the content people write when they diffuse (retweet, quote tweet, or reply to) authoritative risk image tweets. This study takes this further by analyzing not just individual replies, but the back-and-forth conversations that develop around visual risk representations, including interactions between authoritative sources and members of the public. These interactions reveal multiple ways in which members of the public engage with such imagery: issues of what is referred to as "hurricane literacy" involving the comprehension of the visual features of the spaghetti plots, and issues of interpretation, determining both how the portrayed risk impacts the viewer locally or personally as well as what broader impacts it entails.

This study involved analysis of a dataset of microblog interactions around spaghetti plots between members of the public and 76 authoritative sources during the 2017 Atlantic hurricane season and conducted interviews with a sample of the latter. Findings describe how questions arise from the risk depiction and how people make sense of risk dialogically. They address how risk representations are used to simultaneously convey scientific information about a massive weather system and practical information that can help people make decisions such as whether to evacuate. This, together with the expediency and parsimony of social media as well as the immediacy of the hurricane threat, can create a messaging environment that forecloses the inherent uncertainty in an extreme hazard situation. The social media discussion around risk imagery illustrates a fundamental tension in hurricane risk communication between accuracy and ambiguity. In particular, the interactive effort strives for accuracy through communicative acts that maintain the inherent ambiguity of risk. We discuss ways to improve the comprehensibility of risk and uncertainty for hurricanes including how risk information products are designed and mediated.

Within the framing of the dissertation, this study investigates the interpersonal aspects of online hurricane risk communication. Rather than diffusion or individual replies, on which Study 1 focused, here the focus is on interactions between members of the public and authorities to make sense of risk in various ways.

Chapter 4

Accuracy and Ambiguity: How Experts and Laypeople Cooperatively Make Sense of Hurricane Risk Imagery

4.1 Introduction

As natural hazards grow in frequency and degree of destruction, the importance of effective, widespread communication of risk also grows. Risk for many kinds of hazards is modeled as predictions and then communicated with the public in information representations. For hurricanes, risk is often portrayed visually by many types of forecast graphics in terms of the storm's track, intensity, and impacts. Decision makers at all levels, from institutions to individuals, rely upon these hurricane risk representations (Broad et al., 2007) which are now reaching increasingly broader audiences on online social media platforms. The proliferation of hurricane risk graphics brings to light the challenges in communicating uncertain and complex information.

Though much research has investigated the communicability of risk and uncertainty for weather hazards via visual information representations (Padilla et al., 2017; Rickard et al., 2017; Ruginski et al., 2016; Sherman-Morris, 2005a; Sherman-Morris, Antonelli, & Williams, 2015), little has investigated how this occurs on social media, where members of the public make sense of visual representations of probabilistic risk models through interaction with other people, including authoritative weather experts. To this end, this research examines risk communication from the differing perspectives of both the authoritative originators and the public viewers of visual hurricane risk representations. In addition to describing the different ways that the risk representation is engaged

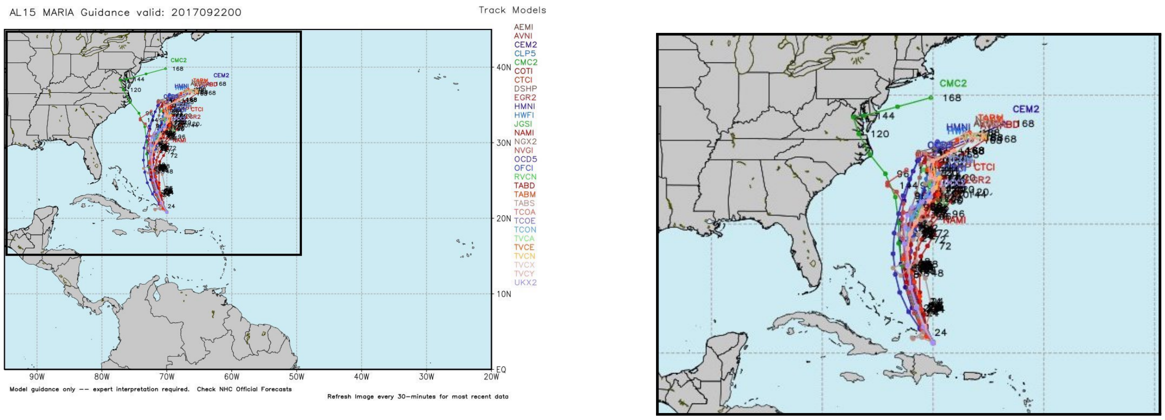


Figure 4.1: Example spaghetti plot image, with detail in box enlarged on right.

dialogically, we show how the interaction between and within authoritative sources and members of the public works to modulate the declarative quality of scientific representations delivered over social media so that the ambiguity of risk is present.

We make use of social media as a data source to study this sociobehavioral phenomenon *in situ*, thereby extending the literature from controlled laboratory studies that tend to study interpretations of risk imagery in isolation to real-life situations that consider the interacting roles of experts and the public. In addition, we propose that the parsimony of communication required for microblog posts and the expediency of its delivery interact with the interpretation of risk imagery, especially under emergency conditions of a hurricane where people have to make protective decisions. For these reasons, we examine the role of social media in the risk communication itself.

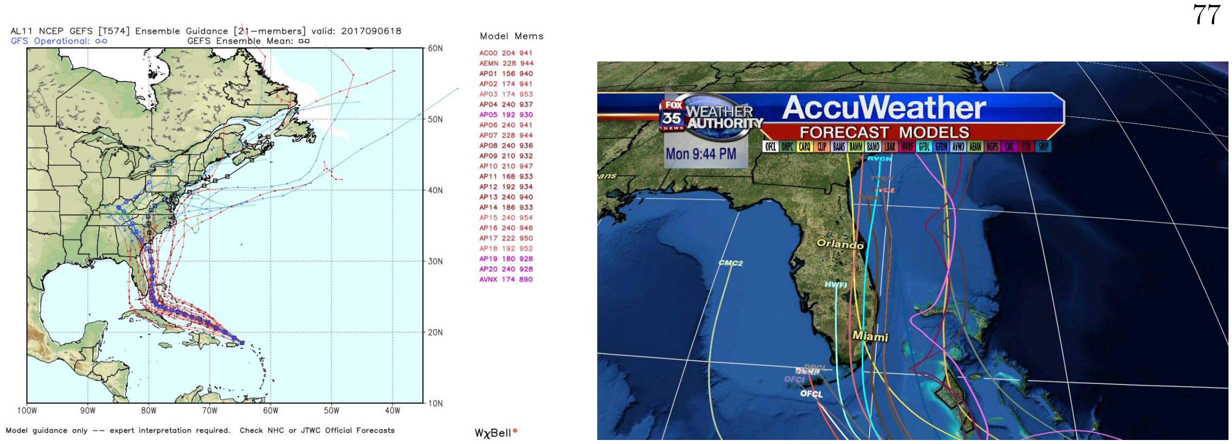
We focus specifically on the *spaghetti plot* or *spaghetti model*, a type of ensemble visualization of various hurricane track forecast models (Figure 4.1) for several reasons. For one, they are used to explicitly convey forecast uncertainty differently than other hurricane risk images by displaying a set of distinct potential paths that are simultaneously possible at a given point in time. Though other types of hurricane forecast graphics also communicate uncertainty, the uncertainty is not always so clearly recognized by wide audiences. For instance, research on the well-known but problematic "cone of uncertainty" used by the National Hurricane Center (NHC) has shown that it is often misinterpreted as portraying certainty based on particular visual features (Broad et al., 2007;

Ruginski et al., 2016). Furthermore, spaghetti models and their interpretation are understudied in relation to the cone of uncertainty or simply “cone” representation, for which there has been much research to examine people’s interpretations of risk and probability (Broad et al., 2007; Eosco, 2008; Meyer, Broad, Orlove, & Petrovic, 2013; Wu, Lindell, Prater, & Samuelson, 2014). Though some research has studied potential alternatives to the cone including ensemble visualizations like the spaghetti plot (Cox, House, & Lindell, 2013; Padilla et al., 2017; Radford, Senkbeil, & Rockman, 2013; Ruginski et al., 2016), none have focused on the spaghetti plot independently of other kinds of graphics. Finally, prior research on the diffusion of various hurricane risk images on Twitter revealed spaghetti plots to be interesting because they received the most response (replies) despite being relatively uncommon compared to other types of risk images (Bica et al., 2019). The response to spaghetti models themselves has proven to be distinctive as well as informative about how people make sense of risk, which we examine in this paper.

Because spaghetti plots require some domain expertise for their interpretation (Hyde, 2017), we are interested in how they are now communicated on social media between authoritative weather and hurricane experts—especially TV broadcast meteorologists—and their diverse audiences. These groups are known to have a “parasocial relationship,” a pseudo-friendship which members of the public develop with their weathercasters (Sherman-Morris, 2005b) and which is further strengthened via social media (Klotz, 2011). This relationship increases viewers’ trust in a meteorologist, which in turn is a significant indicator of whether they will take protective action during hazardous weather, such as finding shelter during a tornado (Sherman-Morris, 2005b).

As a CSCW concern, the interpersonal and sociobehavioral qualities of risk comprehension come into view via social media because of the public interaction between experts and laypeople in the form of questions, answers, commentary, and humor. This allows visibility of the interpersonal sensemaking that might occur parasocially with a meteorologist, but also allows expanded engagement with a population distributed over vast regions. Delivery over social media itself further affects how people interact with interpretations of risk.

We investigate the interactions between experts and their audiences under natural circum-



(a) (b)

Figure 4.2: Two spaghetti plots for Hurricane Irma. (a) GEFS ensemble model. Each line is an ensemble member, or a potential track based on a variation of the same model. (b) "Poor man's ensemble." Each colored line is a potential path that is the result of a different forecast model listed by its acronym in the key.

stances online with data collected from social media during real hurricane events of the 2017 Atlantic hurricane season. In doing so, we capture the dialogue in real-time about queries and responses about hurricane risk *in situ*. We supplement this social media data with interviews with a sample of the experts included in the data to better understand how these interactions happen from their perspective as originators and mediators of spaghetti plots on social media.

4.2 Hurricane Models and Forecasts

Forecasts for hurricanes (as well as other meteorological phenomena) are generated using Numerical Weather Prediction (NWP) models: complex programs that need to be run on supercomputers and take time to generate and are therefore only produced by a limited number of operational forecast centers around the world. An **ensemble model** is a set of such NWP forecasts that are valid for the same forecast parameter (like track, precipitation, or sea level pressure, among others) at the same time. Hurricane *track* ensembles, which are the most available to the public and are the focus of this paper, are sets of forecasts plotted on the same map for the track of a hurricane. Graphics for hurricane track ensembles are often called **spaghetti models or spaghetti plots** because of the way the multiple lines that represent the forecasted tracks look when displayed. In interpreting a spaghetti plot, confidence in the forecast increases the more the potential track lines cluster together, while confidence is lower the less they cluster.

There are two types of ensemble spaghetti model graphics: one shows a set of hurricane track forecasts based on multiple simulations with variations (known as "perturbations") of a single operational forecast center's model. Examples of this type include the "Euro" model produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Global Ensemble Forecast System model (GEFS), produced by the US National Weather Service (NWS)[1] (see Figure 4.2a). The other type of spaghetti model shows a set of tracks based on model simulations from several independent forecast centers, and these are commonly known as "poor man's ensembles" (Ebert, 2001) (see Figure 4.2b). Each model included differs in how it forecasts the complex three-dimensional atmosphere, which results in different forecasted hurricane tracks. Although spaghetti plots can be generated in different ways, they all explicitly represent different possibilities—and thus uncertainty—about the track a hurricane will take.

In contrast to spaghetti plots, research on the communicability of risk of the track forecast cone, commonly known as the cone of uncertainty, has been extensive. The cone of uncertainty is a formal information product released by the NHC. As shown in Figure 4.3, it displays the forecast of the potential track of the center of a tropical cyclone as a black line which is surrounded by a cone. The cone represents the boundaries of two-thirds of historical official forecast errors over the previous five years, and thus indicates where the eye of the storm may travel. Comparisons of the effectiveness of spaghetti plots to the cone of uncertainty are reviewed in Section 3.

4.3 Interaction with Representations of Uncertainty

We review foundational literature which examines how members of the public relate to visual representations of risk and uncertainty, especially those for hurricanes, as well as how such risk information is communicated, perceived, and responded to, especially in the context of social media.

[1] https://www.nhc.noaa.gov/modelsummary.shtml

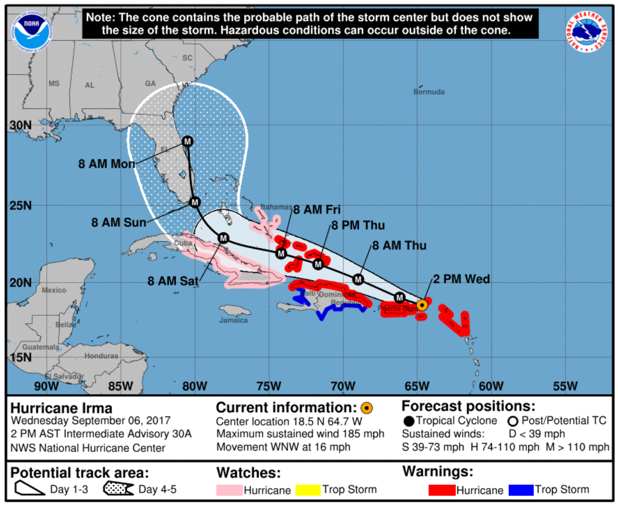


Figure 4.3: Cone of uncertainty for Hurricane Irma. (NHC)

From this review, we see the need for an improved and situated understanding of how people come to make sense of hurricane risk visualizations that are shared on social media and mediated by authoritative sources.

4.3.1 Visualizing Risk and Uncertainty

Risk can be formally represented textually, numerically, and visually. Risk inherently involves uncertainty, often expressed as probabilities. One challenge in any representation of risk is that people struggle to understand probability (Gresh, Deleris, & Gasparini, 2012). Visuals are commonly used for conveying risk and uncertainty. Lipkus and Hollands (1999) discuss three ways in which visualizations help to enhance the communication of risk: by revealing data patterns that may otherwise go unnoticed, by assisting viewers in interpreting numerical information, and by attracting and holding people's attention due to their visual nature.

As a subset of visuals, maps are well-suited for communicating risk, especially to laypeople, because they allow viewers to personalize the abstract notion of risk to their location (Roth, 2012). Maps are superior to text-based representations in terms of people's risk interpretation and decision-making in response to disaster warnings (Canham & Hegarty, 2010; Cao, Boruff, & McNeill, 2016;

Cheong et al., 2016; Liu et al., 2017), and they are strongly preferred over text-based messages for most types of warning information (Cao et al., 2016). However, with respect to hurricane risk communication research in particular, it is not clear that maps can fully resolve the confusion laypeople encounter when interpreting risk imagery because of the more fundamental issue that some people are unable to accurately identify whether they are in a hurricane risk or evacuation area (Arlikatti, Lindell, Prater, & Zhang, 2006; Lazo et al., 2015; Zhang, Prater, & Lindell, 2004).

Hurricane forecasts can be either deterministic, meaning there is a single predicted forecast, or probabilistic, meaning there is a range of forecasts and therefore probability or uncertainty (Tak et al., 2015). Laboratory-based simulation studies have been used to investigate the effectiveness of various probabilistic hurricane risk visualizations for risk interpretation and assessment tasks (Meyer et al., 2014; Wu et al., 2014). Several have compared the effectiveness specifically between summary displays like the cone of uncertainty and ensemble displays like the spaghetti plot. Ruginski et al. (2016) found fewer misinterpretations for ensemble versus cone visualizations. Follow up work by Padilla et al. (2017), however, showed that cognitive biases exist for both visualization types, with individual members of ensemble visualizations given too much weight in people's risk assessments, which we find in our dataset. Overall, while ensemble visualizations may lead to better understanding of the uncertainty and unpredictability of a hurricane forecast, they are more difficult to work with than the cone (Cox et al., 2013). These studies are helpful for determining how visual features correspond to interpretation of the risk images. However, a laboratory setting leaves out the interpersonal elements of risk comprehension when people interact with others to make sense of risk (Eiser et al., 2012). In part due to the rise of social media and its impact on communication around severe weather events, a national report recently highlighted a critical knowledge gap regarding the impact of information and communication technologies on how people interpret and respond to weather and risk information (National Academies of Sciences Engineering and Medicine, 2018). By analyzing social media discussions about spaghetti plots that occurred during the 2017 Atlantic hurricane season, the research presented here studies this complex problem *in situ*.

4.3.2 Risk Communication, Perceptions, and Response

The purpose of risk and crisis communication is to "to inform the public of potential or current events and to persuade the public to adapt their behavior in ways that would improve health and safety" (Latonero & Shklovski, 2011). However, conceptions of risk communication have shifted from a one-way or transmission model to more inclusive models which involve the public (Eosco, 2008; Gui et al., 2018; Morss et al., 2017). Risk communication between authorities and the public can be hindered by their varying definitions and perceptions of risk (Fischhoff, Bostrom, & Quadrel, 1993). While authorities and experts consider risk quantitatively using probabilities, members of the public and laypeople consider risk qualitatively in relation to their prior experience and heuristics (Eosco, 2008; Gresh et al., 2012; Hasan et al., 2011; MacEachren et al., 2005). One study showed the importance for non-experts of the "human contextual quality" of certain risk information formats in relation to others (Schapira, Nattinger, & McHorney, 2001). Recognizing how people interpret risk in personal, qualitative ways is important in understanding the effectiveness of risk communication more generally.

Public response to warning information is influenced by attributes of the warning including source, frequency, and channel, as well as the attributes of the message including consistency, credibility, accuracy, and understandability (Mileti & Sorensen, 1990). Social media is now a common channel for warnings (Blanford et al., 2014; National Research Council, 2013). Studies of how the public engages in risk communication on social media platforms have looked at evolving risk perceptions during a hurricane (Demuth et al., 2018) and interactions between members of the public in the face of unreliable authoritative information during the Zika crisis (Gui et al., 2017).

Regarding weather information, people are more likely to be influenced by forecasts they see on TV if they trust their weathercaster (Bloodhart, Maibach, Myers, & Zhao, 2015). Risk and crisis communication "best practices" often include communicating honestly and openly to build trust with audiences (Seeger, 2006; Veil, Buehner, & Palenchar, 2011). Risk perception and response are also influenced by the extent to which a viewer can personalize the portrayed risk (Liu et al., 2017; Mileti & Sorensen, 1990). For instance, Demuth et al. (2018) found that during a hurricane, people expressed their assessments of risk in personalized ways that explained detailed protective decisions (Lindell & Perry, 2012).

