3B.4 Supercell Storm Evolution Observed by Forecasters Using PAR Data

Pamela Heinselman*[1] and Daphne LaDue[2]

[1]NOAA National Severe Storms Laboratory, [2]Center for Analysis and Prediction of Storms

1. INTRODUCTION

On 22 May 2011, an EF-5 tornado moved through Joplin, Missouri, killing 158 people and producing extensive property damage (Marshall et al. 2012). The rapid intensification of the tornado (Karstens et al. 2013) instigated the recommendation for National Weather Service (NWS) development and implementation of more frequent 0.5° sampling by the NWS Central Region Assessment Team (NOAA 2011). An algorithm called Supplemental Adaptive Intra-Volume Low-Level Scan (SAILS) has been designed that inserts a "split cut" 0.5° scan into either VCP 12 or VCP 212 during the middle of the volume scan (Crum et al. 2013; NOAA 2013). Once operational[1], Weather Surveillance Radar – 1988 Doppler (WSR-88D) locations across the country will have the capability to provide lowest-elevation sampling at update times more similar to those realized at Terminal Doppler Weather Radar (TDWR) sites (when running in Hazardous Weather Mode, described in Vasiloff (2001)). Where TDWRs are located near Weather Forecast Offices (WFOs), forecasters use 1-min lowest-elevation data to attain situation awareness of rapidly evolving low-altitude weather events, such as intensifying storm inflow, a surge in storm outflow, or intensifying cyclonic convergence. Studies by Vasiloff (2001) and Dunn and Vasiloff (2001), for example, demonstrate cases where operational use of 1-min lowest-elevation TDWR data improved the ability to detect and track the onset of tornadogenesis. Of course the ability of a radar system to resolve the development of a tornado or its larger-scale parent circulation depends not only on sampling frequency, but also on azimuthal spatial resolution, radar sensitivity, and relative distance of the storm from the instrument (e.g., Donaldson 1970; Brown et al. 1978; Brown et al. 2002; Bluestein et al. 2010).

The NOAA National Severe Storms Laboratory is demonstrating a different approach to rapid sampling of storms using an S-band phased array radar (PAR) system at the National Weather Radar Testbed in Norman, Oklahoma (Zrnić et al. 2007). Electronic scanning provides more flexibility to scan the atmosphere and storms adaptively compared to mechanical scanning (Heinselman and Torres 2011). Most importantly, electronic scanning facilitates adaptive scanning at each beam position. The goal of both electronic and mechanical adaptive scanning techniques is to provide weather forecasters and other users with radar-based information when and where they need it (e.g., Chrisman 2009; McLaughlin et al. 2009; Heinselman and Torres 2011).

An important question, though, is to what extent might the use of rapid, adaptively scanned radar data aid the warning decision process of forecasters. For instance, when forecasters are provided such data in simulated real time, do they tend to extract useful information from most volume scans? How frequently do they make judgments or projections that steer their analysis in a particular direction? Does use of the data result in favorable lead times for public response to weather hazards?

One framework for explaining the cognition leading to forecasters' warning decisions is Endsely's (1995) theory of situation awareness (SA) in dynamic systems. The NWS Warning Decision Branch, for example, has applied Endsely's theory to help new forecasters learn effective cognitive strategies for making warning decisions http://www.wdtb.noaa.gov/courses/awoc/awoc.html#CoreTrack). The theory has also been used successfully in system design, automation, and team work studies (Wickens 2008). In this paper, the term SA encompasses the three levels of increasing complexity described by Endsely (1995), including the perception of relevant critical cues in the environment, comprehension of the current situation based on the synthesis of critical cues, and projection of what will happen next within the dynamic system.

Because SA is acquired over time, the temporal resolution of environmental data impacts the frequency at which the state of the atmosphere, and our understanding of it, can be attained and updated. As mentioned earlier, advancements in radar sampling techniques employed by the WSR-88D, as well as advancements in future radar technologies, will increase the temporal frequency of observations. Our expectation is that higher temporal resolution of radar data will enhance forecaster SA during events that tend to evolve rapidly, such as initiation of deep convection, microbursts, or tornadogenesis.

The 2010 Phased Array Radar Innovative Sensing Experiment (PARISE) examined the use of rapid-scan PAR data by NWS forecasters in simulated real time (Heinselman et al. 2012). During 2010 PARISE, six forecaster pairs worked the 19 August 2007 tornadic tropical supercell event, with three pairs using 43-s data, and three pairs using 4.5-min data. The event included two supercells storms; the north storm produced an EF1 tornado, while the south storm

[1] Operational implementation is anticipated by December 2013.

produced no tornadoes. The use of rapid-scan PAR data resulted in longer tornado warning lead times on the north storm: 11–18 min vs -1.6–6 min, respectively. The use of rapid-scan PAR data also resulted in more false alarms, as two of the forecaster pairs using the rapid-scan data issued a tornado warning on the south storm, while pairs using the 4.5-min data did not. Post-analysis of 0.5° trends of azimuthal shear values revealed higher magnitude peaks within short-term trends sampled by the full-temporal-resolution PAR data. Based on these results, one might be concerned that while use of rapid-scan PAR data may increase warning lead time, it may come with the cost of more false alarms.

The 2012 PARISE design supports further investigation of this concern. Twelve forecasters worked individually (vs in pairs) to increase participant sample size, and the number of cases increased from one to four. Two cases were tornadic supercells and two were nontornadic supercells. The nontornadic supercell cases chosen had environments that were later conducive to tornadogenesis, but not within 45 min of the case end time. Furthermore, in real time operations, a NWS forecaster issued an unverified warning during one of these cases. Hence, they were chosen to provide some challenge to forecasters. The inclusion of tornadic and nontornadic supercells provided the opportunity to understand the SA forecasters formed while using the rapid-scan PAR data, and whether they discerned differences in tornado potential among cases.

Implicit to understanding forecaster's decision processes is the choice of a suitable data collection method. Two options are concurrent and retrospective verbal reports (Ranyard and Svenson 2011). During the collection of concurrent reports, decision makers think-aloud about what he/she is thinking while accomplishing a task. This type of data collection was used in PARISE 2010 (Heinselman et al. 2012). When collecting retrospective verbal reports, decision makers retrospect aloud about what he/she was doing or thinking while accomplishing a task. Both approaches are prone to issues with validity. We chose retrospective verbal reports due to concerns that concurrent reports would potentially change forecasters' decision process; in particular that thinking aloud would slow down their natural process. For dynamic decision making tasks like forecasting, video-cued recall is an accepted procedure for stimulating forecasters' verbal recall of their decision processes (e.g., Omodei et al. 1997; Lyle 2003; Hoffman 2005; Ranyard and Svenson 2011).

As in Heinselman et al. (2012), this study focuses on EF0- and EF1-rated tornadoes produced by supercells. Though these tornadoes are less destructive to life and property than higher rated tornadoes, they are also the most unwarned (e.g., Brotzge and Erickson 2010). Based on NWS performance statistics from 2000 to 2004, when tornadoes were rated using the F-scale, Brotgze and Erickson (2010) found that 27.7% of tornadoes rated F0 and F1 were unwarned, compared to 15.5% of tornadoes rated F2 or higher. Subsequent to the implementation of storm-based warning verification statistics by the NWS in October 2008 (Sutter and Erickson 2010), the national percentage of both unwarned weak (EF0 and EF1) and strong (≥ EF2) tornadoes had decreased to 21.9% and 9.0%, respectively. These statistics (Table 1) were computed during the 5.7-year period of 1 January 2008 to 1 August 2013 using data from the NWS Performance Management System (https://verification.nws.noaa.gov/). Still, the majority of unwarned tornadoes (94%) and those with either a 0-min or negative lead time (93.7%) were rated EF0 and EF1. During this period the national mean tornado lead time for EF0 and EF1 tornadoes was 12.26 min, almost six minutes less than the lead time for EF2 and higher rated tornadoes (17.95 min). As a result, people in the path of EF0 and EF1 tornadoes were less likely to receive prior warning, and more likely to receive less tornado lead time.

