Warning Decision Making: The Relative Roles of Conceptual Models, Technology, Strategy, and Forecaster Expertise on 3 May 1999

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(Manuscript received 28 February 2001, in final form 1 October 2001)

ABSTRACT

This paper examines concepts related to warning decision making for the 3 May 1999 tornado outbreak in central Oklahoma. Sixty-six tornadoes occurred during this outbreak, with 58 occurring in the Norman, Oklahoma, National Weather Service Weather Forecast Office (WFO) area of responsibility. Verification statistics for the event revealed the WFO issued 48 tornado warnings, with a median lead time of 23 min, a false-alarm rate of 0.29, and a probability of detection of 0.89. WFO Norman meteorologists utilized a warning decision-making methodology that relied upon 1) scientifically based conceptual models of storm types and their environments, 2) Doppler radar data, 3) ground-truth observations, 4) technology, 5) strategy, and 6) human expertise. This methodology was compared with the ability of radar algorithms [e.g., Weather Surveillance Radar-1988 Doppler (WSR-88D) Mesocyclone (MA) and Tornado Detection Algorithms (TDA)] to identify tornado threat. Although the steady-state nature of the isolated long-lived tornadic supercells presumably presented an ideal case for algorithm performance, shortcomings were identified. The most significant finding was the difference in median lead times between the WFO's subjective human tornado warning and signature detection by TDA for the first tornado associated with each supercell. The first tornado is especially significant because ground truth of the tornado is not yet available and radar signatures are less defined at this early stage. Median lead times were 2 min for TDA and 29 min for the WFO. The MA and TDA proved most useful when used as a safety net or check against the WFO warnings. The initial tornado warning for one supercell storm would have been delayed had the TDA not alerted the meteorologist to investigate the storm.

1. Introduction

The primary mission of the National Oceanic and Atmospheric Administration National Weather Service (NWS) is to provide weather forecasts and warnings to protect life and property within the United States (NWS 1999). NWS meteorologists rely on a variety of datasets and techniques to accomplish this mission. In the case of convective storms, Doppler radar and ground-truth reports from volunteer weather observers (i.e., ‘‘spotters’’) form the foundation of most warning decisions. Satellite imagery, shear and buoyancy parameters derived from observations and numerical models, and even nonmeteorological considerations contribute to the decision-making process. Advances in computer technology, coupled with a dramatic increase in both variety and quantity of meteorological datasets resulting from NWS modernization (NWS 1999), have led to efforts to automate recognition of convective weather hazards, especially through radar-based algorithms (NEXRAD 1985).

The meteorologist concerned with flash flooding saves enormous time and resources by using radar-derived rainfall R estimates that rely on algorithms versus manually tracking and integrating reflectivity Z using a Z–R relationship. Likewise, the Weather Surveillance Radar-1988 Doppler (WSR-88D) Mesocyclone Algorithm (MA) and Tornado Detection Algorithm (TDA), when used intelligently, help to focus attention on threatening features of convective storms that might go unnoticed in a busy situation. Nevertheless, they do not replace the need for subjective expert assessment of the basic radar data.

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Misuse or overreliance on automation can impair a decision maker's ability to develop and to maintain expertise. Klein (2000) found that cockpit automation had a negative impact on flight skills and critical decision making when commercial pilots relied on automation instead of ''expert'' manual flight techniques. Similar degradation of skill occurred with U.S. Air Force weather forecasters when training efforts focused on automated forecast products instead of fundamental scientific understanding and physically based conceptual forecast models (Pliske et al. 1997). We similarly believe subjective expertise is required to discriminate important radar signatures given that statistical relationships and simplified conceptual models, which often do not account for complex, rare, or unprecedented events, form the basis for most algorithms. Our view of warning decision making and the role of automation is in many ways analogous to the ideas of Snellman (1977) with respect to general weather forecasting.

The 3 May 1999 tornado outbreak across Oklahoma and southern Kansas was unusually prolific. Some 66 tornadoes occurred in this outbreak, with 58 tornadoes occurring in the Norman, Oklahoma (OUN), NWS Weather Forecast Office (WFO) area of responsibility within about 7 h between 2151 and 0436 UTC (Speheger et al. 2002). Several significant challenges faced the NWS warning meteorologists during the event, including 1) the number of tornadoes, 2) the simultaneous occurrence of up to four tornadoes, 3) the intensity and amount of damage, and 4) the locations of tornadoes relative to population centers.