4.4 Data Collection and Analysis

4.4.1 2017 Atlantic Hurricane Season

The window for this research is the 2017 Atlantic hurricane season, which saw notably heavy hurricane activity with six major hurricanes, the third highest number in a single year over the past century (Lim et al., 2018). It produced 17 total named hurricanes and tropical storms which caused thousands of fatalities and billions of dollars in damage. The social media activity around these hurricane events was extensive and rapid. We focus on the particularly destructive seven-week portion of the season (mid-August through mid-October) which included Hurricanes Harvey, Irma, Jose, Katia, Lee, Maria, and Nate. Much of the season's destruction occurred in Texas (Harvey), Florida (Irma), Caribbean islands, especially Puerto Rico (Maria), and Costa Rica (Nate).

4.4.2 Method

We collected tweets in multiple steps by first identifying a list of 796 authoritative sources of hurricane risk information during the 2017 season, in collaboration with weather sociologists at the US National Center for Atmospheric Research (NCAR). We then collected the "contextual tweet streams" (Palen and Anderson, 2016) for those users; that is, all the tweets they generated in the time period, regardless of whether they pertained to the subject of study, so that discourse could be examined in the context of the longer narrative. This resulted in over 9.8M tweets, of which 85K were original authoritative tweets containing media (images, gifs, or videos). We manually and iteratively coded these 85K tweets for media containing 22 types of hurricane risk imagery, resulting in 16,531 categorized risk image tweets from 489 authoritative source accounts. For full methodological details, please see (Bica et al., 2019).

From this dataset, 478 tweets were coded as containing a spaghetti plot graphic, which served as the starting point for the research presented here. These tweets were filtered down to only those that received one or more replies because they include discourse that can enlighten how people respond to and make sense of these images. In total, the dataset consists of **281 tweets**[2] containing spaghetti plot images shared—and in some cases, but not all, generated—by **76 unique authoritative accounts**, along with each tweet's "conversation," as Twitter refers to the set of replies associated with a post.[3] The conversation includes direct replies to the top-level tweet, which in our set totals 1424 replies, as well as threaded replies-to-replies, which contributed several hundred additional reply tweets (this could not be computationally quantified as the sub-conversation reply counts are not made available by Twitter). The replies are mainly from members of the public but sometimes from authoritative sources, including the originator when they engage in dialogue with others on their own tweets.

The methodological approach was discourse analysis (Gee, 2010) of the tweet data conducted in collaborative group data sessions modelled after Jordan and Henderson (1995), in which the research team carefully reviewed the images and discourse over multiple passes so as to uncover increasingly more detail while limiting biases of any individual analyst. To this end, each of the 281 tweets and their conversation spaces, totaling over 500 pages of content, were printed on paper as they appeared originally on Twitter, maintaining the original threading of replies. This enabled us to annotate tweets manually and collaboratively with the research team while dwelling closely on small details of the spaghetti plot graphic and its surrounding discourse.

With each tweet, the data analysis team noted the ways in which risk was communicated visually and verbally (through the associated tweet text) by the authoritative source and the ways in which risk was perceived, interpreted, and questioned by those who replied to the tweet. We also noted: 1) in which instances and how the original authoritative source responded to questions or other types of replies to their own spaghetti model tweets, 2) in which instances there were

[2] An additional 10 tweets had spaghetti plot imagery and initially received replies, but these replies became unavailable due to deletion or account suspension and thus the tweets are not included in this analysis.

[3] https://help.twitter.com/en/using-twitter/twitter-conversations

threaded conversations (as opposed to singular, unthreaded replies) involving either the authoritative source and/or other people, and 3) the timing or pacing of conversations based on timestamps. We call attention to the point that tweets were analyzed not as individual units but as part of larger interactions and conversations around one top-level spaghetti model tweet. Accounting for context in this way promotes more "responsible interpretation" of people's responses to the spaghetti models (Anderson et al., 2019; Kogan & Palen, 2018; Palen & Anderson, 2016).

We additionally maintained a database of the 281 spaghetti plot tweets with both the metadata originally collected from Twitter (e.g. tweet text, timestamp, user details, media format) and additional details we determined either manually or computationally. Tweet-level details include:

- Number of direct replies: All 281 tweets received at least one reply, with 108 also containing threaded replies (i.e., replies-to-replies within the conversation space).

- Corresponding 2017 hurricane(s): To determine this, we inspected the tweet text, date, and imagery. The majority of spaghetti plot forecasts were for Hurricane Irma (n=162), followed by Maria (n=53), Harvey (n=25), Nate (n=20), Jose (n=18), and Lee (n=2). (Some tweets pertained to more than one hurricane, so the sum is greater than 281.)

- Type of authoritative source who posted the tweet: Each of the 76 original authoritative accounts was exclusively categorized as Weather News (n=57), Non-Weather News (n=16), Weather Other (n=2, a meteorology student and an independent meteorologist), and Weather Government (n=1, NWS Houston).

- Media format of the spaghetti plot imagery: 274 were still images, six were videos, and one was an animated gif.

We include tweet data excerpts throughout the paper to illustrate observations or findings that co-occur with our analytical narrative. These are formatted as:

Image associated with tweet data excerpt(s).

(Not shown for every excerpt.)

`@authoritative-username (UTC timestamp) <tweet text>`
`↪ @username (UTC timestamp) <reply tweet text>`

These excerpts—both textual only and text with images—are denoted by vertical gray bars on the left side. The username is underlined if it is the authoritative source who originally authored the spaghetti plot tweet. Authoritative sources are identified because they are public figures whose accounts are authenticated ("verified") by Twitter. For non-authoritative, public accounts, we follow best practices offered by Fiesler and Proferes (2018) and anonymize usernames (using the convention @person1, @person2, etc.), with the exception of one public username which is deanonymized because it is referenced in an interview. All tweets are from August–October 2017 and were limited to 140 characters (the tweet limit increase to 280 characters occurred later in November 2017). Arrows are used to indicate replies, with threaded replies nested beneath direct replies.

To complement our discourse analysis of the tweet dataset, we conducted semi-structured interviews with a subset of the authoritative sources who shared spaghetti plots to understand how they thought about communicating risk and uncertainty for hurricanes on social media. This was motivated by prior work that suggests the important influence of both the source and the message for risk and warning information on people's risk perceptions and responses (Mileti & Sorensen, 1990). The 76 authoritative source accounts were sampled first by those which represent accounts of individual people rather than organizations (n=57), then by those who interacted to some extent with people in the conversation spaces of their tweets. We invited ten people—all meteorologists—to participate, and six agreed. We interviewed them over time , which allowed us to conduct interim analysis along with the social media data and confirm that we reached saturation with the interview participants. Notably, the weather broadcasters who are not chief meteorologists seemed to have more trouble seeking authorization from their employers to participate. The interviews were conducted via phone or online video call and lasted between 60 and 90 minute and transcribed by the authors.

Table 4.1 shows details for our interview participants, who included broadcast meteorologists

Table 4.1: Authoritative Source Interview Participants

Participant (Twitter Username)	**Role & Organization**	**Region/Local Market**
Eric Berger (@SpaceCityWx)	Independent meteorologist and journalist, Space City Weather	Houston, TX
Greg Dee (@GregDeeWeather)	Meteorologist, WFTS-TV (ABC)	Tampa, FL
Tim Heller (@HellerWeather)	Chief meteorologist, Heller Weather	Houston, TX
John Morales (@JohnMoralesNBC6)	Chief meteorologist, WTVJ (NBC-6)	Miami, FL and Puerto Rico
Brian Shields (@BShieldsWFTV)	Meteorologist, WFTV/ABC	Orlando, FL
James Spann (@spann)	Chief meteorologist, WBMA-LD (ABC 33/40)	Birmingham, AL

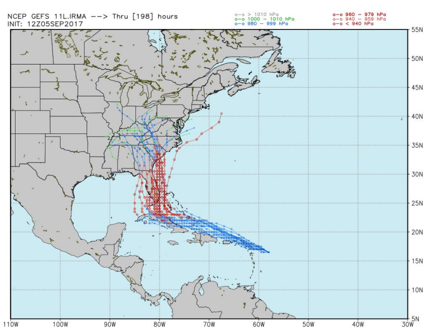
at local TV news stations and one independent meteorologist/journalist. The participants forecasted weather for diverse geographic regions of the US, all of which were impacted during the 2017 Atlantic hurricane season. Their use of spaghetti plots on Twitter during the 2017 season and the responses they received varied, reflecting many different ways that their audiences interacted with them about the graphic to make sense of the portrayed risk. As part of the human subjects protocol, the interview participants agreed to be identified so that we could tie their social media communications to their narrative explanations as obtained from the interviews. In some cases, their remarks are de-identified as appropriate for the research and/or at their request.

4.5 Public-Authoritative Interactions on Spaghetti Plot Social Media Posts

We first describe findings about how members of the public respond to spaghetti plots shared by authoritative sources on Twitter as a proxy for their comprehension of the graphics, and how authoritative sources discursively respond to them in turn. Comprehension includes both the ability to "read" the spaghetti plot and to use information from the graphic to make decisions; interactions revealed diverse (mis)interpretations at both levels of comprehension by members of the public and in some cases, resolutions through interactions with others. Throughout this section, findings from the social media discourse analysis are supplemented with findings from the interviews that reflect how experts see themselves in these interactions.

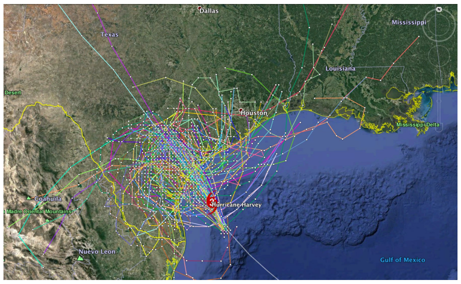
4.5.1 Spaghetti Plot Literacy

We begin by examining discourse that shows how people are trying to make sense of the visual features of the spaghetti plot representation itself so as to comprehend it—the lines, the colors, the numbers, the legend if there is one, and so on—what cognitive science discusses as "encoding" (Canham and Hegarty, 2010). Experts and laypeople alike referred to this as "hurricane literacy" in their posts or interviews. Queries to the authoritative sources often ask what the different aspects of the plots mean, with many people striving for their interpretations to be verified, even though they are often incorrect. The matter is not helped by the fact that spaghetti plots are not standardized across the agencies and people that generate them. For example:



↪ `@person1 (Sep 05 18:29) Is there a meaningful difference between blue/red/green?  I am somewhat hurricane illiterate, but anything in those ranges seems pretty bad?`

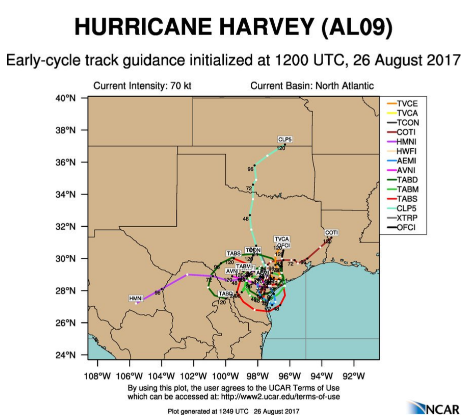
@Person1 poses their question in reference to a graphic for Hurricane Irma that depicts the GEFS ensemble model, where colors represent atmospheric pressure at different points along the forecast tracks, as indicated by the legend. But spaghetti models are not standardized across producers, and there is no "official" version of a spaghetti plot (as there is with the NHC track forecast cone). Alas, @person1 fails to get an answer, which is problematic because in other types of spaghetti models, including the poor man's ensemble, colors do not represent "meaningful difference" except to distinguish each model in the graphic, as we see here for Hurricane Harvey:



↪ @person2 (Aug 25 19:54) Interesting, Are the colors of the lines based on probability?
  ↪ @spann (Aug 25 19:54) No different models.
  ↪ @person2 (Aug 25 19:59) got it, thanks.

This graphic failed to have a color legend at all. Here, the authoritative source, @spann (denoted by the underlining of his name), who is also an interviewee in this research, answers within the minute, though with brevity. This is consistent with Spann's approach, as we learn in his interview, to respond to as many posts as possible, which thereby limits answer depth. In his reply to @person2, he explains that the colors do not map to probabilities, but rather indicate "different models" that predict each track. We wonder if @person2 understands what "models" are given that their question is basic, though not unusual as color is often used as a visual feature that impacts risk perception (Bostrom, Anselin, & Farris, 2008), and even though they close out the conversation following @spann's reply. We return to these issues and what they mean for design implications in the Discussion.

Another person tries to make sense of a graphic shared during Harvey in a different way, this time by considering the legend, perhaps because the storm was behaviorally unusual in its looping and stagnation, with just three possible tracks depicted that would appear to do less concentrated damage. In response to the spaghetti plot, the person asks about the ordering of the models in the key:



↪ @person3 (Aug 26 13:56) Are they listed from highest likelihood to lowest on the key?
  ↪ @SpaceCityWX (Aug 26 13:58) No

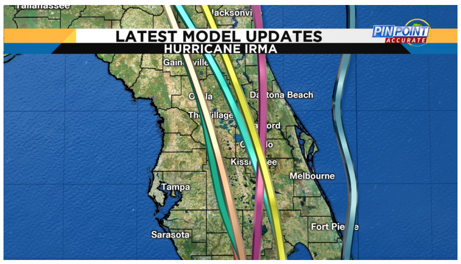
Here, too, the expert @SpaceCityWX answers quickly but definitively so as to limit misunderstanding by @person3 and others who might wonder the same, but perhaps lacks the time or a way to further elaborate. Yet, we see this question repeating itself across other laypeople who are wondering about probabilities and "likelihoods," thereby indicating confusion with these representations (Cox et al., 2013). It is made further confusing, we note, because the legend is not in alphabetical order or any other apparent default ordering. Upon further investigation, communication with the NCAR scientist who generates this specific plot reveals that the order of the models in the legend is based on how he parses the data, which roughly aligns with highest to lowest recent accuracy of each model (Jonathan Vigh, personal communication, 28 March 2019). It then makes sense that @SpaceCityWX responded with a flat "No" because he did not produce the graphic and therefore could not offer more explanation about the ordering; the orderings of models, as well as other graphical choices, for this and all spaghetti plot representations are determined by the person who produces the graphic, who may be different from the person sharing the graphic on social media.

By showing a set of distinct possible tracks the hurricane could follow, the spaghetti plot helps to reduce some misconceptions about hurricane forecasts common with other types of graphics, such as the belief that a hurricane increases in size as represented by the cone of uncertainty (Ruginski et al., 2016). However, it still can bias viewers" judgment in other ways. For instance, they may be more likely to focus on individual tracks, especially ones that happen to overlap with a point of interest such as the viewer's hometown, than larger trends or patterns in the data (Padilla et al., 2017). We found evidence of this bias in replies from members of the public and non-experts who focus on individual hurricane trajectories, especially outlying trajectories. For instance, in response to the same "blue/red/green" spaghetti plot post shown earlier, @person1 also replied:

> ↪ `@person1 (Sep 05 18:24) One of those paths goes directly over the Tampa bay area including St. Petersburg and Sarasota... O_O`

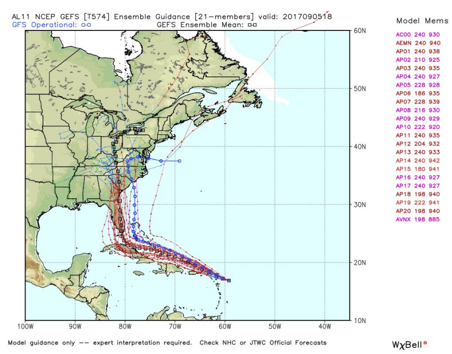
However, the path of any single line in the ensemble graphic is unimportant; rather, for that particular graphic, it is the general trend that almost all the paths travel over or very near Florida that is most important. In other words, every area of the Florida peninsula was portrayed to be at risk regardless of whether a line traveled over that particular area or not.

Other spaghetti plots also received similar replies biased toward identifying outliers, indicating that some people interpret the graphics to be declarative as to where the hurricane will go. The following two examples mention "the one on the right" and the model that goes "onto land through the Carolinas," both in reply to posts about Irma:



@TroyNews6 (Sep 08 13:58) #Irma will move straight up the state from South Florida. Here are the new models. #StaySafe

↪ @person5 (Sep 05 17:17) I like the one on the right!



@spann (Sep 06 02:13) 18Z GEFS ensemble (21 member) guidance...

↪ @person6 (Sep 06 02:44) Which model is the blue one with the circles at short intervals. That model has #Irma going onto land through the Carolina's.

In the interviews, meteorologists weighed in on their perceptions of the public's understanding of spaghetti plots. Several comments were candid, saying that the public's understanding was "not great," "probably pretty poor," and "low, and that is no fault of their own whatsoever," with this last statement showing that they attribute this more to the complexity of spaghetti plots than to individuals" capabilities. In addition, one participant worried about the communicability of map-based forecast graphics in general because "people can't find their house on a map." This is similar to a study that found up to one-third of people in coastal regions who had previously been at risk in a hurricane are unable to identify their hurricane risk area on a map (Zhang et al., 2004). Even so, he thinks that providing spaghetti plots is important because: "I think most people in hurricane prone areas are used to them and quite frankly they expect to see them and if they don't find them from you they are going to go find it from somebody else." Similarly, another authoritative participant explained that he shares spaghetti plots if his audience expresses interest in them.

Despite the many ways which audiences confuse and misinterpret the plots, the expectation of their availability is perceived to be significant. This begs the question as to why. Perhaps it is because readers do not know they do not understand the plots or, if they do know their knowledge is lacking, the spaghetti plot may serve as a reassuring indication that the work of forecasting the hurricane is being done by someone, somewhere. For instance, it may be reassuring that one's local meteorologist can explain the plot, or that agencies that produce the plots are in the background monitoring the activities of earth systems and taking stock of how the hazard will impact the public. This idea provides some basis for thinking about the relationship between science and the public, and the multiple roles of scientific communication, which we return to in the Discussion.

These interactions suggest that while spaghetti plot representations may overcome some of the challenges people face when viewing other risk representations, they still are subject to biases and elicit confusion, especially when shared on social media with limited allowance for explanation by mediators. As such, there is room for improvement in the design of these graphics and their communication on social media to increase their interpretability for the public.

