THE TORNADO WARNING PROCESS

A Review of Current Research, Challenges, and Opportunities

BY J. BROTZGE AND W. DONNER

A review of the entire warning system, from prediction and detection to public response, reveals such fundamental needs as identifying acceptable risks, improving personal preparation, and personalizing warnings.

One of the scientific community's greatest achievements in meteorology during the twentieth century has been the development of a largely effective public tornado warning system. Between 1912 and 1936, tornadoes killed an average 260 persons per year, about 1.8 deaths per million people when normalized by population (Brooks and Doswell 2001). Between 1975 and 2000, that number had declined to 54 deaths per year, or 0.12 deaths per million people in 2000 (Brooks and Doswell 2001), a reduction of 93% from 1925. In 1986 the tornado warning lead time was approximately five minutes, with only 25% of tornadoes warned; by 2004, the mean lead time was 13 min, with about 75% of tornadoes warned (Erickson and Brooks 2006).

Far from simple, the tornado warning process is a complex chain of events, encompassing institutional action and individual responses, that utilizes sensing technologies, conceptual models, numerical weather prediction (NWP), forecaster and emergency management (EM) decision making, warning dissemination technologies, and public experience and education (Fig. 1). The sequential steps of this process—forecast, detection, warning decision, dissemination, and public response—are known as the Integrated Warning System (IWS; Leik et al. 1981; Doswell et al. 1999).

This article reviews the end-to-end tornado warning process and related research, considers the challenges to improving the current system, and explores possible next steps. While this article cannot provide a completely comprehensive review of all research in each specific area, the goal is to provide a broad overview of the tornado warning process and a brief summary of the many avenues of research that could contribute to improvements in the current system.

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TORNADO PREDICTION. The ability to predict a tornado's precise path and intensity days in advance could allow for evacuation to take place well ahead of storm development and the predeployment of assets needed to support emergency response and recovery. While restrained to less accurate forecasts by the inherent limitations imposed by atmospheric predictability, the last decade has seen a growing recognition of the connection between large-scale patterns and large-scale tornado outbreaks.

As high-resolution, convection-allowing (≤4-km grid resolution) NWP becomes more accurate at longer time scales, multivariate model output may be used to a greater extent in identifying and predicting

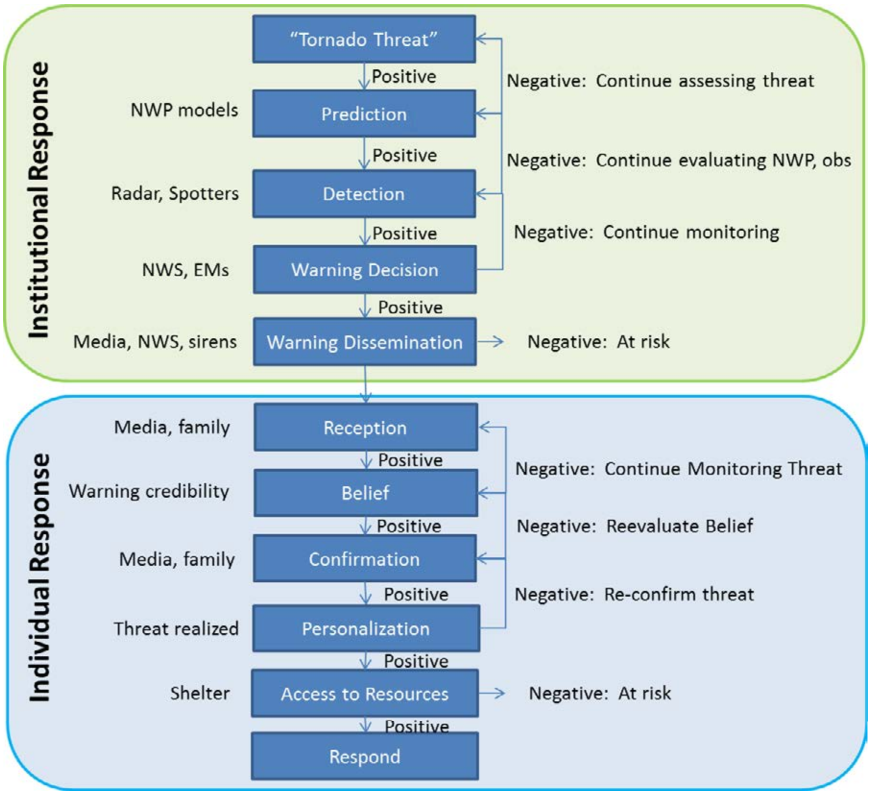

Fig. 1. Summary of the institutional and individual responses that comprise the tornado warning process.

tornado outbreak events. Using observational and modeling analysis, Egentowich et al. (2000a,b,c) identified a series of dynamic precursors during the 6–84 h preceding a major tornado outbreak. Shafer et al. (2009) found that Weather Research and Forecasting (WRF) model output could be used to discriminate between tornadic and nontornadic events up to three days in advance. Using WRF simulation output, Mercer et al. (2009) developed a statistical objective analysis technique to extract relevant predictive variables, yielding statistically significant accuracy scores >0.7 and skill scores >0.5 of these variables one day in advance of storm formation (Shafer et al. 2010).

