CONCEPTUALIZING HOW FORECASTERS THINK ABOUT AND UNDERSTAND UNCERTAINTY IN THE CONTEXT OF SEVERE WEATHER

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ABSTRACT

Uncertainty is inherent in every weather forecast. In order to create better methods to communicate uncertainty to the public and other end users, it is necessary to understand how forecasters think about and understand it. Around twenty hours of observational data from the National Oceanic and Atmospheric Administration (NOAA) Hazardous Weather Tested Spring Experiment (HWT) 2012 was collected in order to analyze the participants' assessment of uncertainty in a real forecasting environment. Also, ten in-depth interviews were carried out in which research and operational forecasters were asked several questions regarding uncertainty. The interviews were recorded and transcribed for analytical purposes. Results show that even though the forecasters in this study were aware of the inherent uncertainty in severe weather, they were unable to quantify it, nor did they have a consensus on its definition. Moreover, the forecasters lacked a conceptual model of uncertainty. Instead, they used their internal climatology as both a tool and a framework to describe and assess uncertainty. Finally, population size was the most important non-meteorological factor that they used to assess spatial uncertainty.

1. INTRODUCTION

Uncertainty plays a role in every severe weather forecast. In the context of weather, uncertainty is defined as ambiguous or imperfect knowledge of future weather conditions (Morss et al. 2008). During severe weather events, recognizing and understanding the uncertainty that is inherent in the forecast is crucial to deliver an accurate forecast. However, the way forecasters think about uncertainty and communicate about it amongst each other and how they handle it differs from forecaster to forecaster. Given that forecasts are not perfect to begin with, the potential inconsistency in communication among forecasters contributes to additional errors (Doswell 2004).

Communicating forecast uncertainty is fundamental in order to avoid conveying false certainty in forecasts, and may help users of forecast information make more informed decisions. The confidence of the general public in severe weather forecasts is expanded when

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uncertainty is well understood and communicated (Morss et al. 2008).

This qualitative study presents new information about how forecasters think about and communicate uncertainty in the context of severe weather. Through observational data collected during the HWT 2012 Spring Experiment and ten face-to-face interviews, we analyze how uncertainty is defined and assessed by operational and research forecasters.

2. BACKGROUND

Uncertainty in weather is ubiquitous; it is derived from the chaotic nature of the atmosphere, sparseness of weather observations, errors inherent in the observing systems, and the amplified use of weather prediction models (Daipha 2012). Inaccurate and incomplete description of the initial three-dimensional state of the atmosphere leads to uncertainty. This, in turn, affects the accuracy and consistency of the numerical models used to forecast severe weather. Also, the errors derived from the inadequacies in the model descriptions of the physical parameters of the atmosphere and their initial conditions are a common source of uncertainty (National Research Council 2006).

As conveyed by Doswell (2004), imperfect meteorological observations–and their associated instrumentation–are a primary source of uncertainty, and are unevenly distributed in time and space. In the same way, model data provides additional uncertainty, owing to scientists' incomplete understanding of the atmosphere. The observations from the initial state might by accurate, but the prediction from the initial state will not be as accurate due to the imperfection of the prognostic model (Doswell 2004).

Data overload also induces uncertainty in forecast decisions. Doswell (2004) compares the amount of data available to forecasters in modern meteorology with attempting to drink water from a fire hose, asserting that "…the torrent of data and products derived from the data threatens to overwhelm them" (Doswell 2004). As more and more data is presented to them, additional education and training become critical, as discovered by Novak in 2008. Additional training on how uncertainty information should be interpreted and communicated became a recurrent theme among operational forecasters who participated in the National Weather Service survey. These forecasters stated that uncertainty guidance can improve current deterministic forecasts (Novak et al. 2008).

Given imperfect models, observations and overwhelming amounts of data, forecasters turn to heuristics to complete their forecast. Their personal experience plays a very significant role in the forecasting process, and the inherent subjectivity in these methods is also accompanied by a measure of uncertainty (Doswell 2004). Specifically, each forecaster has different weather-related experiences that influence their internal climatology. Therefore, their forecast approach varies, resulting in different degrees of uncertainty, even when considering the same weather scenario.