Verification statistics for WFO OUN warning performance show that 79 warnings were issued: 48 for tornadoes and 31 for severe thunderstorms. Statistics were generated by comparing WFO OUN warnings with extensive ground surveys and postevent review of severe-weather reports as described in Speheger et al. (2002). Median warning lead time for all tornadoes was 23 min. The false-alarm rate (FAR) for tornado warnings was 0.29, and the probability of detection (POD) was 0.89. Many factors contributed to the excellent scores attained on 3 May 1999, including well-defined Doppler radar signatures of mesocyclones and tornadic vortices, excellent ground-truth reports by spotters and news media, and careful integration of technology and expertise into the warning decision-making process. Nearly every classic supercell that developed became tornadic and remained so for most of its lifetime. Meteorologists typically face a more diverse convective mode and threat, including a mixture of tornadic supercells, nontornadic supercells, bow echoes, and multicell storms. The steady-state nature of the convective mode and tornado threat on 3 May 1999 helped to streamline the decision-making process. The large isolated storms that resulted were ideal for algorithm identification of features. For the most part, the automated algorithms unfortunately performed poorly for *initial* identification of tornadic threats, and human interpretation of the base data was needed to assess the tornadic threats posed by each storm. It also provided an opportunity to compare the roles of WSR-88D algorithms and human expertise in the warning decision-making process.

Section 2 discusses important elements of the warning decision-making process. Application of the warning decision-making process on 3 May 1999 is discussed in section 3. Section 4 contains concluding remarks.

2. The warning decision-making process

The warning decision-making process employed by WFO Norman endeavors to blend scientifically based conceptual models, certain meteorological datasets, technology, strategy, and, most important, expertise toward the goal of providing clear, concise information about pending dangerous weather conditions. Although the process is subjective in nature and does vary by individual meteorologist, the basic elements of the process share common values and work to help the decision maker to maintain situation awareness (Endsley 1988). The level of situation awareness required in the warning process, in which relevant data are perceived, understood, and projected into future outcomes, is comparable to the highest level Endsley identifies.

a. Scientifically based conceptual models

Before the meteorologist can warn for a particular threat, he or she must first recognize that a threat exists. Many scientifically based conceptual models exist for severe-storm environments (Doswell 1982; Johns and Doswell 1992; Markowski et al. 1998). Recognizing an overall mesoscale environment that favors severe-storm formation and having expectations as to convective mode (e.g., isolated classic supercells vs linear convection) early in the warning decision-making process are important to the meteorologist. These expectations develop in the context of the meteorologist's training and experience with similar environments. The expected evolution of the mesoscale environment, and the likely convective mode, play a large role in WFO staffing decisions and set the stage for the warning decision maker about what types of storm-scale warnings might be necessary. The expected environment and the resulting storm type are an early component of the process, but the meteorologist responsible for issuing warnings must constantly reevaluate these aspects as the event unfolds.

Scientifically based conceptual models remain crucial as the forecast challenge shifts from the mesoscale to the storm scale following convective initiation. A successful warning meteorologist must stay current in the latest severe-storm research and must critically examine any proposed conceptual models. Conceptual models for storm type and evolution presented by Moller et al. (1994) and many others form the template for diagnosing storm structure. Without conceptual models, the meteorologist does not have the means to anticipate intelligently storm evolution and threat and therefore the range of potential outcomes necessary to determine warning content. For example, a tornado is more likely to occur with a classic supercell than a bowing squall line, where damaging wind is often the primary threat. Consider the case of the collapsing supercell: the disappearance of the reflectivity hook and lowering of the storm top could suggest a weakening storm, or, in the eyes of an expert, it might signal tornadogenesis (Lemon 1980). Mesoscale features, such as outflow boundaries, regions of enhanced shear, and locally enhanced CAPE may play a role in tornadogenesis. Spatial and temporal distributions of observations useful for identifying these features are unfortunately often limited, and the integration of these features into conceptual models of storm type remains a topic of debate in the research community.

b. *Important datasets*

Although many datasets play a role in the warning decision-making process, two key datasets have heavy weights in the subjective assessment of storm evolution and threat.

