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Abstract

Extreme rainfall events have increased in parts of the United States and climate models project that trend to continue (Carter et al. 2018; Mullens et al. 2013; Hayhoe et al. 2018). As such, forecasters must be able to effectively communicate the potential threats and impacts associated with these events to their users. How National Weather Service (NWS) meteorologists and hydrologists communicate with their audiences leading up to and during extreme rainfall events has not yet been widely explored. This study aims to help address that knowledge gap.

This research investigated how NWS forecasters processed and communicated information about extreme rainfall events that occurred in the South Central U.S. between 2015 and 2019. An event was included in this study if the NWS Hydrometeorological Design Studies Center determined it to have an Annual Exceedance Probability of 1/500 or less in one of their storm analyses. Nine events were identified. Semi-structured interviews were conducted with 21 NWS forecasters about their experiences with the events and how they or their offices messaged the event(s). Study participants were asked event-specific questions about products disseminated by their offices leading up to and during the event(s) and how they internally processed and externally communicated model outliers and anomalous rainfall events overall. Interviews also explored forecasters' perceptions of the relationship between these events and climate change and if those perceptions impacted the forecasts and messaging for the event.

Using deductive qualitative analysis, components of sensemaking (Weick et al. 2005; Butterworth 2010; and Doswell 2004) and decision-making (Millet et al. 2020) conceptual frameworks as well as principles of forecasting (Armstrong 2001b) were identified in the responses. A simple forecast communication process model was created to illustrate the findings. While the forecast and communication processes are complex and vary between offices and forecasters, these frameworks and the process model provide a high-level understanding of how forecasters translate their knowledge to usable information for their audiences. With an awareness of the purpose of the forecast, forecasters use sensemaking and decision-making frameworks to process data from models and observations. These processes are impacted by forecast uncertainty, which will always be present but is challenging to convey. Then, forecasters consider what sensemaking and decision-making processes their audiences will go through as

they try to understand the forecast information. These principles and frameworks then impact how they present the forecast to their audiences. The study also found that forecasters do not consider the impacts climate change might have on an extreme rainfall event when forecasting such an event. However, climate change is something that they may consider when reflecting on the event after it occurred.

Chapter 1: Introduction

Flooding is one of the most hazardous and costly weather phenomena in the United States (U.S.). Since 2015, the south central region of the U.S. has experienced eight one-billion-dollar disasters associated with extreme rainfall (NOAA NCEI 2021). Behind heat, flooding is the second deadliest weather hazard in the U.S. (NWS 2020). Also, since 2015, 259 people have lost their lives to flooding in the Southern Climate Impacts Planning Program (SCIPP) region (NWS La Crosse 2021). The National Weather Service (NWS) attempts to mitigate the impacts of these events through its mission of protecting life and property by providing data, forecasts, and warnings (NWS 2021). Thanks to numerical weather prediction (NWP) and improving technology, weather forecasts continue to improve (Bauer et al. 2015).

While improvements to the quality of weather forecasts are crucial, it is also important to be able to effectively communicate these forecasts to users (Losee et al. 2017). Effective communication will continue to grow in importance as extreme events such as extreme rainfall events are projected to increase in frequency and intensity (Easterling et al. 2017). The number of studies on how end-users interpret forecast information is growing (e.g., Gigerenzer et al. 2005; Joslyn and Savelli 2010; Morss and Hayden 2010). However, how forecasters process and then communicate weather events has not been well studied (Morss et al. 2015). This study aims to add to the knowledge base of how NWS forecasters translate their meteorological knowledge into information that is usable to their audiences. Specifically, this study examines:

- How forecasters internally process model outliers leading up to and during extreme rainfall events;
- How forecasters communicate to external audiences leading up to and during events; and
- Forecaster perception of climate change and its relationship to extreme rainfall events.

Sensemaking (Weick et al. 2005; Doswell 2004), decision-making (Millet et al. 2020), and principles of forecasting (Armstrong 2001b) are used to create a high-level understanding of the forecast and communication processes of extreme rainfall events in the SCIPP region. Chapter 2 provides an overview of literature on the climatology of extreme rainfall events, forecasting communication and uncertainty, and social science theories that can be applied to the forecast and communication process. Chapter 3 describes the study methodology. Chapter 4 provides the results and presents a simple forecasting process model to visualize the results, while Chapter 5 is a discussion of the results. Chapter 6 concludes the thesis as well as provides recommendations for future works.

Chapter 2: Literature Review

Research on how end users interpret and use forecast information has continued to increase (e.g., Gigregenzer et al. 2005; Joslyn and Savelli 2010; Burgeno and Joslyn 2020; Morss and Hayden 2010; and Perreault et al. 2014). However, less is known about how forecasters use their knowledge of complex atmospheric data and the decisions they make as they translate that information into graphics and text that are useful and usable to end-users (Morss et al. 2015). A knowledge gap exists between the production of scientific knowledge and its decision-making usability (Morss et al. 2011). This knowledge gap can be bridged. Sherman-Morris et al. (2018) found that management across Weather Forecasting Offices (WFOs) have a favorable view of social science. They feel that research should be conducted on what actions are taken in response to warnings and why, the most usable information for decision-makers, how well warnings are understood, and how best to communicate uncertainty. This project aims to add to that knowledge base. This chapter will explore the background of the project by reviewing the region's extreme rainfall climatology, forecasting processes and communication, and social science theories that can be applied to forecasting.

2.1 Climatology of extreme rainfall events in the SCIPP region

Extreme rainfall events are projected to increase in frequency and intensity with climate change (Mullens et al. 2013; Hayhoe et al. 2018; Trenberth et al. 2003). Over the past 25 years, the number of days with three or more inches of rain have been significantly above normal in the Southeast United States (Carter et al. 2018). Groisman et al. (2012) found that in the south central United States, there are about 0.53-0.64 days per year that experience three or more inches of rain. In the Southern Great Plains, rainfall events are projected to decrease in frequency, but increase in intensity, creating periods of extreme drought followed by flood (Kloesel et al. 2018). However, rainfall events at or above the 95^{th} percentile are increasing in frequency in the SCIPP region (Mallakpour and Villarini 2017). In portions of the Southeast United States, hourly rainfall rates are increasing but hours with precipitation are decreasing, signaling that more rain is falling in shorter amounts of time, which can worsen associated impacts (Brown et al. 2019a). For example, in Louisiana 90^{th} percentile rainfall events contribute to half of the annual rainfall in .005% of total annual hours (Brown et al. 2019b).

While it is important to emphasize the link between extreme events and climate change so that the public acknowledges the urgency of the issue (Durran 2020; Felischhut et al. 2020), it is difficult to attribute individual events to climate change due to small-scale processes that are unable to be accounted for in climate models (Durran 2020; Easterling et al. 2017). Hoffman et al. (2017) claim that for this reason, as well as political and social reasons, NWS forecasters are more likely to focus on the data in front of them when facing an extreme event rather than consider if climate change is playing a role.

2.2 Forecasting

Meteorologists have a plethora of information available to them when making forecasts, and they cannot analyze all of it within their time constraints so they must choose what they feel is the most reliable (Daipha 2015; Doswell 2004). One such source of information accessible to forecasters is weather models, including relatively new ensemble guidance, which add value to extreme precipitation forecasts, especially as the models continue to improve (Schumacher 2017). However, each forecaster interprets ensemble model output differently (Evans et al. 2013) and sometimes struggles interpreting probabilistic guidance from ensembles (Wilson et al. 2018). Ensemble flood forecasting presents these issues as well (Demeritt et al. 2010). Struggling with ensemble interpretation likely means that how forecasters perceive and utilize model outliers is not uniform across forecasters. WFOs must work within themselves (Daipha 2015) as well as with neighboring offices, national centers, and partners to ensure that a consistent message is being broadcast agency-wide to avoid any confusion or loss of trust (Childs and Schumacher 2018; Sherman-Morris et al. 2018).

2.2.1 Forecast communication

While models have greatly improved, and consistent model output greatly increases a forecaster's confidence that an event will occur, forecasters have expressed that models struggle to predict event timing well, making it difficult to convey forecast information to their audiences effectively (Childs and Schumacher 2018). Effective communication of a forecast is an increasingly important part of NWS operations. Expanding beyond core partners and National Oceanic and Atmospheric Administration (NOAA) Weather Radios as messaging dispersion tools, the NWS has taken advantage of the evolution of social media to directly reach the public as well as allow the public and other end-users to communicate back (Hubbard 2018). While social media has helped the NWS reach more of their public audience, there is still the issue of the best way to use this communication platform. Research on the subject is still in its infancy but an early investigation showed that posts with more detailed information and strongly worded language received the most attention from the public, meaning they are more likely to act accordingly (Ripberger et al. 2014). However, using strongly worded language must be carefully considered. While strong language can be effective to some people, others may think that it is overly dramatic and may cause them to lose trust in the NWS (Morss and Hayden 2010; Perreault et al. 2014). Information should also be included that can help the end user take proper protective action rather than just informing them that a threat is coming (Eachus and Keim 2019). NWS offices tend to do well in following organizational guidelines and general best practices when it comes to hazard communication but sometimes struggle with including actionable information while the threat is ongoing, conveying what is happening at that moment but not how to deal with it (Olson et al. 2019).

It is also important that the public can understand the forecast products that are published. Using language that is too technical or subjective can make the product difficult to correctly interpret (Sivle and Aamodt 2019). Also, if the product is not presented in an appealing way, it will not be used (Kuonen et al. 2019). Carr et al. (2016) found that their participants felt that many NWS flood products were difficult to understand or visually unappealing. Even after making suggested edits to one product, the public still found it difficult to understand. Sophisticated users felt that changes helped, suggesting that some products cannot serve all audiences (Carr et al. 2018). Bostrom et al. (2016) found that several NWS products are not used at all by their partners. The need for better coordination between the NWS and their partners exists so that efforts to create new and/or maintain unused products are not wasted.

Another communication challenge that forecasters face is being able to address a targeted audience according to their needs. When addressing the public, it is difficult to do so with one uniform message, as it is full of diverse communities (Rouleau 2016). It is important that audiences can understand the forecasts and process them in a way that is relevant to their own needs. Knowing that a hazard exists does not necessarily mean that one believes it will apply to them (Sanders et al. 2020). Many members of the public are solely interested in how an event is going to affect them personally, indicating a desire for localized forecasts that are not currently feasible (Carr et al. 2016; Childs and Schumacher 2018). What is relevant to a person is dynamic as well, as they could be more vulnerable to weather hazards as their activities and locations change throughout the day. Their vulnerability could change as they go from home to work to the store, etc. (Sivle and Aamodt 2019). However, Daipha (2015) saw that some forecasters did not have an interest in learning more about their public to better communicate with them. When WFOs work with end users to better understand these needs and how forecasts are interpreted, there is more trust in both the forecast itself as well as trust that the forecast will be used properly (Kuonen et al. 2019). WFOs feel they work well with partners, especially emergency managers (EMs), to understand their needs (Sherman-Morris et al. 2018). These interactions are crucial, not only educating forecasters on the real-world value of their forecasts and motivating them to learn more about partner needs (Hoffman et al. 2017), but also improving forecast communication systems. To be successful, these interactions should be consistently maintained (Demuth et al. 2012; Liu and Seate 2021), as it is insufficient to only interact when an event is imminent (Senkbeil et al. 2020). To create the best forecast products, it is important for communicators to test the products and tailor them based on audience feedback (Rouleau 2016; Childs and Schumacher 2018; Demuth et al. 2012). Studies have attempted this with end users (Carr et al. 2016, 2018), but less is known about how NWS forecasters treat or react to audience feedback on specific products.

2.2.2 Forecast uncertainty

Uncertainty is inherent in weather forecasts, especially with extreme rainfall, as quantitative precipitation forecasts (QPFs) are reliant on processes that are difficult to model, especially in the longer term (Schumacher 2017). As in Morss et al. (2008) and NRC (2006), in this study uncertainty refers to a forecast that expresses "imperfect knowledge about future weather" (Morss et al. 2008, pp. 975). Forecasters will try and minimize uncertainty in a forecast by monitoring model agreement for as long as they can while still allowing sufficient lead time (Bostrom et al. 2016) but it is not possible to eliminate uncertainty. It is important to include uncertainty in forecast products as it increases the "goodness" of the forecast, specifically boosting the consistency trait of forecast goodness (Murphy 1993).

However, there are challenges associated with conveying uncertainty information. One way that forecasters convey uncertainty is by qualitatively describing their confidence or lack thereof in a forecast. When doing so, forecasters must be careful if they choose the word "uncertainty" as that could cause the audience to lose confidence in the forecast (Rouleau 2016). However, studies have found that audiences are aware of the inherent uncertainty in forecasts (Morss et al. 2008; Joslyn and Savelli 2010). Another method currently used to express uncertainty information is return intervals. However, these pose issues: when people are told they are facing a 100-year flood event, they believe the event can only happen once every 100 years. Grounds et al. (2018) found that using probabilities led to better decisions than return intervals did. Forecasters often feel that the public struggles to interpret probability information and are better off being given deterministic forecasts (Daipha 2015; Stewart et al. 2015; Demeritt et al. 2010). Some studies agree, finding that members of the general public do not understand probability information, as well as other forecast information, in the way that it is officially defined (Gigerenzer et al. 2005; Fleischhut et al. 2020; Morss et al. 2008). Even forecasters themselves have differing interpretations of uncertainty information, such as the Probability of Precipitation (PoP) (Stewart et al. 2015; Daipha 2015; Demeritt et al. 2010).

However, it has been found that end users make better, more informed decisions when uncertainty information is included in the forecast (LeClerc and Joslyn 2015; Fundel et al. 2019; Roulston and Kaplan 2009; McCarthy et al. 2007). Uncertainty information could not only lead to better decision making, but it could also improve forecast evaluation, as rare events are especially difficult to score, which was addressed by Stephenson et al. (2008). They suggested using probabilistic forecasts and establishing a scoring method to be better able to assess extreme event forecast performance. While the NWS is making efforts to incorporate probabilistic information into forecasts (Just and Foley 2020), most products currently issued by the NWS are deterministic (Novak et al. 2008; Hirschberg et al. 2011; Wilson et al. 2018). Studies have found that some forecasters want to include more uncertainty information in their forecasts (Murphy and Winkler 1974) but need additional training to be better able to express that uncertainty (Novak et al. 2008). Wilson et al. (2018) also support the need for more forecaster training on probabilistic guidance and uncertainty information as the weather enterprise expands its use of such products.

As with other types of forecast information, the needs of the audience are important when considering what kind of uncertainty information to convey (Fundel et al. 2019; Carr et al. 2018). For example, the needs of EM officials are not only different from that of the public, but also vary amongst themselves (Kox et al. 2014). By working with their partners, WFOs can establish the kind of uncertainty information that works best for each group. Overall, more research on the subject of communicating uncertainty is needed (Morss et al. 2008). This project aims to add to that knowledge base. Forecaster responses to questions about forecast uncertainty are discussed in chapter four.