4.5.2 Localizing Risk

A prevalent theme found in people's responses to tweets with spaghetti plot images was localized interpretations of the risks, or the desire for such information to be provided. The risk literature refers to how people "personalize" risk, or interpret risk in terms of personal impacts (Lindell & Perry, 2012; Mileti & O'Brien, 1992); we use the slightly different term "localizing risk" here because we find that this theme corresponds to qualities of geographic representation of the data in spaghetti plots while also invoking aspects of "personalization." Understanding this sets the stage for discussion of other kinds of geographic considerations beyond the personal in **Section 5.3**. Most spaghetti plots are superimposed over broad swaths of land, sometimes even displaying the entire map of the United States or the entire Atlantic Ocean (e.g., Figure 4.1). Depending on how closely the track lines cluster, they may also span an exceptionally large geographic region (e.g., Figure 4.2a), therefore putting an equally large population under potential threat. Despite this macro view in spaghetti plot graphics, we see people narrow in on how the risk may affect them personally based on their location and situation, whether they should evacuate, and what the impact will be to their cities and homes, for example:

> ↪ @person7 (Sep 03 22:35) How bad will it be on tampa?

> ↪ @person8 (Sep 05 02:10) Looks like a few green lines running over my house in Homestead

> ↪ @person9 (Sep 07 20:59) Should we leave from Davie? Will our houses make it? Getting insanely scary now.

In this next exchange between two friends, we see one localizing the risk by presuming damage to his home while also interpreting it through the lens of their shared experience with Hurricane Matthew the year prior, and the other offering support while also expressing concern:

> ↪ @person10 (Sep 05 03:01) My home will probably be flattened :(
>   ↪ @person11 (Sep 05 03:03) Praying for you bud
>   ↪ @person10 (Sep 05 03:05) Yeah its not looking good for here. Looks like its gonna go right through central florida
>   ↪ @person11 (Sep 05 03:06) Basically everyone in Florida needs to prepare for the worst.
>   ↪ @person10 (Sep 05 03:08) Yeah we have started preparing. This one scares me alot more than Matthew did
>   ↪ @person11 (Sep 05 03:08) As it should. Matthew wasn't nearly as strong/organized.
>   ↪ @person10 (Sep 05 10:33) Yeah i know

People also localize their interpretations of the visualized hurricane risks by commenting on or asking how the threat affects their future travel plans. Some people expressed uncertainty regarding decisions to travel based on their risk assessments, as seen in other crisis events such as the Zika outbreak (Gui et al., 2017). These examples show such behavior in relation to Hurricane Harvey:

> ↪ @person12 (Aug 29 17:17) What's the ETA for it to hit? We're planning a trip to the Keys this weekend and would rather stay in Orlando if there's a threat ...
>   ↪ @EricBurrisWESH (Aug 29 18:35) not even close to your timeline. But it's too early to see where it goes...
>   ↪ @EricBurrisWESH (Aug 29 18:35) This would be a Sept 12//13//14 IFFFFFF it came close to this way...

...in relation to Irma...

> ↪ @person13 (Sep 05 14:02) James, Supposed to go to Charleston Mon-Fri. Advice?
> ↪ @spann (Sep 05 14:05) Too early to know the specific impact there... But it could be significant

...and in relation to Nate:

> ↪ @person14 (Oct 05 02:02) Any chance it shifts to the west. Going to Panama City beach Saturday. Should I be concerned?
> ↪ @spann (Oct 05 02:06) https://www.alabamawx.com/?p=146232
> ↪ @person14 (Oct 05 02:14) Thanks. I will check back in tomorrow

In the last example, @spann responds with only a link to his weather website, The Alabama Weather Blog, on which he had already provided a detailed forecast for the following days (including the "Saturday" @person14 asks about). In contrast to expressing uncertainty via questions about whether to travel, other people expressed more certainty regarding canceling their plans or having them disrupted based on their risk perceptions, again demonstrating declarative interpretations of the spaghetti plots:

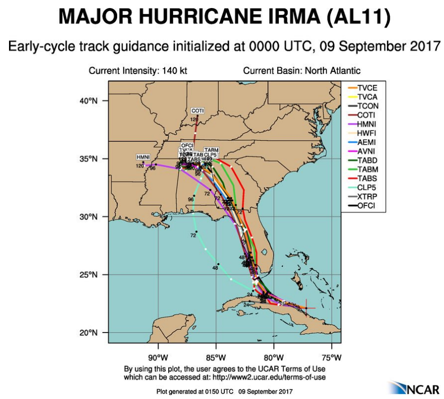
> ↪ @person15 (Aug 22 14:05) I guess I won't be fishing this weekend

> ↪ @person16 (Sep 05 02:16) Looks like Irma is going to make my vacay to Disney suck next week...

> ↪ @person17 (Oct 05 14:47) Dang! Guess I'm not going to the beach this weekend.

4.5.3 Broader Sensitivity to the Larger Region

In contrast to localizing risk, we also see people express concern about risks to others, indicating a broader awareness of the danger that the hazard will yield. We see explicit expressions of sympathy for others" plights, for instance after a hurricane has changed track and no longer threatens oneself. It is as though what might be seen as the public expression of relief for oneself must be mitigated by equal expression of concern for others, for example:

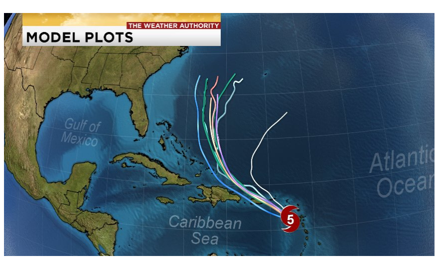


@DaveCocchiarell (Sep 09 02:18) The most recent models take the last few hours of westward movement into account and shift track to the west again.
↪ @person18 (Sep 09 12:44) I really like that CLP5 model (sorry Alabama).

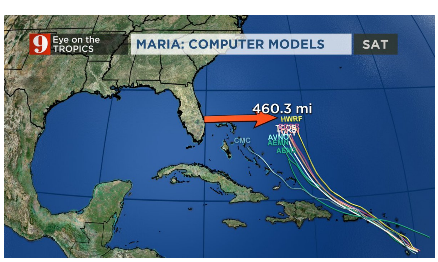
@Person18 finds the leftmost, outlying track ("CLP5") in the plot most satisfactory, perhaps because he is living somewhere near where all the other tracks are clustered. At the same time, the person recognizes that this outcome would be worse for Alabama and expresses sympathy for people there.

We found instances of this phenomenon in response to authoritative sources" original spaghetti plot posts which frame the outlook only as "good" for their local area but neglect to identify what new areas might be threatened:

@FOX35Glenn (Sep 06 01:46) This evenings late night model runs are all shifting east!!! That is a good trend for #Florida #Irma #Fox35
↪ @person19 (Sep 06 02:24) GOOD FOR FLORIDA BUT WHAT ABOUT THE REST OF US



@MattDevittWINK (Sep 19 13:38) #MARIA: Computer models continue to keep the powerful storm away from Florida. Growing agreement. Good news! #swfl
↪ @person20 (Sep 19 22:29) Good for us. Bad for the Caribbean. I'm still not over #IrmaHurricane no power thanks to the swift svc of @insideFPL *(us = people in Florida)*



@BShieldsWFTV (Sep 18 14:21) MARIA MODELS (Monday AM): Models rather tightly clustered well offshore this weekend. If that holds, good for FL!
↪ @person21 (Sep 18 14:42) Creo que nos salvamos de nuevo RD, sorry por las demas islas, seguimos orando *(I think we saved ourselves again Dominican Republic, sorry for the other islands, we keep praying)*

The latter two examples are attached to spaghetti plots for Hurricane Maria. By the time these comments were posted, Florida had already experienced major damage from the previous Hurricane Irma's landfall, and so forecasts that indicated Florida would be safe from Maria were especially reassuring for people there. However, Maria was forecast to (and did) make landfall as a major hurricane over several Caribbean islands, which neither of these initial posts indicates in their text, though is visible in the spaghetti plots. Though @person20 agrees the forecast is "good" for their state of Florida, and @person21 interprets that she is safe in the Dominican Republic, they both note the places that will endure Maria: "the Caribbean" and "the other islands," respectively.

In his interview, Shields discussed the distinction of calling a forecast "good for FL!" as he did in the post above versus "good!" overall, because the latter overlooks that the storm is going to hit somewhere and therefore sends the wrong message. However, he also noted the tension between his professional responsibility to the eight counties he covers in Central Florida, and the fact that he has Twitter followers who have interests in, or are from or located in, other places, including the Dominican Republic and Puerto Rico.

Other participants also offered their insights on balancing these different aspects of their job: forecasting and reporting on hurricanes which have broad geographic impact, and communicating information that is relevant to their local audiences and online followers. Heller, similar to Shields, tailors his forecast communication for his local community:

> I realize that people in South Texas—and I might have some followers down there, and I might have followers that live outside of my area, but there's some meteorologists around the country who like to be everybody's weatherman, and they want to post, you know, whatever the story is... I believe in serving my local community and so that is my focus.

Spann on the other hand uses social media to reach a broader audience than he feels he is able to on TV:

> In the television business we have a designated market area (DMAs) that define your market. My market is Birmingham, Tuscaloosa, Aniston. We have like 23 counties. The digital world doesn't stop at a county line. In the digital world you can reach anybody, so that is very appealing.

This evidence suggests that the collective gaze of members of the public does enable some empathetic understanding of these hazards as they affect others (Sontag, 2003), a point to which we return in the Discussion. Authoritative sources, though also appreciating the wide-reaching impacts of hurricanes, may feel the need to focus on the local impacts as part of their job responsibilities.

4.5.4 Communicative Responsibilities of Authoritative Sources

The communicability of the spaghetti plot as an information artifact is not only a function of the artifact's design, but also of how authoritative sources employ their forms of expertise to convey, and sometimes translate into lay terms, the risk the artifact attempts to communicate. This addresses a gap in previous laboratory-based research of how people interpret and respond to risk imagery in that many people view such imagery on social media where it is mediated by an authoritative source, like a meteorologist, who explains the image and can sometimes answer questions about it. Thus, this section looks at risk communication from the perspective of authoritative sources. We organize these findings around three responsibilities in communicating with the public—interaction, interpretation, and maintaining uncertainty—that were found through both analysis of authoritative source tweets as well as interviews.

4.5.4.1 The Responsibility of Interaction

With the increasing importance of the digital world for communication and information sharing during crisis events, authoritative sources face increasing responsibilities of interaction on multiple platforms for both traditional and social media. We learn from the meteorologists interviewed that interacting with audiences is important to how they see their role, with one participant additionally explaining that communicating with the public on social media is a "requirement" and a "performance metric." At the same time, the demand to always be "on," even when not "on air," makes prioritizing time and resources around public interaction challenging but especially necessary during a severe weather event. For example, during "wall-to-wall" coverage of a hurricane on his TV news station (that is, without interruption from commercials or other news), Morales says,

> I've got a hurricane that's threatening South Florida—so my market is Fort Lauderdale, Miami, and the Florida Keys—if I've got a threat to this market, then that means I'm on TV a lot and...carving out time for social media becomes challenging.

Spann emphasized the effort required to engage across multiple platforms when a major hurricane is approaching: "I do my best to look at everything and it takes *time*—you don't even know how long it takes to look at this stuff.'

Potentially further adding to the weight of their responsibility of interaction, we found that authoritative sources employ different online platforms in different ways to communicate in hazards events. This has been seen in disasters before, such as when an emergency response team used Twitter as a "real time notification tool" but their blog as an "information backbone" during a flood event (St. Denis et al., 2014). Similarly, we found that some meteorologists use tweets to direct people to websites or other forums to elaborate the details of a spaghetti plot as well as other forecast information. In his interview, Berger described Twitter as being "like a cocktail hour" that is "ancillary" to his website, Space City Weather, which he runs with another meteorologist and is where "all [their] best information" goes. Further,

> ...the nature of the medium [Twitter]–I mean it's 280 characters, so you cannot communicate particularly complicated thoughts, you can't communicate nuance, so for that you know I like to write more, and so...it's why we have the site.

Spann, who thinks of Twitter as a "newswire," often posts links to his website, The Alabama Weather Blog, in response to specific questions which he has already addressed in his blog posts. Authoritative professionals who do not operate their own websites may post to other social media platforms which afford longer posts and use Twitter as the way to link to that content, e.g.:

> `@CraigSetzer (Sep 19 14:25) My thoughts on the latest with #Maria and any Florida threat in more than 140 characters. <link to Facebook post>`

Though all participants share the goal of keeping people informed and safe, they described different approaches to prioritizing their audiences" questions about spaghetti plot images and hurricane risks in general. For example, Berger knows that "people may not understand exactly what's happening" and is attuned to the various ways people localize risk, for instance by seeking advice on evacuation or flight schedules. Consequently, he frequently responds to people on Twitter and tries to be as "straightforward" with his answers as possible. Similarly, Heller "thinks there are no dumb questions," and "takes every question very seriously." Morales tries to allocate his time by answering questions he believes "could help not just that one person but many others as well." This approach resembles the purpose of early CSCW research on reusing answers to "commonly asked questions" to build resources for a group over time while avoiding duplication of effort (Ackerman & Malone, 1990).

These expressions demonstrate the multiplicity of responsibilities that meteorologists face in interacting with diverse audiences with social media as part of their communication suite. They live at the intersection of competing goals of serving their local market and educating about the skills of hurricane risk interpretation to anyone who might be listening in.

4.5.4.2 The Responsibility of Interpretation

This responsibility of authoritative sources is to help their audiences interpret the spaghetti plot, which includes what we think of as reading between the (track) lines. One way participants reported doing this was having a way to "tell a story," which follows in the journalistic tradition to which they also identify (Demuth et al., 2012). By telling a story, they provide context for forecasts, as opposed to "regurgitating data") as Heller explains:

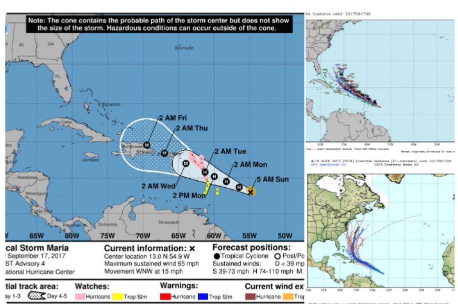
> ...otherwise I'm just regurgitating data for you and that's not my job. My job as a meteorologist is to simulate the data the best I can and to figure out what my message is that I want to put out based on the data that I've looked at...

Berger also noted the importance of explaining the range of potential outcomes:

> ...because you'll often read that even the [National] Hurricane Center forecast discussion, "well we think this'll happen but this could happen," right, and so just to kind of help people understand that that it's not obviously an exact science and so we explain to them that we think this could happen, but this could happen as well, and sometimes that works really well with the graphic.

Spann similarly described that "any graphic I could use that helps me tell a story is important and I think my purpose on social media is to be a storyteller." In the case of hurricanes, the story is one of uncertainty around the forecasts and risks, which change as storms evolve; "storytelling" serves the purpose of creating a kind of abstract of the event. It reduces some of the complexity around the concept of uncertainty by personalizing and localizing the risk, which is important for protective decision-making (Mileti & Peek, 2000). Images support the storytelling and are also seen to draw more attention to social media posts than text only. One participant noted that images are helpful for his market which covers regions where people do not have high literacy. Another developed a communication policy around this which was to "always" include images with his social media posts.

We also see expert interpretation exemplified in how meteorologists frame their social media posts, often providing additional context or explanation for the spaghetti plot. The following tweets demonstrate the use of descriptive text along with helpful imagery. This can be done by including a variety of forecast graphics, such as @spann's post which contains a cone of uncertainty as well as spaghetti plot forecast images to show the development of Maria toward Puerto Rico:

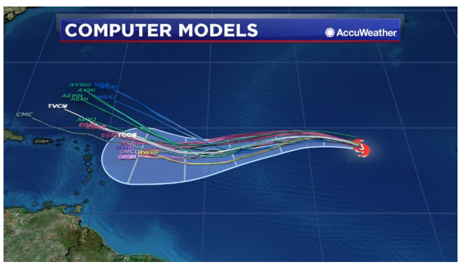


@spann (Sep 17 11:30) Tropical Storm Maria is forecast to be a major hurricane near Puerto Rico late Wednesday or Wednesday night...

Alternatively, some authoritative sources annotate the spaghetti plot image to emphasize an aspect of the forecast, as in @BShieldsWFTV's post which uses a red arrow to show the distance of the forecast tracks for Maria from the coast of Florida:

@BShieldsWFTV (Sep 19 09:54) In the long-term, models are very consistent (Euro included) -- keeping Maria well east of Florida.

Meteorologists also aid public audiences in interpretation by responding directly to their specific questions or doubts regarding spaghetti plots. For instance, @HellerWeather responds to a person who expressed skepticism about a conflicting forecast for Irma he saw from a mainstream news source:



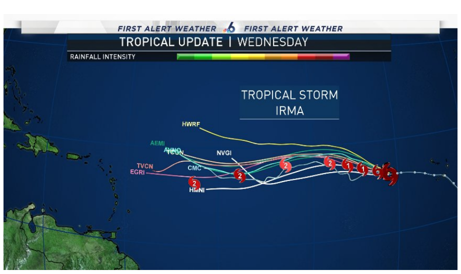
@HellerWeather (Aug 31 22:53) Hurricane Irma now a major category 3 hurricane. Many models turn the storm north before reaching the Caribbean.

↪ @person37 (Oct 05 15:49) I saw a very disturbing model on CNN last night that had the storm going south of Florida and right into the gulf. Hopefully it's wrong.

↪ @HellerWeather (Oct 05 15:49) If you sort thru all the forecast models you'll find one that'll scare you. I prefer to look at the consensus of all tracks.

In this exchange, Heller instructs by empathizing and explaining how he interprets the graphic, even as an expert. Heller further elaborates on this exchange in his interview: "in that particular case he's making a comment that is the opposite of what I just posted, so you know, I don't want to diminish what he saw or what he's saying..." It was a tactful way to manage unhelpful information that was entered into the discussion, despite Heller's initial explanation, with empathetic understanding of the fear that comes with hurricane hazards.

Similarly, @JohnMoralesNBC6 received a question about his interpretation of a spaghetti plot for Irma that specifically asked why he notes that the relative positioning of the models is "important":



@JohnMoralesNBC6 (Aug 30 21:31) Important to note that NHC #Irma forecast lies generally south of dynamic models including consensus, except HMON.

↪ @wxstud (Oct 05 15:49) why is this important? is NHC discounting the dynamic / consensus?