A caveat that requires attention is that the percentage of weak tornadoes produced by supercells and other storm types is not considered in Brotzge and Erickson (2010) or in the NWS data base. Hence, the percentage of unwarned EF0 and EF1 tornadoes produced by supercells only is likely lower than those presented. Similarly, the tornado lead times may vary by storm type (Brotgze et al. 2013). Regardless, we suspect that EF0 and EF1 supercell tornadoes are warned less and are associated with shorter lead times compared to EF2 and higher rated supercell tornadoes, due to their shorter life times.

The purpose of this paper is to document the experiment design and describe the analyzed results. The analysis focuses first on the verification statistics resulting from the use of the rapid-scan PAR data during each of the four cases. These results are then put into context of the situation awareness forecasters formed using 1-min PAR data and their warning decision process while working two of the four cases: one tornadic (11 May 2010) and one nontornadic (14 April 2011).

2. RADAR DATA AND VISUALIZATION

The PARISE 2012 data set includes four supercell cases with durations of 19 to 52 min (Table 1; Fig. 1). Case selection criteria included sufficient longevity and temporal continuity in the data prior to tornadogenesis (for tornadic cases), minimal velocity aliasing, and storm location within 120 km range of the PAR.

Data were collected using interleaved and conventional scan strategies (Table 1). On 11 May

2010, the lowest four elevations were revisited twice between volumetric (22-elevation) scans to prioritize sampling nearest to the ground, where tornadoes develop. Volumetric and interlaced scan times were 59 and 22 s, respectively. During the 2011 cases, storms were sampled with conventional scan strategies with volumetric update times near 60 s. Based on storm coverage and range from the radar, these volumetric update times were lowered during operations by running the Adaptive Digital Signal Processing Algorithm for PAR Timely Scans (Heinselman and Torres 2011).

Base data display was handled using the Advanced Weather Interactive Processing System-2 (AWIPS-2). AWIPS-2 is currently replacing the AWIPS-1 architecture as the baseline forecasting platform at WFOs across the country. Utilizing the AWIPS framework provided forecasters with access to PAR data within a familiar display and warning environment. This allowed for maximum focus to remain on product evaluation instead of software retraining.

For ease in data management and display, the four PAR cases were preprocessed using the Common Operations and Development Environment (CODE) Radar Product Generator software (Johnson et al. 1999). Utilizing CODE, we were able to generate AWIPS-readable reflectivity, velocity, and spectrum width products without data quality degradation.

3. EXPERIMENT DESIGN

3.1 *Participant selection*

Participant selection focused on Central and Southern Regions of the NWS where tornadoes are climatologically most prevalent (e.g., Brooks et al. 2003). First, the Science Support Division Chiefs in these regions were contacted and given an overview of the experiment. They then worked with local offices to identify potential participants. The participant list they provided was used to select 12 forecasters based upon office location and availability. Each forecaster was individually contacted and provided the opportunity to consent to participate. In all reporting from this experiment, pseudonyms are used.

The participants came from nine NWS Offices, and a slight majority was from offices in the Southern Region. They ranged in experience from 1.3–19 years. Six participants had five or less years' experience, and one of these had taken DLOC within the past year. The other six had at least nine years' experience. Participants had worked during 5–25 severe events in the previous year, but had not necessarily issued the warnings. The forecaster with 1.3-yrs experience had issued only one tornado warning prior to this experiment.

3.2 ***Data collection on forecaster warning decisions***

Two participants travelled to Norman, Oklahoma for each of the six weeks. On the first morning, they heard an overview of the characteristics, capabilities and data collection strategies of the PAR. The motivation behind and strategy for PARISE 2012 were then explained. Thereafter, participants received a review of AWIPS-2 and spent about an hour on a workstation to practice loading archived PAR data and drawing polygons using the Warning Generation (WarnGen) tool.

That afternoon and over the next 1.5 days, participants individually worked the four cases in simulated real time (Table 1; Fig. 1), as if they were responsible for real-time warnings. Prior to each case participants viewed a prerecorded weather briefing provided by Jim LaDue of the Warning Decision Training Branch. The weather briefing attempted to bring each participant to a similar understanding of the environment and expectations for the event. During each case, phone calls were timed to coincide with spotter reports received during real-time operations. Other aspects of operations were not simulated. While working each event, recordMyDesktop software recorded participant interactions with the AWIPS-2 software and products issued were saved to a database.

After each case, the forecaster/researcher pairs conducted the Recent Case Walkthrough, a method of cognitive task analysis (Hoffman 2005; Crandall et al. 2006). This method involves three sweeps. In the first sweep they reviewed the video replay of their desktop activity and retrospected aloud about their reasoning and observations. The researcher prompted the forecaster to describe his or her actions and thought processes, and typed out a timeline of these. During the second sweep, the video was reviewed a second time. The descriptions developed in the first Walkthrough were refined, corrected, and/or added to by the forecaster. Reference was made to the draft timeline to support the forecaster in this process. In the third sweep, forecasters were asked to identify key judgments during the case and the information used to make them. These judgments included decisions both to warn and not to warn. Forecasters were also asked probing questions to attain deeper information on their mental models, their preexisting knowledge base, and methods used to interrogate the data.

Some factors that could be anticipated to affect forecaster performance were addressed. To avoid a systematic unintended bias in performance from the order of cases, case order differed each week. Also, researchers switched places after completing two cases, so that each researcher and forecaster worked together. During the experiment overview, participants were instructed to do their "normal good job." This instruction was given to minimize the John Henry Effect (Saretsky 1972), which is above average performance that occurs when participants perceive that they are in competition with another group. In this study, the concern was that in an experimental setting, forecasters might feel the need to exceed their usual performance. Finally, it is possible that the experiment location, which was a room that provided visibility of the Storm Prediction Center on one side and the WFO on the other, may have helped put them into office mindset. Other aspects of a WFO could not be easily simulated.

4. TORNADO VERIFICATION

4.1 *Tornado lead times (TLTs)*

The TLTs resulting from participants' use of rapid-scan PAR data (N=48) range from 0 to 39 min (Fig. 2). The mean TLT for these events is 20.1 min, which exceeds the national-mean TLTs for both weak (12.26 min) and strong tornado events (17.98 min) discussed earlier. A comparison of TLTs by case indicates timelier tornado warning decisions were made for the EF0 11 May 2010 event (A in Fig. 3a) than for the first tornado event on 22 May 2011 (B in Fig. 3a). Mean TLTs are 22.75 min for A, and 13.83 min for B. Tornado A's TLTs tend to fall into two groups: 25–29 min (N=8) or 8–13 min (N=3). Similarly, half of tornado B's TLTs range from 20–23 min, whereas five are 10 min or lower; two are zero. An examination of the 0-min lead times revealed that, in one case, the tornado occurred a few minutes prior to the warning start time. In the other case, the tornado occurred just outside of the west edge of the warning polygon. The occurrence of TLT groupings suggests that forecasters with similar TLTs may have formed analogous mental models from the PAR data and issued warnings near the same time (Fig. 3). In contrast, the occurrence TLTs higher for tornado A than for tornado B suggests some differences in the mental models formed while working these cases.

For 8 of the 12 forecasters, the TLTs for subsequent tornadoes (C and D) exceeded those of B (Fig. 3a). The tendency for first tornadoes of the day to have the shortest lead time is an outcome similar to that found in a five-year NWS tornado verification study by Brotzge and Erickson (2009). For tornado C, individual TLTs ranged from 9 to 34 min (Fig. 3a) and the mean TLT was 18 min. Eleven of the 12 TLTs for tornado D exceeded 18 min (Fig. 3a). The average TLT for tornado D was 24 min. As one might expect, the broad range of TLTs for tornadoes C and D is due to variations in issue times and duration of the participants' initial and subsequent warnings (Figs. 3 and 4).

