11B.4 # IDENTIFYING CRITICAL STRENGTHS AND LIMITATIONS OF CURRENT RADAR SYSTEMS

Jennifer F. Newman[1], Daphne S. LaDue[2], and Pamela L. Heinselman[3]

[2]Center for Analysis and Prediction of Storms
University of Oklahoma, Norman, Oklahoma

[3]Cooperative Institute for Mesoscale Meteorological Studies
University of Oklahoma, Norman, Oklahoma

1. INTRODUCTION

The year 2008 marks the 20th anniversary of the final design for the Weather Surveillance Radar-1988 Doppler (WSR-88D), a mechanically rotating S-band radar. This design milestone was preceded by a ~30-year effort focused on the research and development of Doppler weather radars (Whiton et al. 1998). Prior to its initial acceptance as a replacement radar technology in 1979, was the achievement of nearly 20 years of Doppler weather radar research (1960–1979) and the execution of the Joint Doppler Operational Project (JDOP: 1976–1978). Through the 1980s, the leadership of the Joint System Project Office and continued radar research by scientists of the Interim Operational Test Facility at the National Severe Storms Laboratory (NSSL) brought forth the final design and funding for the WSR-88D network. By 1997 these and other efforts culminated in a network of 158 WSR-88Ds that serve as the primary system used for operational surveillance of radar-detectable weather by the National Oceanic and Atmospheric Administrations' National Weather Service (NOAA NWS; hereafter NWS).

Continuous improvements to the WSR-88D system hardware and products (Crum et al. 1998; Serafin and Wilson 2000) have resulted in significant service improvements, including increased mean warning lead time for tornadoes from 6 to 13 minutes, and reduced tornado-related injuries (40%) and fatalities (45%; Simmons and Sutter 2005). However, the approach of this system toward its 20-year design life cycle (Zrnić et al. 2007), advances in radar technology since the early 1980s, and the lead time involved in the research, development, acquisition, and deployment of new systems have motivated the consideration of a replacement system or family of systems (National Academies 2002; National Academies 2008).

A technology currently under consideration is phased array radar (PAR). PAR technology, employed for decades by the Department of Defense to track aircraft and other airborne targets, is now being examined to assess not only its weather surveillance capabilities (Zrnić et al. 2007; Heinselman et al. 2008), but also its capability to provide simultaneous weather and aircraft surveillance, termed multifunction phased array radar (MPAR; Weber et al. 2007). The unique features of PAR technology are the capabilities to rapidly and adaptively sample storms volumetrically from an S-band antenna in scales of seconds instead of several minutes (Zrnić et al. 2007).

The first comprehensive look at employing MPAR technology was provided by the Joint Action Group for Phased Array Radar Project (JAG/PARP; OFCM 2006). An important component of the JAG/PARP report is a compilation of the current and future federal agency needs that radars can meet. The JAG attained this information through each agency's response, e.g., NOAA/NWS Office of Science and Technology, to a survey. This survey was designed with open-ended questions to attain information about capabilities and requirements of current radar systems, and anticipated additional future needs (Appendix G, OFCM 2006).

Though including federal agency needs in the JAG/PARP report is a noteworthy first step toward the research and development of a replacement radar technology, this research process would strongly benefit by involving a broader spectrum of users of weather radar information. As discussed by Morss et al. (2005),

[1] *Corresponding author address:* Jennifer F. Newman, Cornell Univ. Dept. of Earth and Atmospheric Sciences, Ithaca, NY 14853; e-mail: jfn7@cornell.edu (Newman). Readers may also contact LaDue: dzaras@ou.edu or Heinselman: pam.heinselman@noaa.gov.

incorporating user needs at the beginning and throughout the research and development process is pivotal to producing the most usable scientific knowledge or information. This user inclusive, iterative process is termed “end-to-end-to-end” research (Morss et al. 2005). To maintain the important operational capabilities of the current radar systems, such as the WSR-88D, and address its operational deficiencies, the strengths and limitations of the system and their effects on users must be assessed.

The purpose of this study is to explore the strengths and limitations of current radar systems identified by users within two stakeholder groups: NOAA NWS and broadcast meteorologists. NWS meteorologists were chosen because the mission of the National Weather Service makes clear the central role of the NWS in providing weather forecasts and warnings, as well as most of the weather data then used by others (see "NWS Mission" footnote). Current radar systems, in particular the WSR-88D, are important data sources used in the production of NWS products. Broadcast meteorologists represent a second, critically important stakeholder group. Several studies have confirmed that most people receive and monitor weather information from their local TV broadcasters, be it during severe convective weather (e.g., Legates and Biddle 1999, and Schmidlin and King 1997), flooding (e.g., Hayden et al. 2007), or winter weather (e.g., Drobot 2007).

In this study, PAR is not presupposed as the answer to current radar deficiencies. Instead, the suitability of PAR to stakeholders’ needs is assessed according to users’ lived experiences with weather radars. This approach, called the critical incident technique (CIT), allows us to see and understand users’ current radar needs and how radar capabilities affect operations.

An explanation of the CIT is given in section 2. Section 3 describes the data collection and analysis methodology. The results of the study are discussed in sections 4 and 5, including the role perception of each stakeholder group and the radar strengths and limitations identified by each group. The suitability of phased array radar (PAR) technology to stakeholders’ needs is assessed according to these critical radar capabilities in section 6.

2. CRITICAL INCIDENT TECHNIQUE

The CIT is an effective way of gathering specific, factual information about human behavior. The CIT has been used to conduct studies in a variety of fields and is a popular, easily adaptable method in qualitative research (e.g., Oliver and Roos 2003; Kraaijenbrink 2007; Schluter et al. 2008). The CIT was used for this study to attain specific information about radar capabilities and how these capabilities affect operations.

Flanagan (1954) defines an incident as “any observable human activity that is sufficiently complete in itself to permit inferences and predictions to be made about the person performing the act.” A critical incident must have a clear purpose and consequences with definite effects. In this study a “critical incident” is an event that illustrates how the strengths and weaknesses of weather radar affect a meteorologist’s ability to perform his/her job.

The practice of asking for critical incidents can be traced to the studies of Sir Frances Galton during the 19th century. However, the CIT as it is known today began to evolve during World War II. During that time, the United States Air Force needed a way to select and train pilots as quickly as possible. To help them attain this goal, the Air Force enlisted the help of John C. Flanagan and the newly formed Aviation Psychology Program (Flanagan 1954). Their initial study sought to determine why 1,000 pilots had failed training programs and how these programs could be better designed to produce competent pilots. An examination of the pilots’ evaluations revealed many general, stereotypical statements — “lack of inherent flying ability”, “poor judgment”, “insufficient progress.” Flanagan asserted that it would be much more useful if the evaluations contained incidents in which pilots showed these qualities.

To attain this information, Flanagan developed a questionnaire and distributed it to flight instructors, asking them about pilots’ behavior during critical situations, and why this behavior was either effective or ineffective. The information gained from this study helped to develop a new training program for pilots (Flanagan 1954). Under the guidance of Flanagan, the CIT was developed further and given its present name. The CIT is now a common and well-respected method in qualitative research.

Critical incident interviews tend to each include anywhere from a few to several incidents, depending on the length of the interview and story telling propensity of the particular interviewee. If researchers desire to compile a comprehensive list of needs, as many as 100 incidents may be necessary before no new needs arise in interviews (e.g., Dunn and Hamilton 1986). For the purposes of this demonstration study, we needed to scale the work down to a level that could be completed within a six-month time period. Our goal was to identify at least three major operational deficiencies for each stakeholder group and thus illustrate the value this type of approach brings to the early development stages for new technologies.

3. DATA AND METHODOLOGY

The data for the study were collected through interviews with radar users from two key stakeholder groups. The rational for choosing certain participants is explained, along with how interviews were conducted. Because our study plan involved interaction with individuals to elicit stories about their work experiences, all researchers completed online training in how to properly conduct such research. Our study plan was submitted and approved by The University of Oklahoma's Office of Human Research Participant Protection, a.k.a. Institutional Review Board, before data collection began.