Ever faster computer processing, and increasing memory and storage capacities combined with advances in parallel computing and code efficiency now enable the routine use of mesoscale forecast ensembles at high-resolution hours or even days in advance. Furthermore, analysis of model ensembles provides insight into forecast uncertainty. Stensrud and Weiss (2002) demonstrated that even a relatively coarse (32-km inner grid), small six-member ensemble, while underdispersive, provided some statistical guidance in predicting the relative locations of expected severe weather 24 h in advance. Clark et al. (2010) have since shown that the use of convection-allowing resolutions improves the representation and prediction of severe weather features. As a predictive measure of storm severity, Clark et al. (2012) extracted proxy forecasts of tornado pathlengths from 36-h ensemble forecasts.

One official National Weather Service (NWS) product to alert local weather forecast offices, emergency personnel, and the public of favorable conditions for tornadoes to occur is the *tornado watch*. First issued by the Severe Local Storms Unit [SELS, now the Storm Prediction Center (SPC)] in 17 March 1952 (Galway 1975), the tornado watch is a manually generated product, based upon NWP output and observations, and may be issued up to several hours in advance of initial convective initiation. The skill level of the tornado watch has continued to improve over the years with increased observations, refined conceptual models, and more accurate and higher-resolution NWP (Pearson and Weiss 1979; Ostby 1999). Two additional, increasingly popular products issued by the SPC are the convective outlooks and mesoscale convective discussions (MCDs; Stough et al. 2012). Convective outlooks are issued up to eight days in advance, highlighting areas of the country with the potential for severe weather. MCDs are used to highlight general areas of concern, often issued just hours ahead of convective initiation or just prior to issuance of a watch. Both convective outlooks and MCDs are composed of a discussion briefing and visual map, and provide additional lead time and probabilistic information.

Currently, all official NWS tornado warnings are issued based upon "detections," where an immediate tornado threat is observed either directly by spotters and media or inferred from observations (e.g., radar). However, as the accuracy and precision of short-term (0–3 h) storm predictions continue to improve, model output is expected to become an increasingly important basis upon which to issue NWS tornado warnings. This is the eventual goal of "warn on forecast" (Stensrud et al. 2009), where NWS tornado warnings may be issued based not only on detected tornadoes or observed precursors, but also on model output. Utilizing model output as the basis for some warnings could theoretically extend lead time to tornadogenesis.

Significant advances in computer processing, the utilization of new types and greater numbers of real-time weather observations (NRC 2009), and the development and adoption of new data assimilation (DA) techniques (Kalnay 2003; Park and Xu 2009) are making warn on forecast a reality. Computer processing capabilities continue increasing at an exponential rate, as predicted by Moore's law (Moore 1965). Faster processing permits higher-resolution NWP, which allows for the direct use of convective-resolving physics, bypassing less accurate parameterization schemes. The use of new observations, such as dual-polarimetric radar (e.g., Jung et al. 2008), wind and temperature profilers (e.g., Otkin et al. 2011), data from aircraft [e.g., Aircraft Communication, Addressing, and Reporting System (ACARS); Benjamin et al. 1991], lightning data (Fierro et al. 2012), and new evolving mobile platforms (e.g., Mahoney et al. 2010) facilitates a more accurate, three-dimensional analysis of the initial conditions. Model initialization also has been made easier with greater access to real-time observations through the use of such systems as the Collaborative Radar Acquisition Field Test (CRAFT; Kelleher et al. 2007), the Meteorological Assimilation Data Ingest System (MADIS; Miller et al. 2007), and Thematic Real-time Environmental Distributed Data Services (THREDDS; Unidata 2012); see "Prediction challenges" for more information.