4.2 *PPOD and POFA*

The four tornado paths are fully verified by nine forecaster's warnings (Fig. 3b), resulting in PPODs of one. The two PPOD values of 0.75 are due to the absence of verified points along the 11 May 2010 tornado track. The PPOD of 0.9 is a result of two unverified points along tornado D's track.

POFA values range from 0 to 0.5, and 11 of 12 are below 0.5 (Fig. 3b). Given that half of the playback cases are null events, a POFA of 0.5 is an appropriate baseline value for assessing performance. POFAs lower than 0.5 indicate performance superior to random chance. One forecaster, Randy, did not issue any warnings during the null cases. In this study, the false alarms are a result of the following:

1) One or more warnings issued during one of the null cases only (N=3; Fig. 4c, d),

2) Warnings issued during both of the null cases (N=5; Fig. 4c, d),

3) One warning issued during one null case and an unverified warning issued during a tornadic case (N=3).

The NWS-based verification statistics resulting from forecasters' use of PAR data while working two tornadic and two nontornadic cases suggest that the situation awareness formed from the frequent 1-min volume updates were likely beneficial to most forecasters' warning decision processes. As the sample size is too small to assess the validity of this inference statistically, instead forecasters' timelines are analyzed to determine the time intervals at which the forecasters attained new situation awareness, as well as the time intervals at which forecasters made judgments or warning decisions. The results of this investigation are discussed in context of the forecasters' decision process.

5. May 2010 TORNADIC EVENT

As the forecasters heard during their prebrief, these storms formed in an environment in which several tornadic supercells had developed earlier that afternoon and into the evening across several parts of Oklahoma (NCDC 2010; Palmer et al. 2011). This case differs from the others in terms of the enhanced tornadic environment and the storm pattern, which was right-moving supercell near the tail end of a line, rather than a discrete supercell. At case start time (0035), the line was located about 75–100 km southeast of the PAR (Fig. 1a). Forecasters were provided about 20 min of PAR data prior to 0035, to help orient to the event. Near the end of the case (0112), a tornado occurred within the tail-end storm near Mill Creek, Oklahoma (0105 to 0109).

5.1 *Warning decisions in first few minutes*

Of the 10 forecasters who issued warnings in the first few minutes of the case (Fig. 4a), their warning decisions can be categorized into two groups. One group based their warnings primarily on environment and storm history (N=7). Radar signatures were portrayed as "good enough" given that context. The second group was more confident about radar signatures, and used environment as an important context (N=3). All saw velocities immediately broaden and become weaker after these warnings were issued. Two forecasters did not warn in the first few minutes of the case.

5.1.1 Environment and Evolution of Radar Signatures Group

5.1.1.2 Cyclonic convergence or mesocyclone continuity

Three of this group cited either the cyclonic convergent signature or the mesocyclone continuity with height. **Jay** noted "good balance" between the rear flank downdraft and inflow, with low-level CAPE, was the "big environmental clue" to warn (0037). **Dirk** noted the height continuity of the mesocyclone as important to his decision (0037). Two minutes before warning, **Ben** said there was "no evidence of spin-ups at this time" (0038 UTC; UTC assumed hereafter). But he did not want to "get behind" tornado development, so decided to issue (0040) based on the trend from a cyclonic convergent to cyclonic signature.

5.1.1.3 Increasing gate-to-gate velocity couplet at low-levels

The other four of this group focused on the low levels in their decisions. Three noted the low-level organization and increasing gate-to-gate signature while one noted the history of the gate-to-gate signature. **Randy** verbalized only a "history of a gate-to-gate velocity signature" before his warning decision (0036). **Elmer** was concerned about the environment and initially did not see enough organization (0037). But when the 0038 UTC scan showed a strong couplet (he cites 55kt in/37kt out) forming, he decided to warn "because the signature [was] tightening up a bit." **Bridget** also interpreted what she called "trending toward" gate-to-gate and the trend toward better storm organization (0036). The circulation became "strong enough close enough to the surface" for the environment, and she decided to warn (0038). **Brad** said it was "getting more organized" and interpreted a stronger gate-to-gate couplet in low levels (0038).

5.1.2 Evolution of Multiple Radar Signatures Group

These three forecasters were prompted to warn by changes in the radar depictions. Bob most fully narrated the evolution of signatures this group cited when describing his warning decision. According to Bob, the increasing tornado potential was indicated by the rear flank beginning to swing around, low-level convergence turning into cyclonic rotation, and the updraft persisting, if not strengthening.

Bob said an inflow notch was the "main area of interest" in the domain, and noted that the convergent/cyclonic rotation had vertical continuity (0036). The rear flank had started to push forward over the previous 2 min (0037). The rotation "seem[ed] to be tightening" at 0.5° with an "impressive" gate-to-gate couplet of 80–90 kts (0038).

Avery cited a midlevel circulation with a "pretty tight couplet" (0037), and decided to warn during the next minute when he saw a trend of tightening of velocities at 0.5° (0038). The collocation with the hook was "[not] perfect" and the rear flank downdraft was "not quite the norm; kind of a hybrid." A new scan at 0039 showed a tight circulation, with all four of the lowest tilts showing a "pretty good increase...[in] intensity and tightening," solidifying his decision to warn.

Maggie similarly noted a hook starting to develop (0035), a velocity signature collocated with the hook (0036), and a decent mesocyclone (0037). She based her decision on a velocity couplet tightening on two consecutive scans during the period from 0038–0039[2].

5.1.3 No Warning Decision in First Minutes of Case

The two forecasters who did not warn in the first few minutes had different reasons for their decisions.

Mike saw a tight circulation, but suspected that it was a dealiasing issue (0038) because the rotation had strengthened so quickly in the lowest 4-panel; he chose to wait another scan. This led him to see what others called a weakening and he chose not to warn (0039).

Pat was acclimating to the data and the display during the first few minutes. He had been expecting isolated supercells and did not see that. He saw the tightening of a reflectivity couplet on the tail-end storm at 0038, but was confused by what he interpreted as missing or miss-located features, and had difficulty building his conceptual model. He "felt unprepared" and later thought he "probably would have had a warning out earlier" had he acclimated to the data faster.

5.2 *Warning decisions later in case*

5.2.1 Mesocyclone Lowering (2140 – 2145)

Pat's first decision to warn occurred at 0045, the only forecaster to warn around that time. Most of the others had shifted their focus to monitoring other

[2] We often did not have the full granularity of forecasters' thinking for 20-s update scans during the walk-through narratives.

storms for about 5 min after making warning decisions. At 0040 Pat was looking aloft, and saw a "pretty good meso[cyclone]" at 10,000 ft. He "watch[ed] the area intently" and "started to see more rotation as opposed to convergent rotation" as the mesocyclone was "getting stronger" aloft. He interpreted a BWER in the leading edge area at 0042 and multiple rotations at 1.5° 0044 "at the location you'd expect." When the convergence increased at 0.5°, he said the 1.5° feature was starting to lower. Although he was unsure conceptually what a reflectivity feature was on low levels, he said the rotation aloft, with indications of lowering, was "good enough" and he decided at 0045 to issue a warning.

5.2.2 Anticipation of Tornadgenesis (0053 – 0102)

Six of the judgments about tornado potential clustered between 0057 and 0059, with five others' judgments following by 0101. The majority of forecasters noted the mesocyclone becoming better defined at the lowest tilt, and all focused on the accompanying formation or surging of a rear flank downdraft. Radar signatures led eight forecasters to anticipate of tornadogenesis as early as 00:53 UTC. This led to a cluster of warning decisions by 0057 UTC for those without a previous warning covering the area with more than 10–15 min remaining. Three others anticipated tornadogenesis by 0100–0102.