Data from interviews is rich and complex, requiring a systematic approach to reliably identifying meaning. Our approach is described. This section then closes with a brief discussion of potential issues of trustworthiness relevant to this study.

3.1. ***Participants***

A purposive sampling strategy (Patton 1990) was used to strategically select participants for interviews. Participants were selected based on their roles during weather events and their radar experience. Our goal was to gather information from people who have worked with a variety of radar systems, both before and after the establishment of the current WSR-88D network, and with people who serve in a variety of roles during weather events. Participants were responsible for providing warning information to a variety of users, which, in turn, strongly affected their use of radar.

Two key stakeholder groups were selected for interviews, NWS meteorologists and broadcast meteorologists. NWS meteorologists were chosen because the mission[+] of the National Weather Service makes clear the central role of the NWS in providing weather forecasts and warnings, as well as most of the weather data then used by others (see "NWS Mission" footnote). Broadcast meteorologists represent a second, and critically important stakeholder group. Several studies have confirmed that most people receive and monitor weather information from their local TV broadcasters, be it during severe convective weather (e.g., Legates and Biddle 1999, and Schmidlin and King 1997), flooding (e.g., Hayden et al. 2007), or winter weather (e.g., Drobot 2007).

In the end, nine interviews were conducted with participants in the Southern Plains of the United States, including five NWS forecasters and four meteorologists from the broadcast community. Of the five participants working at NWS offices, four were in management positions where they played a variety of roles during weather events, and one was a lead forecaster who primarily worked the radar desk during severe weather. Of the four participants working as broadcast meteorologists, three primarily worked as on-air meteorologists, one also did field reporting during weather events, and one was primarily a weather producer.

3.2 ***Interviews***

Interviews were conducted at times and locations convenient to the participants, and used the CIT as described by Dunn and Hamilton (1986). Dunn and Hamilton stress the importance of establishing rapport within the first few minutes of an interview, believing it is counter-productive to ask for critical incidents right away. We established rapport at the beginning of each interview by asking participants to describe their

[+] *NWS Mission: "The National Weather Service provides weather, hydrologic , and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, for the protection of life and property and the enhancement of the national economy. NWS data and products form a national information database and infrastructure which can be used by other governmental agencies, the private sector, the public, and the global community (NWS, 2008)."*

roles and responsibilities during weather events. In the main part of the interview, participants were asked to describe critical incidents in which radar affected their ability to perform their job, and the degree to which this was dependent on the type of weather event or the time of day. Finally, the participants were asked to describe the information they can obtain from current radar systems and how this differs from other radar systems they have used. Participants were also asked to describe their ideal radar system.

3.3 *Coding and Thematic Analysis*

Interviews were first transcribed verbatim in order to put the data in a form conducive to analysis. Transcriptions constitute raw, complex, and undigested data. In order to discover and make sense of that data, transcripts were summarized using a technique known as coding. Coding is a systematic way to organize interview data by applying labels that either summarize themes found in portions of text or are *in vivo* codes, literally the words of the interview (Gibbs 2002). By coding interview transcripts, researchers can more easily identify themes emerging in the data, reorganize data according to similar ideas, and compare ideas across interviews (Patton 2002).

Research design drives both the approach to coding as well as the subsequent analysis. Because this study was an open-ended exploration of what two key stakeholder groups perceived as critical strengths and limitations of current radar systems, a data-driven, thematic analysis was appropriate (Boyatzis 1998). In a data-driven approach, themes emerge naturally from the data rather than being pre-conceived. After initially allowing the data to drive code formation, the researcher might then use theory or prior research to guide articulation of the themes. In our case, the maturation of our codes arose from our questions about how critical strengths and weaknesses of current weather radars affected participants' abilities to fulfill their roles.

Over eighty categories and sub-categories were grouped into themes found across the interviews. Several themes related to aspects of how radar strengths and limitations affected the participants' abilities to fulfill their role, with role emerging as an unexpectedly important theme. The participants' roles provided critical context for how radar was used by each stakeholder group. Additional themes included how radar fit into the larger context of the job for different kinds of weather events, methods of mitigating radar deficiencies, and experiences with other radar systems.

3.4*. Interrater Reliability*

Codes that are consistent have achieved inter-rater reliability (Boyatzis 1998). Two of the researchers (Newman and LaDue) independently coded interview transcripts and grouped codes into themes. A thorough comparison was then done on one interview selected at random. Only minor changes were made to what turned out to be extremely consistent coding schemes. A consensus on codes was easily attained. The inter-rater reliability process helped to assure that the coding was likely repeatable and reliable, and that it was unlikely that any important issues were overlooked.

3.5 *Addressing Trustworthiness*

Addressing biases or sources of error is important for any kind of study and is commonly addressed outright in qualitative research to help readers judge the extent to which they can trust the data and results. Such admission and discussion demonstrates that the researcher is aware of his/her prior beliefs or expectations and is working to handle these as effectively as possible. Personal biases are more obviously in play in qualitative research than in the quantitative approaches more common in meteorology, but are present in both. Methodological researchers in the social sciences have therefore proactively incorporated address of personal biases into research design and analysis strategies in a more thorough way than how most quantitative approaches are undertaken in meteorology.

The inter-rater reliability stage is an important step in establishing trustworthiness because two researchers compare independent analyses, thereby revealing at least some personal insights and biases in the interpretation and summary of verbatim transcript information (Patton 2002; addressed in the previous section). For the critical incident technique specifically, researchers have stressed the importance of addressing biases at each step of the critical incident research process — sampling strategy, data collection, and interpretation (e.g., Flanagan 1954).

Significant bias could obviously arise from who participates in the study (sampling strategy) because this kind of study reflects the participants' concerns and points of view. Readers are informed about the sampling strategy for participants and are discouraged from broadly extending results to all NWS meteorologists and TV broadcasters.

Another bias could arise from when and where data were collected: all nine interviews were conducted during the late spring and early summer in the Southern Plains region. Severe convective weather would naturally be at the forefront of everyone's minds. Severe weather events dominated most of the interviews. To help address this bias, we probed for stories involving a variety of other types of significant weather during the interviews.

The last potential bias for a CIT study—interpretation—could involve not only the researchers' personal interests but also professional ties. Professional biases add a layer of complexity: This study was funded through the NOAA National Severe Storms Laboratory's Multifunction Phased Array Radar project. Funding could conceivably influence the researchers' pursuit of information during interviews and choice of information to highlight in reporting. Three actions were taken to mitigate these potential sources of bias. First, the project was sub-contracted to The University of Oklahoma to a Center for Analysis and Prediction of Storms researcher and a Research Experiences for Undergraduates student, neither of whom have been involved in design or development of replacement technologies for the WSR-88D. Second, the critical incident technique is an open-ended questioning technique that elicits information on the problems interviewees encounter while performing their jobs. Further, the interview format, by nature, brings out whatever issues are prominent on a person's mind (Patton 2002). Third, participants were given an early draft of results and asked whether the results fairly represented their points of view.

4. PARTICIPANTS' PERSPECTIVES ON THEIR ROLE

The interview guide designed for this study began with a question asking each person to explain his or her role during weather events. Answers would assure we were not making incorrect assumptions about what each person actually did, but the question had a second purpose as well. Questions about role would put interviewees at ease, help them get into a frame of mind where they become the teacher to the interviewer, and help the interviewer and interviewee to establish some rapport. In most cases, the interviewee and interviewer (LaDue) did not know each other prior to the interview.

During analysis it became clear that participants' views of their role were a fundamental context for understanding how successes and issues with current radar technology manifested in each participant's work. Explanations of the roles interviewees articulated are presented first so the reader may also gain this insight before delving into the weather-specific successes and issues interviewees related in their interviews.

4.1 *National Weather Service Forecasters*

National Weather Service forecasters said their main role is to make the best forecasts and warnings possible using the latest scientific understanding of weather. During weather situations where radar is a primary tool, one or more forecasters may be dedicated to radar interpretation and issuing warnings. During other types of events, including winter weather, routine roles such as the short-term forecast desk may become the office's most critical responsibility. While some forecasters are assessing the current and anticipated state of the atmosphere and issuing public products, others are coordinating and assuring that external communication channels are working to both provide forecasters with weather reports and to assist certain user groups like city or county officials. Occasionally forecasters have the opportunity to work in an incident meteorologist role, such as working directly and on-site at a wildfire command post.