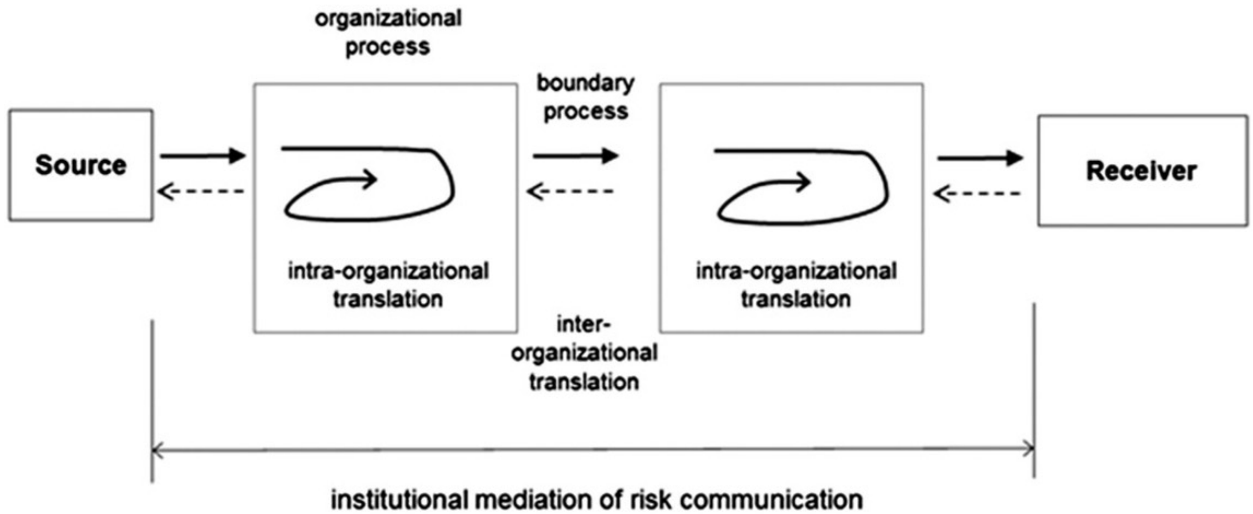


Figure 2.1: Textual processing model of risk communication from Lejano et al. (2016)

2.3: Social science theories and frameworks

Social science theories are utilized in this study to help understand forecast and communication processes. This section will review these theories and how they have been applied to risk communication. Conceptual and mental models are often used to visualize how information is processed and communicated. Meteorologists have used conceptual models to visualize their knowledge for decades (Hoffman et al. 2017). Mental models explore how individual experience shapes reasoning and that though these processes are individual, people in similar situations could develop similar models (Millet et al. 2020). Bostrom et al. (2016) and Morss et al. (2015) both used mental models to obtain an understanding of how forecasters and stakeholders process hurricane and flash flood risks, respectively. Such models frame that process as simplified and one-way. However, it is important to acknowledge that mental models are actually complex and systems (Morss et al. 2017). Lejano et al. (2016) established a model that focuses on how organizational processes impact the risk communication process (Fig. 2.1). This textual processing model of risk communication can be used to analyze how information is transferred from a source to and between organizations and finally to the receiver. This model can also be used to analyze how information is translated within an organization and then passed on to either the next organization or the end user. One step past the Lejano et al. (2016) model, Hoffman et al. (2017) presented The Base Model of expertise (Fig. 2.2). This model details the intra-organizational processes that result in a certain action, in the case of forecasting, the creation of forecast products. Along with process and mental models, conceptual frameworks can

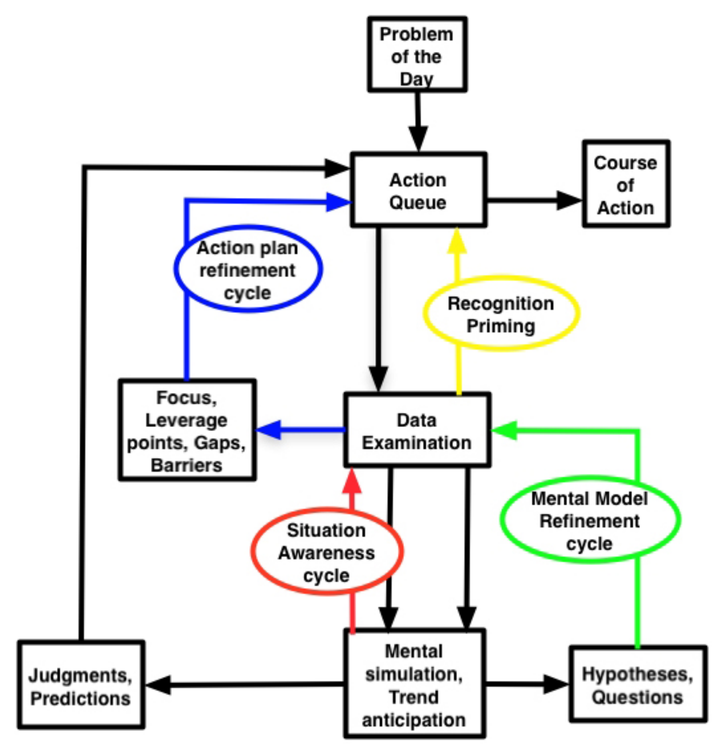


Figure 2.2: The Base Model of expertise reproduced by permission by R.R. Hoffman, all rights reserved 2021. First published in Hoffman (2017).

be applied to understand how forecasters internally process and externally communicate extreme rainfall events. Such frameworks include sensemaking, principles of forecasting, and judgement and decision-making.

2.3.1: Sensemaking

Sensemaking is described as the critical processes that people use to understand unfamiliar situations so that they can take the appropriate actions in those circumstances (Weick et al. 2005; Stigliani and Ravasi 2012; Tisch and Galbreath 2018). While many studies focus on individual sensemaking, these processes can also happen on a community level. When social groups communicate their understanding and decision making, it is called community sensegiving. While this does occur between decision makers and forecasters, there is more trust among peers (Tisch and Galbreath 2018). Different sensemaking processes at different levels can create a disconnect because sensemaking is not always rational and may not result in the same interpretation even in identical situations (Helms Mills and Weatherbee 2006). In fact, Helms Mills and Weatherbee (2006) used sensemaking to explain seemingly poor decisions made during Hurricane Juan by residents of Nova Scotia. Butterworth (2010) applied Weick et al.'s (2005) eight properties of sensemaking to broadcast meteorology. This work will build upon that to apply them further across the weather enterprise, namely NWS forecasters. These properties are organizing flux, noticing and bracketing, labeling, retrospect, presumption, social and systemic, action, and organizing through communication. Doswell (2004) also introduced representativeness as a sensemaking process.

Organizing flux: Organizing flux is the process of finding organization amid chaos and the overwhelming influx of information (Butterworth 2010). When forecasting extreme weather, NWS forecasters must be able to do this, as there is no possible way for them to analyze every piece of information they receive in the forecasting process (Daipha 2015; Graham et al. 2013; Hoffman et al. 2017).

Noticing and bracketing: Noticing and bracketing occurs when one identifies a departure from normal (Weick et al. 2005). NWS forecasters may note certain weather features that have led to large rainfall amounts in the past or a change in climatological patterns.

Labeling: Labeling "describes an event in a particular way" to link the current event to a familiar concept (Butterworth 2010). For example, a forecaster labeling an event as "catastrophic" may pique the attention of their partners and the public.

Retrospect: Forecasters may use past experience to make sense of the ambiguous environment, which can be referred to as retrospect (Butterworth 2010). For example, a forecaster may be less likely to ignore a model outlier if such an outlier had verified in a past event.

Presumption: Presumption is described by Weick et al. (2005, p. 12) as "to connect the abstract with the concrete". In meteorology, this is done when one can forecast how a storm will evolve and its potential impacts (Butterworth 2010). For example, forecasters may recognize that the "ingredients" for an extreme rainfall event are present, giving them more confidence in their forecast.

Social and systemic: Sensemaking can be impacted by social factors, such as organizational constraints (Weick et al. 2005). In the NWS, some forecasters may be hesitant to forecast extreme values due to the general guidelines established by the organization.

Action: The purpose of sensemaking is deciding what action, if any, should be taken (Butterworth 2010). In forecasting, this can be applied to when forecasters assess model output and whether or not they should adjust the forecast or leave it as is.

Organizing through communication: Sensemaking also occurs through communication with others (Butterworth 2010). This is a form of collective sensemaking in which discussions take place in order to come to a mutual understanding and agreement on a course of action (Stigliani and Ravasi 2012). NWS forecasters not only communicate within their office, but with other offices and their partners in media and emergency management to ensure that both the forecasters and users have a common understanding of an event.

Representativeness: Representativeness is better known in the forecasting world as "pattern recognition" where forecasters will make sense of an environment by classifying it among past similar situations (Doswell 2004).

2.3.2: Principles of forecasting

The book *Principles of Forecasting* (Armstrong 2001a) compiled a series of papers that discussed principles of forecasting that can be applied across various fields of study, such as economics, finance, psychology, and meteorology. The chapter "Standards & Practices for Forecasting" (Armstrong 2001b) summarized those papers, discussing 139 principles and sorting them into 16 categories. The description, purpose, conditions when the principle would not apply, and the strength and source of evidence for that principle are provided for each of the 139 principles. Armstrong (2001b) acknowledges that all 139 principles will never be used at once, but that the ones that are used are dependent on the situation. The principles that can be applied to this study have been sorted into three sections: forecast purpose, forecast presentation, and forecast uncertainty.

Forecast purpose: To produce a usable forecast, the forecaster needs to understand what decisions might be made based on the forecast, and what information is needed to make those decisions so that the forecast can be tailored to those needs (Armstrong 2001b). For example, NWS forecasters may present forecasts differently to different audiences depending on the needs of those audiences.

Forecast presentation: For forecasts to be useful, they must be presented in a simple, understandable, and meaningful way, such as presenting possible scenarios (Armstrong 2001b). For example, NWS forecasters often present more complex information to their expert partners than they are to the public.

Forecast uncertainty: Forecasts are inherently uncertain (Hoffman et al. 2017). When presenting the forecast, meteorologists must be careful not to imply false precision by including insignificant digits, be conservative when making changes to the forecast if uncertainty is high, and acknowledge why the forecast could be wrong (Armstrong 2001b). In weather forecasting, NWS meteorologists are better able to forecast a high-impact event when the uncertainty is low.

2.3.3: Judgement and decision-making

Decisions cannot always be rational (Daipha 2015). Studies on Judgement and Decision-Making (JDM) identify heuristics and biases that influence the choices people make when facing uncertainty (Millet et al. 2020). Heuristics are described as "mental shortcuts" that people take when making decisions (Millet et al. 2020; Milch et al. 2018) that could lead to biases that impact decision-making (Millet et al. 2020). Doswell (2004) was one of the first studies to apply heuristics to weather forecasting and emphasized the need for further work on the subject. Millet et al. (2020) suggested using JDM principles to adjust how forecast information is presented, which would in turn improve user decision making. The paper provides an extensive table of the various heuristics and biases they identified in their literature review. These frameworks are affect, anchoring and adjustment, availability bias, confirmation bias, finite pool of worry, gambler's fallacy, loss aversion, and temporal/spatial myopia.

Affect: Affect is the impact of emotions on decision-making based on past experiences (Millet at al. 2020). After an area has experienced an extreme event, residents may be more attentive to the potential for another event and make decisions based on their emotions rather than logic.

Anchoring and adjustment: Anchoring and adjustment happens when someone attaches themselves to an initial value and will incrementally adjust from that value as new information comes in, even if that original value may not have been reliable (Millet et al. 2020; Tversky and Kahneman 1974). This is similar to the forecasting process within the NWS. Forecasters will publish an initial forecast value and have the option to adjust that value as they process more information.

Availability bias: This bias occurs when one cannot think of or recall a similar event, so decides that the likelihood of the incoming event is low (Millet et al. 2020; Milch et al. 2018; Tversky and Kahneman 1974). To adjust for this bias in their end users, meteorologists must produce forecasts that either recall past events or paint an image in their audiences' minds of the potential impacts of the impending event.

Confirmation bias: Confirmation bias is when one will gravitate towards information that aligns with their existing conceptions or that poses the best possible outcome for them (Millet et al. 2020). Forecasters may have to convince an emergency manager that a hurricane is capable of producing impacts that the emergency manager has never seen before to work against their confirmation bias.

Finite pool of worry: When people are faced with many threats, they may not be able to process each one, and instead focus on just one or a few and ignore the others. This heuristic is called finite pool of worry (Millet et al. 2020). For example, during hurricanes, people might be so worried about the winds from the storm that they do not consider flooding so forecasters must be able to message which threat is most dangerous to those people.

Gambler's fallacy: Gambler's fallacy occurs when people feel that because they recently experienced a rare or extreme event, they cannot experience another in the near future because of the rarity of the event (Millet et al. 2020). For example, audiences struggle with return intervals, as they do not understand that a 100-year event does not mean it only happens every 100 years (Grounds et al. 2018).

Loss aversion: When being informed about an event, people are more likely to pay attention to what they could lose depending on the actions they do or do not take rather than what they could gain (Millet et al. 2020). Forecasters may be better off telling their audience what they could lose if they cross that flooded roadway rather than what they could gain by finding a better route.

Temporal/Spatial Myopia: When an event is far away either spatially or temporally, it is not uncommon for the threat associated with that event to be underestimated (Millet et al. 2020). For example, a forecaster may not be willing to publish a product for that event outside of a certain time frame, even with strong evidence that the event will occur as forecast.

Chapter Takeaways:

- While there is research on how end users process forecast information, less is known about how forecasters turn forecast information into products.

- Extreme rainfall events are projected to increase in frequency and intensity in the South Central U.S.
- Forecasters have a lot of information available to them, and how each forecaster interprets this information is different, creating a need for inter- and intra- office communication to ensure message consistency.
- Forecasters must be able to efficiently communicate forecast information to their partners and increasingly, the public.
- Uncertainty is inherent in forecasts and forecasters must find a way to communicate it.
- Social science theories including conceptual models, sensemaking, decision-making, and principles of forecasting can be applied to forecast and communication processes.

Chapter 3: Methodology

National Weather Service forecasters throughout the South Central United States participated in semi-structured phone interviews. During the interviews, the forecasters were asked to discuss their experiences with forecasting and communicating extreme rainfall events. Open-ended interview questions allowed the forecasters to highlight what they felt was most important (Herbst 1993) regarding the communication of extreme rainfall events while also allowing the researcher to guide the conversation to cover the topics of interest. Of the 24 relevant offices in the region (WFOs, River Forecast Centers (RFCs), and National Centers), seven offices were represented in this study (29%) and approximately 6% (21 of about 350) of forecasters in the region were interviewed. While these forecasters represented various roles, the sample size is small enough that results are not generalizable across the region. Instead, this study opens the door to a better understanding of the forecast and communication processes in NWS offices during extreme rainfall events.

3.1 Participant and event selection

This research focused on extreme rainfall events in the area of responsibility of SCIPP, which consists of Oklahoma, Texas, Arkansas, and Louisiana. For this project, extreme rainfall events in the SCIPP region were defined as events that were analyzed by the NWS's Hydrometeorological Designs Studies Center (HDSC) and had an Annual Exceedance Probability (AEP) of less than 1/500 (HDSC 2021). These analyses compared precipitation frequency estimates from NOAA Atlas 14 to the amount of rain that fell over a given time period (HDSC, 2021). NOAA Atlas 14 is a database of precipitation frequency estimates throughout the United States over various time periods and recurrence intervals (Perica et al. 2013). By comparing event precipitation amounts to the precipitation frequency estimate for the appropriate time period and location, event AEPS's were calculated and mapped (Fig. 3.1). These criteria for the analyzed events provided a consistent database of events to analyze. Nine extreme rainfall events occurred in the SCIPP region between 2015 and 2021 that fit the criteria (Table 3.1).