↪ @JohnMoralesNBC6 (Oct 05 15:49) They seem to (I'm not in their heads) be putting HMON (new from NCEP replacing GFDL) at the top of the list. ECMWF has more south track too

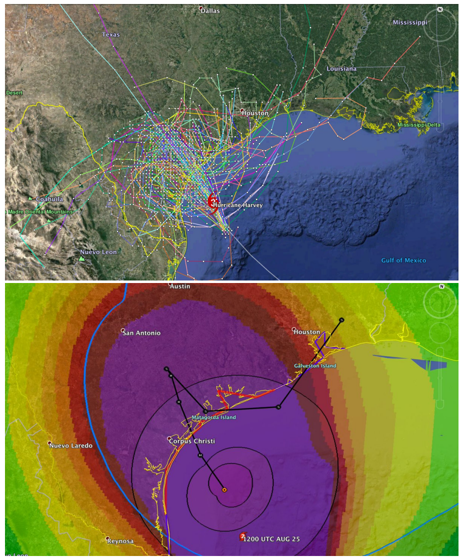
↪ @wxstud (Oct 05 15:49) cool. Thanks.

Compared to Heller's response above, Morales's response here is more technical and not accessible to those unfamiliar with spaghetti plots. Morales also elaborated on this exchange in his interview:

> Look at their handle right, "weather stud." Now I can't recall ever going into this account to figure out who this person is, but [this] person's asking me a question that would probably not come from a layman.

In an instance of recipient design (Palen and Dourish, 2003), we learn that Morales recognized that this person had some level of expertise based on both their username (@wxstud, where "wx" means weather) as well as the content of their question, without knowing them. He provided a response that he felt was appropriate for their level of expertise. This example is an exception to what we learned was Morales's general strategy of carefully allocating time to answer questions that can help people broadly; in this case, he provides a specific, technical answer in a one-to-one interaction with someone he perceives as not a "layman."

Finally, the tweet data reveal that there is a sense among members of the public that some models are better than others, or conversely, that some are worse, and meteorologists aid in interpretation by limiting the worse ("garbage") models in spaghetti plots. One described in his interview how he excludes lines produced by "models that are just not as robust that don't have a good historical track record" in spaghetti plots that he generates with his weather graphics system to show on TV (though this is less feasible with spaghetti plots he shares on Twitter that are generated by other sources online). Another described what are known as poor man's ensembles as graphics "where they're all kind of thrown together, some garbage and some good models. I would not share those in a particularly serious way to get the forecast." The following exchange has a member of the public asking Spann to "clear out all the trash paths" from a spaghetti plot for Harvey and results in Spann providing a new forecast image that seems to fulfill the request:



`@spann` (Aug 25 19:38) Model output for Harvey. Not satire. *(Top image)*
↪ `@person38` (Aug 25 19:50) Can you clear out all the trash paths and just include the ones you trust?
↪ `@spann` (Aug 25 19:54) *(Replies with bottom image)*
↪ `@person38` (Aug 25 21:33) Thank you @spann for clearing up the track

In the interview with Spann, we learned that this second image shows only the official NHC center track of the hurricane. However, he explained that he did not initially share this single-track image because the exact track was not indicative of the primary threat: Harvey at this point was "a flood problem" that would affect a large region beyond what the track line showed.

We learned in interviews that experts find that providing such context in these ways, particularly for spaghetti plots, to be a matter of responsibility:

> You see them [spaghetti plots] everywhere—they're on national newscasts, they're on the cable networks, they're on the local channels, they're on all the social media feeds—but we have to be responsible when we [share them], and give some context to what they're looking at.

> You can get the model plots anywhere, you can get them all over the place, but my job is to help you interpret what that data is actually showing.

4.5.4.3 The Responsibility of Maintaining Uncertainty

Though providing context and explanatory details helps audiences understand spaghetti plots, there often is only so much explanation that even an expert can provide. Hurricane forecasts are inherently uncertain, and spaghetti plots in particular display uncertainty quite explicitly by showing multiple, distinct, valid tracks forecasted for a hurricane. Our analysis revealed that authoritative sources often orient their messaging around the uncertainty underlying these representations. For instance, in their original text attached to spaghetti plots as well as in replies to people's comments about impacts to specific regions, many authoritative sources use some variation of "it's too soon to tell":

> ↪ @person39 (Sep 01 21:02) Does it look a threat for MD and DC and PA or not anytime soon???
>   ↪ @HellerWeather (Sep 01 21:05) Too soon to know.

> @spann (Sep 02 20:21) 18Z model set for Irma... Still way too early to know the final destination

> ↪ @person40 (Sep 05 15:23) Looks like the west coast could be in the clear
>   ↪ @MattDevittWINK (Sep 05 15:24) Too early to tell. We will know more in the next 2 days.

Another interaction adds to "it's too soon to tell" with a response that underscores the unknowability of the storm's path:

> ↪ @person41 (Sep 01 02:08) Do any have it hitting long island ny
>   ↪ @EricBurrisWESH (Sep 01 02:09) it's too far out. I'm showing you everything they're showing...
>   ↪ @person41 (Sep 01 02:12) Thanks

In this case, @EricBurrisWESH's post refers to the agency that produced the model, indicating that the meteorologist is a mediator who can interpret risk for his audience but who cannot predict risk for a large scale earth system—"they" do that, allowing @EricBurrisWESH to point tacitly to applied science as governing what it is we can know.

This last interaction takes an interesting turn around the idea of "honesty," which is used both colloquially and literally in the following exchange:

> ↪ @person42 (Oct 04 23:55) Be honest with me. How bad will this be more the Jackson area
>   ↪ @MichaelHaynes (Oct 05 15:24) We try our best to be honest with everyone. It's simply too early to know for sure, but rain and gusty wind are certainly a possibility

It seems that @person42 is using "be honest with me" as a colloquial phrase, as in "tell me the whole of the threat; I can take it." It is the kind of talk one might have with a doctor who is explaining a diagnosis, with the patient presuming that the doctor is politely holding back the "whole truth" until a patient is ready to hear the bad news. @MichaelHaynes appears to respond more literally ("we try our best to be honest") initially, but then clearly makes an attempt to reframe the lesson into the bigger realm of the difficulty that is inherent in narrowing uncertainty. He is saying that there is no other additional information to help @person42 assess their risk, nor that anything is being hidden. This captures a core idea of conveying uncertainty—*that unequivocality is not authoritative.* Rather, *holding onto ambiguity is authoritative.*

In other words, the job of both a spaghetti plot and the mediators who animate it in the public sphere is to communicate precision or accuracy when possible; knowing something about the possible tracks of the hurricane is better than knowing nothing at all. Mediators like our experts must disambiguate meaning of the spaghetti plot. However, they also must reambiguate when members of the public try to read the plots as overly determined. We see our authoritative participants performing these *acts of ambiguation* in these illustrative exchanges emphasizing the dynamic ("last minute", "changing") and probabilistic ("uncertain") "chance") "possible") nature of the forecasts:

> ↪ @Maddarilke (Aug 30 22:00) Stupid question, but your best guess-how soon will we have any idea of land impacts?
> ↪ @JohnMoralesNBC6 (Aug 30 22:09) There's a chance it could be one of those last minute things. Like a turn out to sea just a day or two before landfall.

> @BShieldsWFTV (Sep 06 17:38) Models/tracks WILL keep changing the next 1-2 days - that is why impacts here are uncertain. They shifted east.

> ↪ @person44 (Sep 07 02:18) that model looks like it will miss Cuba now and Miami might get a 185-mph hurricane direct hit
> ↪ @TMainolfiWESH (Sep 07 04:45) Very possible
> ↪ @person44 (Sep 07 14:26) That is a scary thought

The authoritative sources are deliberately leaving things open rather than foreclosing possible scenarios that could emerge (Soden, Sprain, and Palen, 2017). This is echoed in interviews:

> If it's a weak disorganized tropical storm that's going to be a flood threat, that line means absolutely nothing. you know you've really got to communicate "this could create flooding 300 miles up the coast here, not that little dot." And everyone's

> different, every hurricane's different, every tropical storm is different, the impact is different. (Spann)

> When Harvey was going to make landfall you know and you lived in Southeast Houston we couldn't say whether it was going to rain 10 inches at your house or 40 inches at your house—there's enough uncertainty about the track and rainfall intensities that we just don't know, right, so you need to be prepared for this scenario, but realize that something else may well happen. And it's just part of like being real with people I guess like, you know, not trying to be like uber hot shot forecaster who's got it, "oh it's going to be a hundred and twenty mile per hour storm going to hit Corpus Christi and go here..." I mean it's just sort of like, look you know this could happen or this could happen. (Berger)

Dee specifically described this deliberate maintaining of uncertainty in relation to spaghetti plots:

> I think when you see a bunch lines and you're not sure which ones to look at you feel uncertain. I think it almost the confusion that it generates is almost like the confusion you should feel when you try to forecast a hurricane.

He also noted the importance of designing forecast visuals like the spaghetti plot and the cone in ways that introduce "more ambiguity in the forecast which really should be there."

The problem of unequivocality in authoritative communication was also noted by Spann in the context of "rogue" entities, i.e., weather companies that operate in the private sector and have commercial weather forecasting products that are separate from, and sometimes in competition with, those used in the government/public sector, like NOAA and NHC. He also discussed rogue social media accounts, typically run by "kids who love weather":

> They look for the worst case scenario from any map they can find even if they don't understand it and they're going to throw it out there, and those are the ones that get shared hundreds of thousands of times, and all the clicks and the likes and shares and they learned the trick: the more outrageous the scenario, the better chance you're going to get all the likes on Facebook.

It takes "no skill," according to Spann, to find and share an early, sensationalized, unequivocal forecast that may appear confident but is actually only falsely reassuring. This works at odds with the responsibilities that authoritative sources see themselves as bearing (Starbird et al., 2018).

These observations underscore the idea that visual hurricane risk representations such as spaghetti plots are boundary objects between multiple populations (Bica et al., 2019; MacEachren & Cai, 2006). The authoritative sources who analyze meteorological data and create and share these information representations also bear the burden of communicating them to diverse audiences. While some people (likely more technical members of the public, or other authoritative sources) may see these graphics being shared primarily as scientific representations of an earth system, others see them as a way of assessing risk and making decisions for themselves and their families.

4.6 Discussion and Implications

The interactive nature of social media allows for risk communication to be more fully realized as a "dialogue" (Árvai, 2014) between risk communicators and receivers rather than a one-way process of sending risk messages to a passive public. This allows the communicators to be more aware of the context in which their audiences are making sense of the risk messages—spaghetti plots, in this case—and for the receivers to share their interpretations and ask clarifying questions. These interactions are a form of collaboration that works to reduce confusion around uncertainty by introducing a narrowed field of possibilities to the public. At the same time, the collaboration, as Heller says, "leaves room for changes," or for ambiguity, so as not to foreclose risk too soon (Soden, Sprain, & Palen, 2017), which would only serve to make a risky situation all the more dangerous.

Experts and laypeople alike struggle with communication around representations of hurricane risk, citing matters of dealing with "hurricane literacy'—a literacy that is quite hard to achieve. Spaghetti plots, in spite of their non-standardized practices around colorizing, legend use, and model ordering, are an expected part of hurricane risk communication. They offer a kind of precision that other representations do not, though the interpretability of the tracks is often over-determined, meaning that experts need to battle that over-determinism with reambiguation of risk, such as by sharing additional information or clarifying misunderstandings. We interpret the persistent presence of spaghetti plots in spite of these issues to be an important explicit signal that someone, somewhere is attending in a scientifically authoritative way to major weather systems, even if the protective decision-making (like evacuation) is not necessarily directly linked to the renderings (Bostrom et al., 2008). Instead, mediators like weathercasters are called to serve in that role. Moreover, the collective gaze onto spaghetti plots in the public settings of social media environments begs viewers to acknowledge not just their own risk, but that of others, resulting in expression of concern for others, though at the highest of levels ("sorry Alabama," "bad for the Caribbean"). We wonder, however, if such acknowledgement of the global implications of weather systems can be heightened to increase awareness about climate change issues.

Authoritative communicators of spaghetti plots assume a responsibility of interacting with their audiences even when they are not on the air (in the case of broadcast meteorologists), though working on social media to answer questions requires time they may not have, especially if a hurricane is imminent. In the face of this, there is remarkable dedication by some meteorologists to answer as many questions as possible, even if briefly. Other responses direct readers to blog posts or websites, making Twitter a waystop to long-form content and even narrated video explanations that cover forecasts in more detail. Authoritative communicators also bear responsibility to interpret the risk representations for both those who know little about how they are constructed and those who know much more. There is a sense that answering one person will help others, but the occasional weather hobbyist elicits an expert but necessarily concise answer because of the tweet-length limits, which in turn further limits novices from learning more because the answer has to be parsimonious.

Together, many of these features of communicating risk as represented by authoritative spaghetti plot graphics via social media can seem to make the risk representations more declarative than intended. The over-determinism with which many people interpret the spaghetti plots is combined with other factors, including the urgency of protective decision-making in the face of a hazard, and the space limit of microblogs with respect to how much text can be used to explain complex scientific imagery or answer questions. Finally, the influence of the parasocial relationship—which is likely magnified when the trusted meteorologist speaks directly to people via a platform like Twitter—personalizes the information and requires the meteorologist to further attend to its delivery. The interactions between the public and the experts serve to modulate this declarative quality by allowing experts and sometimes other members of the public to communicate accuracy through *acts of ambiguation* in response to people's questions and (mis)interpretations of the graphics.

4.6.1 Implications of the Research

The implications of this research extend to matters of *design to improve risk representations* while also yielding insight about what acts of design can do to drive systems-level change; of *practice*, with respect to the mediation of risk products to a large audience looking for individual answers; and of *scientific communication*, with respect to how the public can engage with earth systems.

4.6.1.1 Design and Design Demands as Pressure for System-Level Change

Spaghetti plot representations of hurricane risk can be confusing even to "hurricane literate" readers for multiple reasons. For one, they are not standardized, so interpretations of one version of a spaghetti plot do not carry over to other versions. Second, people want to assign visual and graphical features such as color and legend order to have meaning so as to make sense of a complex graphic, but again these do not always have meaning and even if they do the meaning differs across different graphics. Third, some representations are more complete than others in that they include legends and labels for individual models.

Standardizing features of spaghetti plots could certainly help people interpret them. For instance, color is often used meaningfully in other risk and uncertainty visualizations (Bostrom et al., 2008; MacEachren, 1992; Sherman-Morris et al., 2015), however in many cases it is used arbitrarily for spaghetti plots. Colors could be consistently mapped to specific models across spaghetti plots from different producers, so that viewers can always look, for instance, to the black line to see the official NHC track forecast. Additionally, the ordering of forecast models in the legend could be made meaningful, such as ordering by model accuracy or likelihood if such information is available, or otherwise alphabetically based on the model name so as not to introduce an ordering effect. Of course, this sort of standardization is easier said than done, because renderings map to the idiosyncrasies of their origins; standardization would require changes in design policy that align weather agencies and the various groups that generate the plots.

This brings us to a larger point, that of the systems-level role that design can bring to a world where information artifacts are distributed across the organizational boundaries in which they were previously contained. The vast distribution of similar but non-standardized spaghetti plots might create a kind of bottom-up pressure to the origins of the artifacts themselves. Those creators (agencies, institutions and individuals) might be required to rework what a representation that supports risk comprehension across populations would be like, thereby further engaging in and designing the larger informatics milieu in which people are making decisions, together and alone. This might mean that specialized information artifacts, distributed across many people and supported by many intermediaries, could themselves be the drivers for new organizational relationships.

4.6.1.2 Practice

The data give rise to ideas about how hurricane risk communication in general (beyond the spaghetti plot) could be improved to support meteorologists as mediators who need to communicate all aspects of risk succinctly and persuasively. Here, in particular, they need to convey not just where a hurricane will travel, but what it does upon landfall and the journey along its track. Flooding is often a major risk in hurricanes, and even more so if the storm is disorganized and stagnant, as Harvey was over the Houston, Texas region. Both Spann and Heller noted this particular communicative challenge of emphasizing flooding over other features of the forecast. In his interview, Heller imagined a new risk graphic that could improve upon this by outlining day-by-day forecasts both visually and textually— "here's what's going to happen'—so as to emphasize how impacts like flooding continue after the point of landfall. This would support the kinds of questions about interpretation of risks (How bad will it be? Should I be concerned?) and protective actions (Should I evacuate? Should I change my plans?) and from members of the public that we saw in the tweet data. Spann was less worried about any one track on the Harvey spaghetti plot, and instead wished to emphasize the confluence of overlapping tracks which surely would mean flooding.

One participant noted the challenge of using maps in general for visualizing risk because of low map literacy, suggesting that this is a problem within the weather enterprise as a whole. Previous research also supports this, showing that many people are not aware of whether they live in an evacuation zone, even when aided by a map (Arlikatti et al., 2006; Lazo et al., 2015; Zhang et al., 2004). In the tweet data, instances of "localizing risk" show that people are concerned about risk at the level of cities and counties. Communication of hurricane forecasts, including via the spaghetti plot graphics, could better convey risks as they apply at this desired geographic granularity, as well as by including named cities and counties in text along with the visual representation.

4.6.1.3 Scientific Communication

Finally, an area of reflection emerged from this research on the interactivity between people who collectively gaze upon the implications of risk for many, "beyond the personal" (Gui et al., 2018): can the ubiquity of these map-based representations of earth systems influence public understanding of the larger effects of climate change? What opportunities do we see to educate and broaden perspectives? The answers may lie in part in the other implications discussed above, but with elaboration around reconciling how the actual tracks play out against projections, thereby begging the question of how models are created in the first place. Does this become yet another responsibility of producers and mediators of these representations, or is there a place for more human and informational mediation of risk along the pipeline, a pipeline that also extends after a hurricane has wielded its wrath? Social computing has a role to play in scientific communication, as it already does here in hurricane risk assessment.

4.7 Conclusion

This research examined and analyzed the interactions between authoritative, expert sources and members of the public around hurricane risk communication, specifically the spaghetti plot representation. As an enhancement to the existing literature on risk graphics, the interactions took place under natural circumstances online during the 2017 Atlantic hurricane season and thus captured dialogue that represents people's *in situ* concerns, questions, and interpretations, as well as all the situational and interactive context in which these take place, in their pursuit of accuracy about the hurricanes. The communication of risk via the spaghetti plot over social media has a declarative quality due to being rendered with precisely located ensembles of tracks, and that it can only be explained in limited detail over social media. We learn that effective communication of these graphics must include the uncertain nature of the risks through *acts of ambiguation*, which come about through thoughtful management and explanation of the complexity of risk by authoritative sources, often across multiple platforms, and also through interaction with public viewers who offer their interpretations and questions. Finally, we discuss how analysis of these public-expert interactions suggests implications regarding the standardization of spaghetti plots, the organizational relationships among those who create such representations, and the communication of hurricane risks that better aligns with the public's interpretations.