5.2.2.1 First warning decision

Mike's first warning decision for this case was at 0057. He first saw the mesocyclone becoming better defined with a hook at 0048. The hook became even better defined (0049), and Mike noted a "fairly tight couplet" on the third and fourth tilts (1.1° and 1.5°), but not at the lower levels (0050). The mesocyclone fit with the reflectivity structure, but he said he wanted to see how persistent the tight circulation would be. At 0052 he said the circulation started to tighten up at lowest tilts; one couplet was dissipating while the main mesocyclone was becoming better organized and stronger (0053). He identified that the notch at the base of the hook had extended more to the back of the storm. When he saw the reflectivity closing off into a BWER on the 2nd tilt (0.8°), he "felt a tornado [was] now...possible" (0055). At 0056 the BWER extended to the lowest tilt and the tight velocity couplet, now located at the leading edge of the storm, had about 70 kts of shear. The couplet strengthened at 0057 and he decided to issue a tornado warning, saying, "a tornado may have already been produced, or will be soon."

5.2.2.2 Second warning decision

Dirk first indicated a heightened concern at 0044 when he noted a "fresh curl starting on the southern flank." The strong convergence seen in the first few minutes of the case had weakened after he issued his initial tornado warning. A few minutes later (0047) he noted: "looks like a circulation is trying to ramp up there in midlevels." He saw strong outbounds (0052), and strong convergence (0054). The elevated mesocyclone was maintaining intensity and getting close to the edge of his previous warning. He became "pretty concerned" when he saw a "good little notch" (0057), which he explained meant that the circulation had tightened up. He saw rotation "ramp up" to 80 kts gate-to-gate (0057 new), and increase again 20 sec later to 90 kts gate-to-gate, and declared, "Okay, time to [warn]."

Jay had also seen the first circulation weaken and become "broad and loose." Any tornado previously had lifted. Jay's narrative now focused on the lower levels, where the reflectivity structure had remained "conducive for additional tornadoes." At 0050 he first verbalized that "another tornado could form," given the increase in rear flank downdraft winds and a good balance of those with the inflow to the storm. The rear flank downdraft continued to increase (0052), and an inflow notch became evident. At 0054 he was waiting for a tightening circulation that fit with his conceptual model. At 0056 he was still "waiting for the velocity to increase." At 0057 it did. He had been waiting for that, and decided to warn.

Brad first anticipated a tornado developing at 0051 when he saw winds gusting 40–50 mph along the leading edge as a rear flank downdraft began to develop at 0050. He said, "Might get another push and spin-up with this cell." He was "concerned with that push." At 0057 the "new rear flank downdraft push" led to a stronger circulation, with delta-V of about 40 kts gate-to-gate, collocated with a weak echo region. At this point he was "on the fence" regarding a new tornado warning, but in the next minute the "couplet [was] getting stronger and tighter" and he "[became] more concerned" about the increasing tornado threat (0058). He decided to warn.

5.2.2.3 No additional warnings needed during period

Avery focused on the lower levels as well, because the middle levels were tightening and increasing, which could translate downward. He first noted organizing in low levels at 0050, when the broad low level circulation began transitioning to a more cyclonic-convergent pattern. This trend continued (0052), and at 0054 he noticed an arcing feature that "would indicate an rear flank downdraft punch" while the midlevels were steady or intensifying. The tightening at low levels began by 0055, with a tighter couplet developing and the arcing feature continuing at 0057. He said he was now thinking "the cycling is occurring and close to a new tor."

Elmer's first warning was long enough that he did not have to issue another warning until late in the case. He had seen the storm cycle down to a non-tornadic state just after his first warning was issued, but the mesocyclone had remained persistent over the next

10 min (0049). He "felt it would do something at some point — reorganize." By 0055 the inflow notch and rear flank downdraft were becoming better defined. In the next minute the inflow began to increase; he assessed that the mesocyclone was tightening up. At 0057 a new couplet was beginning to develop: 57kts outbound and 40 kts inbound at 0.5°. Also at 0.5°, the mesocyclone continued to increase in size and intensity (0058), leading to his judgment at 0059 that he was "confident in his tornado warning again" because of the persistent, strong mesocyclone in the southeast flank of the storm. "[The storm] was about to produce a tornado."

Maggie first noticed a "tight" mesocyclone at 0053. At 0055 a weak echo region was present, but "nothing jump[ed] out" when looking at velocity in all-tilts. However, by 0057 the original couplet was tightening up, and it seemed time to reissue. There was a broad rotation at 0.5°, and an appendage associated with a mesocyclone (0057). Less time has passed than she thought, however, and she said she would wait until 0110 or 0115 to reissue. She did not wait that long, as explained below.

Finally, **Randy** also belongs in this warning group although, like Maggie, his actual warning decision for this portion of the case occurred at 0109. His previous warning was in effect for the concerned area. By 0053 he noticed a rear flank downdraft surge, with outbound velocities increasing by about 20 kts. He thought the potential existed for this to lead to a "stronger circulation developing in 5–10 min." As expected, by 0057 the leading edge of the rear flank had "strengthened significantly," leading to increased convergence. He stated at this point that convergence would increase if the rear flank continued to push to the front of the line, where it would meet up with the inflow (0057). In the next minute the convergence became stronger, larger, and trended toward gate-to-gate. At 0100 he stated that a "tornado was possible in within the next few minutes."

5.2.3 Require Persistent 0.5° Gate-to-Gate Velocity Couplet Prior to Second Warning

For the next three forecasters, two identified a tightening couplet by 00:54 UTC and the third saw this feature by 00:57 UTC, without much focus on the main storm in the minutes prior to that. All three issued warnings 4–7 min later; all had a previous warning in effect and no urgency to warn upon their key judgments between 0057–0059 UTC. Rather, they required persistence in the low-level gate-to-gate velocity couplet before warning. The fourth required not only persistence, but also seeing particularly strong strength within the couplet prior to warning.

Bob realized that low-level rotation was increasing on the warned storm between 00:53–00:54 UTC, and refocused on that storm by 00:57 UTC when he saw that strengthening increase to 80 kts gate-to-gate. The storm was also getting better inflow at that point. He saw no changes at 0058, and wrote some notes at 0059. At 0101 he saw "persistent rotation," now about 70 kts gate-to-gate at 0.5°. He decided to reissue after seeing the updraft and rotation has persisted and increased by 0101–0102.

For **Ben**, the mesocyclone helped the key storm "really [stick] out" at 0054, though at 0055 he was still concerned that the storms were becoming "just [a] line." At 00:57 UTC he started seeing a tighter circulation and checked spectrum width. Nothing "jumped out" at him, but he "felt like he needed another tor[nado warning] and started to feel more comfortable with this [decision]." He saw rotation strengthening at 1.1° and 1.5°, and increasing inbound and outbound winds at 0.5°, but wanted to "see another scan or two" before warning (0058). "Was this an anomalous trend or one that would last." He was "seeking confidence" at 0059 by looking at the 4-panel and all-tilts displays. This storm had the strongest updraft. His decision to warn came at 0100 after seeing 25–30 kts of shear at 0.5°, and knowing he had 7–8 min to expiration of his previous warning.

Bridget had been unclear about what the multiple rotations meant, until at 00:57 UTC she saw enhanced velocities "finally showing up at 0.5°." She was now "more and more concerned," and by 0059 she became "more confident that [she] would need a new warning." She had time in her previous warning to allow the circulation to move out of one county, and so prepared the warning but delayed hitting send until 0104.