TORNADO DETECTION. Weather radar is the primary tool used by warning forecasters to identify areas of potential tornado development. Radar reflectivity provides forecasters with a clear view of tornadic features, such as the hook echo (Markowski 2002), and Doppler radial velocity shows horizontal wind shear, sometimes an early indicator of tornado formation (Brown et al. 1971). Radar polarimetric data provide storm microphysical information, such as hydrometeor type and shape, that can be used to identify areas of significant low-level wind shear (referred to as Z_{DR} arcs) and tornado debris (Ryzhkov et al. 2005; Bodine et al. 2013).

To better standardize weather radar coverage across the United States, the national Weather Surveillance Radar-1988 Doppler (WSR-88D) network [known as Next Generation Weather

PREDICTION CHALLENGES

Several significant challenges remain to be addressed before routine 0–3-h tornado prediction can be realized. These needs include i) faster computer processing to permit even higher-resolution NWP and more robust ensemble systems; ii) the ability to enable real-time DA of even larger volumes of data; iii) greater numbers of observations at high spatial and temporal resolutions; and iv) the ability to predict marginal, less predictable events with greater accuracy and fewer false alarms. Model grid spacing is tightly coupled with the model physics; for example, Bryan et al. (2003) determined that model grid spacing on the order of 100 m is needed to fully resolve subgrid-scale turbulence. Parameterization schemes, such as cloud microphysics, convective, and planetary boundary layer schemes, fail to capture subgrid-scale processes which can lead to large sensitivities in storm-scale NWP results (e.g., Dawson et al. 2010; Bryan and Morrison 2012).

In a similar manner, storm-scale NWP is equally sensitive to model initialization and analysis. Numerical modeling of convective storms has shown sensitivity to model initialization of low-level thermodynamics (Frame and Markowski 2010), low-level wind profiles (Dawson et al. 2012), surface soil moisture (Martin and Xue 2006), and orography (Markowski and Dotzek 2011). Model assimilation sensitivity may be reduced by increasing the number and use of observations in critical areas (Schenkman et al. 2011; Snook et al. 2012) and at critical times (Richter and Bosart 2002). However, the ability to collect, quality control, and properly assimilate all the necessary data in real time at high resolutions is a significant challenge (e.g., Brewster et al. 2008). To address this issue, an optimally designed national observing network is needed to collect the necessary observations at the high resolutions required (e.g., low-level moisture and wind profiles; Dabberdt et al. 2005; National Research Council 2009).

Finally, while our ability to anticipate and predict significant events is relatively good with a POD of nearly 90% for tornado outbreaks (Brotzge and Erickson 2009), the community faces significant challenges in predicting marginal and/or weakly forced tornado events. Brotzge and Erickson (2009) found the first tornado of the day, solitary tornado events, tornadoes from hurricanes, and weak (F0, F1) tornadoes had a much greater chance of not being warned. The FAR has been found to be highest for weakly forced and isolated events (Brotzge et al. 2011). Nonsupercell tornadoes, such as from tropical storms (Schultz and Cecil 2009; Moore and Dixon 2012) and squall lines (Trapp et al. 2005), pose a significant difficulty for prediction because of their often transient nature. Among the greatest remaining challenges for tornado prediction are the ability to predict exactly when a tornado will initiate (Markowski and Richardson 2009), to differentiate between tornadic and nontornadic supercells (Brooks et al. 1994; Stensrud et al. 1997; Mead 1997; Davies 2004; Schultz and Askelson 2012), and to identify threatening nonsupercell tornadic storms (Wakimoto and Wilson 1989).

Radar (NEXRAD); Crum and Alberty 1993; Crum et al. 1993, 1998] was deployed (Whiton et al. 1998). The WSR-88D scanning geometry was designed to facilitate complete coverage between 610 m (2000 ft) and ~18 km (60,000 ft) AGL, with minimum height coverage at or below 610 m within a range of 102 km from radar (Leone et al. 1989); the final network provided contiguous coverage across the United States at 3.05 km (10,000 ft) and above (Crum and Alberty 1993). Specific radar site locations were chosen based primarily upon population distribution, severe weather climatology, topography, and proximity to other radars; most radars were sited to provide coverage over and slightly upwind of major metropolitan areas (Leone et al. 1989). As of 2012, 160 WSR-88D (S band) systems comprised the NEXRAD network across the United States and territories.

NEXRAD deployment had an immediate and significant positive impact on tornado warning statistics (Polger et al. 1994; NRC 1995). Bieringer and Ray (1996) found that the probability of detection (POD) increased by 10%–15% and that warning lead times increased by several minutes after installation of the WSR-88D network. Analyzing all tornadoes in the conterminous United States (CONUS) between 1986 and 1999, Simmons and Sutter (2005) estimated that the deployment of NEXRAD increased the percentage of tornadoes warned from 35.0% to 59.7%, increased the lead time from 5.3 to 9.5 min, reduced the false alarm ratio (FAR) from 78.6% to 76.0%, and reduced the number of expected fatalities and injuries by 45% and 40%, respectively. Smith (1999), however, noted that verification procedures changed as the NEXRAD system was deployed, possibly accounting for some of the observed increase in the POD.