1) DOPPLER RADAR

Doppler radar reflectivity and radial velocity constitute the base data and are indispensable to the warning decision-making process. Crum and Alberty (1993) outline data formats and resolutions available from the WSR-88D. Besides base data (i.e., reflectivity and velocity fields), the WSR-88D provides a variety of algorithm products intended automatically to recognize specific hazards and to alert the meteorologist to them. Although detail of the design and implementation of these algorithms is beyond the scope of this paper, they in general utilize reflectivity and velocity fields to satisfy simple pattern recognition models. For supercell and tornado threat recognition, the MA (Crum and Alberty 1993) and TDA (Mitchell 1995) are most germane to the warning decision-making process. Both algorithms depend upon velocity data, at multiple elevation angles, as their basis for feature detection.

The algorithms show skill, but they also are unfortunately susceptible to radar sampling limitations and data artifacts (e.g., velocity dealiasing failure). Howard et al. (1997) describe sampling limitations of the WSR-88D radar and the resulting degradation of algorithm radar products. In both the MA and TDA, spurious feature detections often arise from incorrectly dealiased velocity information or occasionally in turbulent high-shear regions such as the gust front. These algorithms may also fail to detect important features that do not fit their parameters for feature recognition precisely, especially in storms far from the radar. For these reasons meteorologists must ‘‘check’’ or verify the algorithm-detected features against the radar base data before issuing a warning. The POD and FAR scores for these algorithms, as outlined in Stumpf et al. (1998) and Mitchell et al. (1998), suggest the algorithms best serve the meteorologist in secondary support roles (i.e., safety nets) rather than as primary tools for feature recognition.

Careful scrutiny of base data serves as the primary tool for feature detection. By examining multiple elevation angles of reflectivity and radial velocity data representing low-, mid-, and high-level regions of the storm, typically at 5-min volume scan intervals, the meteorologist attempts to match the storm’s characteristics to a conceptual model of storm type and thus severe-weather threat. The data are carefully monitored for tornadic vortex signatures, trends in mesocyclone strength and depth (Burgess et al. 1993), and reflectivity signatures associated with severe storms and tornadic supercells (Lemon 1980). Unlike the algorithm, the meteorologist can recognize data artifacts quickly and infer features where sampling limitations might prevent automated recognition of storm features. Furthermore, the meteorologist, unlike the WSR-88D algorithm, is not constrained to wait until the volume scan completes before a feature is recognized. Thus, in the time-sensitive circumstances of the WFO, expert subjective analysis of basic reflectivity and velocity is *critical* both to early warnings and to minimization of false alarms.

2) GROUND TRUTH

Ground truth, or in situ observations of the suspect storm’s visual appearance, is the second key dataset supporting the warning decision maker. The observations usually are qualitative in nature and are obtained from volunteer spotters, emergency management officials, news media, or law enforcement personnel. Most of these observers participate in regional NWS-sponsored seminars intended to provide at least a basic understanding of severe-storm structure and visual identification of important storm features. The observations are relayed from the field to the WFO by telephone or amateur radio (McCarthy 2002).

Ground-truth information is the only confirmation that severe weather is occurring. The reports allow the meteorologist to ‘‘calibrate’’ the radar signatures, learn of severe-weather events that may not have been expected, and in turn assess the validity of the working conceptual model of storm type and hazard. Reports of funnel clouds, rotating wall clouds, or other storm structures associated with tornadoes may even enhance warning lead time, especially when radar signatures are ambiguous. The reports can greatly add to the credibility of the warning message and subsequent statements because they represent the highest level of certainty that a threat actually exists.