The nine events occurred on time scales ranging from hours to months over various spatial scales. The first event identified was the excessive rainfall that occurred over much of Oklahoma in the spring of 2015. Next was the Memorial Day 2015 event in central Texas that caused devastating flooding in many places, including the Blanco River. Texas again saw

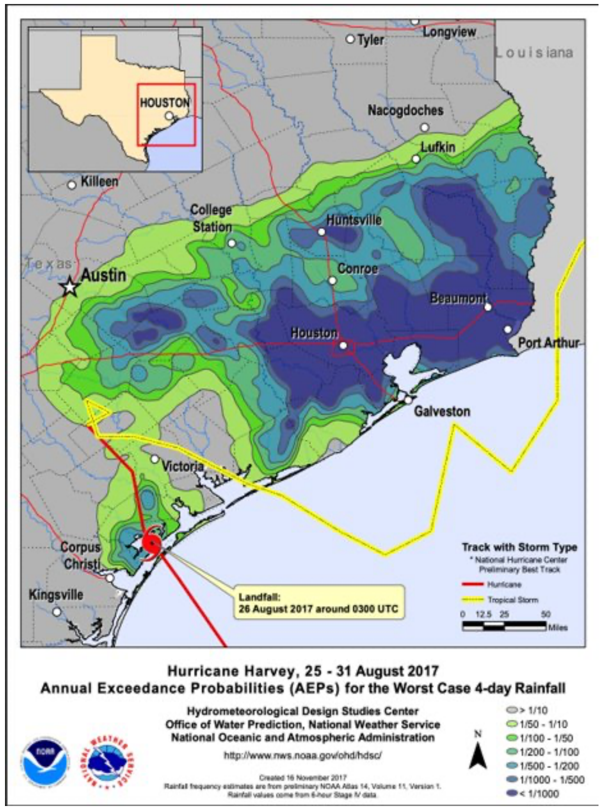


Figure 3.1: Annual Exceedance Probability (AEP) analysis by the NWS's Hydrometeorological Designs Study Center for Hurricane Harvey. (Source: HDSC 2017)

extreme rainfall later that year in October. In March 2016 extreme rainfall caused flooding across northern Louisiana. In August 2016 southern Louisiana was devastated by flooding due to extreme rainfall. There was also the record-smashing rainfall associated with Hurricane Harvey in southeast Texas in 2017. Similar to 2015, flooding in Oklahoma and Arkansas occurred during spring 2019. Also in 2019, while Hurricane Barry did not produce as much rainfall as it was expected to in Louisiana, its remnants did produce large amounts of rain by the time it reached Arkansas. Finally, Tropical Storm Imelda was another prolific rainfall producer in southeast Texas.

Prior to the beginning of the study, the methodology, including the interview questions, was approved by the University of Oklahoma Institutional Review Board (IRB, study #11608). To protect the identities of the participants in accordance with IRB guidelines, for the remainder of the thesis, if a forecaster refers to the event by name in a response, the event name will be substituted with [event]. The exact event the forecaster is referring to in the response is not relevant to the results of this study.

Once the events were identified, a SCIPP researcher[1] obtained approval from NWS headquarters to conduct this study. Then, the researcher determined the NWS WFO(s) that were responsible for forecasting each event. A recruitment email was then sent to the Meteorologist in Charge (MIC) of each office asking for participation and to pass the email on to any forecaster that might be interested. If there was no response, a follow-up email was sent. In some cases, a participant would identify another forecaster that would potentially participate and assist the researcher with getting in contact with that person, creating a snowball effect. Because of this snowball effect, it is difficult to tell exactly how many forecasters received the recruitment email, but the researchers were in direct contact with 28 potential participants. In total, 21NWS forecasters from seven WFOs, RFCs, and national centers were interviewed.

Date	Location	Type	Rainfall Period	Min. AEP	Max Precip. (in)
April-June 2015	OK	Persistent, anomalously wet period	20, 30, 60 day	<1/1000	40.95
May 23-24 2015	Central TX	Convective	6hr	<1/500	12.32
October 24-25, 30 2015	TX	Convective	3, 6, 24hr	<1/500	22.22. 18.03
March 8-12 2016	North LA	Atmospheric River	48hr	<1/1000	24.58
August 11-13 2016	South LA	Tropical moisture	48hr	<1/1000	27.60
August 25-31 2017	Southeast TX	Tropical system (Harvey)	4 day	<1/1000	49.31
April-May 2019	Northern OK	Persistent, anomalously wet period	30 day	<1/1000	24.84
July 15-16 2019	Southwest AR	Tropical system (Barry)	24hr	<1/1000	16.17
September 16-20 2019	Southeast TX	Tropical system (Imelda)	12, 24, 48 hr	<1/1000	32.11

Table 3.1: Table of events included in the study. Includes dates, location, a short description of the type of event, the time period and AEP from the HDSC analysis (HDSC 2021), and the maximum precipitation at a point in the event (Eggleston 2021).

[1] This work was started in 2018 by another researcher and was briefly paused. It was continued and completed in 2019 by the author of this thesis.

The forecasters interviewed held various positions across their offices, with seven participants in meteorologist positions and 14 in management roles. All participants had at least 10 years of experience working in the weather enterprise, including the armed forces, private sector, academia, or the media before working with the NWS. The participants had an average of about 22 years of experience with the NWS. Three participants were female and eighteen were male, which as of 2014, was a ratio representative of NWS meteorologist demographics (Sheffield 2015).

3.2 Interview protocol

This study addressed the questions: How do forecasters internally process model outliers? How do forecasters externally communicate model outliers and outlier events? And do forecasters consider climate change when forecasting extreme rainfall events? In order to address these issues, the researcher developed an interview protocol of open-ended questions. The forecasters were first asked four demographic questions about their forecasting experience. The forecasters were then asked about their involvement in forecasting the event(s) in question. Thirteen questions were tailored to the event(s) that was (were) relevant to each participant. These questions addressed model output, how the event compared to the participant's experience with a prior event(s), confidence leading up to the event(s) and factors that impacted confidence, and how they worked with partners. Five questions addressed forecasting and communicating extreme rainfall events in general, such as how uncertainty information should be conveyed to public audiences, what they want the public to understand about these events, and the importance of using social media to convey forecast information. The forecasters were asked if they thought that extreme rainfall events were increasing in frequency and/or intensity. If the forecaster brought up climate change, they were asked if the background state of climate change had any influence on their real-time forecasts. These questions were general and were asked in most interviews.

The remaining questions were tailored to specific events. The author of this thesis investigated each of the identified events. Relevant social media graphics and text products were identified to get a better meteorological understanding of each event. Based on these products and the knowledge of the event, more specific interview questions were developed. These questions asked forecasters about the processes of issuing such products. For example, forecasters were asked about language choice and how rainfall amounts were expressed. Fig. 3.2

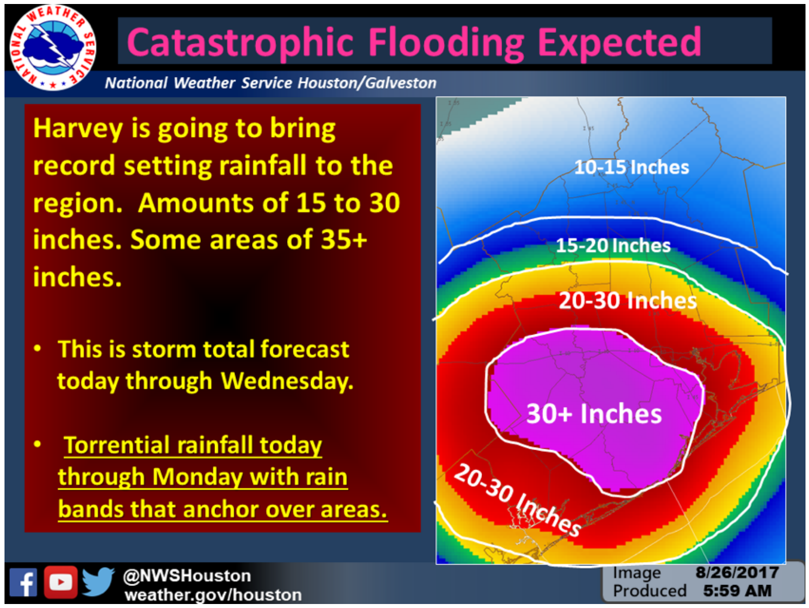


Figure 3.2: Product issued on social media by NWS Houston in preparation for Hurricane Harvey. Such products were used to guide interview questions (US NWS Houston 2017).

is an example of a product used in an interview question. The complete interview protocol can be found in Appendix A.

3.3 Data collection

This project began in spring 2018 when seven interviews were conducted between March and June by a SCIPP researcher. It was then paused until fall 2019 when more attention could be dedicated to the project. The interview protocol was revised and the remaining recruitment and interviews were conducted by the author of this thesis between March and August 2020. While some interviews were conducted up to four years after the event in question, the events were so significant that the forecasters were able to recall the events in vivid detail. By the final interviews, answers to several of the questions were no longer unique, meaning that the sample was saturated.

Once the participant responded to the recruitment email, they were sent further information, including a copy of the interview questions and an IRB consent form to be signed and returned prior to the interview. Then, a time was set up for the interview. The forecaster was told they did not have to look over the questions before the interview, but each one did. The participants were informed that their responses would be anonymized.

While the interviews were intended to be individual phone interviews, one forecaster opted to instead type their answers into the previously provided interview guide (beyond the control of the researcher) and one office suggested a video conference interview between the researcher and three forecasters, allowing the forecasters to feed off of each other's views of the events that transpired. Remote interviews not only allowed forecasters to participate in an environment that was familiar and comfortable to them (Taylor et al. 2016) but also allowed this project to continue uninterrupted by the COVID-19 pandemic. The interviews often started and/or ended with sidebars on various topics such as the weather or working from home, and these would also occasionally occur during the interview. The interviews were recorded using a digital audio recorder and lasted about an hour (M= 56 minutes).

3.4 Data analysis

All interviews were transcribed verbatim by the author of this thesis into Microsoft Word. Once all interviews were transcribed, the responses were organized by interview question in Microsoft Excel to allow for comparison across interviews. Responses were then qualitatively analyzed using deductive reasoning, meaning existing social science theories were applied to the data (Braun and Clarke 2006). The conceptual frameworks of *sensemaking,* the *principles of forecasting*, and *judgement and decision-making* were applied to the responses. A list of relevant responses that applied to each framework component was created that included a small explanation of why the researcher classified the response in that way. The conceptual frameworks were then assembled into a simple forecasting process model. The model and concepts will be discussed in depth in the following chapter.

<u>Chapter takeaways:</u>

- Nine extreme rainfall events in the SCIPP region were identified between 2015 and 2019.
- 21 NWS forecasters were interviewed about those events in semi-structured phone interviews in 2018 and 2020.
- Questions addressed participant demographics, model output, extreme rainfall event experience, confidence in the event(s), forecast communication, uncertainty information related to these events, and how forecasters perceived the events in relation to climate change.
- Data were then qualitatively analyzed using deductive reasoning.

Chapter 4: Results

How forecasters internally process and externally communicate extreme rainfall events can be organized into a model similar to those in Lejano et al. (2016) (Fig. 2.1) and Hoffman et al. (2017) (Fig. 2.2). From the macro scope of Lejano et al. (2016), Figure 4.1 illustrates the movement of information from the source (data) to the organization, in this case, the NWS, where it is translated (intra-organizational processes) by the forecasters into information that can be distributed to the receiver (forecast presentation). Adding more detail, the Hoffman et al. (2017) Base Model of expertise starts the process with identifying the “problem of the day” (forecast purpose), then examining data and going through sensemaking processes to make judgements and taking a “course of action” (forecast presentation). Sensemaking and decision-making processes not only apply to forecasting an event, but they also consider the sensemaking and decision-making processes that their audiences will go through, impacting how the forecast is presented. Forecast uncertainty will always be present (Hoffman et al. 2017), is identified in the intra-organizational processes, and impacts how the forecast is presented. This chapter will discuss how the forecasters’ responses align with these models and frameworks. Forecaster identifiers have been removed to maintain participant anonymity and will be referred to by their interviewee numbers (I1, I2, I3, etc.). Extreme rainfall events will be referred to as [event].

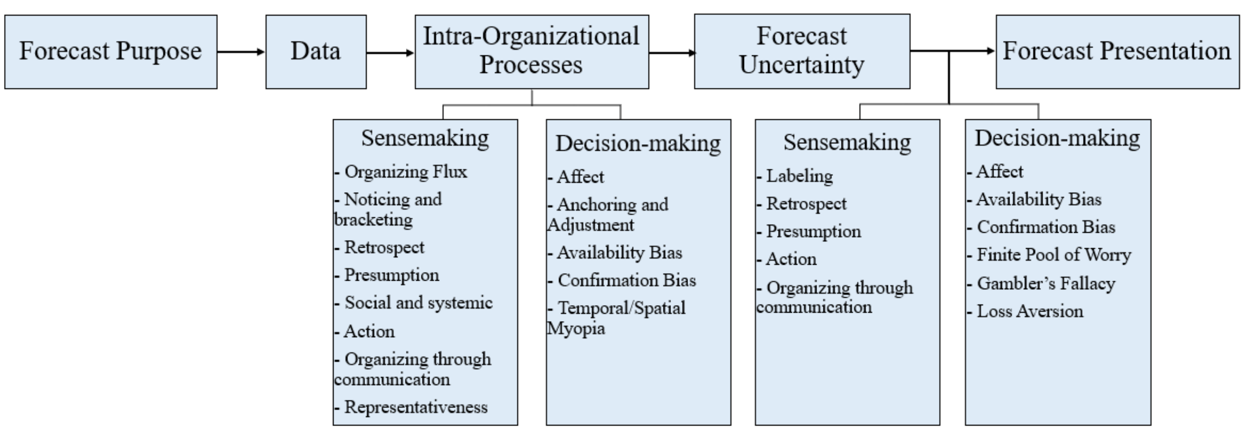
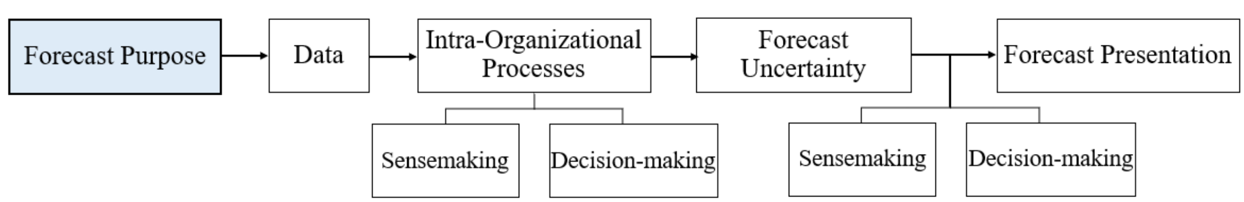


Figure 4.1: A simple forecasting process model that applies sensemaking, decision-making, and principles of forecasting to the extreme rainfall forecast and communication process

4.1 Forecast purpose

Whether it is a “quiet” weather day or an extreme event is imminent, the forecaster must be aware of the true purpose of the forecast they are publishing as they start the forecast process (Fig. 4.2). Forecasters think about what decisions will be made with that forecast and what is needed to make those decisions (Armstrong 2001b). Forecasters talked about the importance of knowing partner thresholds and limits when forecasting an event: “if it takes them [emergency management] three hours to move high water vehicles or to move boats, that helps us better understand if we’re seeing the trends changing within that three-hour time frame, we can give them a heads up” (I16). Occasionally, partners will ask for specific information to be included in a briefing ahead of time (I9). This helps the forecasters narrow down what physical features they need to focus on, as “it’s [the forecast] gotta have a firm foundation in science.” (I14). With the media and the public, the information needed may not be as specific. Forecasters stated that the media “probably would like to know a maximum amount and so forth because that does play well to many viewers” (I4). They also shared that the media had told them that they won’t present probabilistic information on air, as “It kind of gets over the heads of the public and they only have so much time allotted to them” (I6). One forecaster said that they try and keep public forecasts as simple as possible while still making them aware of a potential threat because the public doesn’t “have all the decisions that an EM does. They’re not having to make these large-scale early decisions for a lot of people. Generally, the public wants to know ‘what’s going to happen to me?’” (I18). With the purpose of the forecast in mind, forecasters can begin to process the data in front of them.