Studies regarding how forecasters think about uncertainty are uncommon. Social scientists tend to focus more on the public's perception and attitude towards the weather forecast and how uncertain it is rather than the same for the forecasters (e.g., Morss et al. 2007; Morss et al. 2008). Table 1 shows results to a question that asked public participants to describe the meaning of "*There is a 60% chance of rain tomorrow*", during a nation-wide survey conducted in 2007 (Morss et al. 2008). The results showed the lack of comprehension; eighty-one percent of the participants were unable to answer correctly.

The meaning of the forecast "*There is a 60% chance of rain tomorrow*."	Percent of Respondents
60% of the weather forecasters believe that it will rain tomorrow	22%
It will rain tomorrow in 60% of the region	16%
It will rain tomorrow for 60% of the time	10%
It will rain on 60% of the days like tomorrow *	19%
I don't know	9%
Other	24%
* Technically correct interpretation, according to how Probability of Precipitation (PoP) forecast are verified.	

Table 1. Responses to Q14a-the meaning of the forecast "*There is a 60% chance of rain for tomorrow*" (N=1330; Morss et al. 2008).

Similarly, the public tends to relate higher probabilities to the severity of an event instead of greater chances of the event occurring. Most of the participants in Morss et al.'s (2008) study, when asked to describe the difference between a 30% and a 70% chance of rain, believed that a 70% chance indicated that more rain would fall. In reality, a 70% chance of rain indicates a higher confidence from the forecaster that it will rain.

In order to create better ways of communicating uncertainty to end users, it is crucial to understand how forecasters think about uncertainty in the context of severe weather. Unfortunately, there are few studies on forecasters' assessment and understanding of uncertainty. This might account partially for the incongruous communication between forecasters, and eventually, end-users. If forecasters do not have a consistency on their interpretation and communication of uncertainty, conveying this information efficiently to the public becomes a challenge. Here, we will begin to fill this gap by analyzing qualitative data through observations and interviews with forecasters from the National Oceanic and Atmospheric Administration (NOAA) Hazardous Weather Testbed (HWT) 2012 Spring Experiment.

3. METHODS

3.1 Observations from HWT Spring Experiment

The NOAA HWT Spring Experiment is an annual event in which forecasters and researchers from around the country are brought together for a five-week period. During the HWT Spring Experiment a variety of model output is examined and evaluated daily. Consequently, experimental forecasts are created and verified to test the applicability of cutting-edge tools in a simulated forecasting environment (NOAA Hazardous Weather Testbed 2012).

The HWT is divided into the Experimental Warning Program (EWP) and the Experimental Forecasting Program (EFP). The purpose of the EWP is to help transition severe weather research and technology to operations to improve National Weather Service Weather Forecast Offices' (WFO) severe weather warnings for hail, wind, and tornadoes. EFP's purpose is to help transition severe weather and numerical modeling research to operations to improve the Storm Prediction Center's (SPC) watches and outlooks of hazardous convective weather (NOAA Hazardous Weather Testbed 2012).

Observations were recorded during both the EWP and EFP. Participants of the EFP were allowed two hours to make a regional severe weather forecast using convection-allowing models in the style of SPC's convective outlook (e.g., Figure 1). [1](**IRB #:** 0718)

The role of uncertainty in warning decisions made by forecasters was observed during the EWP. Similarly, one afternoon was spent at the WFO, which added data regarding severe weather warnings.

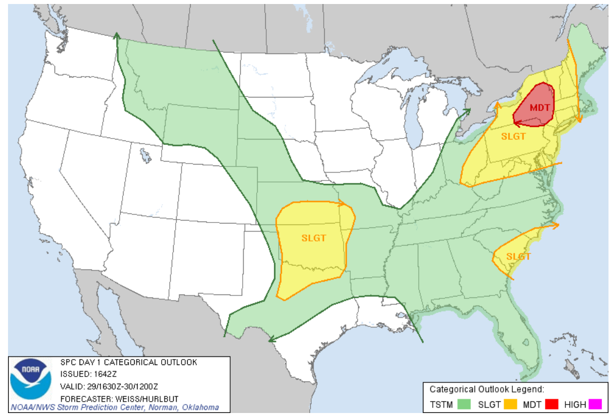

Figure 1. SPC Day 1 Convective Outlook for 5/29/2012

Participant observation is the process of learning through exposure to or improvement in the day-to-day or routine activities of people in a setting (Morss et al. 2007). EFP and EWP observations occurred during the last three weeks of the HWT Spring Experiment. Informal discussions and interaction among participants was observed, especially everything related to uncertainty. Observations from the EWP and EFP were recorded in real time when possible, or soon thereafter.