c. Technology

When applied correctly, technology is invaluable to the warning process. Although the above datasets are technology related, in this section, technology describes principal computer workstations and software that support the warning decision-making process. Without these tools it would be much more challenging for the decision maker to visualize information concerning the environment and radar presentations of storm structure or to compose and to transmit the warning message. In today's modern NWS WFOs, the Advanced Weather Interactive Processing System (AWIPS) is the pivotal piece of technology supporting warning operations. AWIPS is a UNIX-based meteorological workstation that combines information from multiple WSR-88Ds, satellite imagery, other observations, and numerical model forecasts into a common interface. Although the system contains the means to overwhelm meteorologists into ''data paralysis'' by enabling them to display numerous fields in endless combinations, once mastered it becomes a powerful tool. For example, AWIPS enables the meteorologist to monitor mesoscale datasets for changes in stability, shear, and mesoscale boundaries that play potential roles in storm evolution. Most important, AWIPS permits the meteorologist to compare three-dimensional storm structures through matching reflectivity and radial velocity fields at each elevation angle, for up to 32 radar volume scans, for several radars. In practice, most meteorologists find examination of data over four–eight elevation angles and six or fewer volume scans sufficient to identify important trends in storm evolution. Configuring the workstation using a ''four-panel'' or quadrant display mode often aids examination, with each quadrant containing a single elevation angle of paired reflectivity and radial velocity data (Fig. 1). A time lapse of the quadrant display helps the meteorologist to visualize changes to storm structure. The AWIPS software also may display and combine the previously discussed algorithm-derived WSR-88D radar products with other datasets. Thus, from this single workstation, the meteorologist not only can evaluate the changing mesoscale convective environment, but also can examine volumetric Doppler radar imagery and compose the warning message using a graphical warning generation application.

d. Strategy

Strategy combines conceptual models, key datasets, and technology in a way that maximizes the meteorologist's potential for making an accurate and timely warning decision. By using the AWIPS workstation to assess quantities such as shear and buoyancy, the meteorologist develops a conceptual model of the anticipated convective mode. Based on this conceptual model, the forecaster configures the workstation displays with datasets relevant to detecting convective initiation and evolution. If the meteorologist expects a convective mode dominated by deep supercell storms, initial datasets would likely include Doppler reflectivity and storm-relative velocity images. When displayed in a quadrant format, these fields would allow the analyst to examine features qualitatively such as mesocyclogenesis, echo-top location relative to low-level inflow features, and gradients and vertical distribution of reflectivity. If, however, the meteorologist anticipates a shallow linear convective system, reflectivity might still be selected for quadrant display, but the lowest-level velocity data would be ground relative rather than storm relative because damaging winds would likely be the primary threat. This proactive strategy allows the warning decision maker to *anticipate* events—the hallmark of a situationally aware expert—rather than simply to *react* to events (Klein 1998).

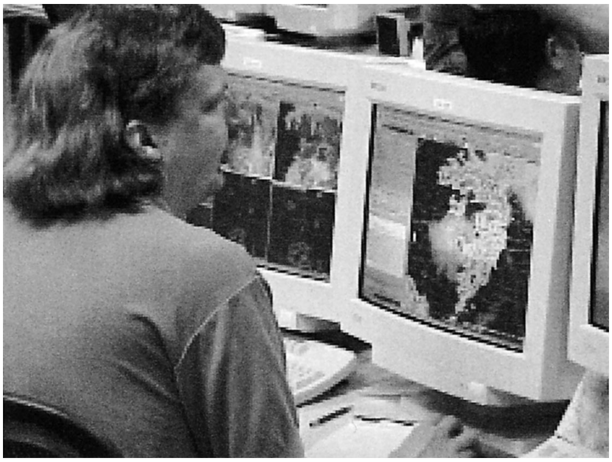

FIG. 1. WFO Norman, OK, meteorologist examining WSR-88D reflectivity and storm-relative velocity imagery in a quadrant display (left monitor) and preparing a tornado warning using AWIPS's ''Warngen'' graphical warning composition software during actual 3 May 1999 warning operations.

The algorithms also play a role in the analysis strategy. When time permits, the meteorologist quickly reviews algorithm results and mentally compares the algorithm-detected features with those found in the subjective analysis. The meteorologist then reconciles any discrepancies (e.g., previously unrecognized mesocyclones) and adjusts the working conceptual model if required. The algorithms sometimes benefit the meteorologist by detecting features overlooked in the subjective analysis (e.g., mesocyclones near the radar site at relatively high elevation angles). In other instances, the algorithm detections are erroneous (e.g., shear arising from velocity dealiasing errors).