For enhanced tornado detection, automated detection algorithms, such as the WSR-88D mesocyclone (Stumpf et al. 1998) and tornado detection algorithms (MDA and TDA, respectively; Mitchell et al. 1998), automatically identify radar-based tornado features and are displayed in real time within the Advanced Weather Interactive Processing System (AWIPS). Radar data can be combined with additional weather information to linearly project storm motion and extrapolate mesocyclone, tornado, and hail core movement (e.g., Smith and Elmore 2004; Lakshmanan et al. 2007; Wang et al. 2008; Ortega et al. 2009; Lakshmanan and Smith 2010; Miller et al. 2013).

Storm reports from individuals in the field can provide timely, critical information to warning officials. Trained "storm spotters" provide a valuable service to the NWS, EMs, and media by providing reliable, real-time information on storm evolution and tornado development (Moller 1978; McCarthy 2002). As well documented by Doswell et al. (1999), storm spotter networks were first organized during World War II largely to protect military installations. By the mid-1960s, spotter groups were organized more formally by the Weather Bureau for more general use under its SKYWARN program. With the advent of cell phone and embedded camera technology, widespread access to the Internet, television station helicopters, volunteer and professional storm chasers, and the rise of social media, warning forecasters now have greater access to real-time information than ever before.

Nearly as important, spotters provide much-needed postevent verification; Brotzge and Erickson (2010) found a systematic increase in the numbers of weak tornadoes verified over densely populated counties when compared with rural counties. However, erroneous reports from the field can impede the warning process; Smith (1999) describes how poor tornado verification overinflates tornado POD and overestimates the FAR. Brotzge et al. (2011) found very high FAR in high-population-density counties and very low FAR in sparsely populated counties, perhaps indicative of lower warning rates across rural areas because of the prevalence (or lack) of field reports available and a subsequent decrease in forecaster confidence for warning in those areas; see "Detection challenges" for more information.

TORNADO WARNING DECISION.

Once the formation of a tornado is considered likely or is reported already in progress, the NWS issues a *tornado warning*, the official NWS product used to warn the public of a tornado. The first tornado warning was issued on 25 March 1948 by U.S. Air Force officers E. Fawbush and R. Miller at Tinker Air Force Base in Oklahoma City, Oklahoma, and was remarkably successful (Miller and Crisp 1999b; Maddox and Crisp 1999). In fact, this first warning was so successful that it provided the scientific underpinning for establishment of the Air Weather Service Severe Weather Warning Center (SWWC), the first national severe weather warning program. During its first year of operation in 1951, the SWWC issued 156 (multicounty) tornado warnings, of which 102 (65%) were verified (Miller and Crisp 1999a). Since that time, tornado warnings, now issued by the local NWS Weather Forecast Offices (WFOs), have continued to improve as measured by the total percentage of tornadoes warned.

The final decision by the operational forecaster on whether to issue a warning is based upon a number of

DETECTION CHALLENGES

The most common reasons for operational warning forecasters for not detecting (and thereby not warning) tornadoes prior to touchdown often can be traced to having either too little information available—because of inadequacies in existing technology (e.g., LaDue et al. 2010), limited spotter networks, and incomplete conceptual models—or too much information, that is, data overload.

As the primary tool used for detecting tornadoes, weather radar is critical for seeing low-level to midlevel rotation prior to tornadogenesis. In areas with limited low-level radar coverage, tornado detection (and prediction) is severely hampered. In a root cause analysis study of 146 unwarned tornadoes between 2004 and 2009, "radar sampling," "no radar signature," and "radar use" were listed as 3 of the top 10 reasons for failure to warn and were cited in over two-thirds of all missed events (Quoetone et al. 2009). Sampling issues were cited in 19 of 31 false alarm events evaluated. Brotzge and Erickson (2010) found a mean 20% increase in the number of tornadoes not warned with increasing distance from radar, once sorted by population density.