Around twenty hours of observational data were collected. These observations helped in the acquisition of specific information on how uncertainty is discussed, treated and incorporated into forecasts, creating a good foundation for the interviews. More importantly, observation may filter some of the bias associated with personal interviews. In these, the interviewee might feel pressured to provide certain answers, or fail to provide clear, concise answers to what is being asked. Table 2 shows the amount of hours spent at each branch of the HWT Spring Experiment.

HWT Spring Experiment Branch	***Hours***
Experimental Forecasting Program (EFP)	10
Experimental Warning Program (EWP)	6
Weather Forecast Office***** (WFO)	4
Total Hours	20
* Not part of the HWT Spring Experiment, but was part of the data collection.	

Table 2. Hours spent at HWT Spring Experiment 2012

[1] **(IRB #: 0718)** - Approval from Institutional Review Board for the Protection of Human Subjects.

3.2 In-Person Interviews

In order to get a more complete understanding of how forecasters think about and communicate uncertainty, interviews were carried out to allow for direct questions about uncertainty to be asked. Some of the research and operational forecasters that participated in the Spring Experiment were asked to take part in the study, depending on their availability and within time constraints. Ten interviews were conducted. Table 3 shows the positions, years of experience and current location of the interviewees. Most of the interviewees were experienced forecasters; 80% had worked for 10 or more years.

Interview	*Position*	*Years of Experience*	*Location*
R01	Research Forecaster	20	Colorado
R02	Operational Forecaster	5	Maryland
R03	Research Forecaster	50	Colorado
R04	Operational Forecaster	32	Oklahoma
R05	Operational Forecaster	14	Oklahoma
R06	Research Forecaster	8	Oklahoma
R07	Operational Forecaster	15	Michigan
R08	Operational Forecaster	10	Oklahoma
R09	Operational Forecaster	13	Oklahoma
R10	Operational Forecaster	25	Oklahoma

Table 3. Position, years of experience, and location in which the participant worked. The location reflects the state in which the interviewee worked at the time of the interview. However, it is likely that most if not all of the interviewees have worked in more than one location during their career due to the dynamic nature of the forecasting field.

The interview questionnaire was originally composed of fifteen open-ended questions that allowed flexibility, follow-up questions and discussion. The questionnaire was refined slightly after the fifth interview. The order of the questions was modified somewhat to allow for a better flow of ideas, and three additional questions were incorporated in order to obtain more information from the interviewees. Appendix A shows the original interview questions; Appendix B shows the additional three questions, plus the modifications made to question numbers five (Q05) and ten (Q10).

The interviews lasted between 30 minutes and 60 minutes, depending on the amount of information the participant chose to provide. Each interview was recorded and transcribed**.** However, no personal information about the interviewees other than their years of experience, position and state in which they worked was retained.

3.3 Data Analysis

All the data obtained from the HWT observations and interviews were analyzed inductively, allowing for specific concepts and relationships to emerge from the data. This involved reading through the data and developing themes to describe and organize the data.

4. FORECASTERS' DEFINITION OF UNCERTAINTY

When asked to describe an event in which uncertainty played a big role during the forecast, every interviewee mentioned that uncertainty was always part of the forecast. It took them some time to think about a specific event, given that they had so many examples. As noted in the interviews, forecasters are aware of the uncertainty present in weather; they know and understand that -- given the dynamic characteristics of the atmosphere – it is impossible not to have at least some degree of uncertainty. However, the interviewees were unable to quantify it. [2]R02 mentioned that "the challenge is quantifying it, and then knowing how to best convey it in a sense that's useful."

Even though the interviewees agreed that uncertainty is inherent in a forecast, the way in which they defined it differed. Half of the interviewees said that uncertainty means not knowing what is going to happen next, while four of them defined it as a range of possible outcomes, like having a spread of possible solutions. Only one of the interviewees defined it in probabilistic terms, mentioning that "if confidence is less than 60%-70%, then there is uncertainty."

The relationship between confidence and uncertainty also varied among the participants. Four participants said that confidence and uncertainty are inversely related, meaning that there is more uncertainty when there is less confidence, and vice versa. However, six of the interviewees said that they are related, but not

[2] R02- Refers to Interview No. 2. See Table 3

quite the same, implying that they are somewhat interchangeable terms.