Forecasters characterized their role as one of driving the warning notification process. Their products are publicly available, and go directly to the public through a few channels like NOAA Weather Radio and some public radio stations. But in many cases NWS information is repackaged by another entity like broadcast meteorologists. While some forecasters are applying current scientific understanding and tools available to assess the weather to issue appropriate forecasts and warnings in a timely manner, other forecasters in each NWS office are receiving and monitoring subsequent communications originating from emergency managers, TV broadcasters, city/county siren systems, etc. The NWS forecasters do what they can to monitor all communications and help drive a consistent warning message.

4.2 *Broadcast Meteorologists*

Broadcast meteorologists stated their main role is to deliver timely, accurate information to the public and inform them of the safety precautions they need to take. All the broadcast meteorologists we spoke with worked at television stations with high-resolution radars that had fast update times of 30 s to one min, which they found extremely useful to do their jobs. By examining their high spatial and temporal resolution data at the lowest elevation angle, broadcast meteorologists are often able to interpret and narrow down the threat area within warnings issued by the NWS.

As part of their role, broadcast meteorologists often show radar images on the air to illustrate the current weather threat to viewers. However, since the general public is not familiar with radar data, they told us that sometimes on-air interpretation was required to help viewers understand what they were seeing. The "big red blobs" were obviously important, but viewers did not necessarily appreciate the importance of a hook echo. Our broadcaster participants all had meteorology degrees (common in the Southern Plains) and so struggled somewhat with being both a meteorologist and a communicator of weather information. They said it is difficult to interpret radar data while the cameras were rolling — while mentally doing a sophisticated radar analysis, they need to be giving simple, understandable information to their viewers.

Although broadcast meteorologists receive up-to-the-minute warnings and other official products issued by the NWS, they wanted to know the reasoning behind these warnings and when the NWS is considering issuing a new warning. All the broadcast meteorologists noted that anticipating warnings issued by the NWS would help them make wiser decisions about when to cut in with severe weather coverage and what information to show or discuss on the air. For example, one broadcast meteorologist mentioned his frustration that on a few occasions, after interrupting regular programming to provide severe weather coverage, he went off-air only to discover that the NWS had just issued a warning. Another broadcaster, however, had the privilege of participating in a chat room with his local NWS office. This broadcaster stated that he greatly benefited from insights provided by the NWS and used the opportunity to provide information from his spotters and viewers back to the NWS.

In closing, the following summary of what interviewees shared about their lived experiences with current radar technology relates strongly to how they view their roles. NWS forecasters are focused more on the pure scientific aspects of weather detection, with attention also given to communication. Broadcasters are focused more on conveying a threat to viewers, with attention also given to a scientific assessment of what is happening. NWS forecasters need to assess the current and likely threats to make warning decisions. Broadcasters need to assess current and likely threats to figure out what their message should be, how urgent it needs to be, and what form that message might take. NWS forecasters focused on radar as a primary decision-making tool. Broadcasters used radar in that way, but focused their stories on how radar could be used to convey a threat to a non-scientist. These complimentary roles are each critically important to what has been called the integrated warning system (Doswell et al. 1999), which is in actuality an ad hoc system of disparate parts that usually desire to function in harmony, each adding value. The integrated warning system does not have an overall structure guiding that interaction and those complementary roles. The functioning of the so-called system depends entirely on the people within it. Our participants were cognizant of playing roles within that ad hoc system and explained their successes and issues with current radar systems within that context.

For the purposes of brevity, "broadcaster" is used to refer to our TV broadcaster participants, "forecaster" to our NWS forecaster participants. Meteorologist is used to refer to both groups at once.

5. SUCCESSES AND ISSUES WITH CURRENT RADAR SYSTEMS

The primary current radar system NWS forecasters used for weather detection was the network of WSR-88Ds. That network was noted for its dependability and availability — unlike many other data sets, such as upper-air, surface, and rain gage data, radar is available throughout the NWS areas of responsibility and is frequently updated. Said one forecaster, “...it’s there twentyfour hours a day and it's pretty reliable, and we've learned to trust the data." Stories focused on radar as a primary tool for many types of weather, such as severe weather, but participants touched into its utility in a wide variety of situations.

Some NWS participants had recently gained access to Terminal Doppler Weather Radar (TDWR). They said TDWR had higher spatial and temporal resolution than WSR-88D, but only specified the time aspect: updates on the order of 1 minute. Stories only conveyed where TDWR added information, neglecting any limitations or problems with that data. Certain types of incidents highlighted the value that high spatial and temporal data is beginning to bring to NWS operations. Those forecaster stories involving TDWR data were very similar to the types of features and information that broadcasters gain from their station radars.

Broadcasters participating in this study all had both a station radar and access to data from the WSR-88D network. WSR-88D data was cited as having better-quality velocity and reflectivity data, detecting echoes at longer ranges and without the major second trip echo problems of television station radars, and always including volumetric scans. At times, WSR-88D reflectivity data were used by itself in a corner or inset graphic to convey threats without breaking into regular programming. One older broadcaster emphatically stated that the WSR-88D, and the subsequent improvement in warnings from the NWS, had made his role much easier to fill.

Broadcasters use WSR-88D information to supplement their own radar data, but update time was a major concern of all broadcast participants. One participant explained that because of financial limitations, his station had to wait up to eight minutes to obtain volumetric scans from the nearest WSR-88D radar. The time delay had a significant impact on them, with the data being essentially "useless" when storms were moving quickly. One pointed out that old data does not help in off-air analyses and cannot be used on-air to convey a *current* threat. One broadcaster characterized the WSR-88D as a "shotgun method" to get an overall picture of everything, but with far less detail and sometimes significant time delay.

All broadcasters spent a significant portion of the interviews talking about how their station radars played a critical part in how they fulfilled their role. When details were given, the station radars were described as 5-cm radars with 0.08° beam widths, approximately 150-m range bins (dependent on choice of PRF), and 30-s to 1-min updates. This high temporal and spatial resolution data was available immediately, providing distinct advantages over WSR-88D data. More than one described how, in a fast scan mode, the station radar data made storms look alive. Station radars were of poorer quality, however, and broadcasters cited many issues that affect their radars. Those radars are subject to the same types of ground clutter issues as the WSR-88D, but then also have a tendency to smear in fast scan modes, have significant 2nd trip echo problems, significant attenuation, and range and velocity folding—the latter beginning as low as 33 mph. None of the broadcaster participants said they were running any local algorithms because of the processing requirements and the length of time needed.

Following are the types of problems or situations that arose in forecaster and broadcaster participants' stories. These problems and situations may not encompass the possible range of ways radar is used in weather contexts; they represent what arose during the nine 1-hour interviews. In most cases, stories helped situate radar in the context of the work challenge, allowing the value and limitations of current radar systems to become clear. The leading section is an example of how more general comments rounded out the content of specific stories. All information in this section arose during interviews.

5.1 *Identifying Storm Type, Strength, and Current and Likely Threats*

NWS forecasters all emphasized, usually at the outset of the interview, that they work to make the best of the science with radar as a primary tool during severe weather situations. Forecasters explained, for example, that science provides 3D conceptual models of severe storm processes that radar then either directly or indirectly indicates, including: bounded weak echo regions, elevated high reflectivity cores, strength of storm updrafts, 3-body scatter spikes, mesocyclones, storm top divergence, rear inflow jets to storm complexes, location and movement of boundaries, surging rear flank downdrafts, tornadoes embedded in precipitation areas, likelihood of widespread wind damage, and storm type. Radar indications of these 3D storm features are critical indicators of storm type, strength, and current and likely threats. In other words, the radar indications of these features are essential to NWS forecasters in making good warning decisions.