As the warning event unfolds, the meteorologist uses predefined command macros (scripts of workstation commands that select products and display format) from a customized menu. These AWIPS macros, called procedures, construct complex combinations of radar imagery or other data with appropriate map backgrounds in seconds, without unduly taxing the meteorologist. Without the preexisting procedures, the meteorologist might take minutes rather than seconds to begin analysis of important information. Assumptions about storm type, storm location relative to the radar, and storm location relative to important geographical features or population centers form the basis for development of various predefined procedures. These procedures represent another strategy to aid the meteorologist and therefore potentially to increase the warning spatial precision, threat definition, lead time, and overall situation awareness.

When severe storms become widespread or affect major population centers, strategy helps to determine workload assignment during WFO warning operations. In these situations, the WFO's area of responsibility may be subdivided among two or more meteorologists, each responsible for storm detection, analysis, and warning for their ''sector.'' Each meteorologist coordinates the passage of storms from one sector to another, much as air traffic controllers manage aircraft. They also share ground-truth reports of severe weather and may consult one another in situations in which the best course of action is unclear. The ability of the AWIPS technology to share key datasets at more than one work position greatly improves the WFO's ability to analyze and to manage severe storms when compared with previous NWS radar display technologies.

e. Expertise

Expertise represents the skill and judgment necessary for the meteorologist to combine the various (and sometimes conflicting) elements of the warning process in a way that results in a sound warning decision. Expertise enables the meteorologist to weigh the mesoscale environment, Doppler radar, and ground-truth reports in the context of a physically based conceptual model of storm type and to render a decision to warn based upon a preponderance of evidence, and not blindly to translate algorithm output into warning messages. According to Klein (2000), expertise is critical to technical decision making (i.e., warning decision making), especially when automation is unreliable or fails. Klein also notes that increased automation may in fact hamper expertise and decrease skill of the decision maker when the automation is unreliable, not understood, or cannot easily be judged for accuracy. Klein points out that expertise is not a static quantity, but develops over time, and that problems often emerge when technology imposes in a way that prevents the application or development of human expertise. According to Pliske (1997), forecast skill (for ceilings and visibility) measurably declined as experienced and presumably expert forecasters increasingly relied on rote application of automated forecast techniques and less on the development of physical understanding of all available datasets, including observations *and* automated techniques. In the context of warning decision making, these findings suggest the importance of well-trained, experienced meteorologists in the decision-making process and suggest caution when automation (e.g., expert systems, algorithms) are introduced. We must take care to ensure that automation does not *interfere with* or *replace* expertise, but serves to *enhance* it!

3. Bringing it together—Warning operations 3 May 1999

Thompson and Edwards (2000) and Roebber et al. (2002) present conceptual models describing the evolution of the mesoscale environment on 3 May 1999, including expectations of NWS meteorologists during the day. These authors note that severe storms, including supercells and tornadoes, were expected. However, forecasters anticipated tornadoes to occur only during a brief period during the early evening. Afterward, expectations were for the storms to evolve into a large squall line, with the primary threats being damaging wind and large hail. WFO staffing was determined based on this expected evolution but was quickly adapted and augmented as observational datasets pointed increasingly toward an outbreak event during the early evening.

WFO meteorologists anticipated supercell storms, based on mesoscale environmental cues (i.e., shear and buoyancy within known limits for supercells) and prepared to search for features associated with supercells. Such features included Doppler-radar-detected mesocyclones and reflectivity structures and spotter observations of wall clouds and tornadoes. Evidence presented by Thompson and Edwards (2000) clearly indicates a convective mode dominated by classic supercells on the evening of 3 May 1999. Thus NWS meteorologists charged with warning decision making were well positioned to anticipate the evolution of the storms and to provide warnings accordingly.