4.1 Verbal and Graphical Representation of Uncertainty

The way forecasters communicate uncertainty verbally depends on the group with whom they are talking. As observed in the interviews and the HWT, forecasters prefer to use probabilistic terms among each other because these probability values reflect their level of confidence. Although they disagree on their definition of uncertainty, they all turn to probability when communicating uncertainty among each other. Murphy (1991) explained that probability is the language of uncertainty because it enables forecasters to have a quantitative framework within which the likelihood of severe weather events can be evaluated. Therefore, forecasters use probability as their common language of uncertainty.

On the other hand, most of the participants said they rarely use probabilities or numbers in general, to communicate uncertainty information to non-scientists. Eight out of ten interviewees said they use hedging terms such as "*May happen*", "*There's a low or a high chance*", "*No doubt this is going to happen*", "*It will definitely rain today*", or "*We'll probably get some snow today*" to explain weather uncertainty to non-scientists. The other two interviewees said they use the odds definitions to explain uncertainty to non-scientists. For example, R01 mentioned that "to someone in the public you can use marbles or flipping a coin a certain number of times and have heads versus tails to describe the probability forecast." Some interviewees thought that the public does not always understand the probabilistic values involved in the forecast. As previously mentioned, the public tends to relate higher probabilities to severity of the event, instead of higher chances of the event occurring. Therefore, most forecasters avoid using probabilistic values when talking to the non-scientists, such as family members and friends.

Conveying uncertainty graphically is more challenging than conveying it verbally. Eight interviewees said that they need words to accompany the image, such as a [3]*"See Text"* area where they can include a brief discussion regarding the event (e.g., Figure 2). These interviewees mentioned that using lines to convey spatial uncertainty graphically is not effective and they need words to support their graphics. Eighty percent of our interviewees stated their concern on the current method of portraying spatial graphical uncertainty and how inefficient it is. "Fuzzy areas are better because they represent the in-and-close spatial areas, while lines represent hard boundaries; they don't represent well the uncertainty you want to depict in the graphics" mentioned R10. Expressing spatial uncertainty with lines might convey false certainty to users, which could affect their decision-making. According to them, there needs to be another method that implies that the boundaries set by these lines are not certain, which means that the severe weather event is not specific to the enclosed region, but also to adjacent areas.

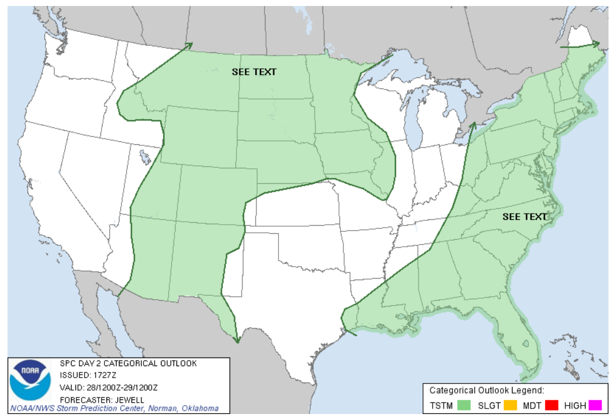

Figure 2. SPC Convective Outlook. *See Text* areas are necessary to explain graphical uncertainty.

4.2 Role of the Internal Climatology

The innumerable amount of observational, model and other types of data forecasters have to go through before issuing their forecast nowadays calls for an internal climatology. In order to assimilate, integrate and interpret all these available data, forecasters refer to this mental tool. The internal climatology is a mental model of weather that forecasters develop after years of experience in the field. They use this tool to recognize meteorological patterns and select meteorological features on which to focus their information-gathering and forecasting skills (Morss 2007). R10 said:

> *You try to learn from mistakes in this business; you learn from unanticipated events, going back to see what happened and that's what makes up your internal climatology. It increases your level of confidence when you have an event you can relate to*.

[3] "See Text" - Refers to a written discussion on the SPC convective outlook product.

Three interviewees pointed out the usefulness of their internal climatology when assessing uncertainty from numerical model solutions. They mentioned that sometimes they see the models coming up with bizarre solutions that they, as experienced forecasters, feel do not portray the real atmospheric conditions. Their internal climatology helps them figure out how to handle these situations, allowing them to see beyond the model solutions.