Along this general theme, forecaster participants told some stories of how other tools interplayed with radar during specific events. A few stories involved wanting to remain aware of the larger environment and how that might be changing through their forecast area over time. One forecaster gave an example of using a fine-scale numerical weather prediction model to see variations in wind shears within his forecast area. On more than one occasion the fine scale model helped his office anticipate changes in storm type and the onset of damaging weather from changes in the environment, the latter being something a radar cannot usually detect. Forecasters also reported an increasing reliance on environmental clues at longer distances from the radar. Characterizing this sentiment, one forecaster commented that it is easy to concentrate on radar information, so he has to remember to "back out" and look at other data to do the best science. By using environmental clues and model data, forecasters said they could anticipate and watch for radar indications, rather than only react once those indications were prominent.

When the subject of volumetric information arose in interviews with broadcasters, it was in context of monitoring storm trends to help them decide when and how to cover early phases of storm events. They mentioned using trend information in part to try to anticipate warnings from the NWS and to generally keep viewers apprised of changes in storm strength, particularly increases in strength. One broadcaster mentioned using volumetric information specifically in the context of downbursts (see later section on Damaging Winds). But as subsequent sections will reveal, broadcasters' self-identified role of adding meaning and narrowing down the threat area within warning messages from the NWS meant their stories emphasized use of low-level, rapid scan information. In addition, one broadcast meteorologist we spoke with explained that the processing time for a volumetric scan with his radar was so long that his station’s radar was often left on the lowest elevation angle. Again, he was more interested in controlling the radar himself, doing sector scans on storms of interest.

Current radar system configuration provides a challenge. Forecasters said they must learn to remain cognizant of the constantly changing height above ground of where radar is sampling within individual storms as those storms move through a radar domain. This results in at least two challenges for forecasters. One of the older forecasters said younger forecasters have to learn how the same storm features will change in appearance as the storm is sampled at different heights. Another forecaster remarked on the constantly changing magnitude of the distance between the sampled storm feature and the ground. The higher the feature, the less certain they are of where—and whether—that feature is impacting the ground. Broadcasters also mentioned that it was a challenge for them and their competitors to remain cognizant of height-above-ground as they attempted to relate radar information to likely impacts on the ground for their viewers.

5.2 *Anticipating and Detecting Tornadoes*

Not surprisingly, tornado situations dominated stories from our early summer interviews with participants from the Southern Plains. Participants from both sectors wanted to anticipate tornado touchdowns, accurately choose not to warn as much as to accurately warn, and frequently update information for their users. Participants, particularly the broadcaster participants, told many stories related to nonroutine situations where they could see complex tornado processes in unprecedented detail. Otherwise, participants had a tendency to gloss over the well-established, now-routine uses of WSR-88D, emphasizing instead those situations where they had to infer beyond what current radar could directly detect and use additional information to best fulfill their roles.

Now that forecasters have the incredibly valuable velocity information that Doppler radar provides, they have become more aware of how quickly storms can evolve. In particular, they have observed many cases where the transition from a nontornadic to tornadic mode took place between WSR-88D volume scans. Three forecasters had seen people in their office re-start a volumetric scan in order to get a faster update at the lowest elevation angle. Doing so took valuable time away from radar interpretation, but forecasters were strongly motivated to have more frequent scans when marginal or rapidly evolving storms were over urban areas so they could make the most accurate warning decisions.

All NWS forecasters said it was as important to correctly choose *not* to warn as it was to warn, but current radar systems only sometimes provided adequate information to enable forecasters' confidence. One particular instance occurred after many people had gone to bed. The storm was close enough to the WSR-88D that the forecaster could see that the mesocyclone had been undercut, preventing tornado formation. The forecaster was happy to have sufficient radar information to make a correct decision not to warn: He was aware of more than one instance where someone lost their life while taking tornado precautions. Warnings also, he said, cause businesses to close and disruption to those who drive to alternate locations for shelter. Storm spotter information is typically helpful in making up for inadequate radar data, but one forecaster mentioned that many of their storms occur after dark, emphasizing the principal role of radar information during warning events.

Radar was also the primary information going into warning situations for many marginally severe events. In some of those marginal events, particularly those outside spring, spotters are not as alert or numerous. One story illustrated how current systems may not be ideal. In this story, a landspout tornado was correctly inferred because a boundary was likely intersecting with a storm. But the storm was just far enough away from the radar that the actual intersection and subsequent low-level circulation was not sampled. The tornado that occurred was brief but did some minor damage.

Some tornadoes occur with rotation initially only at low levels. In some of those cases, the midlevel mesocyclone that current systems could detect develops only after the tornado is already causing damage. In one forecaster story, a tornado was on the ground for over 6 miles before a classic radar signature was sampled.

When midlevel signatures did show tornadic potential, but storms were far from the radar, forecasters reported their warnings were issued with a different mindset that accounted for detection limitations. Because forecasters have less understanding of what is truly happening near ground level, they tend to issue warnings earlier. One participant added that he is more likely to issue a warning for a storm at a long distance because he often does not have sufficient quality information to help him decide when *not* to warn. Storms are generally tilted or sheared from the vertical, meaning the radar-detected circulation may be several miles from the ground contact. The result of the likelihood of storms being tilted from the vertical, one forecaster reported, is that warnings far from the radar must encompass a larger area due to the inherent uncertainty in ground location.

One broadcast participant similarly noted that WSR-88D network coverage was a limitation at a television station where he had previously worked. That station did not operate its own radar, so broadcast meteorologists there relied completely on the WSR-88D network. After having worked at a television station with its own radar, this participant realized the vital information he had been missing.

Forecaster participants who had access to TDWR data discussed the advantage of having rapid, low-level updates. One forecaster mentioned that greater spatial and temporal resolution at low-elevation angles helped him understand the evolution of short-lived features — “tornado cyclones, tornadic vortex signatures, microbursts, circulations that form on gust fronts.” He described a late spring event in which a violent tornado first touched down in a metropolitan area. TDWR was well-positioned to observe the storm, allowing this forecaster to see a rapidly developing mesocyclone with intense convergence. This information gave the forecaster confidence to intensify his warning message, because he knew tornadic development was imminent. TDWR was also cited as helping narrow down the area encompassed within a warning. One forecaster related an instance where he was fairly confident of a tornado location to within about one-quarter mile.

Broadcasters spent most of their interviews talking about their own radars, particularly in the context of tornado situations. Their radars all had fast, low-level scanning capability and were situated in the metro areas where their viewers were most heavily concentrated. Television station radars at all broadcast participants' stations enabled them to detect small-scale signatures that occurred on time scales of one minute or less. One participant spoke about the detailed storm structures she had never seen before. She stressed the importance of being able to react to these rapid changes, because many recent signatures were significant and produced damage.

Particularly once weather is occurring, broadcasters want to add detail to warnings in order to help viewers understand and properly react to the threats. They described instances where they had confidence to specify exactly where the most dangerous part of the storm was located and relate that threat to where people lived. Broadcasters overlaid their station radar reflectivity data with major road arteries and incorporate information from storm spotters and viewers. Often their confidence came during situations where the small beam width and rapid updates of their television station radars could pinpoint the threat. Just as NWS forecasters felt it was important to accurately *not* warn, broadcasters want to help people know when they will *not* be affected just as much as when they will. For instance, one broadcast participant spoke about a spring 2008 event in which two tornadoes touched down within an hour, producing minor damage in a metropolitan area. Warnings were issued in the middle of the night, and people woke up, confused and scared, to emergency sirens. After examining data from his high-resolution radar, the broadcaster issued statements over the radio that related the tornado locations to familiar streets, assuring people that if they lived west of a particular street, for example, they would be safe. He felt that pinpointing the affected area helped keep people calm during this particular event. Although station radars were clearly superior to WSR-88D in pinpointing threats, one broadcaster said he was aware of a few recent minor events that even station radars were not detecting.

5.3 *Other Types of Damaging Wind Events*

Participants from both sectors made it very clear that downbursts and heatbursts are among the most difficult types of damaging weather to detect with current radar systems. Two forecasters and one broadcaster pointed out that the motion of the falling core in a downburst was essentially tangential to the radar, so was not visualized in velocity information. They went on to explain that inadequate sampling of low levels meant that divergence signatures may not be detected at all, but even where radar does sample at ground level, a divergence signature means damage is already occurring. One broadcaster cited a specific example of a recent, undetected downburst that occurred at 8 o'clock in the morning over a place people were congregating.