Solutions to improving radar coverage include the use of lower-elevation scans, deployment of gap filling and rapid-scan radars, and an optimization of the radar network configuration. The WSR-88Ds' lowest scanning angle is 0.5° elevation, as limited by Federal Communications Commission (FCC) regulations. At some mountain sites across the western United States, the WSR-88D radars are located on mountain tops, limiting the views of critical valley areas. One solution now being implemented at a few locations is the use of zero and/or negative elevation angles (R. Brown et al. 2002, 2007; Wood et al. 2003). A second, long-term solution to improve radar coverage is to simply add more radars to the network. However, because of the high cost associated with deploying and operating large antenna, S-band (WSR-88D type) radars, a more cost-effective solution may be to deploy limited numbers of "gap filling" (X or C band) radars to fill in coverage gaps between WSR-88Ds (McLaughlin et al. 2009). Brotzge et al. (2010) and Mahale et al. (2012) demonstrated the value of gap-filling radars for improving detection of tornado radar signatures. A third option for improving radar coverage is to sample more frequently. Replacement of the WSR-88Ds with rapid-scan, phased-array radar (PAR) technology (e.g., Zrnić et al. 2007) could provide 1-min volume scans (or faster single elevation scans), an improvement over the current 4–6-min volume scans provided by the WSR-88Ds. In ongoing evaluations of the impact of PAR data on tornado warnings, Heinselman et al. (2012, 2013) found that the use of faster scans has the potential to extend tornado warning lead times, reduce false alarms, and increase forecaster confidence. Finally, a more rigorous, optimal radar network configuration could improve overall low-level coverage. NEXRAD radars were originally deployed to operate as single autonomous systems; however, merged, multiradar data have proven more effective for extracting severe weather information (Lakshmanan et al. 2006). Geometric, statistical, and genetic algorithm techniques have been developed to optimize the low-level coverage and maximize multi-Doppler overlap (Ray and Sangren 1983; de Elía and Zawadzki 2001; Minciardi et al. 2003; Junyent and Chandrasekar 2009; Kurdzo and Palmer 2012). Nevertheless, the addition and/or replacement of radars will require a significant financial public investment.

Storm spotters provide an equally critical role to the warning forecaster. In the root cause analysis study, a lack of, conflicting or erroneous spotter reports were cited as having contributed to warning failure in nearly two-thirds of all missed events, and a lack of reports contributed to 15 of 31 false alarms (Quoetone et al. 2009). Sustained education and coordination of spotter groups requires dedicated NWS resources. Fortunately, as described previously, access to real-time information and video from the field is becoming easier, with the proliferation of new video and wireless technologies (e.g., Dixon et al. 2012).

A basic understanding of tornado dynamics is still key to good forecasting and detection. In the Quoetone et al. (2009) root cause analysis study, "not anticipated," "conceptual model failure," and "environment" were listed among the top six reasons for warning misses. Poor radar, environmental conceptual models, and environment were listed as three of the top four reasons cited for issuing tornado false alarms. "Fits radar conceptual model" was cited in 30 of the 31 false alarm events studied. Continued improvement in the conceptual models requires sustained advances in basic research. Field programs such as the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX; Rasmussen et al. 1994) and the second VORTEX project (VORTEX2; Wurman et al. 2012) provide valuable observational data from which to study and improve understanding. Continued meteorological training and education are essential for moving research to operations.

Finally, with the plethora of new sensors and model output now available to the warning forecaster, many are now experiencing data overload, which is hampering warning operations. "Workload" was cited in one-third of all missed warnings, with "distractions" cited in one-quarter of all missed warnings (Quoetone et al. 2009). One solution to this is the use of integrated, "fused" and/or assimilated sensor products (e.g., Wang et al. 2008). A second, complementary solution is the advent of multisensor and three-dimensional visualization (e.g., Gibson Ridge Software, LLC).

complex, sometimes competing factors. These factors may include environmental data, access to real-time weather and storm spotter information, forecaster experience, knowledge, distance of event from the nearest radar, population density, population vulnerability, tornado climatology, event anticipation, SPC guidance, and/or storm history. The interpretation of such data may be impacted by such things as personal fatigue, office staffing, and interoffice relationships. Andra et al. (2002) provides an excellent case study of warning decision making during the 3 May 1999 tornado outbreak in central Oklahoma.

Despite the difficulty of each decision, the warning forecaster strives to warn on every tornado, with as much lead time as possible, while minimizing the number of false alarm warnings. Having every tornado warned is essential for public safety; the public is much more likely to take shelter once they have received an official warning (Balluz et al. 2000). However, there is an incentive to keep the warning area size small; the use of smaller warning polygons is estimated to save over $1.9 billion annually in reduced interruption and unnecessary sheltering (Sutter and Erickson 2010). County-based tornado warnings were replaced with storm-based warning polygons in 2007.