Similarly, one of the interviewees mentioned that it can sometimes be challenging to issue a forecast in the allotted time because they do not know what is going to happen. However, saying "I don't know" is not an option. A forecast product is always due no matter how uncertain the forecaster is. At this time, the internal climatology is the only remaining tool the forecaster can employ to deliver the most accurate forecast possible. "You're not going to last very long if you say '*I don't know'*, even if that's how you feel," mentioned R10.

4.3 Absence of Conceptual Model of Uncertainty

When the interviewees were asked if they had a conceptual model of uncertainty, 60% described a conceptual model of weather, but not a conceptual model of uncertainty. The conceptual model of weather is an analog of their internal climatology. R05 said that "the conceptual model builds more around a specific forecast scenario and not so much the uncertainty". Similarly, R06 commented:

> *When I think about a conceptual model I see a given scenario. I have an idea of how the storm will develop given a certain situation, and if a numerical model has a solution that doesn't make any sense, my conceptual model will come into play. However, it is not a way to evaluate uncertainty.*

Nonetheless, R02 said that "my conceptual model was based on a spread of solutions, and how well the models depicted the initial conditions." Based on this, 40% of the interviewees said that their uncertainty will increase or decrease; depending on how accurate the models assimilated the initial conditions. Their conceptual model revolves around how much confidence they derive from the numerical models. If the models are showing agreement, then their uncertainty decreases. However, if a consensus among model solutions does not exist, then the uncertainty increases.

5. SOME UNCERTAINTY FACTORS

5.1 Non-Meteorological Factors Influencing Spatial Uncertainty

As discussed in section 4.1, most forecasters find graphical uncertainty harder to convey than verbal, especially spatial uncertainty. Deciding which areas to include in the severe weather forecast and what probabilities to assign to these areas is a major challenge that forecasters face. On 29 May 2012, HWT participants who were working in the Severe Weather side of the EFP issued high probabilities (>30%) of severe weather for Kansas, Oklahoma and northern Texas. It turned out that population size played a big role in their decision. The models were showing convection developing close to Oklahoma City, where the population is almost 600,000. Even though high uncertainty existed as to whether or not the event was going to unfold, a 30% probability was issued, and the areal coverage was extended beyond the area that the models were showing. One of the participants mentioned that they needed to "*be safe*" about this forecast given the high population in the area.

This expression was quite common in the EFP whenever the forecasters were dealing with heavily populated regions. In contrast, on 6 June 2012 northeastern Colorado and western Nebraska were expected to see severe weather, which are lightly populated. This time, forecasters decided not to issue anything higher than 15% because of the low population.

"Be safe" meant to expand the probability lines farther out than what the models showed. Forecasters used this expression as a method to assess spatial uncertainty. There were two main reasons they tried to keep it "safe" in high population areas: 1) verification and 2) impact.

Figures 3A shows the forecast issued for May 29th, when higher probabilistic values (30%) were assigned given the large population size in the region. On the other hand, Figure 3B shows the forecast issued for June 6th, when lower probabilities (15%) were assigned due to the small population size in this region. Even though forecasters were certain about the event on June 6th, they did not issue probabilities above 15% due to the small population in the area.

