2.4 HOW METEOROLOGISTS LEARN TO FORECAST THE WEATHER: UNDERSTANDING HUMAN LEARNING IN COMPLEX DOMAINS

Daphne S. LaDue

Doctoral Candidate
Adult & Higher Education Program
Educational Leadership and Policy Studies
University of Oklahoma, Norman, Oklahoma

1. INTRODUCTION

When I first began formulating this dissertation research plan in the mid-2000s, the rather dramatic "no surprise" snowstorm of 24 January 2000 was still recent history. Occurring just one week after the National Weather Service announced that its new supercomputer was leading toward an era of a "no surprise" weather service, it provided a humbling reminder that technology is prone to large, dramatic failures when it is needed most. As that particular event began to unfold, numerical weather prediction models consistently developed a major storm sufficiently far offshore to miss the densely populated east coast of the US.

Only as snow began falling hard in North Carolina, at 1 to 2 inch per hour rates, did models finally begin to correctly forecast the storm track. Updates were made in time for the 11 o'clock news, but many on the east coast had gone to bed, leaving most individuals unaware they would need extra time to attempt to commute to work. Corporations and governments also struggled to adapt to a drastically altered forecast, delaying decisions to close and scrambling to activate road and railway crews (Layton & Sipress, 2000a, 2000b). A *Washington Post* headline dramatically captured a fitting sentiment: "Blindsided and Snowed Under" (Sipress, 2000).

Soon after, Bosart pointed out that forecasters were losing skill—in that particular event, ignoring early indications the models were wrong (2003). It is perhaps astounding that forecasters have much skill, given that we essentially fail to deliberately teach meteorologists how to forecast. The science of human learning in complex domains, however, is still an emerging one. There is no theory to explain how humans learn complex things.

It has now been 11 years since that event. Models are beginning to fairly reliably outperform human forecasters for routine forecasts of certain parameters in many places (e.g., Baars & Mass, 2010), though not for all parameters nor only in the near term (Novak et al., 2011), and models still fail spectacularly at times in high-end events (e.g., 26-27 January 2011 New York City snowstorm). While the National Weather Service begins to consider shifting forecaster duties to one of decision support—requiring deep conceptual understanding from which to help core partners name and frame the weather problem—some private sectors in business and industry are becoming aware of the potential of custom weather and climate information to impact their operations (e.g., apparel: Barbaro, 2007; and energy: J. Duncan, 2011, personal communication).

If learning in complex domains such as forecasting were better understood, it could be better supported. Our colleges and universities could at least teach the underlying metacognitive skills needed, if not begin to facilitate that learning. Employers of forecasters could then hone those skills and deliberately support sustained, complex learning, thus increasing the positive impact of our profession on lives and livelihoods.

2. SIGNIFICANCE OF WEATHER FORECASTS

Estimates on the US susceptibility to weather vary from 3.4% of the US economic output (Lazo & Larsen, 2006) to 25% of the US gross domestic product (National Research Council, 2003). The National Research Council summarized several studies to include these and other impacts from weather and climate in its report, *Fair Weather*:

- $6 to $8 billion in losses from drought
- $11.4 billion losses from tornadoes, hurricanes, and floods
- $4.2 billion in lost efficiency in the airline industry, with 70% of air traffic delays being caused by weather
- disease transmission and various human ailments are either due to or exacerbated by weather

Few specifics may be known about weather impacts on corporations. A snapshot from a high-end event is known: Wal-Mart's Director of Business Continuity described damage, some of it heavy, to over 100 Wal-Mart stores during Hurricane Katrina; several stores were submerged (Jackson, 2006).

[1] *Corresponding author address:* Daphne LaDue, OU Center for Analysis and Prediction of Storms, 120 David L. Boren Blvd, Suite 2500, Norman, Oklahoma 73072, email: dzaras@ou.edu

The National Research Council has also documented significant impacts in areas of improved forecasts. As much as $2.5 billion has been saved through better accuracy and precision in hurricane watches and warnings. Altered agricultural practices from El Nino forecasts save between $265 to $300 million annually. Again, relatively little is documented about corporations. Stories continue to emerge about increased employment of meteorologists and the impact of forecasts on business decisions (e.g., J. Duncan, 2011, personal communication). Weather futures and input to trading and agricultural futures is not new, but still advancing as our understanding of climate forecasting improves. Forecasters have apparently become a new face in the $200 billion American apparel industry (Barbaro, 2007).

3. SETTING THE STAGE: INPUT FROM MANY DISCIPLINES

With the magnitude of weather impacts on individuals, corporations and governments, it seems surprising that so little is written about learning to forecast. Literature within and beyond meteorology was explored to establish the basis for this study. While the length of this section suggests a large body of relevant literature, it is at the same time lacking. Human learning in complex domains is still an advancing area of research.

3.1 *Our Literature in Meteorology*

About 150 years ago, as the era modern meteorology was beginning, forecasting was simultaneously disdained as being akin to activities of charlatans and astrologers, yet valued for maritime activities (Hontarrede, 1998). A few decades later, two world wars benefitted from the military forecasters who then sought civilian forecasting opportunities (Spiegler, 1996). Forecasting became increasingly legitimate and useful for a variety of purposes.