Initiation of the first severe storm occurred near 2030 UTC, with the first severe thunderstorm warning issued by the Norman WFO at 2115 UTC based upon Doppler radar reflectivity of greater than 50 dBZ to near 10 km AGL, suggesting large hail. One meteorologist initially was dedicated to warning decision making for the single storm in Comanche County, Oklahoma (Fig. 2). This meteorologist evaluated multiple angles of Frederick (KFDR) and Twin Lakes (KTLX), Oklahoma, WSR-88D reflectivity and velocity data in AWIPS quadrant displays for indications of supercell storm structure. By 2145 UTC, a mesocyclone was evident in the storm-relative velocity fields and was detected by the MA. Trends detected by the subjective analysis of storm-relative velocity data suggested the mesocyclone was strengthening and deepening. These trends were considered to be precursors to tornadogenesis and, when combined with spotter reports of a rotating wall cloud, supported a decision to issue a tornado warning at 2147 UTC. Spotters reported a tornado at 2151 UTC. This

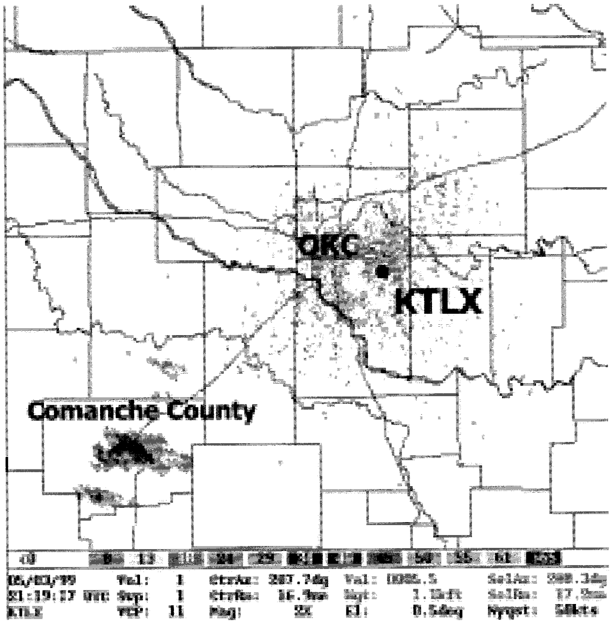

FIG. 2. KTLX 0.5° WSR-88D Doppler radar reflectivity at 2119 UTC, shortly after issuance of the first severe-thunderstorm warning for Comanche County in southwest OK.

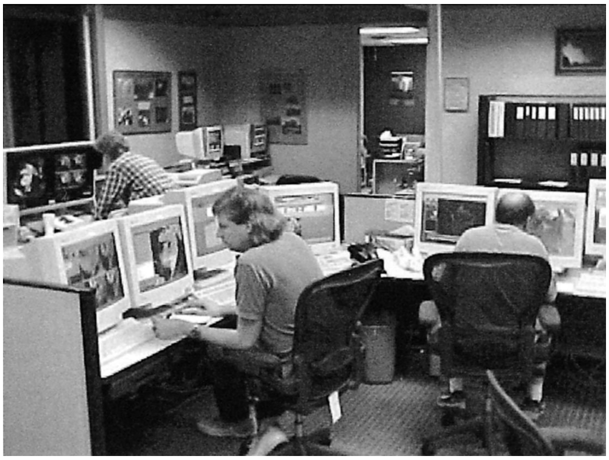

FIG. 3. Two WFO Norman meteorologists conducting sectored warning operations on the evening of 3 May 1999. WDSS, providing access to advanced algorithm guidance, is located between the two meteorologists' AWIPS workstations.

information confirmed the meteorologist's anticipation of a classic tornadic supercell and provided the basis to issue a severe-weather statement to the media and emergency managers that reinforced the warning message.

As additional storms developed between 2200 and 0000 UTC, additional meteorologists participated in the warning decision process by employing the strategy of sectored warning operations (Fig. 3). The sectored approach allowed meteorologists to maintain a high degree of situation awareness for their sector, permitted careful scrutiny of base data radar imagery, and ensured that the workload did not overwhelm any single decision maker. By 0000 UTC, four warning sectors, the maximum for the 3 May outbreak, were in place (Fig. 4) as severe storms stretched from southern Kansas into north Texas and a large F5 tornado approached the suburbs of Oklahoma City. A fifth meteorologist was dedicated to overseeing the warning operation and coordinating any urgent issues among warning decision makers, WFO amateur radio operators, and other staff members. The ''warning coordinator'' also monitored the quasi-experimental Warning Decision Support System (WDSS; Eilts 1997) that provided high-resolution WSR-88D reflectivity and storm-relative velocity data from the KTLX radar along with advanced mesocyclone and tornado detection algorithm information not available from the standard WSR-88D data stream. The warning coordinator compared the warnings in effect with algorithm-identified features to ensure identification of all threats. The TDA alerted meteorologists to one previously undetected signature associated with storm E. Section 4 discusses the circumstances of this detection. By monitoring the flow of WFO warnings and statements, ground-truth reports from amateur radio and television media, and WDSS radar information, the warning coordinator was able to maintain a high level of situation awareness and to provide guidance to warning meteorologists.