Part IV

Reactions to Risk in Highly Constrained Situations

Chapter 5 Prologue

Chapter 5 is a reprint of work currently under review. It is included in this dissertation with the permission of my co-authors, Jen Henderson, Jen Spinney, Joy Weinberg, Erik Nielsen, and Leysia Palen.

This research examines how people respond to highly constrained situations, focusing on the case of Hurricane Florence which had multiple hazards with conflicting protocols for safety: both tornadoes, for which people are instructed to get to lower ground, and flash flooding, for which people are instructed to get to higher ground. This co-occurrence of hazards has been recently labeled as TORFFs in the meteorology community (Nielsen et al., 2015), but the social aspects of what people do in such conditions has not been well studied. The combination of these conflicting hazards with existing and additionally limiting vulnerabilities, we problematize the idea of constraints as affecting the range of possible actions taken in response to threats. Much prior literature defines factors that impact evacuation behaviors, such as age, gender, features of social networks, source of warning information, and perceptions of risk or vulnerability. Though modelling can support some aspects of evacuation prediction by taking these variables into account, it cannot show how those who encounter complex and uncertain conditions act and attempt to improve their plights (Eiser et al., 2012).

We collected social media data from those affected by the co-occurring weather hazards and found distinctively detailed documentation of the disaster experience. Many people's collected tweet narratives throughout Florence documented their risk assessments, decision-making, and actions taken, including reasons for evacuating or not and what barriers they may have faced. Such surprising richness of narrative indicated more was afoot when people are under highly constrained conditions. Inductive analysis led to interpretation of these experiences as liminal, described in anthropology as rites of passage and the feeling of being betwixt and between states of normality. In observing people's moment-to-moment experiences of uncertainty in situ as documented on social media, we learn about the felt experiences of liminality and how these are supported by the social media audience.

This study is part of a larger, multidisciplinary research effort in collaboration with social scientists and meteorologists around concurrent tornadoes and flash floods in hurricanes. There are two broader goals of the research effort: 1) to better understand weather forecasters' processes and challenges when issuing forecasts and warnings for multiple, overlapping hazards during landfalling tropical cyclones; and 2) to better understand the how the public makes sense of risks and vulnerabilities they face from overlapping threats, what information they receive about these risks, and what decisions they make through the analysis of Twitter data. This study addresses goal 2.

This study both builds on and diverges from the previous two. It builds upon the main thread of engaging in sensemaking in investigating not only how people make sense of risk via visual information representations, but how they make sense of risk more generally in an increasingly complex scenario. Moreover, this study does not deal with specific risk representations. It still deals with the process of risk communication in that people still must obtain risk information from somewhere, but the focus is not on the source or content of that information, but rather the reactions: what people who are at risk and in highly constrained situations do when using social media.

The bottom-up approach of identifying people who use social media during an event and then determining something about their communications resembles that used in previous work that I conducted that is not included in the dissertation. The paper, Visual Representations of Disaster (Bica et al., 2017), is motivated by the power of photography to influence people's perceptions of significant events. It investigates the ways that people visually represented the Nepal earthquakes of 2015 through three studies of the imagery shared on Twitter in relation to the events: an analysis of the distribution of geotagged image tweets in relation to the reported damage, a visual content analysis of the types of images shared by populations who were local or global to the event, and an analysis of images that were appropriated from other times, places, or events, and yet were used as part of the story of the earthquakes. Several significant findings were discussed. For one, a pure data science approach may be able to identify statistically significant patterns or trends in a dataset, but it does not get at the nuances of why those patterns or trends exist in the first place, which is typically more in line with my research interests. Thus, even though we found some significant correlations between damage in Nepal and where image tweets were being posted, a qualitative investigation of the images themselves revealed that they did not primarily portray damage, rendering the correlations less meaningful. Second, the research supported other work about differences in how people close to a disaster event versus distant onlookers seek and use information. By examining the images shared and retweeted by people in each group, the research revealed more locally-relevant and actionable information shared amongst locals, and more abstract and dramatic imagery shared amongst globals. Finally, the research discusses two competing expectations of imagery shared on social media during disasters: that of journalistic accuracy and that of compelling a collective gaze. While the former is straightforward and expected, the latter draws on the notion that imagery of a painful or traumatic event such as war or a disaster can attract large viewership through documenting the pain of others (Sontag, 2003). Rather than treating appropriated imagery simply as misinformation, then, the paper considers such imagery as fulfilling another meaningful expectation.

Similarly to the chapter that follows, this study follows my broad research agenda of understanding what people do on social media during disasters by analyzing——in a variety of ways—— systematically curated, in situ social media data that reflects what people think and/or do during actual disaster events.

Chapter 5

The Liminality of Uncertainty: What Happens When Social Media is Employed by Those in Highly Constrained Disaster Situations

5.1 Introduction

Disasters arising from natural hazards have long been sites for scholars to understand social phenomena (Dynes, 1970; Fritz & Mathewson, 1957; Hagar & Haythornthwaite, 2005; Kreps & Bosworth, 1993). They create high levels of uncertainty and constrain decision-making, requiring people to take action in a limited space of options to keep themselves, their loved ones, and their properties safe. Hurricanes in particular are characterized by uncertainty in terms of the forecast for their tracks and intensities. The strong winds and heavy rains constrain where people can go. Additional constraints may arise from people's particular situations and what are known as social vulnerabilities (Singh, Eghdami, & Singh, 2014). For example, hurricanes that frequently hit Florida can affect such a large portion of the state that it is not clear where to evacuate that might be safe. Even worse, people affected by hurricanes in the many island nations of the Caribbean may be unable to evacuate or even be literally "islanded," a term that is also used figuratively to address forms of vulnerability that limit mobility (Sheller, 2013).

A great deal of research that models evacuation behaviors for hurricanes shows how factors such as age (Gladwin et al., 2001; Lazo et al., 2015; Sadri et al., 2017; Sankar et al., 2019), gender (Dash & Gladwin, 2007; Lazo et al., 2015; Morss et al., 2016), features of social networks (Metaxa-Kakavouli et al., 2018; Sadri et al., 2017), source of warning information (Burnside et al., 2007; Hasan et al., 2011), and perceptions of risk or vulnerability (Burnside et al., 2007; Sadri et al., 2017; Solís et al., 2009; Stein et al., 2010) contribute to decisions about evacuation. Though modelling can support some aspects of evacuation prediction by taking these variables into account, it cannot show how those who encounter complex and uncertain conditions act and attempt to improve their plights (Eiser et al., 2012).

We take all these conditions—the various states of being vulnerable, including those newly imposed by a hazard like a hurricane—as constraints (Gross, 1985) on decision-making that any one person has to make in response to threat. We do this for two purposes: first, to avoid essentializing vulnerabilities in the people who may possess them, and instead see that vulnerabilities, like other constraints, though limiting can also lead to creative solutions. By viewing the otherwise classic disaster sociological notion of vulnerabilities (Cutter, 1996) in this way, we do not presume that to be vulnerable yields no paths for solutions. Second, by framing all sorts of limitations as constraints, our analytical treatment neither presumes nor needs to account for (impossibly, for some research) which vulnerabilities may or may not be present. This framing instead allows for investigation of in situ expressions of what one does when needing to make difficult decisions under conditions of uncertainty.

To this end, our primary research question is: How do people use social media to manage constraining circumstances during a disaster? This research investigates the experiences expressed by people facing a multi-hazard severe weather event that sometimes instructs them to take contradictory action: for example, move to higher ground to avoid flash flooding, and move to lower ground to avoid tornadoes. We examine the problems when tornadoes and flash floods co-occur during the larger context of a hurricane. These co-occurring hazards create additional constraints and affect people along with personal constraints. The research considers the collective impact of all constraints on people's actions, using this extreme situation to illuminate the more subtle roles digital platforms play in difficult times.

Such topics have been explored in HCI in relation to wartime in work by Mark, Semaan, and Al-Ani (Al-Ani, Mark, & Semaan, 2010; Mark & Semaan, 2009). They investigated the use of digital communication technology, particularly blogs, within the highly constrained, uncertain, and dangerous conditions people experienced while living in a war zone. People wrote online "war diaries" which reflected personal narratives of their experiences of the war. The blogs provided a safe way to interact with others amid constraints imposed by physical violence (Al-Ani et al., 2010) and also aided in communicating with broader audiences in "normal" environments outside the war zone (Mark & Semaan, 2009).

As a complement and extension to their work, this research uses data from Twitter, which, in the manner collected, offer in situ and near real-time accounts of what people did in the constrained conditions of a hurricane over multiple days. The data set yields rich, narrative monologues of personal experiences, similar to that of blogs yet written more typically in the moment and less journalistically. In our many years of doing social media and disaster research, finding such richness of extended personal narrative has been lost as Twitter ages and the volume of posts increases. In our initial investigations of what people did when facing both flash floods and tornadoes during the 2018 Hurricane Florence, we found that highly constrained situations seemed to result in different Twitter posting phenomena than other disaster events, indicating that something socio-behaviorally important may be at work when decision-making becomes highly constrained.

The case we make in this paper is that, when facing uncertainty, people may find meaning through posting to social media that is different than how research often frames social media inquiry in disaster situations. In much of that research, the pursuit has been on how members of the public and emergency management use social media instrumentally for objectives such as: gaining situational awareness (Ireson, 2009; Tang et al., 2015; Verma et al., 2011; Vieweg et al., 2010), verifying information (Mendoza et al., 2010; Starbird et al., 2016), solving event-specific problems (Palen et al., 2009; Sarcevic et al., 2012; White et al., 2014), seeking information to reduce uncertainty (Fraustino, Liu, & Yan, 2012; Gui et al., 2017), coping with impacts (Frey, 2018), and distributing information, especially in the absence of mainstream media coverage of certain communities or populations (Anderson et al., 2016; Shklovski et al., 2008; Simon et al., 2015). However, when situations become so constrained, these objectives might not even be possible, resulting in other behaviors that are more clearly on display. These behaviors are surely present in other events, too, but they are hard to "see" if the research is not designed to see them or if they are in such a minority as to not be noticeable for what they are.

5.1.1 Vulnerabilities as Constraints

We treat constraints in this paper in the sense of design constraints (e.g., Gross, 1985), where the design of an artifact, system, plan, etc. is optimized around limitations. Translating this to social settings, people regularly invoke creative optimizations to overcome constraints to "design" features of their daily lives (this is what gives rise to the proverb "Necessity is the mother of invention"). For example, the constraint of one's car breaking down could lead to optimizations such as walking or taking the bus. When highly restrictive constraints come to the fore, such as those introduced by co-occurring weather hazards, people may have to conceive new methods to maintain not only the structure of daily life, but their safety and wellbeing.

Hurricane Florence is one such event that imposed heavy restrictions on people's lives given its complexity, behavior, and combination of hazards. The storm had an unusual trajectory toward the US with slow movement once it made landfall, all of which was difficult to predict. For those in its path, there were few precedents to use as a guide for how best to prepare for or mitigate Florence's impact. Thus, one constraint faced by residents in areas forecast to be hit was a lack of familiarity. Past hurricane experiences were less useful than they otherwise would have been for a more typical hurricane, as many online noted, e.g.:

> ...We've had hurricanes before, but not like this one - so I don't know at all what to expect, really

Moreover, when it became clear where the storm would make landfall, it also became clear that its impacts would be devastating. Despite the Saffir Simpson scale rating of a Category 1 at landfall—which accounts only for wind speed and not for other potentially devastating features—the hurricane was considered by many to create impacts more like a Category 5 when accounting for the extreme precipitation it generated (although no such scale exists). Especially problematic was the combination of (flash) flooding caused by storm surge, extreme rainfall, and rivers overtopping their banks with strong winds from the eyewall and tornadoes. Flooding and tornadoes in the US are often accompanied by warning messages issued by the National Weather Service that may contain contradictory safety protocols (Henderson, Nielsen, Schumacher, & Herman, 2019; Nielsen et al., 2015): for flash flooding, warnings often advise people to move to higher ground and to stay off the roads, while for tornadoes, warnings direct people to shelter in the lowest interior room of a sturdy building or to move to a substantial shelter if outdoors, in a vehicle, or in a mobile home. Thus, people may be confused about which actions they should take to stay safe in the presence of multiple, overlapping hazards; this confusion can function as a constraint on risk understanding, decision making, and response.

However, risks arising from environmental threats are not the only constraints that influence people's decision-making. People process risk information along with many other pieces of information through their own social lenses (Eiser et al., 2012). Past research has examined how individual and household factors correspond to hurricane evacuation decisions or intentions, as well as the preparedness and vulnerability of specific populations such as students (Collins et al., 2009), the elderly (Wang, 2018), and ethnic minorities (Elder et al., 2007; Reininger et al., 2013). The research presented here qualitatively examines how all kinds of vulnerabilities acted as constraints to action taken in Hurricane Florence.

5.1.2 Situated Accounts of Liminality

The analytical intention of this work was to understand the situated nature of what people do when using social media in highly constrained situations. Work in HCI, particularly in the tradition of ethnomethodology, has recognized that what people do in particular situations is not attributable only to standard procedures or plans (Suchman, 1987, 1983). Rather, the context of the situation, including contingencies, constraints, and problems that can only be known and addressed once encountered in practice, are what dictate the work of getting things done (Dourish, 2001). Thus, much of human activity pertaining to accomplishing specific tasks, such as office work or, in our case, disaster preparedness and response, is characterized by "approximation, invention, improvisation, and ad hoc-ery" (Dourish, 2001). There are traditional and established protocols for how one should prepare for disasters arising from events like earthquakes (Baker, 2014), hurricanes, floods, and tornadoes, but such protocols are more useful for orienting people to a desired outcome, like safety. Actually achieving safety requires one to respond to the hazard as it occurs using the skills and resources available to them, adjusting as necessary to account for changes that occur throughout the situation (Suchman, 1987).

We draw on **situated action** (Suchman, 1987) to ground the rationale for the research design and objective, and to guide the qualitatively inductive investigation to understand how people behave in highly constrained situations as those situations change. As such, we analytically focused on the string of in situ moment-to-moment experiences people posted about on social media over the extended duration of a hurricane event.

From the rich narratives and the many expressions of uncertainty and constraints, the liminal quality of what it means to experience a disaster came into view as a meaningful interpretation of posting behavior that was neither overtly offered nor treated as instrumental. Liminality was first conceptualized by van Gennep (1960) as a transitional phase during a "rite of passage." Such rites involve a phase of *separation*, upon which normal social structure and order are suspended; a transitional period of *liminality*; and a period of *aggregation* back into society with a new status. Turner (1987) expanded on the notion of liminality as any condition or state that puts a person "betwixt and between" societal norms; it is a feeling and experience associated with ambiguity and uncertainty. Disasters arising from natural hazards have been characterized as liminal experiences that affect a whole society, where social distinctons and normal hierarchy disappear (Thomassen, 2012). Liminality has been used as a conceptual framing for understanding "communitas" among people during a flood crisis (Jencson, 2001).

Turner has also defined liminality as "a realm of pure possibility whence novel configurations of ideas and relations may arise" (Turner, 1987, p. 7). We borrow and extend Turner's conceptualization of liminality, seeing the "novel configurations of ideas and relations" arise in how people respond to disaster under constraint. However, we do not see the liminality of disaster as offering "pure possibility." Rather, we see disaster as a *void*, in that people express a lack of action, knowledge, or capability to stay safe. Unlike classic liminal experiences of transitions like puberty, graduations, or weddings, the liminal period of disaster is not one that can simply be left to unfold; people need to take action to stay safe. Such action is an instance of what Boland (2013, p. 229) describes as a "performance" within the threshold moment—the betwixt and between—which "not only signifies change but also constitutes transformation."

With the ability to use social media narratives that can frequently mark what is happening when people are experiencing liminality, we consider what it is that people were doing in response to Hurricane Florence *in situ*, and what it appears to mean when they engaged with social media as part of the disaster experience. Extending Turner and Boland, we consider social media posts to be small and often frequent public performances through textual acts which serve to fill the void of the liminal disaster experience. When people digitally publicize their evolving decision-making under conditions of persistent uncertainty, we can observe both what it means to be in a state of liminality and the role that social media plays in such an experience.

5.2 Research Site and Study Method

This research interrogates how people used social media to share information about their personal experiences in Hurricane Florence.

5.2.1 Event Description

Hurricane Florence made landfall on Friday 14 September 2018 as a Category 1 storm near Wrightsville Beach, North Carolina, US (Stewart & Berg, 2019). The storm was a particular challenge to weather forecasters and emergency planners because of complex meteorological interactions along the storm's life cycle that affected the certainty of the track forecast. Florence was especially devastating because of its slow forward speed, which meant that in addition to storm surge, persistent rain caused extensive inland and river flooding, breaking multiple flood records set by previous

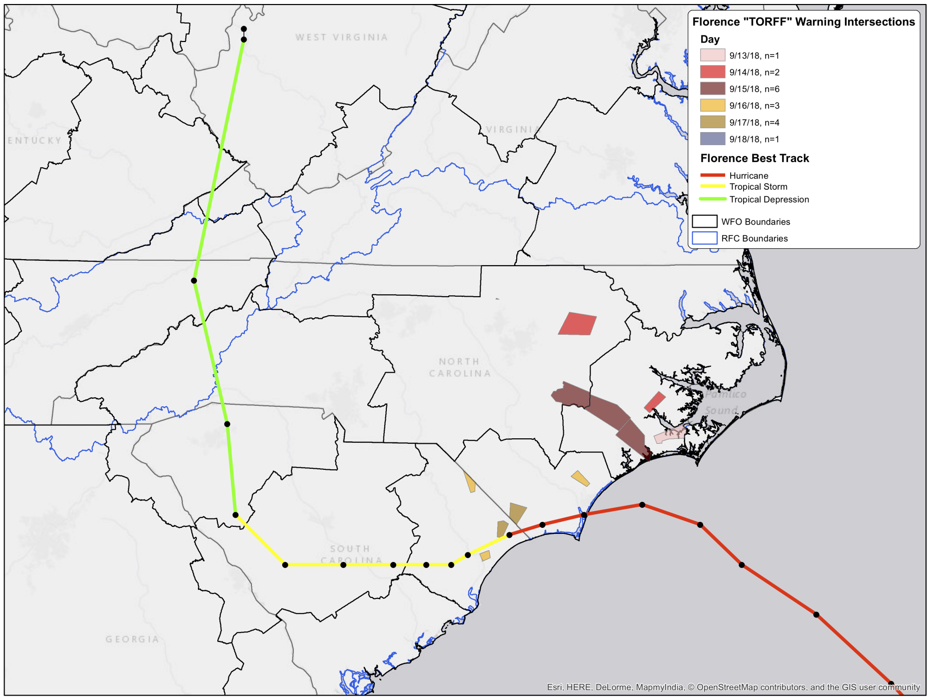


Figure 5.1: Map of TORFFs that occurred in Hurricane Florence.

hurricanes. Tornadoes were also an issue, with 44 tornadoes reported across North Carolina, South Carolina, and Virginia, which sometimes occurred with flooding. A total of 22 deaths were directly caused by Florence, primarily due to flooding, with an additional 30 indirect fatalities. Total damage is estimated at $24 billion, which places Florence in the top 10 most costly US landfall tropical systems.