“if it takes them (emergency management) three hours to move high water vehicles or to move boats, that helps us better understand if we’re seeing trends changing within that three-hour time frame, we can give them a heads up” (I16)

Figure 4.2: The simple forecasting process model, focusing on where the purpose of the forecast fits in, along with an example quote from a participant

4.2 Intra-organizational processes: sensemaking

With the awareness of the purpose of their forecasts, sensemaking processes help NWS meteorologists interpret the various data sources available to them. These sensemaking processes (Weick et al. 2005) include *organizing flux*, *noticing and bracketing*, *retrospect, presumption, social and systemic, organizing through communication, representativeness* (Doswell 2004), and *action*.

4.2.1: Organizing flux

Every day, forecasters have access to more data than they can possibly assess and must determine what is most important to look at and determine which data are most important (Daipha 2015). Forecasters identify organization in the chaos of data overload, or organize flux (Butterworth 2010). When forecasters see multiple models over multiple runs pointing to a high-impact rain event over a large area, they know that outcome is likely not wrong (I3). When the forecasters recognize that the models are pointing to a high-impact rain event, they ask themselves: "'can I debunk what's happening in the model?' If you can't debunk what's happening in the model and write it off to real reasons then you're like 'well, now I am proving why the model is right'" (I7). The forecaster can also start to ask themselves about the potential impacts they need to be concerned with if the event does occur for their area (I4). Forecasters can then work to answer those questions and investigate model output by analyzing specific products, such as I4 looking to specific parameters such as precipitable water, I7 determining what forcing mechanisms will play a role, or even I15 analyzing satellite images (for near-term forecasts). By organizing flux, forecasters can avoid being overwhelmed with information and can focus their attention on the task at hand.

4.2.2 Noticing and bracketing:

Part of the forecasting process, especially with high-impact events, is noting any departures from normal. By noting these differences, forecasters can begin making sense of the situation. For example, when a model produces a precipitation value that is greater than any of the others, the forecasters will take note. To some forecasters, it is an indication that "someone is going to get it" (I4). To others (n=9, 43%), the outlier can be considered the extreme maximum amount possible (I13). Some forecasters (n=5, 24%) felt that outliers were "like a drop in the bucket, I wouldn't put much stock in it" (I3). However, most forecasters (n=15, 71%) agreed that an eye should be kept on that model outlier to see how other models and subsequent model runs behave, as they know just one model with that outcome could be wrong, but if “other models start trending towards their solution, then we feel like they may have picked up on something” (I6).

Forecasters not only use noticing and bracketing sensemaking processes in the short term but the long term as well. Some forecasters stated they noticed increasing frequency and/or intensity in extreme rainfall events. I13 noted that they “get these locally 1000-year frequency events, probably three or four times a year in our forecast area” and I8 observed that “amounts these days are a little higher than they were a decade ago”. However, when asked if that knowledge impacted how they handle major rainfall events, all forecasters said that is not something they consider leading up to or during the event as “it’s not attributed for a single event” (I7). This will be further discussed in later sections.

4.2.3 Retrospect:

Retrospect is the sensemaking process that relies on past experience (Butterworth 2010). Based on previous events, forecasters can go into a potential extreme rainfall event knowing the nuances of different tools, such as a model being “a bit biased on the wet side” (I2) and adjusting accordingly. They can also identify tools that have not been used in the past that will help them make sense of the unfolding situation: “I think getting more experience with tools like that now, it would help us for an [event]-like situation” (I17). Experience with extreme rainfall events in the past also makes forecasters less likely to ignore model outliers: “The forecasters here get exposed to these events. I think what they bring to the table is they don’t ignore the outlier. They do consider it can happen” (I1). Seeing extreme rainfall events occur has opened forecasters’ minds to what used to seem impossible, as I12 put it: “Early in my career: ‘oh, that’ll never happen’ but this is [Gulf Coast state], it happens”. I12 also discussed that forecasters “try to learn from every one [event]” and will “go back and do more model calibration, [if] our models didn’t handle it right” so that they are better able to understand the next event. While past experience does guide forecaster sensemaking, forecasters also noted that each event is unique and that they approach each event differently (I5).

4.2.4 Presumption:

Presumption is a basic sensemaking concept in the forecasting process, as forecasters are tasked with predicting how the situation will unfold and identifying the potential associated impacts. For example, I2 recalled deciding to increase the quantitative precipitation forecast

(QPF) to an extreme value because of the rainfall amounts they were seeing and how they thought the storm was going to evolve. Forecasters are also able to connect certain ingredients to extreme rainfall such as: “is it because it’s predicting the whole system to slow down? Are we gonna be in a much more favorable area for more training? Is it predicting more convection?” (I10). Forecasters are also aware of factors that will worsen impacts: “We knew that we, with the antecedent conditions leading up to this, (the soil was) pretty much saturated and it wasn’t gonna take much to produce high-impact flooding” (I6). However, to most accurately predict how a situation will evolve, sufficient observations are vital. I7 described: “we didn’t have any stream gauges upstream of [riverside town] at all at that time.” Without upstream gauges, they had no way of knowing what to expect outside of reports from local residents. This lack of upstream river stage observations significantly hindered their forecasting ability in that event.

Like noticing and bracketing, forecasters also use presumption when considering extreme rainfall events in the context of climatology and how that climatology is changing. Forecasters connect the predicted increase in frequency and intensity of these events as well as their impacts to what they know to be true, which could be as straightforward as “human activities resulting in increased greenhouse gasses resulting in extra moisture capacity of a warming planet. Also, humans increasing imperviousness of land as well with accordingly more runoff” (I11). Other forecasters took a deeper dive to prove to themselves that these events are increasing: “I’m digging into this because I want to prove to myself, is there something to this? And I’m pretty convinced there is something to this.” (I2). There were also forecasters who felt that the events may not be increasing, but the impacts are worsening due to human development: “The other component of the story is that man is tending to build in areas that are subject to impacts that can be rather dramatic. In other words, what I’m trying to say is, people are building in floodplains.” (I14). While what the forecasters think are causing these events to worsen are different, they are still connecting that trend to what they see as concrete evidence, which fits the presumption sensemaking concept.

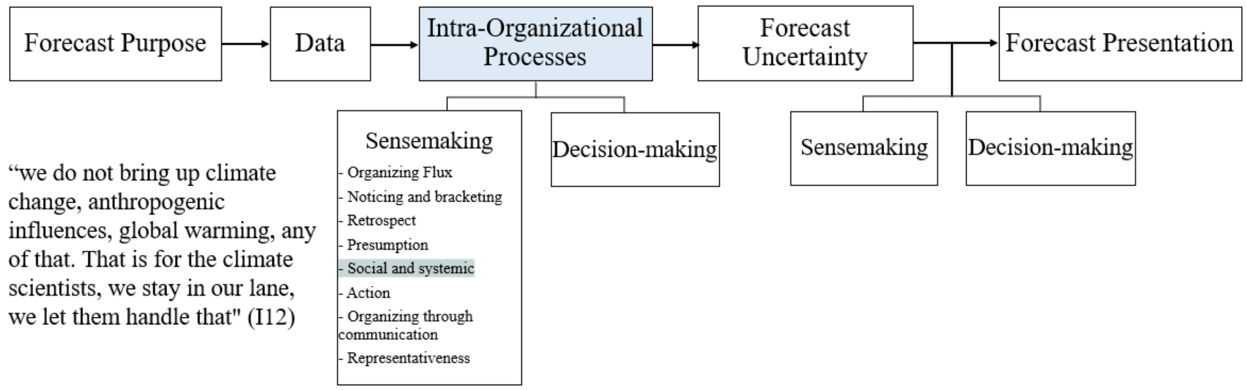


Figure 4.3: As in Fig. 4.2 except focusing on where the sensemaking concept "social and systemic" fits in to the intra-organizational processes step of forecasting and communication.

4.2.5 Social and systemic:

Sensemaking can also be impacted by organizational constraints and other social factors (Weick et al. 2005). For example, forecasters do not think about the possible impacts of climate change when forecasting an event partially because they feel it is not their place: "we do not bring up climate change, anthropogenic influences, global warming, any of that. That is for the climate scientists, we stay in our lane, we let them handle that" (I12). Other forecasters said that linking the events to climate change is just outside of the time and space scale for which they are responsible (I13). Because forecasters have a definitive role of forecasting in the shorter term, they do not think about an event potentially being linked to climate change leading up to or during the event. However, they may think about climate change may be something they think about after the event when retrospectively thinking of the multiple 500-year events their area experienced in short succession (I14). Even then, forecasters are hesitant to focus on climate change in relation to these events as they feel that it is beyond the scope of their duties.

4.2.6 Organizing through communication:

NWS forecasters are not alone when trying to make sense of an event but will work with others both in their office and in other offices to determine what is going on. I20 described looking at a co-worker as they both realized "this is going over the top, this is becoming… the entire entity of everything is becoming something we haven't dealt with before". This realization lead them to the decision that the first flood warning in twenty years for a major river in their area was necessary. WFOs participate in multi-office "conference calls where [national center] takes the lead on it and then each individual office provides input and we basically come to an agreement on amounts near our borders with neighboring offices" (I9). These calls also help the forecaster to see that other offices see what they see: "[Neighbor office] was noticing the same thing, [national center] was obviously coming up with the same thing, all of these independent sources, we were all arriving at the same conclusion and all of that really gives higher confidence" (I10). Through communication with others, both in their office and other offices, forecasters can make better sense of an event.

4.2.7 Representativeness:

The sensemaking framework of representativeness is what NWS forecasters refer to as pattern recognition (Doswell 2004). When forecasters see a meteorological setup that is familiar to them, pattern recognition helps them figure out how the new event might unfold. For example, representativeness can help a forecaster catch an event that the models may not be picking up: "you get used to seeing patterns… you get a feel for everything may not be showing up in the models but 'I've seen this before and there's still something we gotta pay attention to'" (I15). Some forecasters recognize specific characteristics of a storm, such as slow movement or a lot of moisture, that could cause significant impacts somewhere in their area (I4). By recognizing patterns that tend to cause these issues, forecasters are better able to make sense of an impending event.

4.2.8 Action:

The goal of sensemaking is to answer the questions "What is going on here" and then "What do I do next?" (Weick et al. 2005, p. 412). For example, forecasters are tasked with analyzing model output, which continues to improve, and "knowing when to basically say we can't get any better than this and also knowing when we can say we can be better than this" (I2). Forecasters may use any of the above frameworks to distinguish between model output that needs improvement and that which does not. The actions that forecasters take as a result of these frameworks will be further discussed in the following sections.

4.3 Intra-organizational processes: judgement and decision-making

When working an event, forecasters are likely influenced by unconscious heuristics and biases that will influence their decision-making (Millet et al. 2020). These include *affect, anchoring and adjustment, availability bias, confirmation bias,* and *temporal/spatial myopia.*

4.3.1 Affect:

While experience with extreme events expands forecaster knowledge of such events, these events also take an emotional toll on the forecasters as they see the impacts unfold where they live (Smith 2020). This emotional toll can impact decision making, even for these highly-trained professionals. This heuristic is called affect (Millet et al. 2020). An example of affect that impacts forecasting and communication is one office's experience with two similar events. The first event devastated the area it hit, flooding thousands of homes. A few years later, another event looked like it was going to have similar impacts event so the office "put out a contingency forecast for the rivers and we actually put out flood warnings. It was based on getting X inches of rainfall and that would have had a lot of people flooding that did in [event] as well. And what do you know, we didn't get but 2-3 inches of rainfall. It was a bust" (I13). Issuing such products before the rain has fallen is not often done in the NWS. It is entirely possible that the office responsible would not have issued those forecasts if the first event had not had such a significant societal impact on the region, including for families of forecasters.

4.3.2 Anchoring and adjustment:

Anchoring and adjustment happen when one attaches themselves to an initial value and incrementally adjusts as new evidence comes in, even if the original value was not reliable (Millet et al. 2020). The NWS forecasting process works essentially the same way. Forecasters will publish an initial forecast and incrementally nudge that forecast based on the evolving evidence. For example, I8 described how their office adjusted their forecast as the event developed: "we under-forecasted the precip. totals initially but I think when we were in the heat

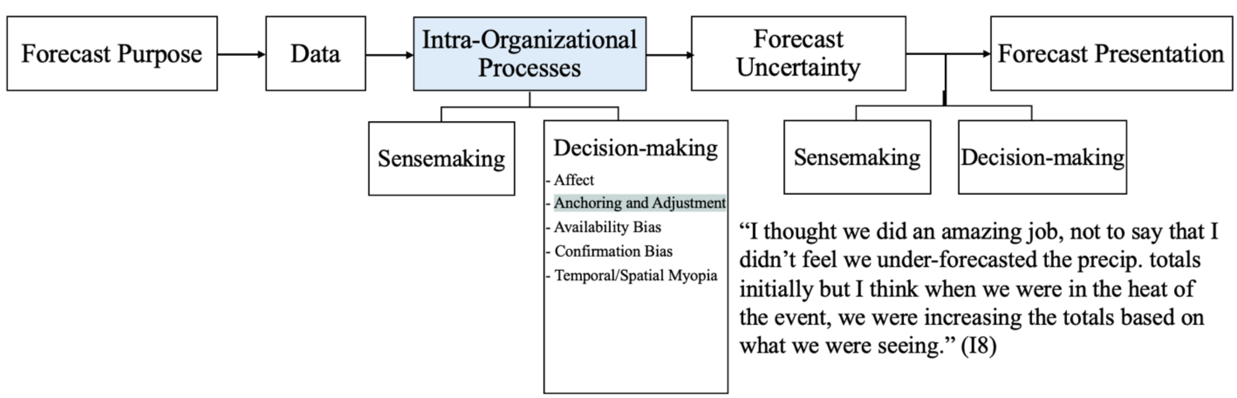


Figure 4.4: As in Fig. 4.2 except focusing on where the decision-making concept "anchoring and adjustment" fits in to the intra-organizational processes step of forecasting and communication

of the event, we were increasing the totals based on what we were seeing." While this heuristic is not necessarily within the control of the forecaster, it does influence how forecasts evolve with time.

4.3.3 Availability bias:

Availability bias (Millet et al. 2020) is when someone cannot picture an event in their head, they are less likely to believe that it is possible. For example, based on experience in the area, one forecaster felt confident going into a significant event: "having grown up in this area and forecasting for this area for so long… I know we can get these [amount] rainfall bullseyes during May, especially during Memorial Day" (I6). While NWS forecasters periodically come across significant events across their careers, there are some events that are so extreme, that the forecaster themselves can barely believe what is happening. If models are predicting an amount of rain early on that seems extreme, forecasters may be wary about communicating that extreme value to their audiences: "We weren't advertising X+ inches at that point yet…. 'hey, it's kind of far out to go all the way in, I think, given we haven't experienced it before'" (I18).