As of 2011, the national tornado POD was 0.75, with a mean lead time of 14.6 min, and a FAR of 0.74 (NOAA 2011b). A review of the long-term trends in these statistics reveals that the POD and mean lead time have increased dramatically since the installation of the WSR-88D network and NWS modernization program (Friday 1994), with a POD of 0.48 and a mean lead time of 7.6 min in 1994. However, nearly all of this increase in lead time was a direct result of greater numbers of tornadoes being warned (Erickson and Brooks 2006); all tornadoes not warned were assigned a lead time of zero, and then included in the calculation of the mean lead time. Using data between 1986 and 2004, Erickson and Brooks recalculated tornado lead time without the missed tornadoes included and found a rather steady lead time of around 18.5 minutes. While greater numbers of tornadoes are being warned in advance (possibly because of improved radar technology, conceptual models, and training), lead time on warned tornadoes has not increased, and the FAR has remained steady at around 0.75 as well; see "Warning decision challenges" for more information.

WARNING DISSEMINATION. Warning the public remains difficult in large part because the "public" is a largely diverse population with tremendous variation in education, physical abilities, family support, and situational awareness. To overcome these challenges, a variety of communication alert systems are used. Warnings may reach the public directly from the NWS through the National Oceanic and Atmospheric Administration (NOAA) Weather Radio (NWR) and the Internet, or indirectly through media, emergency management, and private sector weather providers. Widely adopted following the April 1974 tornado outbreak (Coleman et al. 2011), NWR allows for an in-home method for waking a person from sleep in case of an emergency through its alert tone. Today, over 1,000 NWR transmitters offer 98% national coverage (Zubrick 2010). The NWS also provides direct information to the general public via the Internet with some WFOs now experimenting with social media to distribute warning information.

The public most commonly receives tornado warnings from local media through television and radio (e.g., Hammer and Schmidlin 2002). Media utilize a host of methods to catch each viewer's attention and to convey the necessary information, including the use of "cut-ins," "crawlers," mobile phone apps, Facebook, and Twitter (Coleman et al. 2011). Storm video and radar imagery provide greater spatial and temporal information regarding storm size, severity, storm motion, and geographic impact. Video media also more easily convey nonverbal cues from the television (TV) meteorologist. Indeed, research demonstrates that local populations often develop profound psychological commitments to specific weather stations or forecasters (Sherman-Morris 2006). Television broadcasts are often simulcast over the radio but without the benefit of the images.

WARNING DECISION CHALLENGES

A significant challenge to the forecaster is reducing the FAR while keeping the POD steady or improving (Brooks 2004). Yet the value provided by the statistical measures (POD, FAR) is ambiguous. For example, POD is dependent largely upon the level of verification. FAR fails to account for close calls (Barnes et al. 2007) and varies with parameters such as tornado order, climatology, and distance from radar (Brotzge et al. 2011). While the POD, FAR, and warning lead time are frequently cited indices for measuring our ability to warn, additional improvement in these numbers may not translate necessarily into a reduction in tornado casualty rates. All of the deaths from the 27 April 2011 tornado outbreak occurred from tornadoes within active tornado watches and were preceded by tornado warnings (NOAA 2011a). Reasons for the high number of casualties from the April event include the rapid speed and severity of the event, the high population density of the areas hit, and delays in seeking shelter. Simmons and Sutter (2008) found warning lead times >15 min had little additional impact on fatality rates.

The impact of false alarms on public response is unknown. Early research found that false alarms may unexpectedly *increase* the likelihood of future response (Janis 1962). More intuitively, Simmons and Sutter (2009, p. 38) found that "a one-standard-deviation increase in the false-alarm ratio increases expected fatalities by between 12% and 29% and increases expected injuries by between 14% and 32%." Other studies (mostly qualitative case studies) remain divided on the role of false alarms in the response process (Breznitz 1984; Atwood and Major 1998, Dow and Cutter 1998; Barnes et al. 2007).

A second emergent challenge for the warning forecaster is how to best blend information from automated algorithms, nowcasting, and NWP model output with conceptual models and human experience (Stuart et al. 2006). At least in the short term, such output have limitations (e.g., Andra et al. 2002), and their use may be limited best as a check or calibration against the conceptual model.