Being able to anticipate a downburst was important for our participants and they gave examples of how they attempt to do so. Volumetric information provided the best clues to help forecasters anticipate a downburst. Two forecasters mentioned looking for convergence at midlevels and monitoring surging rear flank downdrafts. One of the forecasters specifically pointed out that the slow volume coverage patterns preclude detecting a rapidly descending core in reflectivity data as the core was still falling. The descending cores typically took place on the order of the time it took to complete a volume scan. TDWR, which is relatively new to NWS operations, was available during one recent downburst situation. The forecaster who mentioned it said TDWR data helped him amplify his warning message. Again, however, the radar was detecting a downburst in-progress.

5.4 *Identifying and Warning For Hail*

Forecasters further explained that because radar is poor at detecting severe winds at ground level, hail is often the basis upon which severe thunderstorm warnings are issued. Current systems do not directly detect hail size. Forecasters cited using 3-body scatter spikes and the height and strength of reflectivities in certain temperature ranges to help them infer the presence of hail. Forecasters also mentioned using environmental information to help decide the likelihood of hail. Most algorithms were unhelpful, though the recent Maximum Expected Hail Size algorithm was citing as being better than past algorithms in indicating storms with hail.

One forecaster illustrated why hail detection can be critical: weather impacts can vary widely depending upon what and how much precipitation is falling. Likewise, warning messages ought to convey the threat accurately. In the case of hail, the same reflectivity signature accompanied by 60 – 70 mph winds could indicate smaller hail that "isn't life threatening" or baseball size hail for which "people ought to be taking tornado precautions." One forecaster related a situation of an early-season, high-precipitation supercell that appeared to have large hail. He was still surprised his office never received reports of anything larger than quarter-size hail during that event.

Broadcasters were also wanting to detect and convey hail threats to viewers. One specifically noted that people can take mitigation actions, such as moving cars into garages, if they have adequate warning of large hail. Broadcasters were all very skeptical of radar-derived hail sizes. One broadcaster, who often reports from the field, said he has become more and more daring to drive into storms to see what is there and has rarely ever found hail as large as radar estimations.

5.5 *Rain Events*

Radar information assists forecasters in knowing the areal extent of rainfall and is sometimes the first indicator of flooding situations. Radar provides information everywhere and approximately every 5 minutes. Gage data varies from manual reports to automated reporting; automated gages may have a slow reporting interval. Although rainfall estimates derived from radar data can be inaccurate, both forecasters and broadcasters said radar at least provides a useful qualitative assessment of where the greatest amounts of rain may have fallen. Forecasters also use storm total, 3-hour, and 1-hour radar-estimates of accumulation. One participant said that he also uses radar during severe weather events to identify the transition from a primarily severe hail and wind phase into a flooding phase, looping base reflectivity to determine where heavy rainfall is starting to occur.

Providing flash flood warnings is a major function of the National Weather Service, but participants said radar-estimated precipitation can be inaccurate, challenging their ability to perform this role well. There are presently two Z-R relationships forecasters use to see the areas of heaviest rainfall. One forecaster said he wished the radar could automatically switch to whichever was the best one for the situation. Broadcasters also had learned not to trust radar-derived rainfall estimates. Participants from both groups emphasized using ground truth to verify amounts.

In the specific case of tropical situations, forecasters pointed out that the radar network configuration hampered adequate sampling. Tropical regime precipitation is generally distributed within the lower levels of storms and so may result in deceivingly light echoes. At far ranges, radar might be sampling above the highest precipitation regions. Tropical rainfall can be intense and surprising in impacts. One forecaster knew of a situation where motorists were caught off-guard when encountering high water on roads that did not normally flood.

5.6 *Monitoring Trends, Evolution, and Transitions*

Time and process are critical in monitoring trends, detecting transitions between weather types, and seeing evolution of the boundary layer and environment prior to the development of weather. Because radar information is available at a 5-min time interval, radar information provides forecasters and broadcasters with a way to monitor many types of trends and transitions, and gain a sense of the processes taking place in the atmosphere.

Forecasters mentioned that they used the time element of radar to help them identify transitions from one type of weather to another. For example, one forecaster noted that because radar was always there and covered a large area, he could use it to look at synoptic-scale changes. Similarly, one broadcaster mentioned using long loops to illustrate the overall movement and development of weather systems to viewers. Another forecaster mentioned using radar loops to anticipate severe thunderstorm winds by watching a precipitation core catch up to the leading edge of thunderstorm outflow. Prior to convection, a forecaster told of a situation where he was waiting for evidence of a deepening surface low. The first indication was when increasing surface winds caused the character of clear air echoes to change. All forecasters and broadcasters told stories of using radar to watch the evolution of mesocyclones and tornadoes.

Broadcasters, and those forecasters who had seen TDWR data, told stories of detecting phenomena that occurred on shorter time scales than what the WSR-88D can detect. As mentioned earlier, storms have rapidly evolved from non-severe to severe modes in between WSR-88D volume scans. Broadcasters told many stories of using the high temporal frequency of station radars to watch incredible detail in tornado formation, evolution, and location. One forecaster said TDWR was helping him see aspects of evolution he knew was happening, but could not see with WSR-88D data.

5.7 *Boundary Detection*

Another strength of radar brought up by all forecaster participants is its ability to detect boundaries; convergence zones and fronts, outflow boundaries, and dry lines are some examples. Boundary identification, evolution, and movement are all critical in anticipating initiation of convection and anticipating likelihood of tornado development. Many stories illustrated various aspects of the importance of boundaries. During the 2008 severe weather season, forecasters watched the evolution and movement of boundaries to anticipate rapid initiation of severe convection. In a different situation, radar information helped forecasters decide *not* to issue a warning because it showed that a rear flank downdraft had undercut a storm circulation. Boundary detection has also been used to predict important wind shifts in nonweather situations. One forecaster recalled a large wildfire that dozens of firefighters were struggling to extinguish. An incoming boundary caused a significant wind shift, and the firefighters had to change their positioning. If radar had not been used to detect this boundary, many firefighters would have been seriously injured or killed. Finally, radar detected the presence of a boundary that likely extended under a storm, helping forecasters correctly infer a landspout tornado that was not otherwise detected. Unfortunately, because boundaries are a relatively low-altitude atmospheric phenomena, radar cannot detect them at distances far from the radar.

5.8 *Frozen Precipitation Events*

In winter situations, forecasters and broadcasters both need to determine the onset, type, and intensity of winter precipitation. They also mentioned that although winter situations generally occur on a large scale, radar helps them identify areas of heavier precipitation or precipitation transitions within the larger event. Participants said they used radar in two additional ways. They looked for an absence of radar echo around the radar to infer that snow was not reaching the ground near the radar. In a different case, one forecaster said he was able to accurately lower forecasted precipitation amounts when those absences of echo near radars did not fill in.

Radar has potential to be a much more useful tool during winter precipitation events. One forecaster mentioned that in certain winter situations snow can grow as it falls, but that the WSR-88D network does not sample low levels in all areas. A light echo has sometimes been deceiving in regard to how much snow was actually falling. Precipitation type and intensity are particularly important in winter situations but are often wrong. "Large, wet snowflakes versus sleet or ice pellets or snow pellets... affects the accumulation," one forecaster said. Both forecasters and broadcasters have found they must supplement radar information with phone calls to obtain ground truth. Such supplementary information is difficult to attain at night, when most people are sleeping. A nighttime start to a recent snow event meant a forecaster had little verification about the event until morning.

5.9 *Detection and Monitoring of Nonweather Events*

Several NWS forecasters stressed the versatility of radar and how it can be used for a variety of different nonweather events. One forecaster mentioned the importance of detecting boundaries and their movement during hazardous material situations. Such information is critical to those officials managing the safety of people nearby. A few participants mentioned using radar to detect smoke plumes from fires and assess how high the smoke was rising. In some of those cases, radar detected wildfires before local officials were aware of them. One participant was able to see debris from a space shuttle reentry on a radar image.