4.3.4 Confirmation bias:

Confirmation bias occurs when one seeks out information that aligns with their beliefs or the best possible outcome (Millet et al. 2020). I14 described that for some forecasters it may be "hard to recognize sometimes, some of these exceptional events because we tend to be in our own comfort zone." They also emphasized the importance of being open to such an event: "I mean, be adaptable and you have to really listen to what the evidence here is trying to tell you. You'll have to use certain tools, techniques, etc. that you wouldn't necessarily use all the time". If a forecaster is hesitant to put out a forecast that pushes them out of their comfort zone, that could result in negative consequences if the event did end up unfolding in an extreme way.

4.3.5 Temporal/spatial myopia:

When a risk is underestimated or actions are not taken because the threat is far away temporally or spatially, that can cause temporal/spatial myopia (Millet et al. 2020). For example, I8 described a high-confidence event where they had to urge another forecaster to issue a watch outside of the normal timeframe. The forecaster was hesitant to do so because typically, that product would not be issued that far in advance. I8 was adamant that they had to "issue the watch now and give people adequate time to prepare and have that message sink in". Forecasters understand the importance of lead time. However, it is difficult to have precision with confidence far ahead of an event: "It would be difficult to say well ahead of time that this subdivision or this town is going to see property damage with homes being underwater and that obviously is an incredibly difficult thing to forecast out in advance" (I21). Like anchoring and adjustment, temporal/spatial myopia is a heuristic that is not necessarily within the control of the forecaster.

4.4 Forecast uncertainty

In the inter-organizational processes of sensemaking and decision-making, forecasters encounter something that is inherent in weather forecasting and complicates forecast presentation: forecast uncertainty (Hoffman et al. 2017). This uncertainty is always present, and forecasters must know when to discuss an event despite the uncertainty as well as message that uncertainty to their audiences.

One example of forecast uncertainty is model consistency, "based on how the models are acting, you can convey your confidence levels. Consistency equals confidence. If they are bouncing around, you can message that you aren't as confident" (I19). "When there's better model consistency leading up to the event, we're able to use stronger wording" (I21). Having increased confidence in an event allows forecasters to start messaging an event to their audiences. I5 recalled saying to their partners: "we're a week out but we've had a lot of rainfall this [month]. The models are beginning to come into agreement, that there could be another heavy rainfall event developing. Please stay tuned everyday as we get more confident." And that the confidence given by model consistency "really helped us to get the message out early that we did [have a] fair degree of high confidence that it was going to be another heavy rainfall event." Two-thirds of the forecasters (n=14, 67%) mentioned that increased confidence allows them to talk about high amounts and significant impacts earlier on.

Not only does confidence in a forecast allow for a longer lead time, it also helps forecasters discuss the potential for an extreme event. Forecasters "would not forecast an extreme amount like that unless there was a lot of model consistency, a lot of agreement among the models and we actually had very high confidence." (I10). On the other hand, a lack of model consistency decreases confidence in an event: "occasionally they'd have a big signal but it would be in the wrong spot and it would be very inconsistent run to run compared to [first event], [second event] was much more uncertain than with [first event]" (I17). However, if an event appears it could be significant, forecasters may generally brief the possibility so that their audiences can be aware, despite the lack of confidence, “that it wasn’t going to take a lot of rainfall to start getting high-impact issues. We used that wording in our email. That’s what we tried to message, even despite seeing in the models, the inconsistency from run to run” (I6). By starting with a general message, the forecasters can then start to add details to the forecast as the event gets closer. At first they are: “very general and give an overview and as the event gets closer then you can zone in on specific impacts, specific amounts that way. We have to adjust our messaging depending on how much lead time we have" (I12).

Even as the event begins, forecasts are still uncertain. Expressing the uncertainty in the forecast is something forecasters know they must do but are not sure how to best do so: “I definitely think that we should try to convey a level of confidence in particular events… how we do that I know is still up for debate on exactly what terms to use: 'likely', 'expected'” (I9). I10 discussed the issues of creating standardized language to express uncertainty: “uncertainty- is very subjective to the forecaster, you could talk to 50 forecasters and probably get 50 different answers on their level of certainty on any event.” I7 noted that expressing probabilities of exceedance can be difficult as those levels may not be entirely accurate. They expressed that NOAA Atlas[2], values may drastically change in places, and expressing those values may not be entirely accurate. While it is difficult to express uncertainty, forecasters cannot imply precision that they do not have. When asked about a forecast graphic that showed rainfall amounts to the hundredth of an inch I18 said that displaying the values that way was "a function of it being quick and easy when you have a lot of workload” but that, “if you go to the hundreds or the tenths that implies an accuracy you don't have. So, definitely when those amounts get up there in the 10s of inches you want to be talking in ranges."

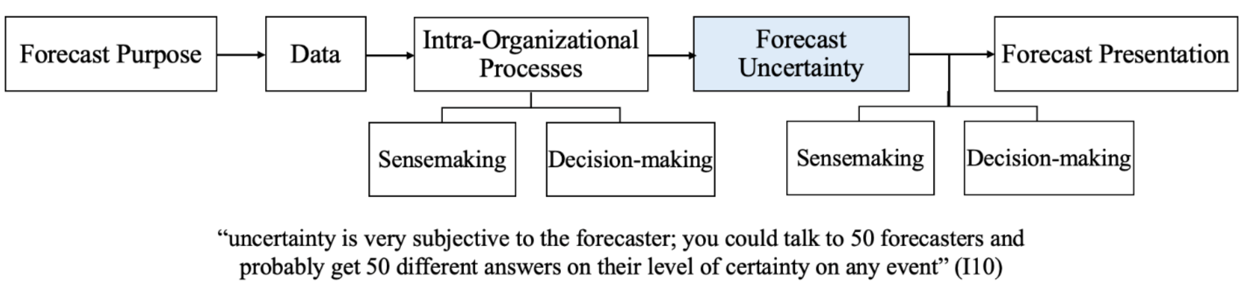


Figure 4.5: As in Fig. 4.2 except focusing on where forecast uncertainty fits in to forecasting and communication processes.

[2] NOAA Atlas 14 is a precipitation frequency estimate database for the United States over various time periods and recurrence intervals (See Chapter 3, Section 1)

Forecasters do not all agree on how uncertainty should be conveyed: “each office is different, each shift in each office can be different depending on the dynamic on the shift and experience and what’s going on” (I20). Forecasters I8, I9, I10, I13, I16, I18, and I20 all stated that they prefer to use ranges of possible rainfall amounts to quantify uncertainty. One forecaster said they must ask themselves: “Are we good enough to give a single point forecast? But, when you have an [event] and you’re not quite sure exactly where it’s gonna set up until you’re in the event I think ranges are the way to go" (I8). I16 preferred ranges because "doing a pinpoint forecast like that tends to kind of handcuff you.” Nine forecasters (43%) discussed adding verbiage like "locally higher amounts" to their ranges and even specifying what those amounts could be. I20 felt it is better to describe it as: "’we expect 3 to 5 inches but there will be local amounts to 9 inches or local amounts of 9 inches are likely.’ instead of just saying ‘locally heavier’ or ‘We could see some 9-inch amounts’” (I20). Nine forecasters (43%) suggested the use of confidence levels, using words like “likely” or “expected”. Three forecasters (14%) said that they would prefer to stay away from the word uncertainty altogether, “I've noticed over my career whenever you talk about the forecast is uncertain, I feel like there is a large part of the population that looks at that as 'they're just flipping a coin' or 'they don't really know.'” (I15). They felt that it would be better to “at least be able to give them the spectrum of how bad it could be, I think is better than just messaging there's uncertainty", especially since they felt that audiences only focus on whether or not the event actually happens. Two (9.5%) forecasters discussed using probabilities of exceedance of a certain return interval while others (n=4, 19%) pointed out that return intervals are not always accurate and are changing. No uniform way to express uncertainty could cause consistency issues on the organizational level.

Not only does the expression of uncertainty vary between forecasters, but how it is expressed varies by the audience it is being presented to. Five (24%) forecasters said that they prefer to not express uncertainty to the public at all: "I don’t (express uncertainty), and I have not seen our office people use probabilities in our public-facing forecasts. Kind of internally talked about it and had a debate about it" (I6). Overall, the information that goes to the public is more general: "we went more away from showing deterministic values in a public forecast and going more towards here’s higher rainfall and here’s lower rainfall" (I7). However, forecasters can give more complicated information to their sophisticated partners and it has been increasingly common to "brief on two things: our expected forecast, so whatever range or deterministic value, our actual expected forecast, and then we go kind of a little bit farther and we say 'But, here is a reasonable worst-case scenario'" (I10).

Forecasters did have suggestions to improve uncertainty communication. For example, I7 suggested creating a program that would display "the range of possibilities for your point and day" based on the type of event they were expecting. However, they also recognized that the technology to run those kinds of models in short amounts of time does not yet exist. A few forecasters discussed the importance of educating their audiences on interpreting uncertainty information. I13 said that "once a year our WCM (Warning Coordination Meteorologist) was going around and doing a Weather 101 for emergency managers so they understand uncertainty and understand the best way to get stuff from us." Such campaigns can ensure that audiences better understand what the NWS is trying to message.

4.5 Forecast production: sensemaking

Once forecasters have a handle on the situation, including the uncertainty, they can think about how exactly they want to message the forecast. When they do so, they think about the sensemaking processes their audiences will go through when they receive this information. These processes include *labeling, retrospect, presumption, action,* and *organizing through communication*.

4.5.1 Labeling:

Labeling connects the event to a word or phrase that will be familiar to the audience (Butterworth 2010). For example, assigning an event to a certain category changes how the event is seen by audiences, such as when the National Hurricane Center (NHC) names a storm. "People paid more attention to Harvey and Imelda because they actually had a name tied to them versus this no-name event... It really did catch people off guard" (I16). I16 also theorized that was the reason that Imelda got named. Forecasters will also use specific words to catch the attention of their audiences. I1 discussed making the decision to use the word "catastrophic": "(we) had to do something, so that's what we did. And it did go viral; I think thankfully it went viral... and also, I think really mobilized the national media and brought attention to the disaster unfolding." I17 discussed adding uncertainty quantifiers to the labels: "I think it's that headline… for example, 'catastrophic flooding expected' the word 'expected' there is a confidence indicator or, 'the

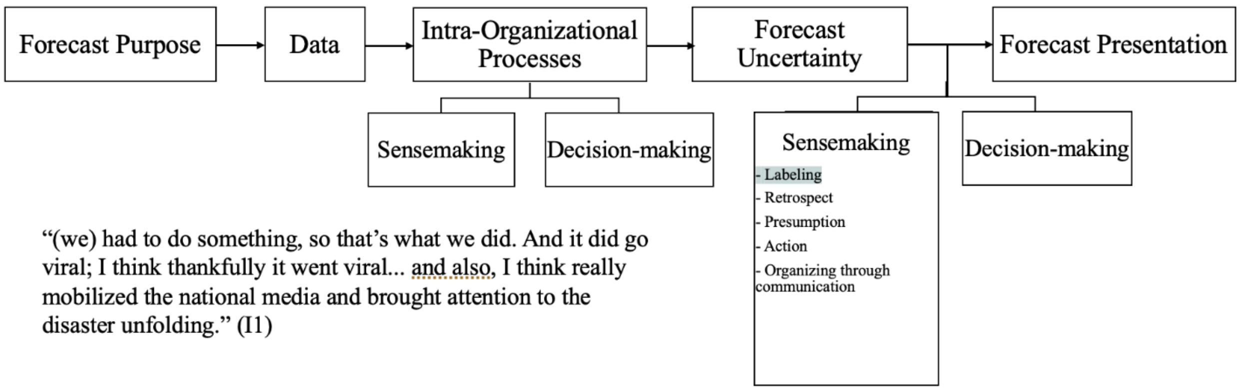


Figure 4.6: As in Fig. 4.2 except focusing on "labeling" and where sensemaking fits in to the step of the forecasting and communication process where forecasters consider the processes their audiences will use.

potential for' you're trying to communicate kind of the headline and that usually gets carried through the media" (I17). However, in order to maintain trust with the audience, it is important to avoid false alarms with such strong language and forecasters must "make sure you're speaking correctly because when you use elevated terminology like this it will get people's attention and you wanna make sure you're correct so we always have people second check it" (I12).

4.5.2 Retrospect:

Not only do forecasters make sense of a situation using retrospect, but they think about how their audiences experience that sensemaking process as well. Forecasters know that partners will be more alert to an extreme rainfall threat if they have experienced an event before. I9 recalled working with partners who had previously experienced a flooding event and noted that "those who had been impacted in [event] were certainly clued into what we were saying and they were very, very alert to the messaging that we were putting out." In addition to being more alert to a flooding threat, past events also inform partners to which areas are more prone to flooding and to give those areas special attention: "EMs told us they had gotten out earlier started telling people from the normal places that flood or whatever to get out" (I5). Since forecasters know what areas concern their partners the most, they know to discuss those problem spots in their briefings: "we start talking about it beforehand, especially with our hydrologist and say, 'Hey, what do you think is gonna happen in these areas and these areas and these areas, because we're gonna get asked'" (I10).

4.5.3 Presumption:

Presumption is another sensemaking component that forecasters anticipate their audiences using as they process an impending event. Like forecasters, partners will connect the current environmental situation to potential impacts later on. I5 recalled that their partners knew that more rain would cause significant impacts based on what they had recently seen: “they already knew that this area was saturated. There had been flooding, much lesser impact events but there had been some flooding events in the weeks leading up to this. They knew already that it couldn’t take much more.” When partners are aware of such a possibility, it raises a sense of urgency and attention to what the NWS forecasters are telling them.

4.5.4 Organizing through communication:

Forecasters will communicate with their audiences to ensure that they understand the situation that is unfolding. For example, if a partner does not understand a situation, they can communicate with that partner individually to make sure they get it, as I18 recalled sitting down with decision-makers that thought the event was going to pass them. They explained: "'No, this band is gonna extend way [south] and through [city] and it's going to be a big feature we’re starting to see in our hi-res modeling' and I said 'you're definitely just as at risk.'” Forecasters will also share information with their decision-making audiences that may not be released to the public yet: "we were saying [amount], but we were actually briefing emergency managers it could be higher because we were starting to see the realization that it could potentially be higher but we didn’t publicize that" (I8). This allows decision-makers more time to act.

When messaging an event, it is extremely important for all entities across the weather enterprise to have a consistent message (Childs and Schumacher 2018). Message consistency is achieved by coordinating with their partners: "If we're saying one thing and then the media is saying another thing or if we’re saying one thing and other partners are saying another, that is where having that big headline that's coordinated is huge" (I16). Forecast and messaging coordination is not always easy, as I6 discussed the frustration of trying to get the media to shift focus from a tornado threat to a flood threat: “We solved it eventually through NWS Chat, getting the media to kind of not focus so much on these little, weak tornadoes and focus on this huge flood wave coming down the [river]. And so that was a challenge” (I6).

To communicate openly with partners and ensure message consistency, trust must be established during “quiet” times, before an event occurs. The NWS encourages this through

Integrated Warning Teams (IWT). IWT relationships are built by working with partners routinely. I14 described conducting weekly briefings with the partners so that: "when the chips are down, they feel more comfortable with us, rather than an occasional voice that they never heard from you in a long time or never heard of period. We build up this level of trust and confidence". I14 also expressed concern that IWT relationships are not as strong as they once were because, "Coronavirus has obviously impacted operations. Everything is remote these days, we haven't been able to get together with our partners for meetings for quite some time, so that's had an impact on us." When these relationships are strong, partners and audiences are more likely to believe the severity of the event.