5.2.2 Overlapping Tornadoes and Flash Floods

Weather phenomena often include multiple hazards. Hurricanes can generate tornadoes, flash flooding, storm surge, winds, rainfall, and high waves. However, warning systems classify hazards into discrete categories to allow forecasters to issue advice for each threat. One consequence is that there can be a mismatch between how people experience weather threats and how experts warn for them, including the kinds of advice offered for each threat, which may conflict as in the case of tornadoes and flash floods. One type of overlapping threats is called a TORFF (**TOR**nado and **F**lash **F**lood) (Henderson et al., 2019; Nielsen et al., 2015) when there are warnings for both threats within 30 minutes of each other for a given area. These occurred in Florence (see Figure 5.1) and are communicated to the public upwards of 400 times each year across the US (Nielsen et al., 2015). Despite the large number of TORFFs, it is not clear how warnings are perceived or acted on by the public (Nielsen et al., 2015), a gap this research addresses.

5.2.3 Data Collection and Analysis

To isolate the people who might have experienced these two hazards during Hurricane Florence, we began by collecting all tweets from 8 September–20 September 2018 containing both a tornado-related keyword and a flash flood-related keyword (including keywords with #), specifically the query:

```
((tornado OR "funnel cloud" OR funnelcloud) AND ("flash flood" OR flood
OR flashflood OR "storm surge" OR stormsurge))
```

This resulted in 3725 tweets from 2299 unique accounts. We classified the accounts based on the content of their tweets as being either from a member of the *public*, from an identifiable *authoritative* source, or *other* (unrelated to Florence, bots, etc.). For this classification, we excluded retweets (n=2803), as these do not include content written by the person of interest that would help determine their category; this left 815 account users who produced 1160 tweets. Two coders coded the accounts and identified 439 as *public* (as well as 175 as *authoritative* and 201 as *other*).

Our research interest is in people who both personally experienced Florence and wrote about those experiences, and so we focus here on *public* accounts only. We collected the entire contextual streams (Palen & Anderson, 2016) for the 439 *public* accounts which include all their tweets posted during the study time period whether they are about the hazard event or not for full context, totaling 48K tweets. We used the Twitter API for data collection for most accounts, and a premium Twitter API for those accounts that had a number of tweets that surpassed regular collection limits. Data could not be collected for 69 accounts because they were deleted, protected, or suspended, and no longer available. An additional 19 accounts were removed from analysis as their accounts were deleted, suspended, or made private after data collection, or because further inspection of their tweet streams revealed that they did not post content related to Hurricane Florence despite the initial keyword hit. The remaining analysis covers 43,783 tweets, not including retweets, from 351 *public* accounts.

The tweets were qualitatively analyzed by person/account. Four of the authors read through all tweets and their associated metadata and collaboratively wrote descriptive narratives to summarize and describe each person. The narratives included basic details when available about where they lived or worked, their general experience of Florence, any decision-making they engaged in, conversations around their tweets, and what types of information or information sources they referenced or used. At this stage, 142 accounts were excluded from further analysis due to having few, if any, contextual tweets related to their experiences of Florence.

Of the remaining 209 public accounts, 44 were identified as having particularly detailed tweet narratives which read as "story arcs" of the liminality of their experiences. They documented their pre-storm concerns and planning, their evacuation and other protective decision-making processes (the threshold of betwixt and between), and some form of a resolution, whether returning to home, work, or school, noting they are safe, or reflecting on the outcomes of their experience. The remaining 165 accounts which had less of a continuous story arc were coded in a second phase after these 44 accounts and were used to further elaborate the identified liminality themes.

Following best research practices regarding the ethical use of public data (Fiesler & Proferes, 2018), we slightly modified the presented tweet texts without changing original meaning. One exception is for tweets directed at public institutions that we deemed to be intentionally meant for public viewing which we report in the original. We pseudonymized Twitter usernames, formatted as @username, using an online username generator to conceal identities.

5.3 Using Social Media When Highly Constrained

We present findings organized by the types of activities people engage in on social media when highly constrained as ways of "filling the liminal void."

5.3.1 Seeking Financial Help

One way of filling the void of liminality in disaster is to eliminate or at least reduce the liminality by getting away from the disaster space. Financial help can enable or create solutions for protective actions, namely evacuation, that aid in getting oneself and one's family out of the liminal space. Here we describe instances in which people made use of the social ties available to them on social media to request financial help in various ways.

In other disaster and social media research, we see documentation of the question-and-answer qualities of interaction during emergent events, including requests for help. Help given can be in the form of in-kind goods such as food and supplies; local information such as what shelters might be open or streets closed; or perhaps more innovatively, offers of information work in the forms of information collation, such as creating and publicizing lists of local hospital capacities and locations and lost pet information (Sarcevic et al., 2012; Starbird & Palen, 2013; White et al., 2014). Though it is not unusual to see donation requests, in Florence the emphasis on financial requests was notable given how it manifested under highly constrained situations. Donating supplies or providing informational assistance presumes some sense of sequencing of subsequent action and an ability to make use of these forms of help, which may not be the case for highly constrained and uncertain conditions. However, with increased financial capacity, it becomes more possible to negotiate the liminal state of uncertainty to bring about a solution. Financial capacity could be said to increase the transformative potential (Boland, 2013) of liminality, specifically the ability to take protective action, such as evacuation.

Evacuation can involve a range of financial burdens: the cost of gas and hotel room, the cost of supplies to take on the road, the cost of missing work, to name a few. In their posts, people disclosed their financial constraints to evacuating, e.g. "Nope. Evacuation costs money that I do not have." Some tried to bring awareness to the financial burdens afflicting those who were already constrained and unable to evacuate:

> Being from Eastern NC [North Carolina][1] , it makes me angry when people say "Why didn't they just evacuate?!" Eastern NC is mainly rural, swamps and poor. Most people don't have money to leave. #NCwx #HurricaneFlorence

In addition to disclosing financial struggles, people also used social media to solicit financial aid. For instance, @juliana posted days before landfall that, despite believing her area was under mandatory evacuation, she could not evacuate for financial reasons:

> ...For those asking why we're still here, because we're just like many others who cannot afford to evacuate. So please keep us in your thoughts.

She then discussed preparations for hunkering down such as buying food, water, and gas and charging electronics and noted she had shelter information in case they lost power. Several hours later, though, she wrote that even though her area was not mandated to evacuate as previously believed, they were encouraged to take precautions because of their proximity to the high-risk coastal area, so she and her family decided to "go further in west to get away from the coast." At that point, the narrative changed as new information led to reevaluation of her physical constraints and safety. As a performance of the threshold moment of liminality, @juliana sought help from others to enable options of removing herself from the liminal experience:

> We're preparing to evacuate. If anyone can help out with gas, hotel, etc. My cashapp is ‹anonymized›. Thanks in advance. I'll update once we make it out from the coast.

By providing her "cashapp," which refers to her username for an instant mobile payment service, she left open the range of possibilities for how others could support her. Though she requested assistance for "gas, hotel, etc.," rather than asking for support for those things directly, she asked for money to be sent via the payment service to cover the range of needs she and her family might have faced. We cannot know based on the public tweet data whether anyone sent her money; however, she reported being "on our way out" and "headed to a hotel" later that same day, leaving us to assume that they acquired the means to evacuate.

[1] Portions of tweet text surrounded by angle brackets ‹› are anonymized. Notes in square brackets [] are additional context by the paper authors.

Financial help can also be needed at different times throughout the process of evacuation. One person, @nelly, sought financial help in multiple ways after she and her family decided to evacuate. First, she attempted to sell a ticket for a concert she could no longer attend due to the storm to liquidate the money to fund an evacuation:

> hi i'm really sad to do this but i need the money to evacuate from the coast because of the hurricane, i'm selling a ticket to a concert in atlanta and have to sell it asap please dm me for a price!!!

She then posted her PayPal link, which, like the previous example, expanded the options for others to directly send her money beyond just the sale of the concert ticket:

> i hate doing this but i need to evacuate because of the hurricane, i'm low on money and have to use all the money i have right now for upcoming bills. if you can help out or just retweet any bit of money helps [PayPal link]

Later, and perhaps with more desperation, she interacted with an account that, based on the username, presumably belonged to someone who identified as a "sugar daddy" and asked for money so she could evacuate South Carolina.

Finally, under yet different circumstances again two days later after having evacuated to Florida with her family, she found that they were in need of something to do amid the stress and boredom. She posted asking for assistance with getting her family tickets to local amusement parks:

> hi twitter do i have any friends who can get my parents and younger siblings into a disney park for free everyone is stressed and they deserve the joy that disney brings

This final example differs in apparent urgency of financial need as compared to her previous posts; it shows the breadth and the evolving nature of how people react to the liminal experiences they face during a disaster. None of @nelly's requests received replies (only likes and retweets), but in a later tweet she noted that she had "gotten multiple dms from people offering to get them in" to Disneyland, where "dms" are direct messages, or private conversations, on Twitter. The earlier requests seem to have been dealt with similarly in a private way. The public requests reached beyond her social network to potentially anyone on the platform.

In another example, @Pepper demonstrated a tactic of soliciting help through her livelihood of "financial domination." This is a subculture in which a person pays or bestows gifts at the demand of another for gratification. @Pepper demanded and received money during routine life, but during Florence adapted this practice to her specific needs associated with preparing for the storm by demanding people to send her money for supplies, including screenshots that showed others had already paid her. Her posts implied that receiving money would alleviate the mental burden of preparation, serving as textual acts that signified liminality as well as the transformation that money can allow in constrained situations.

Money is additionally important because people may not have the ability to use in-kind offers based on the context of their situation. For instance, @Smith posted at length about the constraints he felt in trying to evacuate his home, including living with his parents who did not want to leave and not wanting to evacuate alone. In turn, he received an offer for lodging with another person, but he could not accept it:

> I highly doubt my mom would allow it since she has no clue who you are, she wouldn't even let me stay at a friend's she knows because she didn't want to "give his parents the responsibility to look after you," but thanks anyway.

These examples demonstrate the creative approaches—the "novel configurations of ideas and relations"—people used on social media in the face of constraints to hurricane evacuation or preparation and highlight the "contextual sensitivity" (Baker, 2014) of money over other types of in-kind offers for those who are highly constrained. They also highlight different dynamics of liminality. The uncertain and changing conditions of an event necessitate flexibility in the types of aid that can be used. The timing of needs also becomes relevant because the constraints, and thus financial or other types of needs, may be numerous and persist throughout the course of a disaster situation. Thus, soliciting financial help on social media not only has the potential consequence of receiving money, but also serves to organize or structure one's liminality by enabling options.

5.3.2 Negotiating Structural Power Dynamics

Not everyone who uses social media in highly constrained situations seeks help for enabling new options. We also found some people who used social media to rationalize and defend the choices they had already made—in particular, not evacuating. They responded to power plays and exercised power to influence others and regain a sense of control and order in the liminal space, a time when many circumstances are out of one's control.

5.3.2.1 Deflecting Judgment

Research on past hurricanes has found that the majority of people affected by a hurricane do not evacuate their homes (Hasan et al., 2011; Metaxa-Kakavouli et al., 2018). It is not a surprise, then, that many people in the dataset (for whom we could determine their evacuation status) apparently did not evacuate even despite mandatory evacuation orders across South Carolina, North Carolina, and Virginia. However, what is interesting is that so many disclosed why, apparently in response to sensing others' disapproval as we see explicitly in this data set:

> They should've evacuated. How difficult is it to get out of the way of a slow, lumbering giant? They were given enough advance warning, so what gives?

Those who did not evacuate may have been highly constrained, and leaving home may have been difficult to impossible. Several people used social media to explain or justify decisions so as not to be judged for them. This was demonstrated by @Jarley, a risk communication expert who also lived in an at-risk region in the Carolinas and faced the same kinds of constrained decision-making as regular citizens. She first reprimanded people who shamed others for deciding not to evacuate:

> And for the love of god, people outside of the areas impacted, don't evacuation or decision shame. People make decisions based on many factors and your twitter feed isn't one of them.

Days later, she experienced this sort of shaming herself before even finalizing whether she would evacuate or shelter in place (the shaming was that she had not evacuated "yet"), precisely because of her authoritative status/expertise about hurricane risk. In response, she posted:

> [...] I'm being shamed by people who have never lived on the coast for not evacuating yet and scorned by neighbors because I *might* be evacuating. Social ties, y'all.
>
> Why people do what they do may seem completely absurd if you're not from their world. I'd like to NOT leave for many reasons unless things look really dire. But I worry not leaving will deem me a hypocrite to my constituents.

In these posts, @Jarley emphasized what research has also seen: that people's decisions are personal and based on interpretations of risk in the context of their own "world," or "social lenses" (Dash & Gladwin, 2007). She later posted her decision to not evacuate as part of a long thread, explaining that her "reasoning is complex and incorporates a huge amount of local knowledge and experience." This included knowledge of the area's tolerance for rain based on her experience with Hurricane Matthew in 2016 as well as her own compromised health vulnerability that made it difficult to eat away from home for a long duration. Finally, she wrote on behalf of herself and other non-evacuees to justify not evacuating as an informed decision:

> Let me reiterate that: I know the risks in staying and I am assuming them. I've prepared the best I can and will re-evaluate as needed. Most people won't explicitly state that, but that is in fact what they are doing.

Similar sentiments were expressed by @UniSally, but in regard to her parents' (who lived separately from her) choice not to evacuate. In response to a post that stated that people at risk who have survived past hurricanes without evacuating should not feel safe doing the same for Florence, she wrote: "My parents live in Wilmington and didn't leave. It's going to be a long few days ())" (Wilmington was directly hit at landfall). This response was a way to deflect judgment by exposing the true, situated nature in which people make decisions and that some people's decisions may not adhere to official orders. It also seemed to appeal to the other person's emotions (pathos) by giving a personal example of her parents—it is harder to be judgmental of a specific person's parents as opposed to the general category of "people who don't evacuate." This emotional appeal appeared to be effective in that the other person then showed compassion— "Oh how scary! I hope they are ok."—and even reflected on her own parents' flooding from Hurricane Irma the year prior.

Deflecting judgment can have useful personal consequences in that one's decision to not evacuate becomes a more viable and socially acceptable option, reducing one's own uncertainty about what to do. As in these examples, this behavior could itself be seen as a form of public shaming in response to others' shaming, but done in the name of public good rather than to make people feel badly for their decisions or actions. By personalizing the experiences and constrained decision-making involved in disaster, deflecting judgment thus also serves to enlighten others as to the realities of disaster response and to combat assumptions and stereotypes that negatively portray people who are already facing challenging circumstances. In addition, the emotional support that can arise as a by-product from exchanges with others about not evacuating may be a form of unexpected help. We learn more about the ways in which people experience liminality in disaster, in this case by defending decisions even in the face of pressure from others to act differently.

5.3.2.2 Interplay of Power and Liminality

People affected by the disaster also **rendered** judgment about others' behaviors. The previous section showed how judgment about others' (non-)evacuation was expressed, though this was often done by people who were unaffected by the storm. People who were affected rendered judgment on others similarly affected, especially when influenced by structural power dynamics, which may make a person either powerful or powerless depending on the situation, their role, and the others involved. Social roles and structures are known to shift or even disappear in disasters (Turner, 1969; Weick, 1993). Liminality brings on feelings of powerlessness, which leaves those who are experiencing heightened uncertainty to act in a way that establishes or re-establishes power.

@Maggy discussed her unwillingness to go to work because the hazardous conditions of tornadoes and flash floods made her feel unsafe. She also posted a series of messages about employees at restaurants and other local businesses, expressing that she found it "selfish" of people in impacted areas to visit these places because that required employees to be at work rather than safely elsewhere:

> To be honest I think it's really selfish for people to go out to restaurants and other places of business right now. Those workers deserve to be inside and safe with their family but as long as you go there they won't get to leave... As long as people come, they have to be at work.

This sentiment matched her feelings about her own situation as a person whose concern for her safety amid multiple hazards outweighed her sense of responsibility to be at work. We might see both these acts by @Maggy as ways to regain lost power. In her expressions of discontent, she recognized the little power she had in the situation and challenged the structural power differential that existed between herself and her employer. She saw the power differential again in relationships between patrons, servers, and the imperatives of the servers' employers. Her advocacy could also be seen as a form of structuring her own liminal experience by taking action to help others.

However, there is flexibility in how people relate to the broader power dynamics at work. @Sydney described her positive experience with respect to her workplace, specifically her manager's support of her deciding for herself whether to travel for work the week of Florence. Yet just days later, she complained about a package—an anti-anxiety product for her pet—not arriving on time via Amazon.com, and she expressed disbelief that it could not be delivered from the local warehouse before the storm arrived:

> My ‹items› were scheduled for delivery yesterday from Amazon. They didn't arrive. I was told they'd arrive today or tomorrow. Assuming it won't show by then since their email claims it's due to the hurricane. The package is IN THE NEXT TOWN OVER and has been since yesterday.
>
> Apparently it's impossible to get my items from the warehouse that is like 9 miles (being overly generous) away. Because of the sunshine we had yesterday and the 12mph winds today. Looking forward to anxious pets because Prime fails to meet their set delivery schedule.

While @Sydney accepted flexibility of the power dynamic at work where she was less powerful as an employee, she was not so willing to be flexible when the power dynamic shifted, making her more powerful given her position as a consumer. @Sydney's Amazon experience also shows how posting to social media during the liminal situation made more obvious and reinforced the structural power differential that exists in producer/consumer relationships.

An additional complexity of liminality demonstrated by these uses of social media for exercising power is that people are not isolated to only their own liminality but are made witness to others' experiences as well. This places people in the position of being able to empathetically advocate for others who may be even more constrained. However, there is also demonstration of blind spots in which people fail to recognize that others are also highly constrained—blind spots that appear to map to the situational power one feels they have in the dynamic. Social media adds an audience to the liminal experience, making admonishments, mistakes, or defenses performative acts that are no longer only interpersonal, but potentially highly public, thereby enacting the structural power dynamic. Injustices are admonished, but also newly performed, depending on one's situational power.