5.10 *Clean and Accurate Data*

Although information about the movement of hydrometeors has been one of the greatest advantages of current radar systems, and has revolutionized storm detection and warning, velocity information from current radar systems remains imperfect. Forecasters cited cases where a storm moved into an area of “purple haze” in WSR-88D data. One forecaster, currently in a management role, said he actively watches for this potential and proactively changes the PRF so his warning forecasters do not have interrupted or “dirty” data.

Because broadcasters had access to relatively clean, high-quality WSR-88D data, they could generally work around the de-aliasing and second-trip echo problems that appeared to be characteristic of both specifications (e.g., 5-cm wavelength) and user settings (e.g., PRF) of their station radars. For example, when showing a particular case of an early-season tornado, one broadcaster showed how his radar had a significant amount of second-trip echoes dirtying the display. He zoomed in on the storm of interest, which he then presented in the very clean, high-resolution image he showed on-air during the event. His station radar clearly showed the defined tornado circulation that was not detectable on the nearby WSR-88D, only 12 miles away, due to its poorer spatial resolution.

No negative comments were made about the quality of TDWR data. Such absence of comments does not mean problems did not exist.

5.11 *Radar Algorithm and Display Tools*

Study participants were also asked about how algorithm output and display tools for radar helped them do their job. These questions were part of the closure phase of the interviews; stories of critical incidents were not requested.

Regarding algorithms, participants in this study generally considered algorithms to be a strength of current radar systems, but they cited significant problems as well. Certain algorithms were used frequently: storm-relative velocity, various precipitation totals for keeping track of rainfall, hail and rotation swaths to monitor potential damage corridors, and reflectivity cores above certain temperatures to assess likelihood of hail. Other algorithms were primarily used as a safety net, particularly when several storms were occurring simultaneously. As mentioned previously, Z-R calculations can lead to inaccurate precipitation estimates, particularly during tropical rain events. Two broadcasters specifically noted that they are hesitant to show the storm total precipitation image on the air, because they know it is often an over or underestimate of the actual rainfall.

Two forecasters discussed the Maximum Expected Size of Hail (MESH) algorithm, which uses a composite of radar data to calculate hail size. These participants found MESH to be much more reliable than traditional hail size algorithms, stating that it is a “quick way to confirm that this [storm] is severe or probably it’s not.”

All the broadcast meteorologists discussed how algorithm information both assists and complicates their role. They have generally become skeptical of algorithm information, though they need and value the potential that algorithms can bring to their role. Algorithm icons can assist them in conveying where tornado threats are most likely, but most situations have many areas flagged where the signature is not necessarily indicative of a tornado. Viewers understand that “big red blobs” (storm cores) are dangerous, but they do not necessarily appreciate how a tornado signature might appear in radar data. One broadcaster mentioned that he has become reluctant to show algorithm output on the air because the numerous icons caused confusion in viewers. But not showing algorithm output had an unanticipated consequence: a viewer called in, accusing him of not caring enough about her area enough to show the little circles. All the broadcast meteorologists stressed the importance of gaining ground truth information to assess the reliability of algorithm output.

Regarding displays, a few forecasters—and all broadcasters—mentioned using Gibson Ridge (GR) software (see http://www.grlevelx.com/) to visualize radar data. Broadcasters said their storm spotters were plotting their GPS position on radar data using the GR software in order to position themselves. Forecasters were using 3D tools, though one specifically said he was not interested in "flying through" a thunderstorm. He did, however, appreciate being able to display radar data akin to the way a storm chaser might visualize the storm from the field. Other participants said they created cross sections of radar reflectivity using the GR software.

Forecasters valued conventional display tools as well. One in particular specifically mentioned using a 4-panel display to monitor storm top divergence and low-level signatures simultaneously. Another mentioned how incredibly useful it was to directly overlay velocity and reflectivity to better understand how features related between the two types of radar information.

Ultimately one forecaster said he created certain displays that "get to the point," showing critical information he had learned to trust, that related to what was "impacting people on the ground." Another said he valued things like the "Springfield curve," that were scientifically based ways to color data to highlight features of significance. Displays needed only to help them distill the important features from data; he did not want to be distracted with long procedures to set them up.

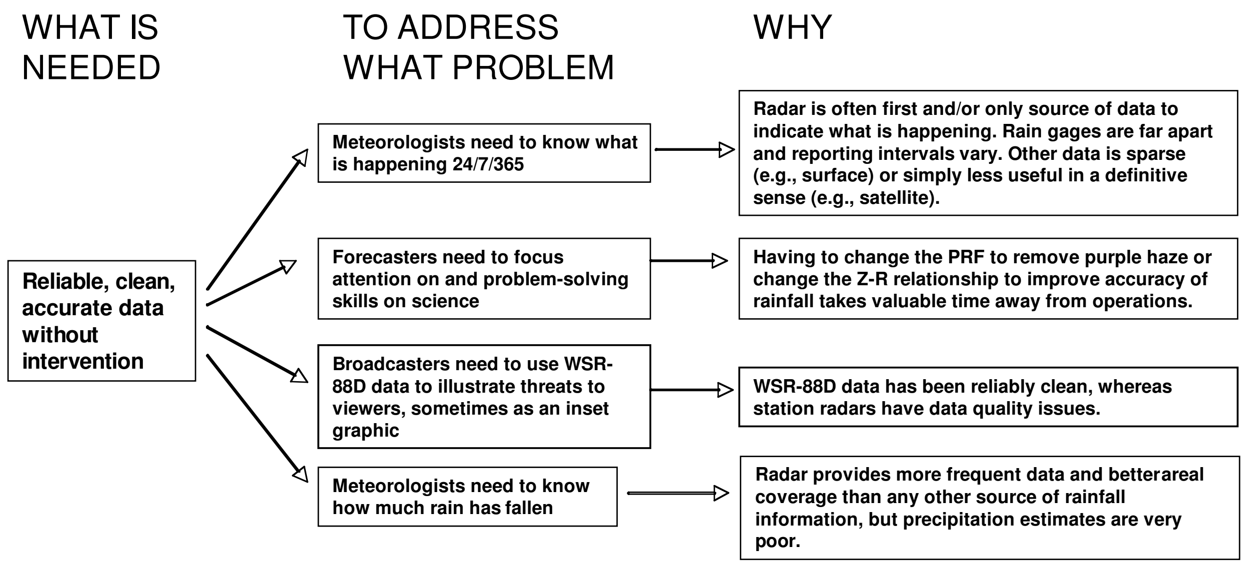

Figure 1: The set of issues in this figure (middle column) are related to one or more radar characteristic or capability that would mitigate that problem (first column). Issues are explained in the last box in each row. This figure shows the issues participants raised that are associated with not having reliable, clean, accurate data or having to manually intervene to assure data is that way.

6. DISCUSSION

The unique strength of study design like this one is that it begins not by asking for a mere summary of what people think, but by asking them to share incidents that demonstrate how successes and issues with weather radars affected their ability to fulfill their roles. This study does not leave the reader wondering what was meant by what a participant said or why they believed a certain item or capability was important. The first section below summarizes the needs participants had in a new system and relates those needs to the issues they raised.

Now that analysis of interviews is complete, the authors reflect on how participants' needs relate to one of the replacement technologies currently under consideration, the multifunction phased array radar, or MPAR.

6.1 *Needs in a New System*

Nearly all issues could be easily summarized into diagrams showing the capabilities or characteristics of weather radar that are needed, what problems that capability or characteristic would address, and why participants said it was important. A few issues appeared related to more than one radar capability. One such issue (precipitation) is listed twice and two others (conceptual models and wildfire smoke detection) are linked to two capabilities. In a big-picture sense, meteorologists said they needed the reliable, clean, and accurate data that WSR-88D currently provides. There were just a few data quality exceptions that required their intervention to mitigate or at least lessen (Fig. 1). Rainfall estimation was included here because of issues with accuracy. Precipitation characteristics are more fully addressed as separate need discussed later in this section.

Figure 2 shows two related needs: high-temporal and high-spatial resolution data. These needs were somewhat separable when considering the issues those characteristics would address. One probable exception was data that would allow meteorologists to recognize conceptual models of storms. Depending on the conceptual model, both capabilities might be necessary.