Forecasters also rely on communication from their audiences to help make sense of a situation. Social media has increasingly become an avenue for storm report submission that anyone can use: "If they can click a picture and send it to us or they send it to someone else and we happen to see it, we can look up radar and things and get an idea of its validity" (I15). Keeping track of what the media is covering also helps with situational awareness when partners such as emergency managers are too busy to send in storm reports. For example, I10 recalled an instance where the office saw a traffic cam feed on The Weather Channel where "a body [of water] that was completely flooded over the interstate… it looked like they were driving through a river and it was the interstate and we all went 'where is that and why haven't we heard about this?'" Social media and TV coverage greatly help forecasters with situational awareness.

4.5.5 Action:

Once the audience has made sense of the impending event, they should be moved to action. Forecasters can provide actionable information to their audiences as they prepare for the event, such as having enough supplies to last a multi-day event (I8). Forecasters provide such information in hopes that their audiences take the threat seriously and do not put themselves in harm's way during the event.

4.6 Forecast creation: decision-making

Similar to sensemaking, forecasters also consider the decision-making frameworks that their audiences will use when handling an extreme rainfall event. These frameworks include *affect, availability bias, confirmation bias, finite pool of worry, gambler's fallacy,* and *loss aversion.*

4.6.1 Affect:

Similar to forecasters, their audience's decision-making can be influenced by emotion. I5 stated that "people are still very sensitive about rainfall" in the area that the event hit the hardest. I10 shared a similar experience, saying that people who live in a flood-prone region will become concerned "as soon as you mention heavy rain and flooding down here everybody's ears perk up and everybody starts paying attention and we just get swarmed with questions and swarmed with concerns." These emotions towards extreme rainfall events could mean that audiences are more likely to decide to take appropriate action.

4.6.2 Availability bias:

When a forecast end-user can picture an event in their head, they are more likely to be able to react appropriately. This means that forecasters must be able to communicate such imagery. Audiences can have trouble understanding numbers, as I17 described such an interaction with partners who didn't quite grasp what the forecast meant: "there were some partners that were thinking 'Okay, that's 40 inches of rain but it's going to be spread out evenly so we'll be okay, right?'" I3 also expressed frustration in the public's interest in the numbers, and not in the actual message, and that message is, "'You're all gonna get a massive amount of water and the rivers can't handle that, nothing can… Your homes are gonna flood and roads are gonna be impassable.'" By relaying impacts rather than numbers, forecasters may provide a clearer message for their audiences. However, I3 also noted that sometimes it can be difficult to do that in a way that the public can relate to.

Some forecasters will use past events to help their end-users understand the situation, "'Do you remember when this happened? You had flooding of this magnitude, well what we are expecting is an event to be very similar to that'" (I2). However, it is important to keep in mind that some events or event details could have been forgotten about. I7 discussed each event having a "shelf life" of "less than ten years" with the exception of major events, meaning that people won't necessarily remember the impacts to which forecasters are referring. It is also important for forecasters to keep in mind that people may be new to the area and may not have experienced that past event. I16 described that their area is growing so much in population that even though they frequently experience extreme rainfall events new residents: "when they hear of these rainfall rates or these rainfall amounts, they don't comprehend it because they've never experienced it before". Forecasters also need to keep in mind that using past events to message the impending threat is “effective but it’s also dangerous because some people will say 'Well, I didn't get flooded in [past event] so I don't have to prepare now' but it’s like 'No, this is a different event'" (I12). Referring to past events can be helpful, but each event is still unique. Sometimes, there are no past events to compare to, and forecasters must find a way to illustrate potentially unprecedented impacts. I13 described the challenge of messaging to their end-users that an event is "something that hasn’t happened before, so you have to prepare for worse than you’ve seen. That’s our biggest challenge… I think, how to convey stuff like that. People… they can only reference what they know or what they’ve seen before.”

4.6.3 Confirmation bias:

Like forecasters, audiences also have a confirmation bias. For example, when briefing partners and thinking, “you're speaking very forcefully and you think you really laid out and nailed the forecast and half of them might get it, half of them still won't get it” (I17). With the public, forecasters are careful to avoid deterministic values, I8 felt that "people focus on 'they said we are gonna get 10.75 inches of rain and that’s what we’re gonna get and we won’t get any more' that’s the reason I stay away from specific deterministic values." When the audience latches on to a value like that and it doesn’t verify, it is possible that they will lose trust in NWS forecasts. The same goes for a missed location: “that leads to perception issues with the public that we’re missing events” (I6) even if the event did happen, just in a different location. Similarly, confirmation bias is why forecasters are hesitant to give the public the worst-case scenario an event could produce and that they have to let the public know “exactly how bad it can be, but not to fixate so much on the very highest end because people tend to have a thing where… they focus on what the worst thing could be” (I15). Message consistency across the weather enterprise plays a large role in making sure that the public does not latch on to a worst-case scenario. Unfortunately, that’s not always the case and there could be “certain TV meteorologists at certain stations showing individual model run accumulations on the air that sometimes don’t agree with the messaging we’re saying. Sometimes they’re very worst-case scenario, sometimes they’re way under-done” (I6). Not only can this create confusion, but some members of the public may not be able to be convinced out of what they saw on television, meaning they could take too much or too little action or lose trust in future event forecasts if that particular scenario did not play out.

4.6.4 Finite pool of worry:

When facing an event, one can be overloaded with too many threats and will only focus on one or a few and ignore the others (Millet et al. 2020). For example, with one event, in the media "heavy rainfall and flooding was being mentioned but it was competing too much with 'ooh look at this amazing storm on satellite and that it's about to make landfall'" (I3). The media was so focused on the size of the storm, that they were not discussing the actual threats it was posing. For the same event, I2 discussed decision-making partners focusing on the wind and landfall of the storm and that they had to emphasize "the heavy rain and the devastating flooding… so that they understand that it's gonna be a real problem for them and bring their attention back to the inland flood threat because that's something they're going to be dealing with." It is up to the forecasters to make sure that their audiences are focused on the most imminent threat.

4.6.5 Gambler's fallacy:

While extreme rainfall events are rare, that does not necessarily mean that they cannot occur in short succession. NWS forecasters must be able to convince their audiences of this. Expressing event probabilities as return intervals complicates this, as the public may believe that a 100-year event can only happen once every 100 years. I12 notes that they have seen people in interviews say, "I don't understand how I could have three 100-year floods in two years." For this reason, many forecasters may stay away from presenting uncertainty information using return intervals.

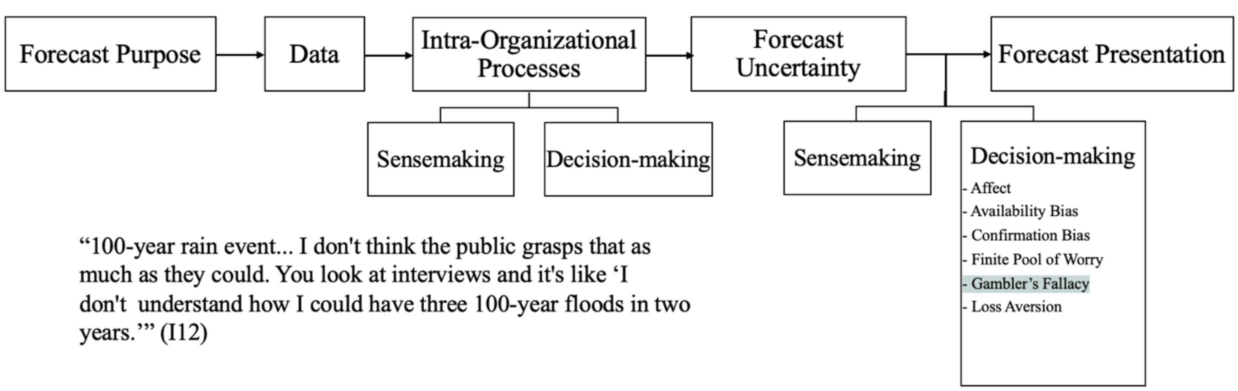


Figure 4.7: As in Fig. 4.2 except, focusing on "gambler's fallacy" and where decision-making fits in to the step of the forecasting and communication process where forecasters consider the processes their audiences will use.

4.6.6 Loss aversion:

People are more likely to heed safety information if it is framed as what could be lost rather than what could be gained if specific actions are taken (or not taken) (Millet et al. 2020). NWS forecasters can use this to their advantage when relaying safety information to their audiences. They want their audiences to understand just how dangerous flooding can be, but often the public does not grasp that danger. I21 discussed the issue of people trying to cross flooded roadways overnight and that the public should understand that as long as their home isn't flooding, they "need to shelter in place, stay there and not be on the roadways during some of these events because that's what we see, somebody will drive through a low water crossing and then lose their lives." I14 said that the biggest thing they want their audience to understand is that they: "you really need to pay attention and take measures to protect yourself and the best you can with your property. If you don't, you could run into some bad things such as drowning, losing your property." They hope that describing possible consequences will help their end-users make decisions that will save lives.

4.7 Forecast presentation

The culmination of the forecast purpose, intra-organizational processes, forecast uncertainty, and the sensemaking and decision-making frameworks influenced by outside forces is the presentation of the forecast. This is the product that is seen by end-users and used for their decision-making. If the forecast is not presented in a useful way, even if it is a great forecast, it will have very little value if it cannot be used.

Not every forecast is presented in the same way. For example, not every meteorological variable is presented in the same way. I1 discussed being able to use numbers when presenting variables like heat index or snowfall to their audiences but that they try and stay more qualitative

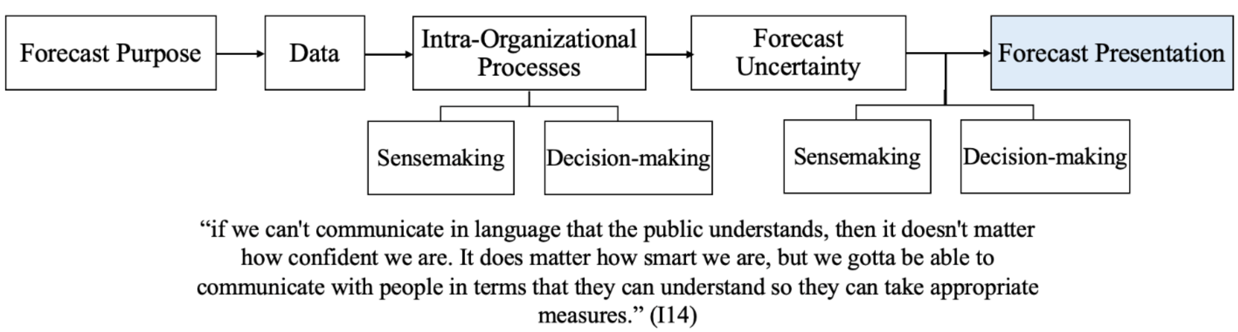


Figure 4.8: As in Fig. 4.2 except focusing on where forecast presentation fits in to forecasting and communication processes.

with things like rainfall impacts, and that how they express the forecast “does vary by element”. I4 recalled using numerical rainfall forecasts for an extended event but that they “didn’t really go for the storm total, more or less we tried to keep it along the lines of 12-24-hour amounts, additional this, additional that" to help their audiences understand the event as it happened. Sometimes, both numbers and actions to mitigate potential impacts will be presented: "When we were briefing to the public, we were saying 8-12 inches of rain, prepare sandbags, take actions that you need to take now before flooding starts" (I8). However, the forecasters seemed to agree that when they are forecasting extreme rainfall events, overall impacts are much more meaningful than numbers, especially “once you get to a certain amount, little differences in numbers don't matter anymore, it's about impacts” (I7). Forecasters also wanted to focus on impacts as they felt that their audiences may not understand what quantitative forecasts were saying:. I12 discussed avoiding "sayng a rainfall QPF without context of the impacts… we realize that you just can't throw out a QPF forecast and expect everyone to be able to read it the way it’s meant to be read" (I12). For this reason, forecasters will push “more impacts and safety in the emails” (I6). They still provided numbers but emphasized the impacts and proper precautions to take. While impacts are important, I18 said that forecasters still need to focus on the science of the impacts: “our focus has really been on trying to complete the picture with inundation but that requires fairly accurate rainfall.” Without a good forecast, they cannot accurately convey the impacts.

How the forecast is presented also depends on the audience that is being addressed, as different audiences have different levels of understanding. I7 expressed that they had little faith in what the public could handle: "I don’t think that the public is capable of understanding much in math, I just don’t. I think that they need survival skills education." Generally, the forecasters try and keep public-facing information as simple as possible. I19 described providing a straightforward forecast that was a “best guess, which may be a little deterministic. With the public, you have to be careful because they have a confirmation bias. If it didn’t rain where they were or isn’t as much as you say, it didn’t happen anywhere.” However, with partners “you can give a broader scope. You can provide different scenarios to them.” But, “the media cannot be included on those scenarios because you don’t want them to run off with what are just scenarios” (I19). Overall, the forecasters seemed to agree that when giving forecast information, with the “general public there’s probably more qualitative language and then as you get towards emergency management it’s more quantitative" (I1).

When working with sophisticated partners such as emergency management, forecasters rely heavily on in-person, conference call, and/or e-mail briefings when dealing with high-impact events. I15 described the “constant flow of communication” between their office and emergency managers up to three to five days leading up to an event: "email communication, phone communication, and maybe even in-person briefings depending on the event, we've done that multiple times or they can even be video briefings, now in this COVID environment. But it just ramps up as we get closer". During these briefings, the forecasters focus on messages such as "what the various threats are, what our degree of confidence in these threats are, when will the onset of threatening conditions occur, how bad could it be… when do we expect things to get better, and any lingering impacts" (I14). By hosting “many conference calls and meetings” (I11) forecasters make sure that their partners are receiving the message. Some offices will have forecasters practice giving briefings by conducting them routinely even when the weather is quiet “our forecasters get the practice so they go through presenting basically a briefing-type of scenario but it's just a generic 90 seconds 'Hey, here's a look ahead through the week' or 'this is a look into your weekend'” (I20).

When briefing partners, forecasters will provide them with various possible scenarios. For example, in a briefing I17 described potential storm tracks that would result in different outcomes, "We had to kind of present both scenarios that if it follows that eastern track, we're on the drier side. So, you almost have to kind of verbally flush some of this out when you're talking to partners" (I17). Forecasters also talked about using briefings to help their partners prepare by telling them "the worst possibilities so they can make the decisions themselves instead of being caught in the middle of an event, having to catch up… they want to have that sand ready for people to put in bags" (I13). For example, in addition to what is communicated to the public and the media, they will “take it a step further saying, 'we could see a worst-case scenario of X inches” (I8) with their emergency managers. Discussing these scenarios are a possible way for forecasters to figure out "how to properly communicate outliers in the models and how to use, not worse-case scenarios, but reasonable worst-case scenarios and how to brief that." (I6). Forecasters hesitate to share this information with the public because “you don't want them to get so fixated on either the best-case scenario or the worst-case scenario because people tend to gravitate to those extremes" (I15). As far as sharing the worst-case scenario with the media, forecaster’s opinions were divided. Some forecasters felt that as far as media understanding that they are only possible situations, “they get it” (I15) while others were worried about the media sensationalizing the worst-case scenario for reasons discussed in section 4.6.3.