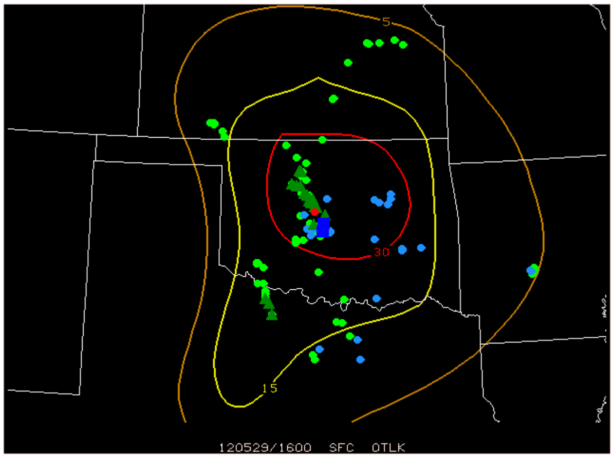

Figure 3A. 16-12Z Manual Forecasts for 5/29/2012

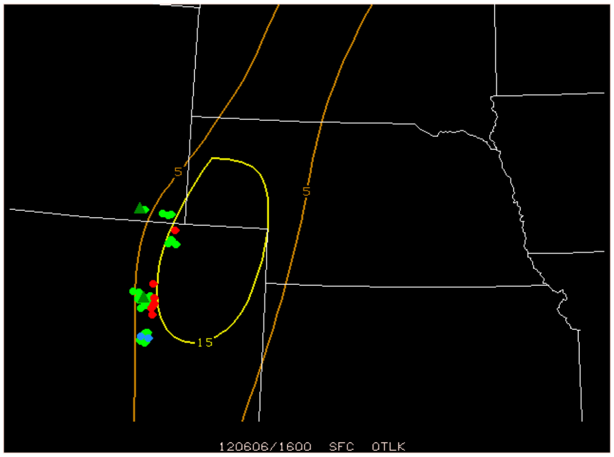

Figure 3B. 16-12Z Manual Forecasts for 6/06/2012

5.1.1 Verification

As population size increases, so does the probability of receiving verification for the issued forecast. Given that forecasters are graded on verification of the watches and warnings they issue, population size is an important non-meteorological factor during warning decisions. If a forecaster issues a tornado warning and does not receive verification of it, then he or she does not know whether it actually occurred or not. Also, the forecaster's statistics drop, and so do those of the weather forecasting office. Verification is a very important aspect of the forecast because it increases the credibility of the forecast and, as mentioned by R01:

> Y*our office statistics are gonna look good. Verification is really subject to a lot of gaming; if there's severe weather going on in a place where there's no one, forecasters are not gonna worry about it, they won't issue a warning*.

Therefore, knowing whether their forecast will be verified or not affects the spatial coverage of the forecast, and the probability they assign to this area. Forecasters keep it "safe" by covering as much area as necessary during severe weather events where population is large to increase their chances of getting verification. All of the interviewees mentioned that population is the most important non-meteorological variable they consider during severe weather forecasts.

5.1.2 Impact-Based Decision-Making

There is a higher probability that severe weather will impact someone in a highly populated area. Expanding the spatial coverage not only helps with forecast verification, but also with saving lives. Areas of high population density are more prone to considerable damage and loss of life than those with very low population density. Forecasters are more likely to increase the spatial coverage of their forecast and issue higher probabilistic values (>30%) in these areas in order to create awareness of the severe weather event among the public. R07 mentioned that:

> *Population is a big one (or lack of it). That's our big one to the point that if we know there's heavy snow falling on No Man's Land, we just look the other way and hope it goes down. It's not the best thing, but it's what we do.*

Similarly, R10 said:

> *I issued a watch in large U.S city during Memorial Day Weekend. It wasn't a very high-end event, and I knew the chances were pretty low, but I didn't want a damaging wind-event during Memorial Day Weekend in such a big city without a watch*.

The way the forecasters in this study assessed spatial uncertainty was based on population size, at least in part, because it affects the chances of verifying the forecast and it helps minimize the socio-economic impact the unfolding event will have by creating awareness through higher probabilistic values.

5.2 Data-Overload

Increasing the amount of available data and numerical model solutions can hurt as much as they can help forecasters during severe weather events. Having more information available does not always mean that it will improve the forecast.

As mentioned by Doswell (2004), it is a concern that this data overload makes it harder for forecasters to know which products are the most helpful and how to use them.

Most of the data overload uncertainty comes from numerical models used in the weather forecasting offices. Question 17 from the revised interview protocol dealt with this topic. Seven of the eight participants who were asked the question said that having too many model solutions available tends to increase their uncertainty in the forecast. When the model solutions are in agreement, there is more certainty in the forecast; when they are not, uncertainty increases. Given that- during severe weather events- models are generally in disagreement, it is fair to say that model solution increases uncertainty in the context of severe weather. R05 mentioned that "with few models you learned biases; you knew if a model was too moist or too cold. With so many different models you simply lose track. It's way too many models to comprehend and to learn from."

In order to assess the uncertainty presented by numerical model solutions, forecasters tend to favor models that consistently do better. They consider the performance of the models based on their knowledge and experience. R02 stated that "forecasters develop a comfort level with different models. Models which consistently demonstrate better skills become preferred, particularly when uncertainty is high. When you don't know what to do, you go with what has been more successful."