Although WFO warning operations are usually stressful, the events of 3 May 1999 were especially so. As

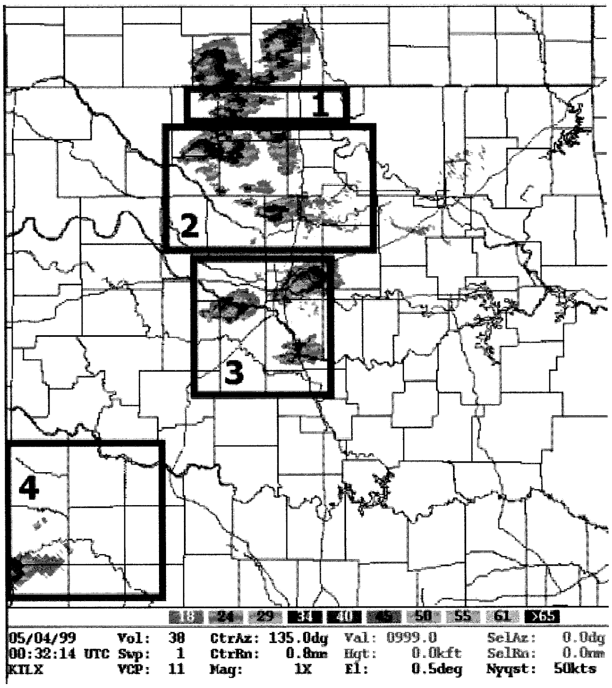

FIG. 4. KTLX 0.5° WSR-88D reflectivity image provides the backdrop to sectors defined for warning operations at 0032 UTC. The devastating F5 tornado was moving into south Oklahoma City (sector 3) at this time.