3.1.a. Formal & Professional Preparation

Underscoring the youth of this field, there were only about five graduate programs in meteorology in the 1940s (Allen, 2001). Turner describes some of the shift toward a scientific basis in the twenty years leading up to World War II (2006); today's university meteorology programs are situated in both natural history and physical science departments (Koelsch, 1996). Despite universities training the weather cadets that served in two world wars, Baum (1975) asserted to the World Meteorological Organization that universities should not specifically teach forecasting because it is a particular application of the science.

Today the situation appears mainly as Baum envisioned. My own scan of approximately 20 meteorology department web sites show few list a forecasting course. Many schools are known to promote forecasting activities, however. Such activities have been used to motivate learning in a course for non-majors (Yarger, Gallus Jr., Taber, Boysen, & Castleberry, 2000), and portrayed as a scalable way to engage students and encourage learning from high school through college (Harrington, Cerveny, & Hobgood, 1991). Meaningful forecasting exercises are generally incorporated—after the bulk of science is learned—into courses such as synoptic meteorology (e.g., G. Lackmann, 2011, personal communication; a participant who attended the University of Missouri; and personal experience).

Many papers describe experiences with forecasting contests, but only one studied learning. Most departments run or encourage participation in intercollegiate forecasting contests, the latter begun by the mid 1970s (Meyer, 1986). The experiences seem counterintuitive. Although forecasting is an application of the science, students' skill seems to level off by the 30th forecast (Gedzelman, 1978), students gain skills faster than faculty expect them to (Sanders, 1973), and faculty are apparently unable to outperform students despite having a deeper knowledge of the science (Roebber & Bosart, 1996). Only one study was located that investigated learning in forecasting contests. Market (2006) used writing as a reflective exercise on the forecast process, and studied the impact it had on verification scores. Students had significantly higher skill for precipitation forecasting on days when they wrote a forecast discussion. Temperature scores were not statistically significantly different.

Little is documented about the professional preparation of forecasters. Private sector forecasters participating in this study report mixed experiences; some experienced a training program while others did not. The National Weather Service has a Forecaster Development Course (National Weather Service Training Center, 2006). Units three and four appear by title to cover forecasting, but focus on atmospheric dynamics, specific types of instrumentation and analysis, numerical weather prediction models, and rules for issuing forecast products. There is no ending integration module. This course may not be in wide use any longer, as younger participants either did not mention it or had not taken it.

3.1.b. Nature of Forecasting and Role of Humans

The nature of the forecast task and role of the forecaster are evolving. The latter is certainly becoming better defined as numerical weather prediction continues to improve in accuracy. The consensus of at least two forums on the subject appears to underscore Bosart's (2003) characterization of the weather analysis and forecast task. His six paired elements are: Forecasters must consider what *recently* happened and why, what *is* happening and why, and what *will* happen and why. He pointed out that increasingly good numerical weather prediction encourages forecasters to focus only on what will happen. When models consistently provide a bad forecast, forecasters who do not engage in all six elements may gain confidence in a bad forecast.

The outcome of two recent forums suggests that a reliance on models and shallow engagement with weather is the opposite of what human forecasters should be doing (Sills, 2009; Stuart et al., 2006). Some assert humans retain an important role. For now, forecasters play an important role in for high-end, significant events (e.g. Bosart, 2003; Sills, 2009; Targett, 1994). The day may come very soon when forecasters are able to improve only the short-term forecast (Baars & Mass, 2010) or only certain aspects of forecasts (Novak et al., 2011). Whether forecasters continue to beat models is in question, but not that they continue to add value to users. The National Weather Service (2010) envisions forecasters as providing decision support to users by maintaining situational awareness, focusing on scientific interpretation, and monitoring forecast challenges.

The role of humans could be more than simply assisting decision makers. Homar, Stensrud, Levit & Bright (2006) experimented with having forecasters identify the critical structures likely to impact weather in the following 48 h. Ensembles were then run that specifically perturbed those features. The human-generated perturbations improved model forecasts on days with moderate-to-high probability of severe weather or moderate probability of heavy precipitation. Unfortunately, computing limitations meant that forecasters were not able to learn from experience with the exercise. The authors concluded there was even greater potential to exploit the skill and experience of human forecasters. The work was promising, but continued studies were not funded (D. Stensrud, 2011, personal communication).

3.1.c. Consensus Opinion on Characteristics of a Good Forecaster

The likely shift of the role of forecaster from choosing and tweaking model forecasts to providing sophisticated decision assistance underscores the value of better understanding and facilitating forecaster learning. What skills will be required? Although the question has not been asked in that way, the consensus on 18 characteristics of a good forecaster may apply (Stuart et al., 2006). This "remarkable consensus" was the result of a forum at the 2004 Annual Meeting of the American Meteorological Society (p. 1498). The approximately 200 members who participated widely represented the international meteorological community. I sorted their list of 18 characteristics into two categories:

- <u>Meteorological/technical Skills</u>
    - technologically proficient
    - technologically adaptable
    - synthesize knowledge to useable information
    - learn from past events
    - good diagnosis and prognosis skills
    - assimilate and integrate wide variety of data/information
    - retain objectivity about the forecast
- <u>Personality Components</u>
    - aware of user needs, knowledge, and expectations
    - learn from peers
    - strong interest and passion for meteorology
    - good management and people skills
    - acknowledge others' perspectives
    - honest in communication with other forecasters
    - withstand criticism
    - accept accountability for mistakes
    - stamina for shift work and long hours
    - dedicated to the profession
    - provide feedback to developers/researchers

Participants in the AMS forum underscored notions documented elsewhere as well (e.g., Sills, 2009): that more than ever, forecasters need to have a strong conceptual understanding of the weather, and good analysis and diagnosis skills. Models provide valuable information that can be even more effectively exploited if forecasters are freed from mundane, high-cognitive load tasks to focus on conceptual understanding, assessment of uncertainty, and interpretation and communication to a variety of users and their needs.