The relationships between the NWS forecasters and their audiences strengthen the presentation of the forecasts. With in-person, video, and phone briefings body language and tone of voice go a long way in conveying the severity of the situation. I20 recalled people telling them that "they could judge the severity of my concern about the event based on my tone of voice and what words I was using even though it was something that was just unintentional, I was just being more conversational." I18 recalled a time that an emergency manager asked them if they should prepare for evacuations and that they “looked up and he didn’t even wait for me to answer the question, he saw how worried I was from some of the stuff that was coming in, some of the information we were seeing in the modeling.” Partners also know that they can reach out for more information: "we'll brief something and then we'll get a call from the EM and the elected official saying, 'Are you serious?, 'Is that really what you think? We're going to have to make some decisions'" (I17). In fact, I20 talked about how “pretty much every EM in our area is comfortable with shooting us a text message saying, ‘what you think?’ which is kind of cool.” A few forecasters expressed concern that such connections with partners could be lost or weakened due to the remote nature of things due to the pandemic.

In addition to briefings and one on one interactions, offices also have email lists that distribute briefing information to their audiences. I4 described, "when we do our webinars, we email our slides out, the slides are shared on social media.” These emails are distributed to a large audience, I5 estimated that about 1000 people received the slides and could forward the slides to others. Forecasters will also use NWS Chat to distribute information, especially to the media who are usually not involved in the briefings. The media can ask questions in chat and the forecasters can also give them a heads up that they’re going to “put out warnings we might put into chat that, 'Hey, tornado warning or a flash flood warning is about to come out for this specific area.' so NWS chat is definitely a huge communication aspect between with the media" (I16). The media can also request to interview NWS forecasters, "some over the telephone, sometimes a crew would come out and do a stand up interview, now we’ve got the capability of producing a video outside at our station for a video interview" (I14).

The NWS now also has the opportunity to become more public facing through their use of social media. Before, “the only way that people could, members of the general public, could ask us questions would be to maybe email the office, which wouldn't necessarily be a prompt response, or they would have to call the office” (I10). With social media, the forecasters can reach a large portion of their public: "I think it is probably the greatest tool we have. I think it's drastically better than NOAA Weather Radio and it's just the fastest way to get information out and we get so many more reports that way as well" (I13). Forecasters can use social media to share more detailed information with the public. They can discuss the development of the situation, possible rainfall amounts, and how things could change and that it is a “good way to at least give the public a little bit more of what we're thinking as far as uncertainty and the actual threat” (I21). However, forecasters are aware that social media is not without flaws. I19 expressed concern that “on social media, you are dealing with so many different people, not just a few that it is difficult to establish relationships” (I19). A few forecasters also expressed concern that the graphics they post could be manipulated, "There's been examples of people taking like an NHC graphic, keeping the logo and then changing the information on the graphic… trying to emulate official sources. " (I18). Although social media is not perfect, forecasters felt like it has become an incredibly useful tool.

There are many tools available to a forecaster when they present forecast information. It doesn’t matter what format is used, but as long as it is usable by their audiences. As I14 said, “If we can't communicate in language that the public understands, then it doesn't matter how confident we are. It does matter how smart we are, but we gotta be able to communicate with people in terms that they can understand.” There are certain things that forecasters specifically want to convey to the public. They want to make sure that people are prepared and in a safe place before the event starts: “if you live in a low-lying area that's prone to flooding, maybe you should consider going to a relative’s home or trying to find an alternate place to stay during that time" (I9). They want each person to know potential impacts and to be able to “understand how my forecast relates to their danger level and what it could mean with potentially being in harm’s way and what kind of actions they need to take to stay safe." (I10).

Chapter Takeaways

- The extreme rainfall forecast and communication process can be depicted in a simple forecasting process model.

- Forecasters start by identifying the purpose of their forecast, especially what decisions will be made using the forecast and what information is needed to make those decisions.
- Forecasters use sensemaking processes to understand the evolving weather situation.
- Their decisions leading up to and during the event are impacted by heuristics and biases.
- Forecast uncertainty is inherent and forecasters do not agree on how to express it.
- Forecasters also consider the sensemaking and decision-making processes that their audiences will go through.
- Finally, forecasters decide how to effectively present forecasts to various audiences.

Chapter 5: Discussion

How forecasters translate their meteorological knowledge into useful forecast information for their audiences has not been widely studied (Morss et al. 2015, 2011). This study helps address that knowledge gap. A basic understanding of the forecasting and communication processes of extreme rainfall events can be depicted in a simple forecasting process model (Fig. 4.1). This model combines two pre-existing models (Lejano et al. 2016 and Hoffman et al. 2017, Figs. 2.1 And 2.2, respectively) as well as forecasting principles (Armstrong 2001b) and the conceptual frameworks of sensemaking (Weick et al. 2005; Butterworth 2010; and Doswell 2004) and decision-making (Millet et al. 2020). Applying these frameworks and principles to the interview data provide insight into how NWS forecasters operate leading up to and during extreme rainfall events. Specifically, how they process model outliers, communicate those outliers and outlying events, and whether they connect these events to climate change.

Forecasters go through sensemaking processes as they address the evolving weather situation, including extreme rainfall events. Forecasters get better at handling these events as they gain experience and can use retrospect to identify things like how certain tools are biased. Forecasters who have seen extreme rainfall events before are also more likely to see an extreme amount of precipitation in the models and accept it as a possibility. However, when forecasters have not seen an event of that magnitude, and cannot imagine such an event, they may be more hesitant to put out that forecast, especially without strong evidence (availability bias). Seventeen (81%) of the forecasters mentioned recognizing which current features could lead to potential impacts (presumption), like seeing that a system is moving slower than expected, so it will dump more rain over the area. They will use pattern recognition (representativeness) as well to make sense of an event and are able to identify ingredients to an extreme rainfall event in their area. However, it is important to realize that these forecasters are human, and some of their decisions can be impacted by emotion, especially if they have worked a significant, impactful event and an incoming event has the potential to lead to similar outcomes (affect). Also, forecasters never process these events alone. Sixteen of the forecasters (76%) talked about communicating with other forecasters, both in their own office and in other offices as well to make sure that everyone is aware of the same features and on the same page (organizing through communication). By calling on their own experiences as well as their colleagues' expertise, forecasters can make better sense of the weather situation, and experience with extreme rainfall events will make them more open to acknowledging model outliers as a possibility.

There are also organizational policies that dictate operations in a WFO and impact forecaster sensemaking and decision-making. For example, with QPF products forecasters will anchor themselves to an initial forecast, and only adjust that forecast incrementally as new evidence comes in (anchoring and adjustment) based on NWS procedures. This prevents drastic changes between products, which could create confusion or a lack of trust (Daipha, 2015). There is also guidance on how far out from the event certain products should be published, which may make some forecasters hesitant to issue the product further in advance, even if there is high confidence that the product will be needed (social and systemic). Other forecasters may want to issue the product anyway, to give more lead time to their audiences. These policies exist to provide structure for operations, and it is important to note that they impact the forecast and communication process.

Model output is a major input to the forecasting process, especially as model output continues to improve (Schumacher 2017). Forecasters are increasingly tasked with the challenge of whether or not to keep the output as is or take action and adjust it according to other evidence they are seeing. While forecasters have a lot of information to process (Daipha 2015; Doswell 2004) and forecasters may struggle interpreting ensemble guidance (Wilson et al. 2018), consistent model output helps them organize that chaos. Twenty forecasters (95%) said that when models are consistent run-to-run and with each other in signaling an extreme rainfall event, that event will likely come to fruition. This helps the forecasters identify what they need to focus on and look for in the data (organizing flux). If the model consistency continues, the forecasters will have more confidence in the event. With that confidence, forecasters can start to message the possibility of an extreme event with greater lead time Forecasters use model guidance to gain an understanding of an event. When models consistently point to an extreme rainfall event, that primes forecasters' attention towards that event. Continued consistency and agreement help forecasters communicate these events with greater lead time and confidence. Model outliers are closely monitored by the forecasters as a potential outcome.

Even if every model in every model run was showing the same outcome, there will always be uncertainty in the forecast (Schumacher 2017) and forecasters must decide how to communicate that uncertainty, as they do not want to imply accuracy that they do not have. How forecasters convey uncertainty is a significant challenge, especially since that uncertainty is not objective and forecasters will each express how confident they are in a forecast in their own way. When asked how they felt how uncertainty should be conveyed, forecasters provided a variety of answers. Forecasters suggested the use of confidence levels, probabilities of exceedance, and ranges of possible amounts. Some forecasters even try to avoid uncertainty with the public in general as they felt that the public is not capable of understanding such information without losing trust in the forecast (Rouleau 2016). Previous studies have found that forecasters do not feel like the public can understand probabilistic uncertainty information (Daipha 2015; Stewart et al. 2015; and Demeritt et al. 2010). While audiences and forecasters alike struggle with the correct definition of probabilistic information (Gigerenzer et al. 2005; Morss et al. 2008; Stewart et al. 2015; Daipha 2015), better decisions are made with uncertainty expressed in the forecast (LeClerc and Joslyn 2015; Fundel et al. 2019; Roulston and Kaplan 2009). Grounds et al. (2018) also found that probabilistic information also leads to better decisions than using return intervals to convey uncertainty. In this study, five (24%) forecasters felt that they could use probabilities effectively with the public, while six (29%) said that the public cannot understand probabilities. However, four (19%) forecasters said that the public uses probabilistic information every day, like in fantasy football apps, so they should be able to understand it in the context of weather as well.

As far as solutions to expressing uncertainty, three forecasters simply said that they did not know what the solution would be. One forecaster suggested creating a model that provides a range of possibilities for a point and time but acknowledged that the technology for that does not exist yet. Three forecasters discussed using education campaigns to help users understand uncertainty information. One forecaster said that they need help from social scientists to figure out the best way to express uncertainty. While there is no consensus on how uncertainty information related to extreme rainfall events should be communicated, forecasters have ideas and are willing to work with researchers to establish the best way to do so.

When communicating these events, forecasters also must ensure that the messages being sent to users are consistent. Consistent with previous findings (Daipha 2015; Childs and Schumacher 2018; Sherman-Morris et al. 2018), forecasters ensure consistency by discussing the message within their offices, with other NWS offices, and with their decision-making and media partners (organizing through communication). They will make sure that their decision-making users are properly understanding what is happening in the event as well as try to make sure that their media partners are sticking to the same message that they are. Six (29%) forecasters said that if the media happens to broadcast a worst-case scenario model run, the public may latch on to that scenario (confirmation bias), which can cause unnecessary panic or decrease trust in forecasts when that worst-case scenario does not pan out. This is something that the forecasters try to discourage, but it is not always within their control. Through communication within the NWS and with partners, forecasters ensure that the communication of extreme rainfall events is consistent across the weather enterprise.

How forecasters present forecast information depends on a few factors. The meteorological variable in question is one example. Forecasters felt that variables like heat index could be presented numerically while others like hail size should be presented qualitatively. With rainfall, some forecasters said that ranges of variables could be presented, but most (n=15, 71%) agreed that communicating the impacts associated with that rainfall is more effective than the actual amount of rain. By describing potential impacts and even recommended protective actions, users are better able to picture the threat in their head than they are just amounts of rainfall, and thus will better understand the event (availability bias). How the event is communicated is also dependent on lead time. Further out from the event, uncertainty is high and fewer details are known. For this reason, forecasters will start out with general messaging that there will be a heavy rainfall event, then as the event gets closer and more information is available, they can start narrowing down locations, amounts, and especially impacts and convey that to their users. This is consistent with Bostrom et al. (2016).

Consistent with existing literature (e.g.: Rouleau 2016 and Sanders et al. 2020), forecasters discussed that the audience also impacts how forecasts for these events are communicated. How forecasters communicate with the public has grown in importance over the last several years. Seventeen (81%) forecasters discussed how social media has allowed them to interact more with the public. Social media allows the public to directly ask them questions as well as easily submit storm reports, helping with forecasters' situational awareness. For the public, nine (43%) forecasters felt that the information should be kept relatively simple. The public is mostly concerned with what will happen to them personally, and do not have as many decisions to make as sophisticated partners like emergency managers. Forecasters felt that the only information that needs to be communicated to the public is impact information and how they can protect themselves and their property.

With sophisticated partners like emergency managers, forecasters can provide more complicated information. Forecasters give weather briefings to these partners, and they are a main channel of communication between the forecasters and these sophisticated users. Eleven forecasters (52%) said that in these briefings, they can give partners various possible scenarios, such as the most likely scenario or the worst-case scenario. The worst-case scenario can be based on model outliers. Forecasters also try to be aware of thresholds that partners have for certain decisions (forecast purpose). That way, they can prioritize that information in their briefings. Nine (43%) forecasters said that by conducting regular briefings and meetings, even when the weather is “quiet”, they establish relationships with these partners, which will then increase partner trust in the forecasts (Bostrom et al. 2016; Kuonen et al. 2019). Six (29%) forecasters said that these relationships allow partners to feel comfortable asking for specific information and three (14%) said that partners know them so well that they can understand the severity of the threat off of body language and tone of voice. Forecasters can also use these relationships to directly communicate with partners that they feel are not properly understanding the severity of the threat. They can directly tell that partner what they think will happen and why, making sure they are on the same page (organizing through communication). For some offices, these briefings are solely for decision-makers and the media is rarely involved in the meetings or calls while others do include the media. However, the slides from the briefings are often mailed out to a wider group of people that could include the media. However, five (24%) forecasters said that they mostly interact with the media through NWS chat and occasionally will do interviews with them. When communicating with these more sophisticated partners, forecasters can incorporate more complex information, such as various possible outcomes. Some forecasters said that they use model outliers as possible worst-case scenarios.

No matter who they are presenting the forecast to, forecasters need their audiences to be able to understand the significance of an impending extreme rainfall event. In order to convey the events in ways that will help this understanding, forecasters consider the sensemaking and decision-making processes that their audiences will go through to understand the event. One-third (n=7) of forecasters felt that audiences are better able to understand and react to an extreme rainfall event if they have experienced an extreme rainfall event in the past (retrospect). Four

(19%) forecasters said that they use this to their advantage and use past events to message the incoming event so that the audience can better picture the incoming event (availability bias). However, seven (33%) forecasters were hesitant to use past events, as no two events will be alike and even if the flooding will be similar, it will likely be in different places, which may not be something that the public understands. It is also possible that a forecast user may not believe that a storm can behave in a certain way if no storm they have seen before has done that (confirmation bias). Users may also believe that if they have recently experienced a rare rainfall event that it is not possible for another one to come in short succession (gambler's fallacy), which is another challenge forecasters face when communicating these events. Just over half (n=11, 52%) of the forecasters said that they will label events using words like "catastrophic" to message the event in a way that allows audiences to link the event to a word that they are familiar with, and will be able to better understand the significance of the event. Forecasters also know that their users, especially the high-end users, can connect current conditions to future ones (presumption). For example, they know that when there has been a lot of rain recently that it will not take much more to get significant flooding impacts. Once the audience understands the significance of the event, they can decide which actions they should or should not take. These decisions can be emotionally driven, especially if the user has experienced an extreme rainfall event in a way the negatively impacted them, creating fear when another extreme rainfall event is approaching, which can adversely impact the decisions they make (affect). To help their audiences make rational decisions, forecasters first make sure that the messaging is focusing on the most dangerous threat. When faced with multiple threats, it is not uncommon for people to focus on just one (finite pool of worry), so forecasters will try and make sure both they and their partners are messaging whichever threat poses the most danger. They will also message to the audience what could be lost if the correct actions are not taken, as that is more effective than messaging what could be gained (loss aversion). Eight (38%) forecasters discussed the importance of making sure that their audiences can properly understand the potential impacts of an extreme rainfall event and then take the correct actions to protect themselves, their families, and their property. Forecasters consider the sensemaking and decision-making processes that their audiences will go through in order to better communicate extreme rainfall events.