Another tool used by forecasters when dealing with data overload is the previously discussed internal climatology. Going back to previous weather events in order to minimize uncertainty often seems to be a reasonable approach. R08 commented that "your internal climatology helps you recognize model data that is not making sense."

5.1.3 Office Dynamics and Uncertainty

Office dynamics play an important role in the way uncertainty is inherited from forecaster to forecaster. Forecasters incorporate inherited uncertainty from their colleagues during shift changes through forecast products and discussion, and also through scheduled and spontaneous interactions. Forecasters' knowledge, experience and interpretations are incorporated into the forecast, creating a human-based ensemble (Morss et al. 2007). R10 mentioned that:

> *The decisions you make are clearly influenced by the people you interact with. All the interaction plays into the decisions that are made, which can be both a good and a bad thing; you're dealing with is a human ensemble*.

As observed by Murphy (1993), communicating forecast uncertainty from forecaster to forecaster represents an extreme form of inconsistency, resulting in reductions in quality and value of the forecast. As mentioned earlier, if forecasters do not have a consistent method to interpret and communicate uncertainty, conveying this information efficiently to the public becomes a challenge.

6. DISCUSSION

In college, future forecasters are taught to observe meteorological parameters such as temperature, dew point, surface pressure among others. This is the first step towards creating a forecast, along with studying surface and upper air maps, sounding analysis and satellite imagery. As students, forecasters are taught to recognize meteorological patterns that help them identify weather scenarios, which build their conceptual model of weather. However, they are never explicitly taught about uncertainty and the role it will play in forecasting. The concept is rather implicitly discussed, given that uncertainty is inherent in weather. It seems very ironic that such an undeniable and significant part of weather forecasting is rarely part of a meteorological education. Once they work in an operational setting, junior forecasters are unprepared to deal with uncertainty.

As observed in this study, even experienced forecasters have difficulty understanding, communicating and assessing uncertainty. After decades of forecasting experience, they lack a conceptual model of uncertainty, and they do not have a consistent method to interpret and communicate uncertainty. This results in ineffective communication among themselves and end-users.

Uncertainty guidance and training should be part of meteorology students' education. As discussed by Novak et al. (2008) and Doswell (2004), education and training on uncertainty interpretation, communication and assessment is necessary to have a better understanding of what uncertainty is in the context of weather.

7. CONCLUSION

This study presented new information about how forecasters think about and communicate uncertainty in the context of severe weather. Through observational data collected during the HWT 2012 Spring Experiment and ten in-person interviews, we analyzed how uncertainty is defined and assessed by research and operational forecasters.

The results showed that, although forecasters are aware of the uncertainty inherent in weather, they are not able to quantify it very well, nor do they have a consensus on its definition. The data from this study revealed that the concept of uncertainty is a very ambiguous term that is hard to define, especially in weather. Forecasters tend to just deal with it in various forms, other than quantifying this uncertainty.

Also, the forecasters did not have a conceptual model of uncertainty. Instead, they had a conceptual model of weather, which is part of their internal climatology, based on previous weather events and recognizable weather patterns. This internal climatology serves as both a tool and a framework to describe and assess uncertainty.

Population is the primary non-meteorological variable that forecasters use to assess spatial uncertainty. Severe weather events unfolding in high population areas are treated with higher probabilistic values and expanded probability areas in order to increase the chances of verification and to minimize impacts by creating awareness of the severe weather event among the public.

Finally, forecasters address uncertainty induced by data overload by developing favoritism for models that consistently demonstrate better skill, particularly when uncertainty is high. Also, forecasters refer to their internal climatology, especially when models are in disagreement and there is a lot of uncertainty. They use their conceptual model of weather to deliver the best forecast.

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9. REFERENCES

Daipha, P., 2012: Weather Risk: Uncertainty, Weather Forecasting, and Expertise. *Sociology Compass,* **6**, 15, doi:http://onlinelibrary.wiley.com/doi/10.1111/j.1751-9020.2011.00437.x/pdf.

Doswell III, C. A., 2004: Weather Forecasting by Humans- Heuristics and Decision Making. *Forecaster's Forum,* **19**, 1115, doi:http://journals.ametsoc.org/doi/pdf/10.1175/WAF-821.1.