3.1.d. Studies of Forecasters

There are approximately four studies of forecasters that vary in focus from identifying the knowledge and skills of expert weather forecasters to a task analysis of warning forecasters. The studies all used decision-making frameworks as their basis to study what forecasters do. Most had a goal of improving training with that information. Most studies involved military forecasters.

Klein Associates scientists led two of the studies. First, a contract with the U.S. Air Force aimed to improve forecaster performance by identifying the knowledge and skills of expert weather forecasters (Pliske et al., 1997). Using the Critical Decision Method in 1–2 hour interviews, 29 Air Force Weather forecasters were initially studied. The researchers added 13 National Weather Service forecasters, eventually concluding the following distinguishing characteristics between expert and non-expert forecasters. Experts identified the challenge of the day, included large-scale perspective, used their own senses in addition to data, formed a mental representation of current weather, and applied that model to forecasts and requests for weather information. The researchers stated they had never studied such a "widely divergent" group of people.

In the second Klein Associates study, the Critical Decision Method was again used in 1.5–2 hour interviews with seven National Weather Service forecasters; all but one had extensive experience (12–20 years) and were in management positions (Hahn, Rall, & Klinger, 2003). This time researchers grouped findings into seven categories. For brevity, one of these categories was a description of the approach to forecasting. Engagement with weather began before they arrived at work. They took a dynamic approach, constantly looking for signals of an unusual event. They used mental models, forming initial models before work and projecting those models in time to watch for signals of an event unfolding other than as anticipated.

The third study also falls under decision making studies, though with the distinction of being naturalistic decision making research, or macrocognition (defined as cognition in natural contexts; Joslyn & Jones, 2008). Four Navy weather forecasters ranging from six months to twenty years experience were recorded and questioned over a two-day period while they made terminal aerodrome forecasts. A follow-up questionnaire verified results. Joslyn and Jones also saw behavior characteristic of both experts and non-experts. Forecast processes had to fit into time constraints, be effective with interruptions, and work for those with limited experience. Most Navy forecasters relied on rules of thumb rather than elaborate mental models, and limited their information-gathering to favored procedures rather than adapting to each situation.

The fourth is documentation of an Air Force contract to elicit expert forecasters' knowledge to create concept maps for training (Hoffman, Coffey, Ford, & Novak, 2006). In this case, the Air Force was interested in capturing not only expertise, but knowledge of local effects. These researchers also found wide variation among the forecasters studied, eventually determining only four of the eight to be experts. The research resulted in 24 concept maps, each with an average of 46 propositions, to form a core of knowledge for that station. A single person reviewed the maps before they were put into use. Younger forecasters liked the resulting interactive, computer-based tool, but older ones did not. The researchers did not report comparing the efficacy of the tool with previous methods for learning.

3.2 Contributions from Other Literatures

The science of human learning in complex domains is an emerging one. There is no theory to explain this learning (nor human learning in general; e.g., Illeris, 2009, is one of several who compiled their works to illustrate the continued development and debate). Many researchers are studying complex learning. Of those literatures, I focus on a few literatures involving adults that appear to study activities similar to forecasting the weather.

3.2.a. Expertise

Forecasting appears similar to how Glaser and Chi (1988) characterize how experts organize knowledge. First, experts excel in their domain, but not necessarily in others. Second, experts recognize large, complex patterns quickly. Third, experts solve problems in their domain much faster than novices. Fourth, experts perform beyond the limitations of working memory because they have automated portions of their thinking. Fifth, experts see more complexity and depth in problems than novices. Sixth, experts spend time understanding a problem before engaging in problem solving. And finally, experts are more likely to realize errors and better monitor their performance.

Expertise and expert performance research studies attempt to identify what distinguishes an expert from a novice or less experienced person. That strand of research has just matured to the point of its first handbook, *The Cambridge Handbook of Expertise and Expert Performance* (Ericsson, Charness, Feltovich, & Hoffman, 2006). Despite the many studies of what constitutes expertise and how to properly study it, there is relatively little on how one learns to become an expert, and there is currently no model encompassing all variables involved in the phenomenon of expertise (Amirault & Branson, 2006). There is also vigorous disagreement in the literature (Howe, Davidson, & Sloboda, 1998) about whether deliberate practice (Ericsson, Krampe, & Tesch-Römer, 1993) or innate ability (Gagné, 2004) account for development of expertise.

A few researchers have developed models that have stood some testing (Alexander, 2003; Prins, Veenman, & Elshout, 2006). Taken together, these studies suggest deliberate practice alone cannot account for development of expertise. This literature is as yet incomplete and does not address how a forecaster could learn skill without knowing the science, or before having learned much of the science. In the domains studied thus far, expertise generally requires 10 years to develop.