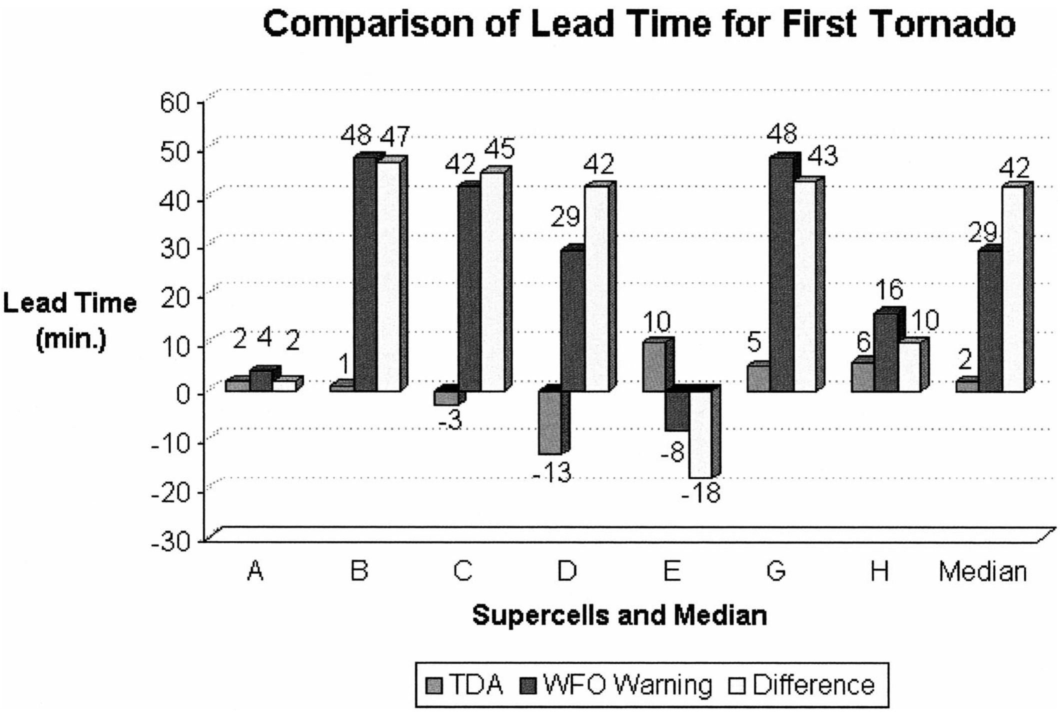

FIG. 5. Comparison of WFO Norman tornado warning lead time for the first tornado produced from each tornadic supercell vs detection of shear by TDA. For TDA shear detections to be valid, they must have been present within a 10-min window prior to tornado occurrence. Because initial shear signatures were less organized and were more distant from the radar (KTLX), these statistics were less favorable for TDA than statistics for subsequent tornadoes (not shown). (Statistics courtesy of R. Lee, Applications Branch, WSR-88D Radar Operations Center, Norman.)

the large F5 tornado approached the Oklahoma City suburbs, the WFO staff notified surrounding WFOs of the potential the tornado would pass near OUN and possibly render the WFO incapable of continued operation. Family and friends of WFO staff, including those of the meteorologist charged with warning for the Oklahoma City area, were in the path of the tornado. These considerations weighed on the minds of the staff as they struggled to handle the unfolding disaster and to express the grave danger to those in the paths of the tornadoes. Terms such as, "tornado emergency," "extremely dangerous and life threatening," and "large devastating tornado" were used in warnings and statements that evening as a means to convey the unusually dangerous nature of the outbreak to a potentially complacent population that had survived, with only minimal impact, two direct hits by lesser tornadoes during the prior 11 months. Before 3 May 1999, WFO OUN had not used terms with this degree of urgency as part of a tornado warning or severe-weather statement. Postevent analysis of radio and television media programming and interviews of on-air staff indicated these terms contributed to their awareness of the situation and helped them to provide a stronger sense of danger to their listeners. Because of the high stress levels and personal involvement of several staff members, the two primary warning decision makers were replaced following the central Oklahoma F5 tornado. Warning operations unfortunately remained very active for several hours following the central Oklahoma tornado as up to four tornadoes occurred simultaneously during the late evening, in one instance striking a town twice within approximately 1 h.

4. Observations and conclusions

Review of WFO product issuance showed one severe-weather-related warning or statement issued by the WFO every 3.8 min for 8 h during the late afternoon and evening. The rapid flow of information would not have been possible even a few years ago without AWIPS workstations that permitted sectoring of warning operations and graphical warning generation software.

Figure 5 compares WFO OUN tornado warning lead time for the *first* tornado from each supercell (after Speheger et al. 2002) versus lead time by the TDA algorithm. We chose to examine the first tornado for each storm because the initial tornado warning decision is often the most challenging for the meteorologist. A tornado usually has not yet formed, and radar signatures are less definitive than later as the storm becomes mature. At this point in the warning decision process, the meteorologist would benefit greatly from algorithm guidance that suggests a tornado threat exists. Although TDA did very well overall, it generally was of minimal assistance for recognizing rotational signatures associated with the *initial* tornadoes. Meteorologists found the most effective tools for threat identification to be subjective analysis of Doppler radar reflectivity and storm-relative velocity and ground truth of wall clouds, funnel clouds, and other storm-scale features, as detailed in section 3. However, an exception occurred with storm E. TDA alerted the warning coordinator to investigate the storm that developed rapidly. Had this alert not taken place, more time likely would have elapsed before warning issuance. Figure 5 not only illustrates the value of human expertise in the warning process, but also shows the important role algorithms can play when used as ‘‘safety nets’’ (e.g., storm E).

Acknowledgments. The authors thank the staff of WFO Norman, Oklahoma, for their willingness to discuss and to share their experiences related to warning decision making. The authors also appreciate the willingness of Robert Lee of the WSR-88D Radar Operations Center to share the 3 May 1999 TDA lead-time statistics and Doug Speheger of WFO Norman to provide warning lead-time statistics. Comments and suggestions provided by Kim Elmore of NSSL and by two anonymous reviewers improved the quality and clarity of this manuscript.

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