Extreme rainfall events are projected to increase in frequency and intensity due to climate change (Mullens et al. 2013; Hayhoe et al. 2018). However, when forecasters are working these events, they are not thinking about the potential impacts that climate change could have on the event. Most (n=18, 86%) forecasters are noticing that these events are happening more frequently or are becoming more intense when they happen (noticing and bracketing). However, they feel that connecting the impacts of climate change on these events is beyond their role as forecaster (social and systemic), which Hoffman et al. (2017) also discussed. Forecasters also mentioned that they already have so much information in front of them that they also do not have the time to make those connections. However, they may consider the impact that climate changed could have played in an event after the event has passed.

Applying sensemaking and decision-making frameworks, as well as principles of forecasting, can create a basic understanding of extreme rainfall forecast and communication processes by NWS forecasters. In previous studies, models have been created to depict forecasting processes (Morss et al. 2015; Bostrom et al. 2016; Hoffman et al. 2017). Similarly, these concepts can be put into a simple forecasting process model (Fig. 4.1) to help visualize this high-level understanding of extreme rainfall event forecast and communication processes. It is important to note that this model is simpler than the actual forecast process, but it does still provide insight. This simple model helps answer the research questions investigated by this project. When forecasters see a model outlier in their data, they will not immediately dismiss it, but they also will not accept it right away. Instead, they will monitor the model output to see if it disappears or if other models and runs come into agreement. Some forecasters, especially those who have experienced extreme rainfall events, may acknowledge model outliers as possible maximum amounts and might even brief them as worst-case scenarios to their sophisticated partners. Communication of extreme rainfall events is dependent on confidence in the event as well as the audience being addressed. For example, forecasters tend to provide simpler, more impacts-based information to the public and more complicated information to their sophisticated partners. Finally, while most forecasters are aware of climate change and the expected increase in these events, it is not something that is considered when forecasting or communicating extreme rainfall events during and leading up to the event. However, it is something that the forecasters may consider when they reflect on the event after it occurs.

While this study addressed the research questions and provided insight into the forecast and communication process, it also highlighted challenges that forecasters face when working extreme rainfall events. First, forecaster confidence is highly dependent on consistent model output. However, that is not always the case, and models may not be in agreement or there could be outliers in the output. In those situations, forecasters stated that they will monitor model output until the guidance is a little clearer, especially when dealing with model outlier suggesting a rainfall amount that the forecaster has never seen before and they have to decide whether or not that outlier is believable. While this works, it also can decrease forecast lead time, giving audiences less time to prepare for what could be significant impacts. To address this challenge, a model verification suite could be developed for forecasters to refer to. This suite would provide information on how models performed in previous events. This information would include the distribution of model output, especially the cluster of output and the outliers, as well as what actually happened. Forecasters could use this information to get an idea of how models have handled similar events in the past and use that knowledge to help decide how to interpret model output from the current event. Many forecasters did say that they communicated model outliers to their partners as a potential worst-case scenario for localized areas. This tool could also prove or disprove that way of thinking. If it is found that high-end model outliers do end up coming to fruition as localized maximum rainfall amounts, that could be something that forecasters could start briefing to all audiences, although there would need to be additional work done on how to do so effectively.

Forecasters also struggle with forecast uncertainty. Uncertainty can be subjective, so each forecaster might have a different level of confidence. Forecasters also do not agree on how forecast uncertainty can be expressed to various audiences. The most common suggestion was ranges and many forecasters felt that the public cannot understand probabilistic information. However, a few forecasters and the literature (Fundel et al. 2019; Roulston and Kaplan 2009) feel that the public can understand probabilities when they are presented in an understandable way. To address this issue, work should be done to ensure that uncertainty information is expressed consistently across the NWS. To accomplish this, research on the production and interpretation of probabilistic information in weather forecasts should be expanded. For example, some WFOs have started to publish graphics on their social media pages that include probabilistic information. Studies into how the public views that information as well as how the offices decided on using that information should be done. It would also be useful to conduct workshops with NWS, decision-maker, media, and public participants to attempt to determine what kind of uncertainty information is usable and effective for all users. Using information from studies along those lines could help create a uniform method of expressing uncertainty information. Creating a tool to help forecasters interpret model guidance and a uniform way to communicate uncertainty would eliminate a few of the many challenges forecasters face when forecasting extreme rainfall events.

This study did have a few limitations. First, forecaster recollection of events may not have been perfect. Some forecasters were interviewed about events that had occurred four years prior. While forecasters did say that these events were significant enough that they remembered them in vivid detail, it should be noted that memories are not perfect. Another limitation of this study is that it was conducted in an area that sees significant rainfall events relatively frequently, especially in recent years. Because of these forecasters' experience with these events, their responses would likely differ from forecasters in regions where such events do not happen that frequently or of that magnitude. Another limitation is the possible bias of the author when coding the interview responses. While deductive reasoning provided pre-established concepts to apply to the responses, coding can be subjective. The author made every effort to be as unbiased as possible, but adding another coder may have resulted in slight differences.

Chapter Takeaways:

- Although research has shown that including uncertainty information improves decisions made based on the forecast, forecasters did not feel that uncertainty should be provided to the public.
- How forecasts are conveyed depends on the audience. More complicated information is given to sophisticated users and in line with previous research, forecasters emphasized the importance of relationships with these users.
- Previous research has applied mental and conceptual models to the weather forecasting process and this project expanded on that by incorporating sensemaking, judgement and decision-making, and principles of forecasting into a simple process model.

Chapter 6: Conclusions

This study investigated the forecast and communication processes used by NWS forecasters leading up to and during extreme rainfall events. This study asked and provided practical conclusions to the following questions: how do forecasters process model outliers? How do they communicate those outliers and outlying events? And, do they consider the impacts of climate change on these events? A high-level, theoretical understanding of these processes can be gained through the application of sensemaking (Weick et al. 2005; Doswell 2004) and decision-making (Millet et al. 2020) frameworks and the principles of forecasting (Armstrong 2001b) to the responses, which are depicted in the simple forecasting process model (Fig. 4.1).

Forecasters will use the sensemaking frameworks of retrospect, presumption, representativeness, and organizing through communication and the decision-making frameworks of availability bias and affect, calling on their expertise and experience as they work to comprehend the evolving weather situation. This comprehension is also impacted by organizational guidelines, to which the social and systemic sensemaking concept and the anchoring and adjustment decision-making concept can be applied. When forecasters are processing model output, the sensemaking processes of action and organizing flux play a role. Forecasters must decide if the model output is valid or if it needs adjustment, and consistent model output signals to the forecasters that an extreme rainfall event is likely and their attention should be shifted in that direction. However, models are not always consistent, and forecasters stated that when they see a model outlier, they will likely keep an eye on it to see how it and other models evolve in subsequent model runs. That outlier may also be communicated as a possible worst-case scenario, especially to sophisticated users like Emergency Managers.

Forecasters are constantly dealing with forecast uncertainty and how to convey that uncertainty to their audiences. The forecasters did not agree on how they should convey uncertainty. Suggestions included: qualitative confidence levels like “expected”, probabilities of exceedance, ranges, and probability of precipitation. There was also no consensus on what kind of uncertainty information that the forecasters felt the general public could understand. Some forecasters said that they need help from social scientists and educational campaigns to be able to convey uncertainty in a way that is understandable and useful to their audiences.

When communicating these events to their partners, forecasters must consider the forecast presentation. They must ensure that their messaging is consistent and do this through the sensemaking framework of organizing through communication. One clear, consistent message will reduce the chance that the audiences will experience the decision-making bias of confirmation bias, meaning that they stick to a worst (or best) case scenario rather than the most likely scenario. How the forecast is presented also depends on the variable being presented, and forecasters felt that extreme rainfall events are best communicated through impacts rather than numbers. By describing impacts, forecasters can help their audience better picture what an event could look like, which reduces the decision-making bias of availability bias.

How the forecast is presented also depends on the audience to which the forecast is being presented. Forecasters thought that for the public, information should be kept relatively simple. With partners, they feel that they can provide slightly more complex information. For example, when briefing such partners, they can include various possible scenarios. Forecasters emphasized the importance of the relationships with these partners and building trust with them even when the weather is "quiet". They will use the sensemaking process of organizing through communication to make sure that their partners are understanding the event properly. Interaction with the media varied from office to office. Some offices included the media on their briefings while others did not. It seemed that the main vehicle for interaction with the media was NWS Chat.

The most important part of the forecast presentation is that it is understandable and usable. When creating these forecast products, forecasters will consider the sensemaking and decision-making processes that their users will go through. These processes include the sensemaking frameworks of retrospect, labeling, and presumption and the decision-making frameworks of availability bias, confirmation bias, gambler's fallacy, affect, finite pool of worry, and loss aversion. By considering these frameworks, forecasters are better able to communicate effectively to their audiences.

Most forecasters stated that they are noticing an increase in extreme rainfall events, to which the noticing and bracketing component of the sensemaking framework can be applied. However, they do not link this increase to climate change when making forecasts. This can be explained by the sensemaking framework of social and systemic. Forecasters felt that thinking about climate change was something that is beyond their role as a meteorologist and something that should be left to climate scientists. However, some considered climate change as a factor after the event occurred.

The data indicated that sensemaking and decision-making frameworks and the principles of forecasting help describe the forecast and communication process for extreme rainfall events (Fig. 4.1). It is important to note that only a small sample of forecasters was interviewed, so these results cannot be generalized across the NWS in the SCIPP region or nationally. The forecasting process is also a lot more complex than what the model depicts, and each forecaster has their own unique forecasting process. However, these results provide a high-level understanding of the process. This understanding can help add to the knowledge base of how forecasters turn their expertise into usable information.

These results open the door to several future research projects. It would be of interest to follow up with participants when another extreme rainfall event impacts their region and ask them if participating in this study led them to think more about how climate change could have played a role in that event. This study could be expanded outside of the SCIPP region or conducted in another region and results could be compared. Adding more participants to the study would also make the results more representative of NWS forecasters in the SCIPP region or the entire organization. Using these results to create an online survey would allow a larger pool of forecasters to be reached. Studies specific to how end-users (on all levels of sophistication) understand uncertainty information pertaining to extreme rainfall events could be conducted to find what these users prefer and understand can be compared. Workshops that include forecasters, decision-makers, media, and public users could be conducted to educate on how to convey and interpret uncertainty information and even develop products that benefit all audiences.

These results provide theoretical and practical understandings of forecast and communication processes prior to and during extreme rainfall events and could help guide future research. NWS forecasters want to improve communication so that their audiences can be better prepared to protect themselves in the face of a significant rainfall event and are open to working with social scientists to do that.

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Appendix A: Interview Protocol

Note that not all questions were asked for each participant. The questions asked depended on the event, the WFO, and the forecaster.

Demographic Information:

1. How long have you worked at [WFO LOCATION]?
   a) (If participant has changed locations since the event) How long had you worked at [PREVIOUS WFO] at the time of the event?
2. What is your job title?
3. How long have you been a forecaster?
4. Were you working during [EVENT]?
   a) If not, were you aware of and following the event?

Event Questions:

5. How accurate were the models leading up to the event?
   a) Were they consistent?
   b) Did that (in)consistency affect your messaging about the event?
   c) Which model do you feel performed the best?
6. Had you ever forecasted an event of similar magnitude prior to this one?
   a) (If yes) how did this one compare?
   b) Did that experience shape your decision making during the event? If so, how?
   c) Alternatively: had you ever worked a rainfall event that was expected to be extreme, but was over-forecasted?
7. How long before the event did you realize that it would be of such an extreme magnitude?
8. (If applicable) Leading up to and during this event, there were historically high values of precipitable water. What do you think caused the atmosphere to be able to hold this much moisture?

Communication:

9. What type of uncertainty information do you think is appropriate for the public?
   a) Do you prefer providing ranges of possibilities or to describe them qualitatively?
   b) Does the way you express uncertainty vary between audiences? (Public vs. EM's vs. Media, etc.) If so, how?

10. What was your interaction with Emergency Management before and during the event?
    a) Do you have any sense as to whether your message about high rainfall totals was received by them?
11. Did you work with the media?
    a) Do you have any sense as to whether your message about high rainfall totals was received by them?
12. At [TIME], your office published [PRODUCT] forecasting [RANGE] inches of rain. How confident were you that [MAX] would be the maximum amount?
    a) Was there another value that was in your mind as a possible maximum?
    b) If so, what factors led you (or your office) to go with [PUBLISHED MAX]?
    c) What additional evidence would you want in order to go with the higher maximum value?
13. i) On [DATE/TIME] a forecast graphic was published [INSERT GRAPHIC] that provided ranges of potential precipitation amounts. This implies uncertainty. What factors led you (or your office) to communicate it this way rather than providing a deterministic forecast?

    -OR-

    ii) On [DATE/TIME] a forecast graphic was published [INSERT GRAPHIC] that provided a deterministic forecast precipitation amount. This implies certainty. What factors led you (or your office) to communicate it this way rather than providing a range of values?

    -OR-

    iii) On [DATE/TIME] a forecast graphic was published [INSERT GRAPHIC] provided both a range of forecasted precipitation amounts and deterministic values. What factors led you (or your office) to communicate it this way rather than choosing between the two?
14. i) Before the event, the WPC was forecasting [Amount of rain]. What factors informed your (or your office's) decision to forecast a lower amount of rain?

    -OR-

    ii) Before the event, the WPC was forecasting [Amount of rain]. What factors informed your (or your office's) decision to forecast a higher amount of rain?

    -OR-

    iii) Before the event, the WPC was forecasting [Amount of rain]. What factors informed your (or your office's) decision to issue a similar (or the same) forecast?

15. [IF APPLICABLE] One product issued stated that this event was "Historic" (or unique in some way) [INSERT PRODUCT]. What thoughts were going through your mind when that post went out?
16. i) Your office started talking about the potential for a very heavy event early on. Describe the factors that contributed to your high confidence that this would be a significant event.
    -OR-
    ii)There was no discussion about the severity of this event until just before the event began. Describe the factors that kept you from forecasting that event ahead of time?
17. (if applicable) On [DATE], this product [INSERT PRODUCT] forecasted [AMOUNT OF RAIN] falling in a [TIME PERIOD (i.e. twelve hours)] period within the event.
    a) What evidence led you to forecast such a high amount of rain in that amount of time?
    b) What did you want your audience to understand about a rainfall amount of that magnitude in such a short amount of time?
18. How important is it to have social media as a communication tool during an event like this?
    a) Has your (or your office's) use of social media evolved since this event?

Post-Event

19. After the event, when storm totals started coming in at record numbers, how did you react?
20. Has this event changed how you or others in your office approach rainfall forecasts, extreme or otherwise?

General Questions:

21. When you see a model outlier predicting a large amount of rainfall, what is your thought process?
    a) If you decide to acknowledge said outlier- what do you look for as far as evidence to support that model? (Other Models, synoptic set-up, climatology, etc.)
    b) How confident do you have to be to account for the outlier in your forecast?
22. What are the main points you want your audience to understand when communicating the potential for extreme rainfall? (Threat to life/property, magnitude, no precedence, etc.)
23. Do you think the frequency of heavy precipitation events is increasing?
    a) (If they bring up climate change) Is climate change on your mind during the forecast process?

b) (If yes) When you are doing a forecast, how often does climate change affect your decisions? (Always, Sometimes, Never, etc.)

24. Is there anything else that you think is important to bring up regarding forecasting extreme rainfall, in terms of how you interpret outliers or communicate outliers.