3.2.b. Reflective Practice

Donald Schön's notion of a reflective practitioner sounds like a description of a good forecaster. Reflection refers to the thinking one does about what is happening or what has happened, something Bosart asserted was critical to a forecaster (2003). A reflective practitioner is someone who routinely engages in reflection in and/or on their actions because they work in a messy, indeterminate domain where the important problems are not solvable a in straightforward, prescriptive manner (Schön, 1983, 1987). Reflective practice has been studied in many professions and is specifically identified as a competence in some (e.g., medicine: Academy of Medical Royal Colleges, 2005; and nursing: College of Nurses of Ontario, 2005). Using excess cognition to improve practice helps one become an expert and perform at their highest capability. This seems intuitive.

Similar to expertise, however, reflective practice similarly has a mixed literature basis. It may be that some competent adults do not engage in reflective practice (Ferry & Ross-Gordon, 1998), and some professionals do not regard reflection as uniformly positive (Orland-Barak, 2005). A few researchers have shown that reflective practice cannot be considered independently from the larger organization in which the professional works (Heath, 1998; Jones & Stubbe, 2004; Mantzoukas & Jasper, 2004).

3.2.c. Adult Education

The science of human learning is still an emerging one. Researchers have amassed a significant body of literature on experiences, observations, studies, and frameworks for attempting to understand learning, yet these remain at a stage of providing descriptions and a few models—but no theories[1] (Merriam, Caffarella, & Baumgartner, 2007).

Some key concepts from the field include that nearly all adults engage in learning projects in some realm of their lives (Tough, 1979), and that adults are motivated to learn to solve problems (M. S. Knowles, Holton, & Swanson, 1998). The latter is one of what became six characteristics of adult learners that Malcolm Knowles began identifying forty years ago (M. Knowles, 1973). Knowles went on to describe a construct of self-directed learning (1975). Hammon and Collins (1991, p. 13) then expanded on Knowles's definition to emphasize the role of social awareness on learning. In their view, *critical self-directed learning* is defined as:

> ...a process in which learners take the initiative, with the support and collaboration of others, for increasing self- and social awareness; critically analyzing and reflecting on their situations; diagnosing their learning needs with specific reference to competencies they have helped identify; formulating socially and personally relevant learning goals; identifying human and material resources for learning; choosing and implementing appropriate learning strategies; and reflecting on and evaluating their learning.

Some writers suggest there is always a facilitator of some kind (Brockett & Hiemstra, 1993), while others point out the importance of the situation or "organizing circumstance" of the learner (Spear & Mocker, 1984).

Studies of professionals have focused around readiness to self-direct (e.g., Beitler, 2000; Durr, Guglielmino, & Guglielmino, 1996; Guglielmino & Roberts, 1992), identification of self-directing continuing learners (Oddi, 1986), self-directing behaviors (Varlejs, 1999), and indidividual's orientation to self-direction (Merriam et al., 2007). In medicine researchers looked at how physicians sought information online (Casebeer, Bennett, Kristofco, Carillo, & Centor, 2002), and how Schön's reflective practice model might help identify gaps in proficiency to promote self-directed learning (Borduas, Gagnon, Lacoursiere, & Laprise, 2001). The Self-Directed Learning Readiness Scale has been studied more than others, but has serious validity issues (Merriam et al., 2007). Researchers in medicine attempted to create and validate their own scale (Hojat, Veloski, Nasca, Erdmann, & Gonnella, 2006).

The construct of self-directed learning may be one of the most important to consider in forecaster learning, but it does not provide a learning theory to test. If development of forecasting expertise requires the ~10 years found in other domains, then much of a forecaster's competence is gained through self-directed learning. The limitations section of this paper touches into whether all adults can effectively self-direct.

3.2.d. Career Stage and Development

Finally, conceptual work and studies discuss the impact of career stage and development on professional learning. Professionals do not simply climb a ladder of development, but may move sideways, or even downward to begin learning in a new specialty (Houle, 1980). This literature was not studied as extensively as others.

Two studies of learning in professions appear to address learning as affected by career stage and development. Both found that younger professionals tended to prefer informal, social learning resources (Ramming, 1992) or experiential learning methods (Fox, Mazmanian, & Putnam, 1989) when solving specific problems. Young professionals find it difficult to reconcile the complexity of practice with what was learned during formal schooling. Fox et al. investigated how a variety of forces from personal (e.g., a new baby at home) to professional (e.g., the desire to distinguish one's practice) further impacted learning.

The above set of constructs intertwine yet fail to intersect. They have been applied in many domains, but none have been able to establish a comprehensive theory for learning. The educational and related literature cannot provide a single theory of learning that could be applied and tested with how meteorologists learn to forecast.

[1] The authors cited are consistent with others in education in defining theory as "a set of interrelated concepts that explain some aspect of the field in a parsimonious manner" (p. 79).

4. TAKING A GROUNDED THEORY APPROACH

Because there appeared to be no theory of learning that would apply, a grounded theory approach was taken. Grounded theory is an inductive process aimed at identifying the *how* and *why*. Its many tools help researchers to synthesize, develop concepts, and generalize (Morse et al., 2009). This work initially followed Strauss & Corbin's 2nd edition (1998) most closely because it allowed literature as a source for research problems, and provided tools for helping researchers overcome biases resulting from awareness of other researchers' ways of seeing the phenomenon under study.