Pat, who had a warning in effect until 01:15, had "a hard time figuring out ...[his] conceptual model" until the case was ending. He also held a high bar for the strength of gate-to-gate signatures. At 00:57 UTC, he could "clearly see" two circulations at 1.5°, but was not satisfied with the magnitude given the distance from the radar. His late recognition of tornadogenesis and warning decision occurred at the end of the tornado lifecycle (0108) when he "finally [saw] something with the right colors." At 0109 he stated, "there is obviously something happening, though we're getting far away."

6. 14 APRIL 2011 NONTORNADIC EVENT

The 14 April 2011 event spanned from 2055 to 2121. At case start time (2055), two potentially severe storms existed within the domain (Fig. 1c). During the simulation, forecasters received a report of two-inch hail in the vicinity of the south storm at 2100 (NCDC 2011).

In real-time operations at the Norman, Oklahoma Weather Forecast Office, an unverified tornado warning was issued on the southern supercell at 2112. Hence, this event was a useful null case for exploring whether forecasters working the event with rapid-scan radar data would perform differently. While working this case, 8 of the 12 forecasters also decided to issue a tornado warning on this storm, whereas the other four did not (Fig. 4b). As seen in Fig. 4b, times at which forecasters issued tornado warnings tend to cluster. Three forecasters (Pat, Elmer, and Bridget) issued warnings near 2102, whereas four others (Ben, Jay, Avery, and Mike) issued warnings about 5 min later, near 2109—three minutes prior to unverified warning issued by the Norman WFO. Five made decisions not to warn near this time (Brad, Bob, Maggie, Randy, and Dirk). Two forecasters, Dirk and Pat, decided to issue warnings as the case ended (2121). Interestingly, this was Pat's second warning, and it was issued on the north storm. He is the only forecaster who issued a warning on this storm.

During the case, forecasters focused their radar analysis on evolution such as trends in intensity of the midlevel mesocyclone, the storm's updraft, and inflow. Once they decided that tornado development was likely, they tended to continuously monitor the lowest four velocity elevations for evidence of rear flank downdraft onset and/or formation of rotation at increasingly lower tilts. This radar analysis is recalled by forecasters mostly on a minute-by-minute basis, which indicates that the forecasters mentally processed radar information relevant to them as each volume scan updated.

6.1 *Decisions to warn on south storm*

6.1.1 Mesocyclone Starting to Descend (2056 – 2103)

While retelling their decision processes, Pat, Elmer and Bridget recalled observing the descent of the mesocyclone in the preceding minute(s). Each also cited storm signatures aloft influenced their decisions to warn.

Pat was the first to warn. After deciding to focus on the south storm (2056), he noted divergence aloft and thought he saw a smaller-scale circulation within the midlevel mesocyclone. Looking at lower tilts, he judged "[there is] nothing in low levels to warn [on] off the bat." During the next scan, however, he decided to issue a warning, explaining that "rotation was moving down from aloft, strengthening and getting lower. [It] [w]as not at 0.5° yet, but it had all the rest of it: a supercell, a BWER, an appendage (possibly aloft)." The process of issuing the warning (e.g., drawing the polygon, determining storm track, etc.) lasted five minutes, resulting in a warning issue time of 2103. During that period, Pat shared that "sometimes he doesn't wait to see the indications of something forming before issuing a warning." And, that in his forecast area, "if you have a supercell you'd better have a warning out."

At 2057, **Elmer** decided, "[the] storm's very strong inflow and overall reflectivity" warranted starting WARNGEN, "should the storm produce a reliable couplet at 0.5°." He said that setting-up WARNGEN 5–10 min prior to the time he anticipates issuing a warning was his usual practice. During the next four minutes, Elmer assessed that the storm was cycling, and noted "very strong inflow just east of the hook" (2058). Three minutes later (2101), he observes the strengthening of that inflow, and that it is beginning to intersect the storm's outflow. At midlevels he noted the mesocyclone was starting to tighten up. During the next minute, he recalled the trends that instigated his decision to warn: the meso starting to descend, outflow increasing a bit, and the hook and bounded weak echo region (BWER) re-forming. He noted the report of large hail at 2100 also influenced his decision to warn.

Early on (2057), **Bridget** surmised "there was some nice midlevel rotation that was strengthening, but [the] low-level velocity signature was not tight or strong enough". Like Elmer, she investigated storm structure aloft, where she detected divergence and a BWER that was looking more defined. Together, these signatures implied a strengthening updraft. She then decided (2058) the storm's intensity was strong enough that she might issue a warning, and started WARNGEN. At 2059 she noted the strengthening rotation was still at midlevels only, and that the rotation and reflectivity storm structures matched spatially. Bridget noticed trends at 2101: an upward trend in rotation at 3.5°, and higher outbound velocities that were descending toward the surface. At 2103 she decided to issue a tornado warning. She explained, "Seeing strong enough rotation at midlevels and stronger descending outbound velocities (RFD) making it to the surface" warranted a warning. These cues suggested to her that she'd see tightening of a low-level circulation soon.

6.1.2 Mesocyclone Descent to 0.5° and Favorable Environment (2103 – 2105)

At 2103, both Ben and Jay were concerned that tornadogenesis was likely in the next few minutes. **Ben's** concern arose from having seen "good circulation from about 3 – 5°, but …less tight rotation, and weaker [circulation] in the lowest levels" at 2101. With this in mind, at 2103 Ben stated that "reflectivity-wise, and environment-wise, I needed to be a bit more ready." He firmed up the storm motion in WARNGEN (which he prepped at the start of the case). At 2104, he saw a jump in inbounds at 0.5°. Checking the lowest four tilts, he also saw strong inbounds through 1.5°. He decided to issue a tornado warning at 2105, when the "circulation at 0.5 had tightened up and had continuity aloft." Having seen that evolution occur in an environment with low lifting condensation levels, he knew it was time to issue a warning. The warning issue time was 2109.

Jay had also been tracking the development of rotation at lower tilts. At 2103, he was "watching 0.5° to see if tightening of the mesocyclone seen at 0.8° would evolve to this level." He then started WARNGEN (2104) and waited for the next scan, as he wanted to see confirmation of mesocyclone descent to 0.5 before warning. At 2105 he saw what he was expecting happen, the mesocyclone descended to 0.5° and it had gate-to-gate circulation. He also noted "[the environment had the] right type of low-level shear available for tornadoes." Like Jay, his warning issue time was 2109.

6.1.3 Midlevel Mesocyclone Tightens, BWER Descends, and Rotation Develops at Lower Tilts (2103 – 2110)

Near 2103 was also a turning point in Avery's and Mike's decision processes. **Avery** recalled, "upper bounds of [the] BWER [was] starting to fill some." He explained that this "lowering of the BWER may start [a] cycle where it could tornado." At 2104 he noticed a an artifact in the 0.5° velocity, which he termed "[a] three-body scatter velocity." But what led him to consider warning was seeing midlevel rotation tightening up and occurring within the descending BWER. After starting WARNGEN, at 2105 he noticed the rotation at lower levels, 1.1 and 1.5°, also started to increase and tighten. At 2106 he decided to issue a tornado warning. He explained that rotation starting to develop at lower tilts (not 0.5) and the coincident collapse of the BWER with tightening circulation at all midlevel tilts, instigated this decision. The warning issue time was 2108.

At 2104, **Mike** noticed not only that the "BWER might be closing off a little", but also saw tightening of rotation at both 1.1 and 1.5°. He "was thinking the rotation might be becoming more concentrated,…so [may be] getting close to tornadogenesis." Mike's projection of the storm's future state led him to consider warning (2105). After starting WARNGEN, he wanted to wait a couple of more scans. He explained, "If things continued to persist the way they were, I was going to go ahead and issue the warning." In the next scan, he noticed some velocity dealiasing issues on the lowest two tilts, and tried to make sense of the data by comparing patterns seen there with those seen at the two tilts above. Following these data issues, at 2108, Mike decided to issue a tornado warning due to the "persistent indication of [a] potentially tornadic storm." Specifically, he cited the overall trend of the descending mesocyclone, more persistent rotation at the lowest scan, and the BWER becoming "less defined."