The characteristic most prominent in participants' stories was the need for consistent data and low-altitude data throughout the forecast or coverage area (Fig. 3). Many important, radar-detectable weather features occur at low altitudes either before or in the absence of midaltitude signatures. Some weather processes only occur at relatively low altitudes: precipitation processes in tropical regimes and snow growth.

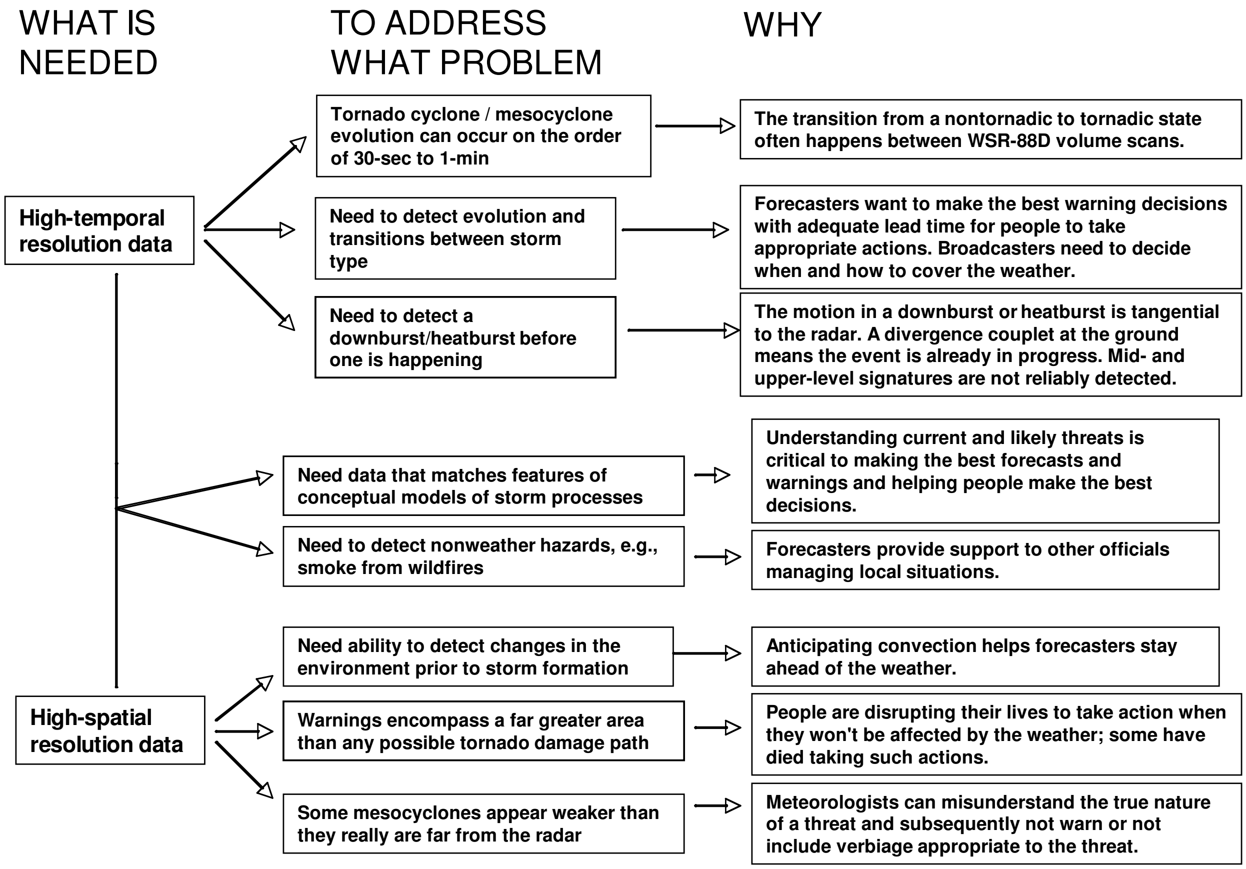

Figure 2: Like Figure 1, except these are issues associated with low temporal or spatial data.

The last several issues, shown in Fig. 4, concerned precipitation type, size, distribution of sizes, and intensity. Meteorologists appreciated the areal coverage of radar and the qualitative sense of how rainfall or other precipitation was distributed across the area, but had learned not to trust radar-derived precipitation totals.

In closing, WSR-88D has revolutionized warnings to the point that forecasters and broadcasters alike are looking beyond to what they believe is possible. Some stories related the inadequacies of WSR-88D while most stories focused on how TDWR or station radars added a great deal of value to the warning and dissemination process.

6.2 *Suitability of PAR to Stakeholders' Needs*

Some aspects of the four major radar needs found in this study (Figs. 1–4) are attainable by the implementation of PAR technology, while others are only attainable by changing current radar characteristics, such as wavelength, beamwidth, or network density.

The need for reliable, clean, and accurate data (Fig. 1) is one that the Radar Operations Center has adeptly attended to since the deployment of the WSR-88D in the 1990s. This need also drove the design decision to deploy S-band rather than C-band radars, because S-band radars are impacted less by undesirable issues such as attenuation, for example (Whiton et al. 1998). As mentioned by interviewees, some methods for producing the data quality needed to best do their job required their intervention. Examples mentioned necessitated adjustments to the PRF or Z-R relationships, or even restarting a volume scan in midcycle to attain higher-temporal resolution data at low elevations. A potential solution to these important issues would be situation-driven adaptive scanning, an advantageous capability of PAR. Additionally, PAR can provide rapid scanning of low elevations without human intervention. Another component to this proposed solution is the implementation of

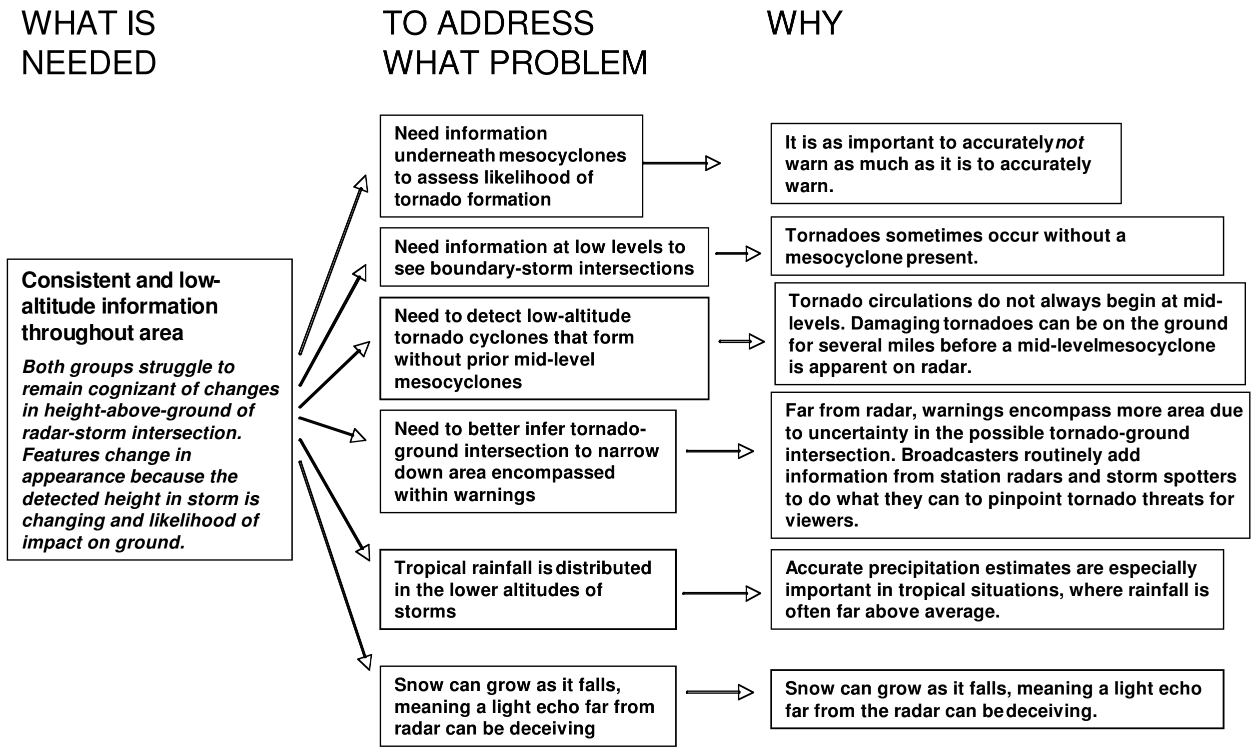

Figure 3: Like Figure 1, except these are issues associated with constantly changing height-above-ground of radar measurements and with the related issue of lack of low-altitude information throughout the radar domain.

dual-polarization, which promises to improve precipitation estimates and employ smart applications of Z-R relations where and when needed (e.g., Giangrande and Ryzhkov 2008).