This work was later informed by additional writings on this evolving research process. After beginning this research, Corbin published a 3rd edition of the work (2008), adding an example to illustrate the process of how she works through interviews. Also extremely helpful in understanding this complex, non-linear process was the book resulting from a dialogue between several researchers who are advancing grounded theory from several epistemological stances (Morse et al., 2009).

A pilot was done with three forecasters ranging from 0 to 40 years experience. The pilot interview focused around critical incidents (e.g., Dunn & Hamilton, 1986). The youngest could recall many incidents, but the middle and late career forecasters had difficulty with this interview approach. The interview guide was modified to several open-ended questions about learning (see Appendix A).

Literature and personal experience suggested there might be at least three factors from which learning might vary. These were: 1) type of forecast, 2) environment being forecasted, and 3) time-in-service. Gender was also considered as a possible factor. Race and ethnicity may be a factor, but could not be studied adequately here (see limitations). All but the last factor were assessed during analysis, and additional factors were considered that analysis suggested might be important. This is a critical element of the process of grounded theory and is referred to as theoretical sampling.

At the point of this writing, 11 participant interviews have been analyzed. Analysis began with the first interview, which was coded in depth. Codes were generalized and grouped. Axial coding explored interrelations between them, and diagrams were created to further explore relationships. Attempt to apply the code set to a second interview was frustrating. A loss of confidence in my initial code set led to trying Lincoln & Guba's (1985) approach to unitizing, sorting, and creating propositions for the sorted units that comprised the seven interviews collected by that point. Diagramming was again done, and this time the resulting code set applied well to the remaining four interviews.

Participants were added according to the factors above, then by including differences in social support and the forecaster's sense of identity as a forecaster. The resulting demographics:

- Time in service:
  - 3 at 1yr
  - 2 at ~4 yrs
  - 3 at ~8 yrs
  - 3 at ~17 yrs
- Employment sector:
  - 4 private sector
  - 7 public sector
- Type of forecasting:
  - 6 routine public sector
  - 1 hydrology
  - 1 agricultural
  - 1 utilities
  - 1 aviation
  - 1 marine
- Gender:
  - 8 males
  - 3 females
- Sense of identity*:
  - very strong as a forecaster
  - mixed with many other life roles

**I am still considering how to best specify the forecaster's sense of identity as I explore its impact on learning.*

After assembling the rough model, stories within each interview were reviewed to verify that the model captured the essence of the story. Small adjustments were made to further simplify the model to the underlying ideas and tentative propositions were drawn which could become a basis for testing.

4.2 *Limitations*

The following limitations may apply to this research. First, forecasters with poor metacognitive skills may be unaware that they are incompetent (Kruger & Dunning, 1999), and thus not engaging in needed learning efforts. Second, Kruger & Dunning showed that the learning strategies undertaken by the less competent were relatively less effective. These two factors will impact the resulting model, but some researchers studying expertise discourage attempting to define "good" or "bad" by any means other than an objective definition of an expert (Sosniak, 2006). Researchers who have studied forecasters presumed it was an area of expertise but then struggled to define an expert forecaster (see literature). More importantly, this study sought to capture learning across time so would require identifying an expert before he or she becomes one.

Third, neither gender nor race/ethnicity were represented well. The small number of participants and lack of funds for travel made it difficult to consider this possible factor in learning. Members of these groups tend to advance quickly or leave shift work for family considerations.

Finally, many researchers favor studying in parallel what people *actually* do (Atkinson, 1997). A prolonged engagement was not possible due to work and time constraints, and this study focuses on several aspects of learning that are not directly observable: what initiates learning, and how resources and strategies are chosen. Grounded theory is a good choice of method to begin this line of study because it takes an open, exploratory approach to seek answers to *how* and *why* meteorologists learn to forecast. Those who continue this line of research can expand our collective understanding by taking different perspectives and approaches.

5. THE EMERGING THEORY

This study is not yet complete. An emerging model, presented in part here, includes four paths through which forecasters built the knowledge structure necessary for forecasting. Additional diagrams illustrate a progression of understanding and how the triggers for learning varied by career stage.

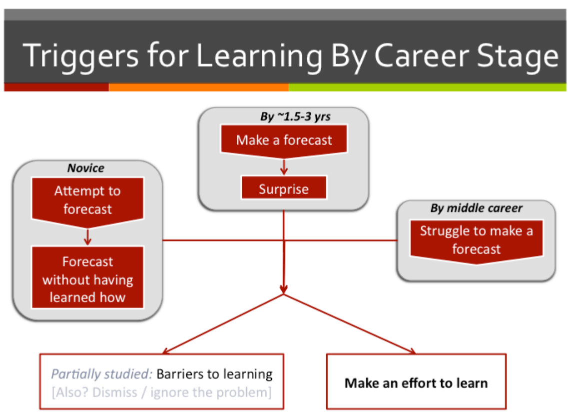

Figure 1: Participants' descriptions of what triggered learning events tended to vary by how long a forecaster had been forecasting a particular type of weather.

5.1 *Triggers for Learning*

Triggers for learning at different career stages is shown in Figure 1. The most common learning trigger for young participants was attempting to forecast without having learned how. Only two participants—both at the same company—went through a formal training program. Young NWS forecasters did not mention the Forecaster Development Course or had not yet taken it.