5.3.3 Confronting Institutional Demands

Constraints were imposed by institutional authorities, including schools, universities, and workplaces. People used social media to externalize the responsibility of these institutions for exacerbating the liminality of the disaster, and sometimes to lobby for change. In contrast to the power dynamics described previously, here we examine cases in which the power belongs to institutions, not to oneself, to fill the liminal void.

5.3.3.1 Lobbying Schools

One institution in particular received a great deal of attention in the direct aftermath of the storm. Durham Public Schools, a school district in North Carolina, made the decision early Monday morning, three days after Florence's landfall, to reopen schools that day. However, the area was experiencing flash flooding and also had a tornado warning in effect. Photos of children standing in the rain during the tornado warning waiting for their buses and videos of school buses driving through flooded roads spread online.

Parents, students, and other concerned people began posting to question and criticize the school district's choice to hold school under such conditions:

> hey @DurhamPublicSch don't know if you've heard but where i live i'm under a tornado warning & flash flood. roads near my highschool are flooded. thought y'all wanted us to be safe? i'm going to be late for school bc school starts 9 and this tornado warning is over at 8:45.... [posted at 8:21AM with a phone screenshot of an emergency alert for a tornado warning]

> @DurhamPublicSch It's flooded AT DSA. Why did you make me drive here? ["DSA" is Durham School of the Arts, a secondary school in the district]

> @DurhamPublicSch For The Sake of the students please cancel school, thousands of people are still evacuated, and even more are stuck due to flooding, it could be potentially dangerous for students to go to school, please cancel, for them.

The requirement to go to school constrained students and parents and left them feeling powerless ("Why did you make me drive here?"). By using the @ convention to tweet directly to the school district's account, these instances demonstrate textual acts performed at threshold moments when uncertainty was heightened regarding school closures. By appealing to the district about its decision, these posts attempted to establish a semblance of structure in the liminal situation.

University students documented the struggles they similarly faced in relation to their university's decisions about holding classes in the days leading up to the storm and restarting classes after the storm had passed while its impacts were still very much present. @anne, who attended East Carolina University in eastern North Carolina, a region at high risk, noted how she could not make her plans regarding evacuation before hearing the official decision of her university:

> All right well I hope if we have to evacuate they'll give us enough time to get our shit together otherwise this will be me before I jump in my car and hit the road [gif of a person hastily packing a suitcase]

In particular, she required significant time to make her evacuation plans because her family's home was a 12-hour drive away. The following day, four days prior to landfall, she tweeted directly to the university, also quoting an official hurricane advisory posted by the National Hurricane Center, to pressure the university to make a decision about whether classes would be held:

> @EastCarolina please please please make an announcement sooner than later I live 12 hours away in Rhode Island so I have to plan accordingly!!! :)

She found out later that day that classes were canceled, as evidenced by her quote tweet of the university's announcement from its official "alerts" account to which she expressed gratitude: "Praise da lawd." She immediately drove home upon this news:

> Believe me I'm jumping on the highway and getting the hell out of the south ()

After evacuating, @anne still faced constraints. As she prepared to return to school, all the major roads were closed and/or dangerous to drive through due to tornadoes and flash flooding. The traffic and treacherous drive even made her consider, seemingly in a sarcastic way, suing the university "for emotional trauma/distress." The "resolution" for this user was finally returning to school:

> The best part of the 8 hour drive back to school was seeing about a dozen signs in multiple states saying to not travel through North Carolina if at all possible AND to top it off a lovely tornado/flash flood warning [meme, laughing and "I'm in danger"]

We do not know why in one direction the drive took 12 hours, and in the other 8. It could have been because of traffic or splitting up the drive; it could have also been that her message to the university employed hyperbole to affect change. In this final tweet that discusses her Florence experiences, @anne described the uncertainty she felt about needing to return to school but not feeling safe doing so. Not only was there signage warning her not to drive where she was headed, but there were concurrent tornado and flash flood warnings issued which made driving even more unsafe. We suggest that posting about these liminal experiences of not knowing what to do can be seen as providing some structure to situations that are uncertain, making them more tangible as a public record, which we talk about at greater length in the Discussion section. The instance also shows that who is perceived as powerful—in this case, who has the authority to influence evacuation decisions—also shapes the liminal experience.

Another student at the same university, @cecilia, expressed similar sentiments before the storm's arrival. She had already planned to evacuate five days in advance of landfall due to the likelihood of flooding:

> It's safe to say I'll be heading home on Wednesday, not sticking around when a hurricane is headed this way, and it floods like crazy here in Greenville

However, the following day she expressed her desire for the university to make an official announcement about holding classes, signaling that perhaps she could not commit to her earlier decision without this information: "Really wish ECU would make a decision regarding the hurricane" The official university announcement that classes were canceled came shortly after, and she retweeted it less than 30 minutes later. Upon this news, she did laundry and packed in preparation to leave for her family home. In response to a friend who showed concern and asked if she was being evacuated, she responded:

> Pretty much! Classes are canceled for the rest of the week and we were told to go home if we can, so that's what I'll be doing tomorrow morning ()

Though she had already made evacuation plans earlier in the week on which she seemed quite resolute ("It's safe to say..."), it became clear through her narrative that the university's decisions heavily influenced her own felt experiences about what she perceived as a constraint (i.e., that she must go to school), and therefore her evacuation decisions. It was not until learning the official status of classes and that students were encouraged to go home that she could truly feel safe with her evacuation decision, and even leave earlier than she had originally planned. Similar to @anne, @cecilia also continued to experience constrained decision-making about her return. She decided not to risk driving back to make it in time for classes because of bad road conditions from both flooding and heavy traffic, and instead intended to return two days later. Though she was appreciative that her school would excuse her absences, she still was concerned: "I'm tired of feeling so behind in all of my classes ()" This illustrates feelings of powerlessness that arise during liminal situations, as well as ways liminality can be in part defined by institutional decisions and policies.

5.3.3.2 Documenting Unfair Workplace Expectations

Workers also felt constrained by the institutional demands of their employers. The structure and social order imposed in times of liminality may not have the same effect for employees with less power. @Maggy expressed resistance in reaction to her boss' discussion of upcoming work occurring on the day of landfall, because "there is a full blown hurricane on the way and I am not planning to be at work." On the first workday after the storm, she posted:

> The road I live on is flooded and there's a tornado warning so I told my boss I felt unsafe driving in it and he is really picking me up [gif of person with disgusted expression]

This example demonstrates a reinforcement of the power dynamic. Though her boss may have felt generous about driving, he seemed to miss her main point, and interpreted her concerns to be a fear of driving, rather than being on the road and thereby exposed to the hazards: being in a car is explicitly warned against for both the floodwater and tornado risks they both faced. It is also possible that the boss was himself beholden to managers who outranked him and felt compelled to get himself and his staff to work under any circumstances. This instance shows how attempts made by others to establish social order in liminal situations is not always perceived as comforting or desirable. Here, the worker did not desire to go to work but had little choice given the power dynamic. It also shows the heterogeneity of the liminal experience and how structural and social order for one (the boss, in this case) does not mean structural and social order for all.

A person who lived in North Carolina and worked at a chain restaurant expressed concern starting days before the arrival of the storm about the possibility of having to go to work immediately after the hurricane, and especially about having to work on "the trailer when it doesn't even have air conditioning and is literally just one big oven." His fear was realized when he was expected to open the restaurant a few days later. When he arrived at work, he found the roof destroyed, food spoiled, and overall "unsanitary and unsafe conditions" and yet, he and the other employees were threatened by the franchise owner to be fired if they did not show up to work. This occurred at a time when employees were affected by evacuation orders, flooding, and tornadoes. He used social media to document the store's condition and his interactions with the insurance team. Though he did not name the owner nor the business, this documentation of events reflected the struggle in dealing with what were perceived as unfair demands of his job, showing how his liminal experience was shaped by the power of others.

@Cyrus shared the pressure he felt from his job at a retail store to work on the day the storm made landfall when flooding was a major concern in his area:

> my store wanted to stay open and I was like you realize your manager (ME) lives the farthest away??? I'm not risking my car for the Halloween store bitch

The following day he was asked to assess damage at the store, but did not feel responsible to do so due to his subordinate (assistant manager) position:

> my manager messaged me and said we were asked to go "assess the damage" from the floods and I was like nope!!! I'm just an assistant manager!!

These excerpts illustrate the ways people confronted institutional demands during the hurricane. Such posts are unlikely to receive actionable suggestions in reply, nor do we assume that that is the goal; rather, posting such issues aids in the liminal experience by documenting and thereby using the public as witness to what is perceived as unfair. These posts mark people's threshold moments of transformation from feeling powerless to restructuring the liminal situation to recast their power as they made sense of it.

5.3.4 Publicizing Action

Finally, in perhaps the most literal way of "filling the void," we found that people simply documented their status, actions, or preparations in a way that implied there was nothing else they could do amid high constraints by both social and environmental factors: in these cases, all that was left to do appeared to be posting to social media. This behavior enlightens our understanding of other behaviors we have examined throughout the paper; this consideration will carry into the Discussion.

One group of people who externalized their experiences was those who had not been through hurricanes before. For in-stance, @Betty, who was often asked for status updates by others, discussed her risk assessments and uncertainty about the storm. This post was in response to a friend asking how she was doing:

> So far, so good. I'm expecting we'll lose power sometime tomorrow and that it will maybe be restored sometime early next week. It doesn't take very strong wind to knock down power lines around here. I'm thankful we have generators. As far as the rain goes I live on a hill, but I figure that the creek that runs through the property will overflow before the storm's over.

Note that in this post, she provided both the problems or constraints she expected to face—losing power, an overflowing creek—as well as her capacity to adapt to these problems—having generators, living on a hill—leaving little room for suggestion or input from others.

Another person @Pyegrave, who had just moved to North Carolina three months prior to Florence and thus declared himself a "novice" at hurricanes, similarly posted in detail about his household's preparations, risk interpretations, and actions taken. In one case, he checked with others whether he was "doing it right," referencing a photo of his supply of backup food, water, and power. Even in seeking reassurance, he was simultaneously externalizing what he had done to prepare rather than only asking for help, and in so doing attempted to establish a sense of order in the midst of the liminal situation. @Bella also shared her detailed experiences of the storm—not as a novice, but as someone who was both well-informed, for example by being aware of rainfall projections, and well-prepared, for example by gathering gallons of bottled water. Even though her posts reflected concern about the storm generally, she expressed feeling as ready as she could be: "Can't think of anything more to do." She is managing the liminality of the situation by addressing the void outright in this post.

5.4 Discussion

We have presented a range of ways in which people used social media under the highly constrained and liminal conditions of Hurricane Florence. People were constrained not only by the physical hazards, which created a particularly dangerous situation when tornadoes and floods coincided (TORFFs), but also by their vulnerabilities. In this way, we see the disaster as a liminal void in which people had to continuously make decisions based on changing information and conditions to keep safe, and yet were constrained in doing so.

Using data systematically collected from social media, we observed the situated nature of these experiences during Hurricane Florence and social media's role in that situation. Our approach enabled an interpretation of people's documented, moment-to-moment experiences of and responses to the disaster as expressions of liminality, or small "performances" (Boland, 2013) of transformation throughout the larger experience of disruption. Amid such conditions, people who analytically emerged on social media as storytellers of their situations actively prepared for and responded to the disaster and recorded these actions. We consider these actions, and the act of posting about them to social media, as ways of filling the liminal void in that they aim to reduce feelings of liminality or ambiguity, albeit in different ways.

First, people used social media to explicitly ask for help in the form of financial assistance in order to enable or create solutions for protective actions like evacuation to remove themselves from the liminal space. Second, people used social media as a way to regain or impose a sense of control over the liminal space, when imbalances or shifts in power dynamics leave people feeling less in control of their decisions or actions. In other cases, people used social media to exercise power that they enjoyed in so-called "routine" life, expecting normalcy but not finding it in their liminal state. Third, people confronted the institutional demands they faced from their schools or workplaces thereby placing the responsibility of reducing the liminality—such as the uncertainties about whether school or work were canceled—on them. Fourth, people shared their detailed experiences on social media as a way to anchor into something tangible or material during the liminal time——the act of posting to social media was a literal way to fill the void when there was nothing left to do.

We can draw parallels between these findings and those of Mark, Semaan, and Al-Ani in their research of blogging by those living in regions of conflict (Al-Ani et al., 2010; Mark & Semaan, 2009). We see both their work and ours as kinds of technologically mediated expressions of liminality. In both cases, people encountering a crisis event used digital communication tools to write narratively about their liminal, transitional experiences of the crisis and to share these with broader audiences. However, these expressions differ due to differences in the nature of the crisis event, in the anticipated audience, and in the tempo of the digital communication platform.

Regarding the nature of the crisis, it is not necessarily clear when the liminal phase of a war will be over, while in a hurricane, the end is typically in sight or at least can be imagined within a number of days or weeks. This is just one attribute of these crises that creates a qualitatively different experience for people experiencing each one. Thus, while the blog posts of those in conflict zones have a citizen journalist quality to them (Al-Ani et al., 2010; Mark & Semaan, 2009), the social media posts of those experiencing a hurricane tend to demonstrate the moment-to-moment, often more raw expressions of liminality.

This also relates to the intended audiences of each type of communication. The intention of blog posts recording experiences of war is often to raise geopolitical awareness, for instance to manage the impression of one's culture or to provide "real" accounts of events that the mainstream media gets wrong (Mark & Semaan, 2009). With this, there is the expectation of a broader audience of people outside the borders of the bloggers' country. Perhaps also with such writing, there is the expectation that the content will become memorialized in some way because of the citizen journalism of such a significant world event. It is very unlikely that those who write microblog posts during a hurricane would have the same expectations of readership of their posts. Of course, writing to social media has some expectation of readership given the "social" nature of the platform and the public nature of their accounts. However, individual tweets are typically not designed to be memorialized as artifacts of the event, but fleeting accounts of one's experiences.

Finally, the affordances of blog and microblog platforms also contribute to the different expressions of liminality. Most significant are the different tempos afforded by each platform. Blogs and emailed diary newsletters are designed to be sent out at regular intervals, perhaps daily for dedicated writers or less frequently for others. They are also long-form, meaning they can take a significant amount of time to prepare and write, but also to read and respond to. Social media, and microblogs in particular, are characterized by their short-form posts and also their real-time, high-tempo nature in which people post and reply to others frequently. The monologues produced by a person's collective posts result in a narrative structure similar to blogs, yet each component is independent and therefore may reflect a greater breadth of concerns and decision-making over the liminal period.

This research contributes a new perspective of technologically mediated expressions of liminality in crisis. While past work has used long-form blogs to study the liminal experiences of those facing the continual disruption of war, technology has also evolved to allow for similar expressions on microblog social media platforms. The use of social media during Hurricane Florence further demonstrates the importance of digital communication tools for reducing liminality and transitioning to safety during times of crisis.

5.5 Conclusion

This research examined how people responded to the highly constrained situations during Hurricane Florence due to multiple overlapping weather hazards in combination with existing vulnerabilities that are exacerbated in disasters. We examined the surprisingly rich record of tweet monologues that emerged from data collection to understand in situ experiences of the storm. Inductive analysis led to interpretation of these as experiences of liminality that arise during periods of uncertainty. In such times, social media posting may be seen as expressions of what it means to be liminal: explicitly requesting forms of help that provide the most latitude in actions that can be taken; using the social media audience as a witness to injustice; publicizing actions to exercise control over uncertain situations; and grounding one's experiences in an external reality that documents the transformative quality of the liminal experience and perhaps mitigates feelings of uncertainty.

Part V

Discussion & Implications

Chapter 6

Discussion

6.1 Discussion of Research Studies and Implications

This mixed-methods, multidisciplinary research collectively has investigated how people use social media to communicate about risk for hurricanes. A central tenet of risk communication is that it is meant to be a dialogue between experts and laypeople (Árvai, 2014). Each of the three empirical studies (Chapters 3–5) addresses a component of this dialogue as it occurs on social media during real hurricane events, including what kinds of risk information are shared by authorities or experts, what members of the public do with that information, how these two groups interact to make sense of the uncertainty surrounding risk information, and how members of the public express their own experiences of risk, uncertainty, and decision-making.

The diffusion study (Chapter 3) was conducted first as a way to understand broadly what kinds of image-based hurricane risk messages are initiated by authoritative sources on social media and how they diffuse. Risk messages are just one component of the process of risk communication, and comprise the one-way messages that are sent by experts to a particular audience or audiences (National Research Council, 1989). This definition resembles the top-down data collection approach used for this study in which we first identified expert or authoritative sources of risk information and then collected all their risk image tweets. However, given the social media context of the messages, the research was not limited to studying the flow of messages in this one direction (from authorities to public) only. This study was an important starting point to the research as it elucidated the kinds of risk imagery that could be studied in more depth based on how frequently they are shared on social media in the first place and how much people pay attention to them. Because of the data collection approach used, the imagery used in the study can be reasonably assumed to constitute the entire body of images that authorities share to communicate such information. While some of these images are meant to communicate about hurricane risk for public audiences, others are intended for scientific purposes.

This study was conducted in collaboration with two researchers who have strong statistical backgrounds. This multidisciplinary collaboration was important for this study as it facilitated the development of novel diffusion metrics and application of the metrics to the dataset. These metrics are rate and duration, which denote the speed at which a tweet diffuses and the period of time for which it diffuses, respectively. Rate and diffusion can be calculated for a given tweet based on its replies, retweets, or quote tweets. A more intuitive metric is the count, or the total number of replies, retweets, or quote tweets for a given tweet, which is what much prior diffusion research relies on (e.g., (Lerman & Ghosh, 2010; Starbird & Palen, 2012)). However, the count turned out to be insignificant between risk image categories and authoritative source user categories in the diffusion analyses, and thus was excluded from the results. Though other research has used similar metrics to rate and/or duration for quantifying the diffusion of individual tweets (Goel et al., 2016; Yang & Counts, 2010), the metrics have not been dimensionalized along with replies, retweets, and quote tweets as done here and have primarily been used as predictors of diffusion rather than as subjects of analysis themselves.

One main takeaway from the diffusion study is that diffusion metrics alone do not tell the full story of risk communication. The fact that one image or category of images diffuses “a lot”—in terms of diffusing at a faster rate or for a longer duration, for instance—cannot be ascribed to a particular reason such as having high value for decision-making purposes. The qualitative analysis portion of this study showed that diffusion can in fact be attributed to a variety of reasons that differ at least in part by the type of risk image. There were two particularly notable instances of this: images of past hurricanes and radar and satellite images.