6.1.4 Descending Mesocyclone Approaching a City (2117 – 2118)

Though **Dirk** decided not to warn earlier in the case, at 2118 (section 6.2.1, below) he decided to issue a tornado warning on the south storm. He began to monitor low levels intensely after noticing the stronger mesocyclone aloft was beginning to descend, and he saw stronger rotation at 1.5° than before (2117). His apparent tipping point at 2118 was not only the maintenance of the mesocyclone he saw at 1.5° and its new development at 1° in the next scan (2119). He explained that his decision to warn was also influenced by the storm heading toward the town of Sulphur, Oklahoma. As described in section 6.2.1, descent of the mesocyclone toward lower tilts was not sufficient for him to issue a warning. Rather, he wanted to see a persistent circulation at the lowest tilt before issuing a tornado warning. The discernible difference between his former decision process (not to warn) and the one discussed here was societal: he was concerned about the storm heading toward a populated area.

6.2 Decisions not to warn on south storm (2102 – 2112)

During 2102 to 2112, five other forecasters also observed the intensification of the mesocyclone and were monitoring low levels for rotation development. Three of these forecasters, Randy, Dirk, and Maggie considered issuing a tornado warning, but decided against doing so. For Brad and Bob, their decision process never escalated beyond monitoring.

6.2.1 Consider Warning But Don't See Anticipated Low-Level Velocity Evolution

During this period, **Randy** and **Dirk's** storm interrogation focused on evolution of the radial velocity field at mid and low levels. Both Randy and Dirk were impressed by the intensification of the mesocyclone at 2104. Randy recalled (at 1.1 and1.5°), "[a] dramatic increase in inbounds and outbounds." He noted this velocity signature was "not purely rotational yet." And at 3°, he measured a 100kt velocity difference." Dirk described the mesocyclone as having "really intense, "tremendous rotation." Below the mesocyclone, they also noticed a surge in the inbound velocities, which had reached a magnitude of 60 kts at 0.5° at 2105.

At 2106, Randy and Dirk's concern that a warning may be needed was heightened by the development of rotation at tilts above 0.5°. When the next scan comes in at 2108, Randy continues to interrogate the south storm, whereas Dirk refocuses his attention on the broader domain. While broadening his situation awareness, he noticed another splitting supercell to the south, and was concerned that the left mover would eventually "come up and choke off the main storm." Returning his attention to the storm of warning concern at 2109, Dirk noticed a "brief 40kt gate-to-gate signature at 0.5°" on this scan. Randy notices a similar signature, but at 1.1 and 1.5°. In response to this evolution, both start WARNGEN, and then wait for the next scan.

At 2110, Randy saw that the couplet he wanted to see at the lowest two scans had not developed, and that the couplet above was a bit weaker and less organized. As result, he decided not to warn. A few minutes later, at 2112, Dirk noted that he was "satisfied that he had not warned" as there was "not as good of a velocity signature at 0.5° as seen at 2109."

Maggie's decision process differs from that of Randy and Dirk in that she questioned the data quality of the gate-to-gate velocity signature that she first observed at 2105. Zooming in, she saw "one to two pixels of red next to green in [the] west part of [the] storm", and noted a lack of confidence in what she was seeing. Seeing the signature again at 2106, she was still "suspect of the data, because [of] only one gate on each side." During that scan, she also indicated there were still a BWER and "good divergence" in higher tilts, features absent from Randy and Dirk's recollections. Regardless of her uncertainty in gate-to-gate velocity signature, at 2108 she started WARNGEN and considered issuing a warning, saying, "Pixels are not there yet, but should they get closer, [I] will issue." When the next scan comes in at 2109, she exclaimed, "Pixels seen gate-to-gate are gone!" Then, after noting the inflow was weaker, exclaimed, "Enough with that! [I'm] Not issuing a warning now!"

6.2.2 Don't Consider Warning, and Don't See Anticipated Low-Level Velocity Evolution

Neither Bob nor Brad considered warning during this event. Unlike the other forecasters, they never saw the development of low-level circulation below the midlevel mesocyclone that they wanted to see.

From **Bob's** perspective, he noticed the 0.5° inflow and associated convergence increasing from 2104 through 2106 seen by others, including the 60 kt inflow noted by Randy and Dirk. Bob called this inflow "impressive." Like the others, he saw the mesocyclone strengthening aloft at all levels (2104), also noting reformation of the BWER a few minutes later (2106). Continuously interrogating low-levels, scan-after-scan he reiterated, "Still strong midlevel meso, still waiting to see higher velocities down low. Want to see that tightening." but no "significant tightening in [the] low-level circulation."

During **Brad's** interrogation of the 0.5° velocity**,** he noticed data quality issues in and around the storm's inflow (2102), which were also mentioned by Maggie. He interpreted the "bad velocity data" south of the reflectivity gradient as side lobe caused by strong vertical reflectivity gradients within the BWER. From 2102 to 2103, he was "not worried about it masking anything, but didn't give that data much weight." Thereafter he successfully interpreted the low-level inflow increasing (2104), and the coincident development of a "tighter couplet aloft", within the mesocyclone (2105). During that scan he checked to see if that tightening had transition to lower levels, and saw it did not. Like Bob, he noted that the inflow is still strong at 2106. He is the only forecaster who also observed an arc of reflectivity streaming into the storm at this time. Thereafter, he focused his attention on the reflectivity pendent. He started to see some outbound velocities, but thought they were potentially bad data. In the next scan, he noticed the inbounds had weakened, though a "moderate mesocyclone [was still] at midlevels, fairly tight gate-to-gate." At 2110, his body language and narrative indicated that the storm was not evolving as he thought it might: He shook his head, and said, "Nothing has changed."

7. SUMMARY

Twelve NWS forecasters participated in the 2012 PARISE, which ran for six weeks during June – August 2012. Each forecaster worked four cases ranging from 18–52 min in length. Tornadoes were reported in 2 of the 4 cases, which allowed us to examine how rapid-scan data may help forecasters discern between tornadic and non-tornadic supercells.

Verification statistics show that during the experiment 79% of tornado lead times exceeded the 12.26-min national mean lead time for EF0 and EF1 tornadoes (computed 1 January 2008 through 1 August 2013). 64.5% of lead times exceeded the 17.9-min national mean lead time for tornadoes rated EF2 and higher. The mean and median lead time across forecasters was 20 min. Polygon Probability of Detection values, defined as the average percent of tornado paths warned, were all 75% or higher. All False Alarm Ratios were 0.5 or lower. These quantitative results indicate the use of rapid-scan PAR data resulted overall in longer lead times.

The decision processes associated with these statistics were analyzed for two of the cases: 11 May 2010 and 14 April 2011. An examination of the timelines showed that forecasters usually attained SA from the PAR data on a minute-by-minute basis. Hence they were mentally processing radar information relevant to them as each volume scan updated.

7.1 *11 May 2010 case.*

The 11 May 2010 case differed from the other four cases due to a continued enhanced tornadic environment at case time, but a non-isolated supercell embedded on the southern end of a line of storms. Forecasters had to decide whether warnings were merited during the case time of 0036 – 0111.

Although we had not intended for forecasters to make warning decisions during the first few minutes of any case, most forecasters (N=10) made the judgment to issue a tornado warning by 0038. Their decisions clustered by which factors they weighted most in their warning decision: environment and history, with radar being "good enough," or confidence in radar signatures. Just after 0041, the velocity signatures broadened and weakened as the storm cycled. Two forecasters did not warn in the first few minutes of the case.