Most forecasters spoke of mentoring, shadowing other forecasters, and experience forecasting as their primary learning methods as they began their careers. Mentoring was cited most frequently. At three of the four private companies represented, mentoring was the main method of learning. Two of those companies had small staffs and the mentoring was deliberate. Mentoring was also most common among NWS forecasters, but appeared to vary widely. Certain experienced forecasters were particularly meaningful mentors. NWS forecasters did not all experience mentoring and the mentoring experienced varied widely in quality, amount and style.

As forecasters gained some competence, triggers for learning shifted to surprise that a forecast did not verify. This shift appeared to occur most commonly 1.5–3 years into the job. Forecasters reported being able to recognize precursors to phenomena that impacted the weather after seeing them a few times. They also reported a shift from completely missing forecasts of phenomena to beginning to learn the nuances of them.

By middle career, the most common trigger for learning beyond simply staying abreast of gradual changes in numerical weather prediction, was persistent forecast challenges—where the state of art was not sufficient and bothered them. Of the three middle career participants, one was actively pushing the state of art through research. Another was improving his ability to do his job well by collaborating with external partners on data and communication issues. The third had developed a new way of visualizing instability.

While this diagram implies total years experience, at the core was experience with the weather being forecasted. Two forecasters moved to a coastal office and found they were ill-prepared to forecast marine impacts on weather. Others moved to a tropical location after having learned to forecast mid-latitude weather, or from the far northeastern U.S.—where instability will almost always cause severe weather—to Florida, where the atmosphere is frequently unstable and not necessarily causing severe weather. These types of dramatic changes in geography and weather took forecasters back toward, but not quite all the way to a novice position.

5.2 *Progression of Understanding*

Figure 2 is result of information contained within several forecasters' stories and was created while diagramming how code categories related to one another. When looking across forecasters' stories, particularly across those with different numbers of years of experience, a progression of understanding began to emerge. It was checked with two informants, meaning two members of the subject group (forecasters) that were not participants. The concept was stated directly by one participant:

> Probably the most basic change would be in the early years, everything was based on analogs, and pattern recognition, because that's all I had. I didn't have the broader understanding. I have become a little more knowledgeable in the dynamic processes and I can apply that to a pattern and not always come up with what I might have come up with without the dynamic understanding.

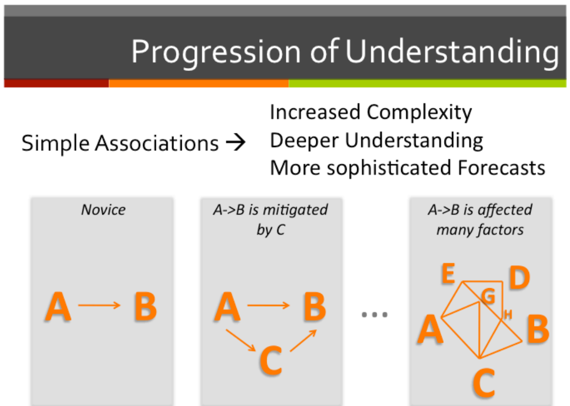

Figure 2: Forecasters appear to be transitioning from initially using rules of thumb and simple associations to gaining a complex, nuanced understanding of those same associations.

Of relevance at this point is the degree to which the participants in this study thought conceptually about the weather when forecasting. Not having queried that directly, information gleaned from participants indicated variation in the extent to which they relied upon and trusted numerical weather prediction. The primary factor was time-in-service, with younger forecasters at times overwhelmed with figuring out which data to focus on, and on task processes such as the use of tools like the graphical forecast editor.

5.3 *Four Paths to Learning*

Four paths to learning represent the learning described by the 11 participants (Fig. 3). These paths do not depend upon time in service, though some are more common at certain experience levels. All four paths end in increased knowledge, though the quality of that knowledge is not assessed in this study.

Moving left to right in Figure 3, Path 1 is one of fast, easy learning, where most of the requisite knowledge is already in place and relatively simple "ah ha!" connections are made. This is the only path that did not necessarily include social interaction. Forest described a particular forecast challenge for which "It took me three months. I kept busting," he said. By working through Path 4, he set the stage for the final connection to be made when working through a COMET module on cold air drainage.

Paths 2 and 3 are very similar, but Path 3 involves requires the forecaster to seek help rather than others initiating help. When others are able to provide help to learn, Path 3 completes in learning. It can also branch into more extensive effort represented in Path 4, and can end in no learning.

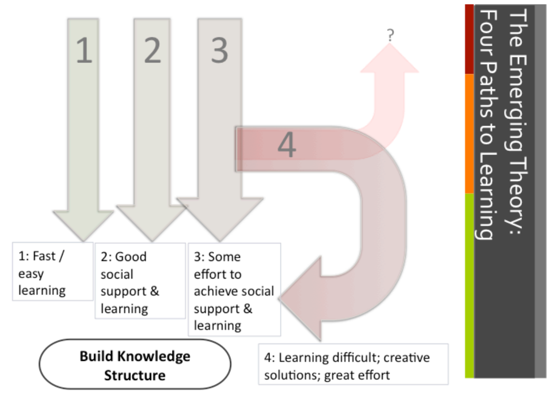

Figure 3: Simplified view of the four paths forecasters took as they learned how to forecast the weather.