The need for high-temporal resolution data to better identify and monitor fast evolving precursors to hazardous weather can be resolved by the fast scanning capability of PAR (Fig. 2; Zrnić et al. 2007; Heinselman et al. 2008). An operational, four-faced PAR would volumetrically sample a storm at least four times faster than the WSR-88D. Heinselman et al. (2008) showed the improved depiction of storm processes resulting from volumetric scanning on the order of 1-min for three storm types: a microburst, reintensifying supercell, and hail storm.

In the short term, another option for attaining high-temporal resolution data is to continue the current trend of making TDWR data, which samples the 0.5° elevation angle every min, accessible to the NWS (Istok et al. 2005). Because the TDWR is a C-band radar, it also provides, in the near term, a source for the high-spatial resolution data that meteorologists have found useful (Fig. 2).

Other radar design options could also attain higher resolution data than the current WSR-88D system. Higher spatial sampling may be attained by designing S-band radars with smaller beamwidths, or designing new radars with smaller wavelengths that would be part of a more dense radar network (e.g., McLaughlin et al. 2005). These radar design options also offer a way to provide the consistent and low-altitude information needed by meteorologists.

The need for more accurate information about precipitation type, size, distribution, and intensity is one that will be addressed in the near future by the addition of dual-polarization capability to the WSR-88D network (e.g., Ryzhkov et al. 2005; Scharfenberg et al. 2005). The dual-polarization upgrade will include algorithms that discriminate meteorological from nonmeteorological echoes and classifies a suite of hydrometeor types, such as rain, hail, and snow, for example (e.g., Ryzhkov et al. 2005). This upgrade will also include precipitation estimation

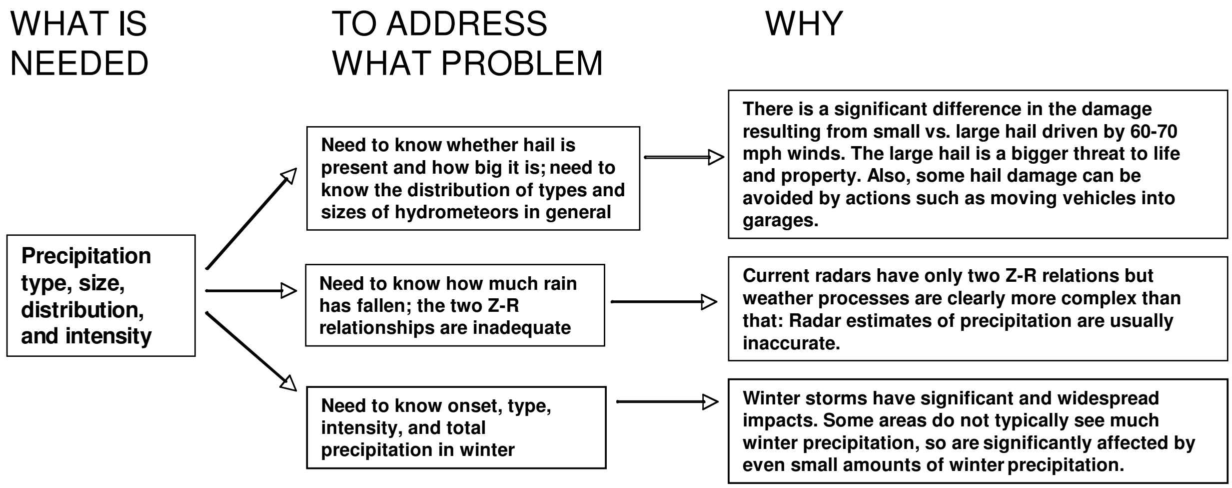

Figure 4: Like Figure 1, except these are issues related to inaccurate information about precipitation.

algorithms that statistically show improvements in accuracy of rainfall rates and amounts (Giangrande and Ryzhkov 2008).

In summary, while PAR technology will not directly fix every radar deficiency in the WSR-88D, its adaptive scanning capabilities have strong potential to address the need for reliable, clean, and accurate data without user intervention. The inherent rapid scanning capabilities of PAR could also provide the high-temporal resolution data needed to better identify and monitor fast evolving precursors of hazardous weather. If, as a community, we decide to take advantage of PAR capabilities, the other stakeholder needs found in this study could be addressed through the development of dual-polarization PAR technology, and the implementation of radars with the wavelengths and network density needed to provide more consistent, low-elevation coverage.

7. SUMMARY

This study is a first interaction with users to provide the kind of information needed for decision-making during early developmental stages of radar technologies new to meteorology. As Morss et al. (2005) point out, this process must become iterative throughout the development if the resulting system is to best meet the information needs of users. This study explores user experiences with the current state of operational technologies and the current state of the science. That background condition will change, especially if WSR-88D replacement is a 20-year development process. An immediate change is on the horizon: dual polarization technology will likely be deployed beginning in 2010.

Nine meteorologists from two key stakeholder groups in the Southern Plains, NWS forecasters and TV broadcasters, were interviewed for this study using the critical incident technique. Through focusing interviews around critical incidents, specific information was attained about current radar capabilities and how those capabilities helped or hindered participants' ability to fulfill their roles. The incidents revealed specific, underlying problems behind participants' needs in weather radar.

The stories told by our participants illustrated why there are still issues with the radar and radar-derived information meteorologists needed to do their jobs. Forecasters spent much of their interviews describing how weather radar played—or could play—a critical role to help them make the most of the science to create the best forecasts and warnings. Broadcasters spent much of their interviews illustrating where and how station radars added critical information that helped them narrow down and specify weather threats to viewers. The resulting portrayal of the needs of these two groups was intertwined. Both have very similar and complementary needs that parallel their self-defined roles. Forecasters focus more on the science with an eye toward communication, whereas broadcasters focus more on communication with attention also paid to the science.

The problems participants spoke of fell into four basic needs. First, meteorologists clearly conveyed the need for reliable, clean, and accurate radar data. Because both groups have intensive responsibilities during hazardous weather situations, they need to attain high quality radar data without their intervention. Second, several stories involved weather situations that evolved more rapidly and on smaller spatial scales than WSR-88D can sample. Third, both groups told stories illustrating advantages of high-resolution and low-altitude station or TDWR radar data, and how the lack of that information in other areas hampered their awareness of the weather that was occurring. Finally, size, distribution and type of hydrometeors in both warm and cold season events were critical information participants could only partially infer in data from current radar systems. For example, both groups told stories where rainfall estimates were only qualitatively useful, and where radar data indicated large hail that was never reported.

These four needs are informative to radar developments currently underway. They indicate potential design requirements for both the technology and the network configuration. The adaptive scanning capability of PAR technology can provide optimized scanning strategies with PRFs and rainfall estimation algorithms appropriate to the current weather situation(s). The complementary fast scanning capability of PAR technology could also provide the high-temporal resolution data needed to better identify and monitor fast evolving precursors of hazardous weather. The need for consistent and low-altitude weather radar information could be partly met by a denser radar network. The fourth need for comprehensive hydrometeor information is already being addressed by the planned upgrade of the WSR-88D network to dual-polarization capability. If the dual-polarization upgrade results in the significant service improvements anticipated, an iteration of this type of study would reveal whether—and why—this capability must be maintained in any new radar system or family of systems.

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