Emergency managers also play a critical role in disseminating weather information to the local community. As part of their responsibilities, EMs operate local warning systems, such as local outdoor warning sirens or reverse 911 systems, and coordinate disaster response and recovery efforts. An instant messaging service called NWSChat was created to facilitate direct communication between the NWS and EMs and to better support EM services. However, there are few consistent criteria applied across jurisdictions for warning dissemination. A number of meteorological (e.g., presence of a wall cloud) and nonweather-related (e.g., public backlash for issuing false alarms) factors influence the judgment of EMs on whether to activate warning systems (Sorensen and Mileti 1987; Stewart and Lusk 1994; Donner 2008); see "Warning dissemination challenges" for more information.

PUBLIC RESPONSE.

Warning dissemination sets into motion a process of public response, a complex and multidimensional activity. While research on risk and warning response has been conducted since the 1950s, it was not until the 1990s that scholars began to systematize findings into a general model. Mileti and Sorensen (1990) and Lindell and Perry (1992) shared the common conclusion that warning response was not a single act, but a set of stages through which the public progressed in responding to disseminated warnings. Before taking action, the public must receive, understand, believe, confirm, and personalize warnings.

Reception. Community members receive warning information through *formal* and *informal* channels. Formal communication includes NWS, media, emergency management, and reverse 911, or any official

WARNING DISSEMINATION CHALLENGES

A significant challenge in improving warning dissemination is to integrate new technologies in such a manner that those less able to afford such tools can still be warned. The Commercial Mobile Alert System (CMAS), Wireless Emergency Alerts (WEA), and Interactive NWS (iNWS) were recently created to disseminate warnings to mobile devices. However, many are ill equipped to receive text messaging, and so older warning systems, such as outdoor warning sirens, must still play a critical role within an integrated warning system, even as new, more informative services are made available.

The limitations of dissemination tools must be clearly recognized when building a public warning dissemination system. For example, mobile phone applications fail if and when cell phone towers and communications are disabled, a frequent problem in storm-ravaged areas. Similarly, outdoor warning sirens fail when power is lost to those sirens, such as occurred in some areas during the Alabama tornadoes of 27 April 2011. The use of outdoor sirens also varies significantly among jurisdictions, with some districts using them to warn on all severe thunderstorm (and sometimes nonweather)-related warnings, while other municipalities limit the use of sirens to tornado warnings only. Furthermore, many areas simply do not have sirens available, nor would it be cost effective to install sirens in many regions of the country. However, the consequences of not having sirens can be deadly; two people died in the 2011 Alabama tornadoes when early morning storms knocked out power to their trailer, and because they lived out of range of the nearest sirens, had no warning before they were hit (Ammons 2011). Some jurisdictions have replaced all outdoor sirens with calling systems such as reverse 911. However, these systems have been known to take tens of minutes to call all those in the tornado path, with no guarantee that those called would be alerted prior to tornado impact. A battery-operated NWR provides an immediate and direct warning method, but NWR ownership is low with limited surveys showing ownership of ~10%–33% (Manning 2007; Kupec 2008). NWR often is cited as the least-used method for obtaining warnings; only 3% of 1,650 persons surveyed just after the 3 May 1999 tornado in Moore, Oklahoma, indicated they had received their warning from NWR (S. Brown et al. 2002). While each system has certain limitations, an integrated and redundant dissemination system is more robust. In a survey following the 3 May 1999 Moore, Oklahoma, tornado, 55% of residents interviewed received the warning from more than one source (Hammer and Schmidlin 2002).

Another challenge for the operational forecaster is how to effectively communicate scientific information to the general public. Instantaneous communication and the growth of meteorological support companies have had a significant impact on the warning process (Golden and Adams 2000). As a result, institutions now communicate risk with unprecedented speed. Nevertheless, problems related to the expertise of institutions may affect the process of risk communication. For example, a recent experiment simulating a tornado outbreak tasked EMs with accessing and interpreting radar data (Baumgart et al. 2008). Despite general competence, study participants experienced significant difficulties interpreting wind velocity data and, more importantly, synthesizing multiple forms of radar data to produce overall judgments, which affected the risk communication process.

Effective communication also entails that the public understands and makes effective use of warnings (Lazo 2012). The risk communication process is most effective when those at risk hold a "perceived shared experience" with those already victimized (Aldoorya et al. 2010). When those warned could relate to victims (e.g., similar gender or race), threat acknowledgment and information seeking increased. Thus, risk communication may be taken more seriously if nearby communities are affected. How warnings are communicated also may shape risk communication. Numerical representations of risk often fail to persuade (Lipkus and Hollands 1999). In an experiment on risk perception of flooding, images depicting flood damage reinforced perceived risks (Keller et al. 2006). NOAA is now conducting an impact-based warning experiment (Maximuk and Hudson 2012) to evaluate ways in which to improve NWS communication to motivate improved public response.

warning system. Informal communication includes family, friends, and coworkers. Each form of communication channels warning information to the public, but each does so in dramatically different ways. Formal communication tends to reach members of upper- and middle-class populations, while informal communication often better serves the poor, ethnic minorities, and recent migrants. For instance, warnings issued during the 1987 Saragosa, Texas, tornadoes failed to reach local Hispanic populations (Aguirre 1988; Ahlborn and Franc 2012). Latinos prefer friends and family as sources of warning information (Peguero 2006) and receive tornado warning information from informal networks (Donner 2007). Poorer populations also were less likely to receive formal warnings (Schmidlin and King 1997).