Two paths are covered in some detail. The first is Path 2 (Fig. 4), which could be referred to as *smooth sailing.* The entry point is an inability to forecast, often the general inability of a beginning forecaster. In this path, other forecasters take it upon themselves to help you learn. You benefit a great deal from these interactions that help you to see connections and build knowledge. A potential proposition from this path is: *Forecasters build a useful knowledge structure faster with help from others.*

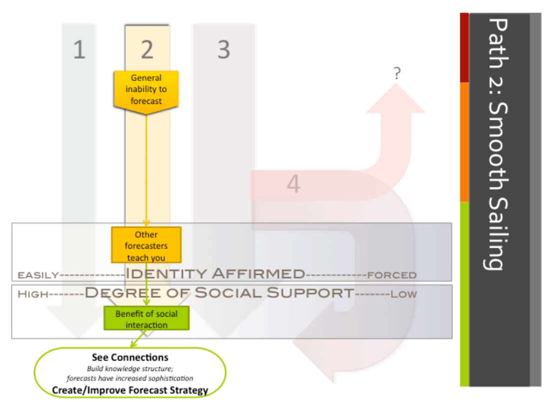

Figure 4: Path 2 represents a fast, easy path to learning because others take initiative to teach.

Examples of beginning forecasters in this path include Raymond, in first job. He "pretty much emulated" his boss when the duties became his. The forecast methods were the basis for Raymond's early forecasting efforts. Tyler "got the most attention" from a retiring meteorologist in that person's last few months. Henry said veteran forecasters were "really helpful" and he "was able to learn a lot faster on how to overcome problems or biases" because of them. In all these instances, the young forecaster did not have to seek help. Further, the young forecaster was readily affirmed by those around them, who had inclination to help and include them.

This learning was sometimes triggered at a particular moment. Forest had a few years experience in other locations before moving to a coastal office. He described the lead forecaster looking over his shoulder on his first weekend there, exclaiming, "You have no idea what you're doing, do you?" Shawn similarly found himself being mentored by an experienced forecaster in his second office.

The notion of the interactions as affirming the forecaster's sense of identity is included in all stories falling here, and was stated outright by some. Cassie started her career in an office where, in stark contrast, she felt unwelcome. The reception in her new office was quite different, with others initiating learning. She no longer had to ask for help. She no longer felt like she was "bothering" others when she sought help from them. Several other participants also made a point of stating they were welcome to ask questions.

Experienced forecasters are in this path as well, using this relatively quick, easy learning to stay abreast of the latest science. They used this path for relatively simple learning tasks. For example, Mike said they talk about events often at work, "especially those of us who've been there for at least 10–15 years...and know each others' interests." Further, Raymond, Lisa, and Forest all spoke of taking initiation to help younger forecasters.

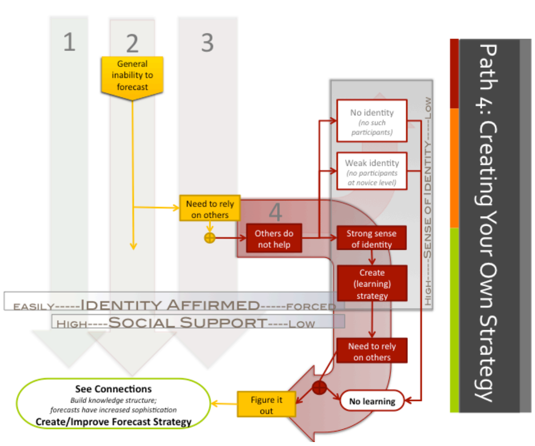

Figure 5: Forecasters had to create their own learning strategy when others either could not or would not help them learn.

Path 4 (Fig. 5) is the longest and contains elements that were particularly significant to the participants. This path branches from either Path 2 or 3—it began either with a general inability or a particular forecast problem in which there was not enough to latch onto to easily solve. Other forecasters either did not or could not help. In diagramming this flow of concepts and how they related, the forecaster's sense of identity drove—and was echoed within—their persistence in creating their own strategies to resolve the situation. The data strongly support the bold, downward portion of the Path 4 arrow, with bits of data to suggest the upward branch. Path 4 ended either with no learning or eventually figuring out the forecast challenge to see connections and build new knowledge. A potential proposition Path 4 is: *Forecasters with a strong sense of identity persist through learning challenges by creating learning strategies.*

Younger forecasters used Path 4 to learn the job and understand the science. Cassie, for example, knew she learned best when she could apply knowledge. When the marine focal point in her office merely referred her to some books, she pitched a compromise that he accepted: "if I do these modules and then if we sit down and talk about it...and show me...I'll learn a lot better and I'll be satisfied. And so we did that." Lisa created a memory trick to help her remember something an experienced forecaster taught her, and conveyed how that helped her remember to look for a particular feature.

Experienced forecasters created strategies to extend the science, build or improve upon their ability to do their job, or keep up with new technology. Henry told of needing to find ways to train and help others maintain their abilities in his specialty area. He also worked hard to identify problems during events and then find solutions to those problems to lessen the chance of the same problem arising again.

Tyler had to both create strategies to learn the science and to extend it, because he does seasonal climate forecasts applied to agriculture. He had created a strategy to carefully document his forecast processes this season so he could assess how well they worked and apply successful aspects again.

Three forecasters provided evidence for an upward branching that may exist to some extent with all forecasters. For Mike, it was a clear sense of what he specialized in. He was conscious of how his strengths complemented others, and at times conducted problem definition studies for others to pursue. Henry had a forecasting challenge for which a new high-resolution research model might assist, so was actively collaborating on a project.