Morss, R. E., J. L. Demuth, and J. K. Lazo, 2008: Communicating Uncertainty in Weather Forecasts: A Survey of the U.S Public. *Weather and Forecasting,* **23**, 974, doi:http://www.sip.ucar.edu/publications/PDF/Communicating_Uncertainty_WAF_2008.pdf.

Morss, R. E., M. F. Ralph, 2007: Use of Information by National Weather Service Forecasters and Emergency Managers during CALJET and PACJET- 2001. *Weather and Forecasting,* **22**, 539, doi:http://journals.ametsoc.org/doi/pdf/10.1175/WAF1001.1.

Murphy, A. H., 1991: Probabilities, Odds, and Forecasts of Rare Events. *Weather and Forecasting,* **6**, 302, doi:http://www.swpc.noaa.gov/forecast_verification/Assets/Bibliography/i1520-0434-006-02-0302.pdf.

Murphy, A. H., 1993: What is a Good Forecast?: An Essay on the Nature of Goodness in Weather Forecasting. *Weather and Forecasting,* **8**, 281, doi:http://journals.ametsoc.org/doi/pdf/10.1175/1520-0434%281993%29008%3C0281%3AWIAGFA%3E2.0.CO%3B2.

National Research Council of the National Academies, 2006: *Completing the Forecast: Characterizing and Communicating Uncertainty* *for Better Decisions Using Weather and Climate Forecasts.* The National Academies Press, 112 pp.

NOAA Hazardous Weather Testbed: Bringing Severe Storm Research into Operations. 2012: [Available online at http://hwt.nssl.noaa.gov/].

Novak, D. R., D. R. Bright, and M. J. Brennan, 2008: Operational Forecaster Uncertainty Needs and Future Roles. *Weather and Forecasting,* **23**, 1069, doi:http://journals.ametsoc.org/doi/pdf/10.1175/2008WAF2222142.1.

Appendix A: Interview Protocol

Q1. First of all I'd like to know what your position is (researcher or operational forecaster).

Q2. How long have you worked as a meteorologist?

Q3. What state do you work in?

Q4. Is this the first time you're participating in the HWT? If not, how many years have you participated?

Q5. Can you recall an experience or event in which uncertainty has played a big role? If so, please describe the experience.

Q6. Can you tell us one way or another exactly how you define uncertainty as it relates to weather?

Q7. Do you have a preferred way of explaining uncertainty to somebody else?

Q8. Usually what words or phrases do you use to imply uncertainty?

Q9. And how do you convey uncertainty graphically?

Q10. Is uncertainty something that can be explained without a context (e.g in weather)?

Q11. Do you think that confidence and uncertainty are related?

Q12. Do you use a conceptual model to evaluate uncertainty?

Q13. What meteorological variables do you consider influence major forecast decisions and uncertainties?

Q14. What are social implications or circumstances that affect the decisions in your forecast?

Q15. Which have more weight on your decision-making, objective or subjective measures of uncertainty? Or do they have equal weight?

Appendix B: Revised Protocol with Added Questions

Q1. First of all I'd like to know what your position is (researcher or operational forecaster).

Q2. How long have you worked as a meteorologist?

Q3. What state do you work in?

Q4. Is this the first time you're participating in the HWT? If not, how many years have you participated?

Q5. Can you describe an experience or event in which uncertainty has played a big role during a major forecast decision?

Q6. Can you tell us one way or another exactly how you define uncertainty as it relates to weather?

Q7. Do you have a preferred way of explaining uncertainty to somebody else?

Q8. Usually what words or phrases do you use to imply uncertainty?

Q9. And how do you convey uncertainty graphically?

Q10. Do you draw from your internal climatology when assessing uncertainty during a forecast?

Q11. Do you use a conceptual model to evaluate uncertainty? Do you think that confidence and uncertainty are related?

Q12. Do you think that confidence and uncertainty are related?

Q13. What meteorological variables do you consider influence major forecast decisions and uncertainties?

Q14. Do you think that some models are better than others at evaluating certain meteorological parameters? And does this impact your assessment of uncertainty?

Q15. Do you believe that having many forecast model solutions increases or decreases uncertainty? Why?

Q16. Do you usually take into consideration instrumental error or inaccurate data when making a forecast? And how does this impact your assessment of uncertainty?

Q17. What are social implications or circumstances that affect the decisions in your forecast?

Q18. Which have more weight on your decision-making, objective or subjective measures of uncertainty? Or do they have equal weight?