All but one forecaster correctly became concerned about early signals of tornadogenesis prior to the tornado. Eight of these forecasters made their judgment by 0059. Three others made their judgment by 0100–0102. Key features noted in the few minutes prior to their judgment:

1) Persistent strong and strengthening mesocyclone (N=4)
2) Formation and surging of a rear flank downdraft (N=8)
3) Tightening of velocity at the lowest tilt (N=11)

The tornado occurred between 0105 and 0109.

7.2 *14 April 2011 case.*

As expected, 14 April 2011 was a fairly tough nontornadic case: 8 of 12 forecasters decided to issue a tornado warning during the event. Warning decisions clustered within two periods: 2056 – 2103 and 2103 – 2112. The projected storm evolution forecasters wanted to see prior to warning increased in complexity from the first period to the second period. In basic terms, the three different sets of evolutionary requirements included:

1) Strengthening midlevel mesocyclone starting to descend (2156 – 2103; N=3)
2) Strengthening midlevel mesocyclone descending to 0.5° and favorable environment (2103 – 2105; N=2), and
3) Midlevel mesocyclone tightens, BWER descends, and rotation develops at lower tilts (2103 – 2112; N=2).

Only one forecaster decided to warn on the south storm at 2118. For Dirk, his decision to warn was based on the onset of mesocyclone descent coincident with the storm moving toward a populated area.

The four forecasters who correctly decided not to warn during the case interpreted the low-level storm evolution differently than those who decided to warn during the second and third warning decision clusters. Most importantly, they did not see the strength and/or persistence of low-level circulation they wanted to see.

Acknowledgments. We thank the 12 NWS forecasters for their participation in this study, the Southern and Central Region SSD Chiefs, MICs, and SOOs for aiding recruitment, and Les Lemon and Steve Martinaitis for their participation in our experiment test run. We also thank the following colleagues for their contributions to this research. Knowledge elicitation and cognitive task analysis expert Dr. Robert Hoffman; Experimental Warning Program leads Greg Stumpf, Travis Smith, and David Andra; AWIPS-II and LINUX expert Darrel Kingfield; A/V specialist James Murnan; GIS expert Ami Arthur; WDSS-II expert Kiel Ortega; simulation expert Dale Morris; software experts Eddie Forren and Hoyt Burcham. Finally, thanks to Jimmy Correia for helping with data collection, Jim LaDue for preparing the weather briefings, and Harold Brooks for his thought-provoking discussions on this research.

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Table 1. National NWS verification statistics from 1 January 2008 to 1 August 2013 for tornado events, listed by EF rating. PPOD is polygon probably of detection and TLT is mean tornado lead time.

EF Rating	Total # Tornadoes	# Warned	# Not Warned	PPOD	# 0 TLT	Mean TLT (min)
0 and 1	9062	7072	1990	0.682	2230	12.26
≥ 2	1374	1250	124	0.852	150	17.98
Combined	10436	8322	2114	0.707	2380	13.12

Table 2. Case dates and times, radar update time(s), and tornado occurrence during the event.

Date	**Duration (UTC)**	**Scan Strategy Update Time (s)**	**EF Rating and Duration (UTC)**
11 May 2010	0035–0111	59 4 lowest elevations: 22	EF0: 0105–0109
14 April 2011	2055–2120	70	None
22 April 2011	2339–2358	54	None
22 May 2011	0050–0142	56	EF0: 0118–0120 EF0: 0129–0133 EF1: 0141–0147

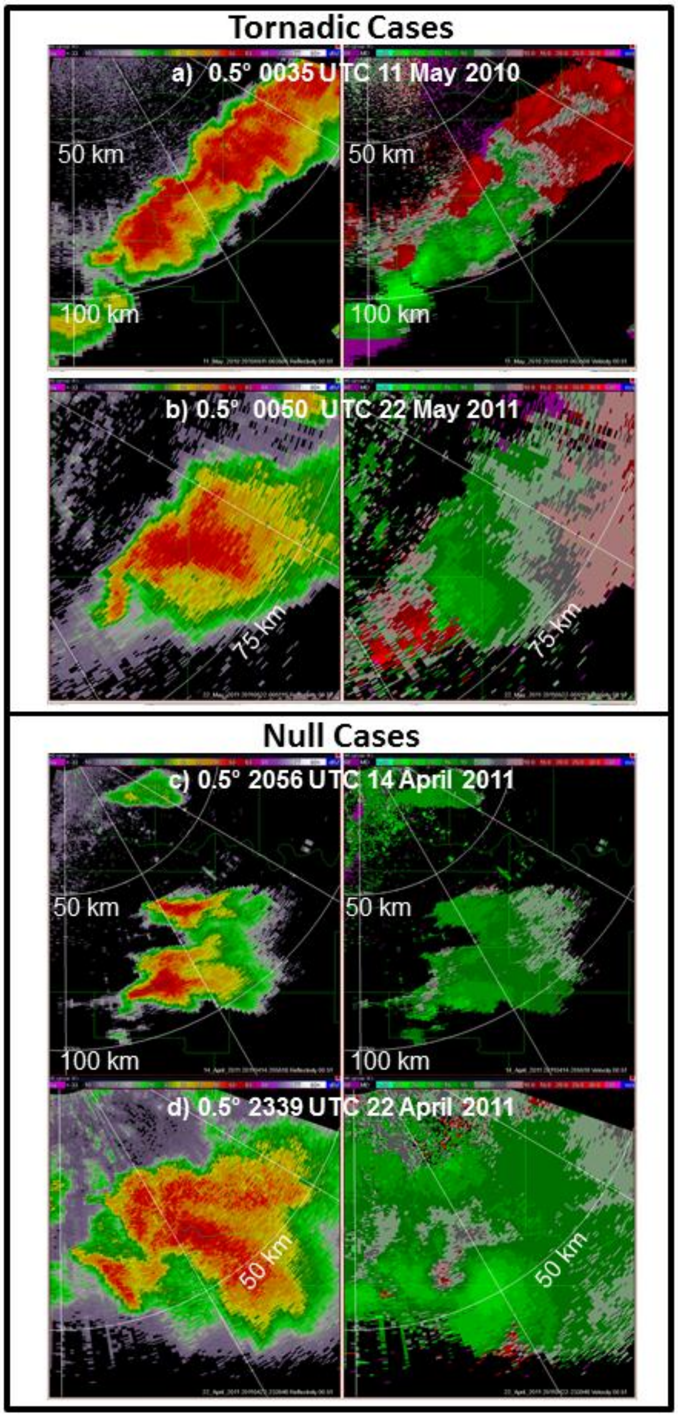

Figure 1. Snapshots of 0.5° reflectivity and velocity near the beginning of each case — Tornadic: (a) 0035 UTC 11 May 2012 and (b) 0050 UTC 22 May 2011; Null: (c) 2056 UTC 14 April 2011 and (d) 2339 UTC 22 April 2011. Range rings are labeled in km.