There is also an example of someone with a partial identity, strong in one area but weak in another. Raymond was leading his office in severe weather forecasting and research, but self-identified as poor in snow forecasting. He had previously attempted to learn directly from another forecaster who was good at it, but the other forecaster was not able to articulate what he did. Raymond was still pursuing a strategy at the time of the interview: to have that person or another good snow forecaster in the office lead a simulation on a snow event. Raymond thought that if either forecaster were put into a coaching position, that would begin to figure out how to explain what they did.

Learning did not always happen in the stories forecasters shared. The far right of Figure 5 shows that Paths 2, 3, and 4 can end in no learning. In some cases, there was no time to pursue learning. In others, participants' learning efforts were not successful. In two cases, younger forecasters followed the process of investigation of an event carefully. They related how a more experienced forecaster reviewed data seeking evidence of several possible causes without confirming any of them. Forecasters reported being frustrated when they reviewed events they missed but could not figure out why. Event review was one of their primary strategies for learning.

6. NEXT STEPS

The diagram in Figure 3 was the result of analysis of seven interviews that became the core of the study. Theoretical sampling was done throughout, toward the end pursuing a sense of identity that emerged as a factor in learning. After the additional four participants are fully integrated, the model will be revised, if needed.

It may also be reformulated during completion of the research. Grounded theory is an extensive process. Once a researcher is satisfied with a set of elements and relationships characteristic of a theory that represents the data well, they return to literature to compare their findings. They may then also add additional participants in attempt to confirm and confound the theory. These processes can result in a reformulation of the theory to better reflect how the new ideas fit into the current understanding—and it can also help clarify where the emerging theory provides new or different information.

7. CONCLUDING REMARKS

The science of human learning in general—and in complex domains in particular—is still quite young. There are descriptions, frameworks, and a few models, but no theories. This work currently constitutes a model that contributes to the general science of human learning while studying a particular domain: weather forecasting.

The preliminary findings of this work are that knowledge gained in school is not organized for the particular use of forecasting: forecasters begin their job with a general inability to forecast. Second, many forecasters experience a progression of understanding, moving from simple associations to a deep and complex understanding of weather. The majority of that learning is accomplished in and on the job, and is assisted by others. The processes used to learn appear stable over the course of a career, and independent of geography or type of weather. Finally, forecasters with the strongest senses of vocational identity persist and create strategies to learn (young), or to push the state of the art in their ability to do their job (experienced).

The title of this work is perhaps grand but often used for a first foray into a new area of study. It would also suit a compilation of several series of studies that take complementary approaches to more fully explore how meteorologists learn to forecast, and then to investigate and discover nuances in forecaster learning. Grounded theory is an appropriate process to use in an early, exploratory study. Other studies will use other methods, each with unique analysis power to view forecaster learning in different ways.

The role of the human forecaster is not yet lost, though it may presently be moving in a contradictory way from where it will need to be. If visions of the role of the forecaster becoming one of interpreter to a multitude of decision makers are realized, then the forecaster may more than ever need high-quality learning to understand weather processes and impacts. If the forecaster becomes in essence a coach to decision makers, it means the forecaster transitions from tweaking model output to someone who takes a larger view to help another type of professional name and frame how weather impacts their domain (Schön, 1987). In that latter world, a deep understanding of weather processes becomes critical and forecaster learning becomes a priority.

8. ACKNOWLEDGMENTS

Many, many thanks go to the forecasters who shared their trials, tribulations, and successes with learning to forecast. In addition to the useful references cited, I am grateful for the clarity in research processes my original advisor, Dr. Robert D. Fox, and a professor of research methods, Dr. Barbara Greene, instilled in me. As it happened, there was still much to learn about grounded theory in particular, an inherently non-linear process of conducting qualitative research. My journey continued far beyond their mentorship. At this point, my understanding (and any misunderstanding) of the process of grounded theory is mine alone. Finally, this work could not have happened without huge sacrifices of time and the support of my spouse.

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Appendix A

Interview Guide

v.3, 3/5/08
Daphne LaDue
Study: **How meteorologists learn to forecast**

This study follows grounded theory methodology, thus this is a topic-based interview rather than question-specific. Topics are the major headings below.

I. Initiators of learning
  a. When did you first start forecasting?
  b. Did you learn before formal schooling in meteorology?
  c. Where did you earn your meteorology degree(s)?
  d. How long have you been forecasting for your job?
  e. [Main Interview Question:] What has been on your mind in the past year?

II. Reasons for learning
  a. Why? Can you describe how that came to be a focus of your thinking?
  b. Can you describe why that topic stuck when others didn't?

III. How resources and strategies are chosen
  a. What kinds of things have you done to learn / improve / grow that skill or knowledge?
  b. When you've learned about things in the past, how were your actions the same?
    i. ... How were they different?
  c. What is your favorite way to learn now?
    i. ... How has that changed over time?

IV. Role of social interaction
  a. What role have others played in your learning?

V. Role of context
  a. Would this effort have taken place if you were working in another setting? Why or why not?
  b. Does the kind of weather you are learning about make a difference in how you learn?
  c. Do you learn differently for different places?
  d. What barriers or obstacles make learning more difficult or impossible?