Images of past hurricanes were found to have the longest duration of all the risk image types studied, which seemed counterintuitive given their lack of relevance to the current hurricane season. Some of the diffusion of these was about comparing past hurricanes to present ones, such as emphasizing how much larger 2017 Hurricane Irma was forecast to be in relation to 1992 Hurricane Andrew, which was the most destructive hurricane to affect Florida prior to Irma. Though this kind of response makes sense given the image content, it alone cannot account for why these past hurricane tweets diffused for a significantly longer time than tweets that only show the current hurricane. Further qualitative investigation revealed that past hurricane image tweets were often used as the starting point for politicized debates about topics like climate change and geoengineering. Discussions would likely last longer than discussions centered around the time-bound and arguably more concrete aspects of risk related to the imminent hurricane threat, which fluctuates regularly. This could be an informative implication for weather agencies and other authoritative sources of hurricane information who may not be aware of the impacts/outcomes of sharing past hurricane imagery on social media. Though they may find it valuable to compare past and current hurricanes through sharing such images, and this may certainly be the case for some recipients of the images, the images also tend to generate discussions that may be undesirable or distracting to the risk communication for the hurricane.

Radar and satellite imagery also diffused more than other images in that they had a faster reply rate. This was a surprising finding as such images are purely observational and do not offer forecast information. Moreover, these images are technically complex and it is unlikely many laypeople know how to interpret them. For these reasons, we would expect them to diffuse less than images that convey information about what will happen and that may be more informative for people's decision making. As discovered in the qualitative analysis, these images in fact did not diffuse so quickly because of their utility in decision making, but because of their visual appeal. Replies such as "She's beautiful. In a graphic way", "Lovely/terrifying", and "Magnificent" all point to the ways audiences are captivated by the appearance of the hurricane in these images, and that the technical details are less important. People also responded to these images to make sense of risk, but the visual intrigue is unique to this category. This presents another implication for authoritative generators and communicators of visual hurricane risk information: visual appeal seems to be associated with greater (faster) diffusion. Thus, an additional implication for the generators of such forecast and risk images is that making them more visually appealing, or perhaps incorporating radar or satellite imagery into other visual representations, may help to get the information out more quickly over social media.

As these examples show, quantifiable metrics of tweet diffusion such as rate and duration do not indicate the reasons for diffusion. Hurricane risk images diffuse for a variety of reasons, including because of the value people find in the risk information, because the image is appealing, or because the image is an opportune place to start up a climate change debate, for instance. The diffusion metrics are valuable, however, for gaining insight into the exposure and attention that content on social media receives, two components which are necessary precursors in the protective decision making process (Lindell & Perry, 2012). They can also inform where to allocate resources for more fine-grained analyses such as those presented above for past hurricane and radar/satellite images and the extended study analyzing interactions around the spaghetti plot (Chapter 4). Use of the metrics may be differently valuable to different authoritative communicators based on their risk communication intentions as well. An organization may be interested in examining why certain types of images do or do not diffuse. Additionally, the metrics can be used to guide toward understanding different types of responses, especially when considering replies versus retweets and quote tweets. Focusing on the former is likely to uncover more responses that are directly tied to the information shared, whereas the latter will uncover responses that are more personal and emotive as they are shared on a person's own timeline rather than attached to the original tweet.

The following study on risk interpretation and interaction (Chapter 4) expands on the kinds of insights around risk communication derived by qualitative analysis in Chapter 3, but is scoped to one particular kind of risk image: the spaghetti plot. By analyzing the discourse of interactions around spaghetti plot tweets, this study goes beyond the study of risk messages as one-way communications with the goal of educating the public; it begins to consider the risk communication process more wholly as a two-way dialogue between authoritative sources and their audiences, which is possible via social media. Though the data are derived from the same top-down data collection as used in the previous study, more emphasis is placed on the communications derived from audiences in response to the messages as well as the interactions that result when the original authoritative sources engage in dialogue. My interest in this study was understanding the interpretation of the spaghetti plot risk messages by the recipients: "what does this mean *to me*?" Yet, interpretation necessarily requires a viewer to be able to first comprehend the image—"what does this *mean*?"—and so we also consider comprehension as part of the study. In addition to understanding and gaining insight for the specific spaghetti plot image, we also identified insights that would apply more broadly to other types of images shared by authoritative sources.

A reasonable interpretation requires good comprehension. Spaghetti plots in particular are complex graphics which portray uncertainty through the mapping of discrete potential paths of the hurricane as a result of various computer models. Because there is no standard spaghetti plot, and they are instead unique to the person or organization that generates them, there is no consistency to visual features such as the colors, the choice of models to include, or the ordering of models in the legend, for instance. Thus, the images almost require some expert interpretation—it is unreasonable to expect laypeople to comprehend, and much less interpret, the images in a particular prescribed way. The two-way nature of the discussions that arose on social media around these images helped to reintroduce some of the elements of the image that were lost in the initial attempts at comprehension. People responded to the images with comments and questions to clarify their understanding of the image, whether regarding the meaning of specific visual features or the implications for impacts locally and regionally. This means the authoritative risk communicators' responsibilities continue beyond just the initial posting of such information. We characterized three responsiibilities of their risk communication: interaction, interpretation, and maintaining uncertainty. Interaction is about the need to engage with the public and respond to their questions as scientific experts. Interpretation is about not just putting data out there for the public to see, but putting it in context and even telling a story so that people know what the data actually imply for them. Maintaining uncertainty is about relaying information only to the extent of what the technology can accurately forecast and being honest when specific outcomes cannot be known, i.e., "it's too soon to know."

This study can bring awareness to risk communicators about the implications for using social media platforms like Twitter for the purpose of sharing complex hurricane risk information. Given the kinds of (mis)interpretations of spaghetti plots and the lack of understanding of fundamental aspects of probability displayed by many members of the public, this begs the question of whether such platforms are appropriate for communicating such information in the first place. Though this dissertation is not intended to directly address this issue, it has demonstrated the importance of authoritative risk communicators engaging with audiences on their social media posts. Greater engagement, as opposed to passive broadcasting of information, allows the risk communicators to answer questions and to both gauge and shape the public's understandings of risk.

The first two studies studies were conducted primarily in a top-down manner, where the data consisted of risk messages from pre-identified authoritative sources. In the study of people's experiences of highly constrained situations (Chapter 5), we took a different, bottom-up approach to account for the two-way nature of risk communication. This study started by identifying people at risk during Hurricane Florence, which brought co-occurring tornadoes and flash floods to many people along the US East Coast. We collected their tweets to understand their perspectives of risk and how they used social media for grappling with the complexities and ambiguities of their situations. Constraints to protective decisions and actions were imposed both by the combination of multiple hazards as well as people's various individual and household factors that affect their vulnerability (Bowser & Cutter, 2015). We treated a person's collective tweets as a narrative of their experience of the event. Their reactions and decision-making as portrayed through their narratives were not necessarily informed by any specific risk information or source, which are less relevant to the goals of this study. By taking this bottom-up approach we were able to get insight into a wider view of the role that social media played for people at-risk during the unfolding of a complex disaster.

People's narratives revealed diverse uses of social media during highly constrained situations, including seeking financial help, negotiating structural power dynamics, confronting institutional demands, and publicizing action. In this study, I do not claim to know the motivations for posting in these different ways, as this would require speaking with the people themselves, and even then it is hard for people to recall why they might have posted a particular message on social media. Rather, I can only observe the outcomes that arise when people post, such as replies from others who offer advice or help or later posts by the same person indicating a change in their risk assessment or decision making. Again, the narratives and specific reactions to risk are not explicitly tied to authoritative information such as how people's posts were examined in Studies 1 and 2. This study considers more broadly that people get risk information from a variety of sources that may inform their decision-making and behaviors, including friends and family and other informal sources such as others experiencing the event, in addition to the traditional/authoritative sources.

Thus, regardless of the information people are exposed to or use, or the source of that information—neither of which is explicitly sought out in this study—the findings show the value of social media in helping to enable options or reassure people their choices are valid. This brings about a potential area for further investigation: what kinds or sources of information inform or motivate people to use social media in the ways examined in this study? This question is of interest to researchers and forecasters in the weather community (National Academies of Sciences Engineering and Medicine, 2018). For instance, how are students, who were a large portion of the people in this study, influenced by information that comes directly from their schools and universities about hurricane risk as opposed to from their parents, or their local meteorologists, or the NHC? Does a particular type or source of information motivate people to ask for help, such as more declarative warnings or more uncertain forecasts? Do any of the types of formal risk imagery studied in Chapters 3 and 4 lead to increased indecisiveness around protective actions? A blending of methods and approaches (top-down and bottom-up) from all three studies—including categorization of types and sources of information and analysis of narratives and interactions—could be used to address these types of questions.

The multidisciplinary collaborations for this study were important in shaping the research from the start and in producing a wide range of contributions. First, the idea to look at the co-occurrence of tornadoes and flash floods in a hurricane came from collaborators in meteorology who had conducted research on the phenomenon previously. They noted the need for social science-based research to understand how people make sense of uncertain communications for the concurrent threats given the potential for hazardous outcomes if people are not adequately prepared. Additionally, the idea of framing the findings in terms of liminality came about through collaborators in anthropology. Liminality was not a concept that I initially approached the data analysis with, but one that arose as a fitting way to describe the kinds of experiences we observed people posting about during a complex, highly constrained situation.

Given these collaborations and their influence on the research, the study in turn makes contributions to these disciplines. The findings are important for meteorology because they demonstrate how people respond to multi-hazard TORFF events as well as the broader ways that regular people might conceive of TORFFs in relation to the highly precise definitions used by meteorologists. Anthropologists may find value in a new conception of liminality in high-constraint disaster scenarios. In this case, liminality may not be characterized by "pure possibility" as suggested by Turner but instead presents a void in which people must act immediately to keep themselves safe. Additionally, the extended monologues that people post to social media during during disasters or other classic "liminal" periods may be an interesting new source of studying liminiality in this field. Finally, this study makes contributions to HCI by offering a different perspective of using social media data than is often used in crisis informatics research. While much research seeks to make use of data opportunistically for specific purposes, like identifying situational awareness information or content that confirms or denies rumors, we read the data as individual monologues during a time of transition with no expectations of what the content would reveal. This research design meant that we could come to insightful findings that reflect people's experiences of disaster from their own perspective.

6.2 Additional Practical Implications

This dissertation has presented research on risk communication for hurricanes with an HCI sensibility. Crisis informatics has long applied methods and theory from HCI to the study of how people communicate and behave in disasters, but this work newly provides an account of such topics as they relate to the communication of risk and uncertainty information. While the weather community has recognized the need for integrating research on social and behavioral sciences, utilizing both social science and computer and information sciences offers the ability to study what people do around risk information in real hurricane events at scale through social media data. As discussed in Section 2.3.1, much prior work that has made use of social media data for studying issues of risk communication and weather-related disaster events has done so in cursory ways. These studies often analyze the top-level tweet data, such as counts of tweets or frequency of words, which result in limited insights. Throughout this dissertation, I have demonstrated the potential value of social media data as far more than simple counts of keywords or retweets through deep engagement with the data both quantitatively and qualitatively. Importantly, social media data analysis should consider the human elements of content production and dissemination, and that these reflect interactions between actual people in the real world (of course, with some exceptions).

Additionally, my experiences participating in research events centered around meteorology, including the American Meteorological Society (AMS) Annual Meeting in 2019 and several webinars and conference calls organized by people at NOAA, also reflected the nascence in these communities of using social media data in studies of human behavior in weather events. After presenting at the AMS meeting on work which is part of Study 2 (Chapter 4) around spaghetti plots and how people interact with them on Twitter, I was approached by several meteorology students who were curious about Twitter but unsure how to make use of it in their research. I shared results about the diffusion work with a scientist at the NHC who posted a tweet in the 2017 season that happened to be among the most highly diffused tweets in the entire dataset, and he was fascinated both to learn of this accomplishment and that tweets could be measured in this way at all. The NSF CHIME (Communicating Hazard Information in the Modern Environment) research grant, which involved collaborators from NCAR and our Project EPIC group at CU and was my introduction to issues of risk communication and hazardous weather, was in large part formed because the use of social media data to understanding these issues had not yet been done, and yet offered great potential for valuable insights through the multidisciplinary collaborations between weather, risk, social science, and information science. This dissertation is largely a result of this collaboration, which I have continued to maintain by working with collaborators at NCAR (and through them, with people at NOAA as well) even after the conclusion of the CHIME grant. Thus, I hope that this dissertation can serve as an example and a starting point for how to incorporate social media data meaningfully into the study of sociobehavioral phenomena related to weather: how people make use of different types of weather information, how to categorize these different types in the first place, how to track the spread of such information among different kinds of stakeholders (beyond the simplistic insights or statistics provided by platforms like Twitter), and so on.

Moreover, in terms of risk communication specifically, the incorporation of social media into this field of research allows for understanding risk communications as they occur both in real events (as opposed to in hypothetical disaster scenarios), and in multiple directions. That is, much risk communication research still focuses primarily on risk messages and the transmission of these from experts or authorities to the public, with the hope or expectation that people will understand, listen to, and follow the information. Risk messages are an important component of the risk communication process, and Study 1 provides new methods for assessing the effectiveness of social media risk messaging and for categorizing risk messages into meaningful ways. However, this is not the entirety of the risk communication process, nor all that people consider in reality. Even though the field has long come to accept this as a two-way process (National Research Council, 1989), research is still often devoted to the one-way transmission view (Árvai, 2014). TV, one of the most popular platforms for risk communication during a hurricane, can be difficult to study beyond the transmission of information, because there is no active engagement or interaction of viewers with the broadcasters. However, social media affords such interactions between experts and the public, and even more importantly for research, it is documented in ways such that data of the interactions can be collected and analyzed systematically. The three research studies presented here additionally show the kinds of engagement and interaction that occur around hurricane risk information over social media. While the research has offered insight into several aspects of risk communication including diffusion, comprehension, interpretation, and reaction, there are still many more questions that could potentially be addressed about what people do with such information in real events, both within these topics and beyond.

By applying HCI knowledge and methods to the specific application area of meteorology and risk communication, this work has shown what HCI research is capable of. From this perspective, understanding people, their cognition, and their behaviors systematically requires studying what people actually do in situated contexts. Thus, for understanding how people use hurricane risk information or what they do when faced with multiple hazards, we take the natural experiments that present themselves when hurricanes occur and the affordances of social media for recording what people actually do during these events. As mentioned earlier, the application of crisis informatics and information science sensibilities to this domain area is new, and this can hopefully serve as a model for applying similar approaches to other domain areas, or for continuing research on this same topic. With the effects of climate change posing increasing threat to people and property across the world, it is becoming increasingly critical to understand how to communicate complex and uncertain information about risk and natural hazards among experts and the public.

6.3 Contributions of Resources to Future Research

In Study 1, I developed a coding scheme to classify the kinds of hurricane risk graphics shared by authoritative sources on social media. This enabled the measurement and analysis of diffusion among different categories of images to determine if there were differences in how different images diffused and why this might be. The full coding scheme is available in Appendix A. It can serve as a starting point for future researchers who want to understand other aspects of hurricane images or risk communication. It could also serve as a model for developing similar image coding schemes for other weather hazards.

We also developed two diffusion metrics for measuring temporal aspect of how tweets diffuse. These metrics can be calculated using replies, retweets, or quote tweets. The first is **duration**, which represents the period of time for which a tweet diffuses, and is measured from the time a tweet was first posted to when it received its final reply, retweet, or quote tweet; it represents the "life span" of the tweet. The other is **rate**, which is calculated as the gradient of the count of diffusion tweets over time, starting from the original tweet through the first 95% of its diffusion. These metrics are valuable for gaining insight into the exposure and attention that content on social media receives, two components which are necessary precursors in the protective decision making process (Lindell & Perry, 2012). They can also inform where to allocate resources for more fine-grained analyses such as those presented in Section 6.1 for past hurricane and radar/satellite images and the extended study analyzing interactions around the spaghetti plot (Chapter 4). Use of the metrics may be differently valuable to different authoritative communicators based on their risk communication intentions as well. An organization may be interested in examining why certain types of images or content do or do not diffuse. Additionally, the metrics can be used to guide toward understanding different types of responses, especially when considering replies versus retweets and quote tweets. Focusing on the former is likely to uncover more responses that are directly tied to the information shared, whereas the latter will uncover responses that are more personal and emotive as they are shared on a person's own timeline rather than attached to the original tweet.

Additionally, in Study 1 I compiled and classified over 16K hurricane risk image tweets according to this coding scheme. This data includes all the original metadata for individual tweets, the hand-coded classifications of the attached imagery according to the coding scheme, classification of the type of authoritative source user (Weather-News/Media, Weather-Government, Weather-Other, News/Media [non-weather-specific], or Government; described in Section 3.4.1.1), as well as the diffusion metrics (rate and duration) for replies, retweets, and quote tweets. This serves as a high quality dataset that could be used in a range of future research applications. For instance, it could be used as an input to a machine learning model to determine what attributes of such tweets contribute to their diffusion.

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Appendix A

Risk Image Coding Scheme

As described in Section 3.4.1.3, I developed a coding scheme to classify all images identified as portraying hurricane risk or forecast or information. The following coding scheme contains 22 codes, all of which are non-mutually exclusive, so any number of codes could be applied to a single hurricane risk image.

Representations of the Hurricane Phenomenon, Current or Forecasted

Hurricane location or path

- Cone of uncertainty (*cone*)
- Spaghetti/ensemble models (*ensemble*)
- Potential development, pre-named storm (tropical depression/wave, invest) (*developing*)
- Other mapped visualization types, including models (*other hurricane*)

Properties of the hurricane itself (current/observed or forecasted)

- Pressure graphs/maps (*pressure*)
- Wind (*wind*)
- Other properties of the hurricane, e.g., sea surface temperature, tropical moisture (*other properties*)

Purely observational data

- Radar imagery/satellite imagery (*radar/satellite*)
- Reconnaissance data (*recon*)

Physical and Societal Impacts

- Evacuation maps (*evacuation*)
- Storm surge (*surge*)
- Precipitation (*precipitation*)

- (Flash) flood watch/warning (*flash flood*)
- Tornado/severe weather watch/warning (*tornado*)
- Tropical advisories (hurricane/tropical storm watch/warning) (*advisories*)
- Other types of forecast visualizations, models, or graphs related to a hurricane's associated weather events/impacts, e.g. wave heights/water levels that are not storm surge, boat/beach forecasts, mudslides, power outages (*other impact*)

General/Format

- Mapped visualization/imagery (*map*)
- Graph/plot (*graph*)
- Textual (or audio) information describing forecast (*text*)
- NWS/NOAA or other official government graphic (*nws/noaa*)
- Explicit uncertainty, including probabilistic forecasts (*uncertainty*)
- About a past hurricane, especially as relevant to current/impending storms (*past*)