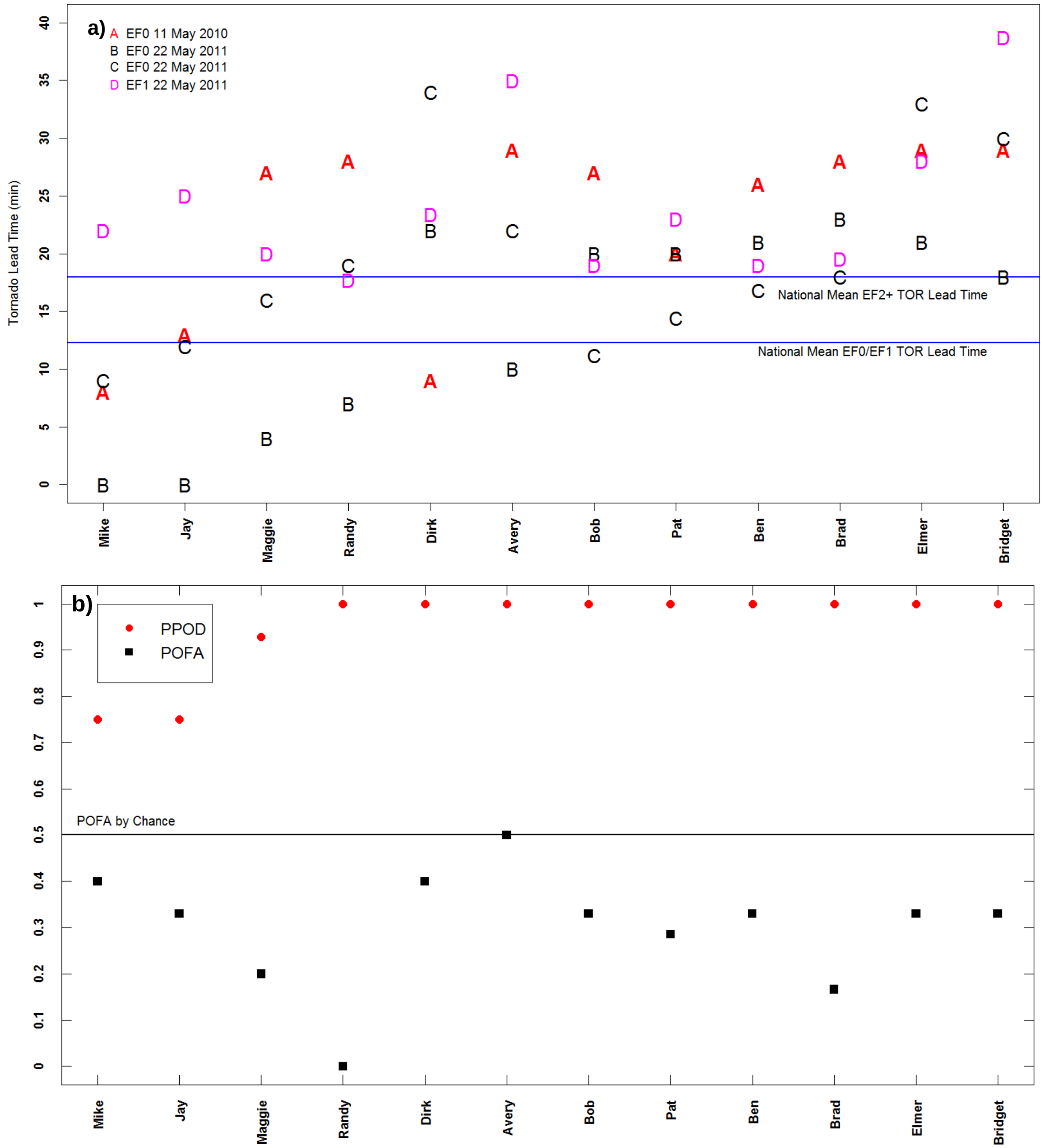

Figure 2. (a) Distribution of tornado lead times (min) computed for 11 May 2010 and 22 May 2011 events: EF0-rated tornado on 11 May 2010 (A) and 3 tornadoes on 22 May 2011 (B,C,D), listed in chronological order. Horizontal blue lines denote the mean national lead time computed from 1 January 2008 to 31 October 2013 for EF0 and EF1 tornadoes (12.5 min) and EF2 and higher rated tornadoes (18 min). (b) Distribution of polygon probability of detection (PPOD) and probability of false alarm (POFA) computed for 11 May 2010 and 22 May 2011 events. The horizontal line at 0.5 indicates the POFA attainable by chance.

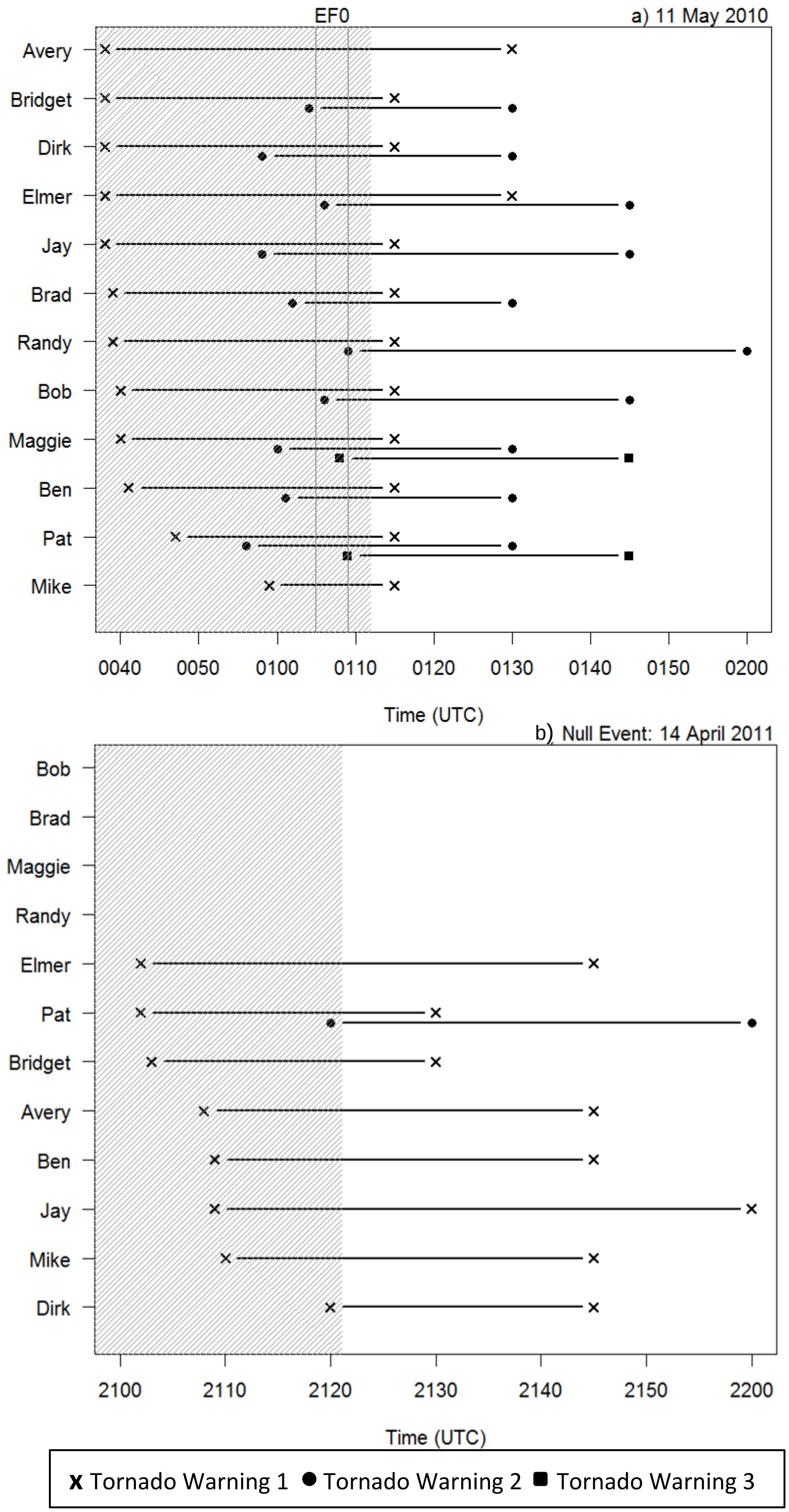

Figure 3. Start and end times of tornado warnings issued by participants on a) 11 May 2010 and b) 22 April 2011. The first, second, and third tornado warnings are denoted by an x, filled circle, and filled square, respectively. Case duration is shaded grey and tornado duration is shown by vertical grey lines.