Social networks may play a key role in reception. For instance, Nagarajan et al. (2012) documented the importance of warning dissemination among neighbors in a series of computer simulations. Frequent interaction of family members (Lardry and Rogers 1982), strong community or network involvement (Turner et al. 1979; Sorensen and Gersmehl 1980; Perry and Greene 1983; Rogers and Nehnevajsa 1987; Rogers and Sorensen 1991), regular association with a subculture or voluntary association (Perry et al. 1981), and more frequent community interaction (Scanlon and Frizzell 1979) improved the likelihood of message reception among individuals within the community.

Understanding. How recipients understand and make sense of warning information is deeply connected to human psychology and past experience. With the exception of Quarantelli (1980), research overwhelmingly demonstrates that long-term residents generally tend to hold a better understanding of warning information (Haas et al. 1977; Foster 1980; Perry and Greene 1983; Perry and Lindell 1986; Blanchard-Boehm 1998). Psychologically, the public is more likely to understand warning information if conveyed along with local information and maps (Berry 1999). Multiple warning sources increase chances of comprehension (Mileti and Darlington 1995), while at the same time excessive information within a single message may lead to higher rates of misunderstanding (DiGiovanni et al. 2002). Probability information attached to tornado warnings (e.g., the tornado has a 30% chance of occurring), for instance, may confuse rather than clarify risks for the public (Morss et al. 2010).

One concern is whether individuals understand the difference between warnings and watches. In a study of Austin, Texas, residents, Schultz et al. (2010) found that 90% of the sample could adequately distinguish between watches and warnings. Other studies found similar rates of understanding (Balluz et al. 2000; Biddle and Legates 1999), while others encountered more modest results (Mitchem 2003). Still other research suggests much lower rates of comprehension. In a broad survey of 769 residents across Texas, Oklahoma, and California, only 58% of all participants correctly understood the difference between a watch and a warning, though the percentage improved among residents in Oklahoma and Texas and among older and more educated survey participants (Powell and O'Hair 2008).

Social scientists have identified a number of social and cultural factors that account for variation in warning comprehension between individuals. Education is consistently associated with greater understanding (Turner et al. 1979), and those with a greater familiarity with science and scientific concepts generally hold a stronger understanding of warnings (Blanchard-Boehm 1998). Age, too, shows a direct correlation with understanding (Turner et al. 1979; Blanchard-Boehm 1998).

Belief. After understanding a warning message, the recipient evaluates the credibility of the message. Will there really be a tornado or is the warning a false alarm? In other words, should the message be taken seriously? Rarely, however, at this stage do recipients arrive at a concrete conclusion about whether a tornado *will* or *will not* occur. On the contrary, recipients crudely evaluate the probability of severe weather. The psychological qualities, past experiences, and unique demographic characteristics of the individual play a significant role in shaping these judgments of likelihood.

Those closer to a hazard are more likely to believe a warning (Diggory 1956; Sorensen 1982), which may be because of the greater likelihood of experiencing environmental cues (Drabek 1969; Quarantelli 1980; Sorensen 1982; Tierney 1987; Mileti and Fitzpatrick 1993; Hammer and Schmidlin 2002). Additional psychological processes also may play a significant role in the process of believing warnings. There are mixed findings regarding whether certain sources are more or less believable. Some research shows the public places greater faith in "official sources" (e.g., NWS warnings; Li 1991; Drabek 1994), whereas other studies routinely demonstrate "unofficial sources" (e.g., family) to hold greater credibility among the communities (Sorensen 1982; Perry 1983; Li 1991). It may be that the particular source may play a lesser role in credibility when compared to source familiarity. Warning sources to which individuals are personally or emotionally attached (e.g., a favorite weather forecaster) or with which they are more familiar may appear more credible (Mileti and Fitzpatrick 1993).

Demographic factors have some influence as well. Women appear more likely to believe warnings (Drabek 1969; Farley et al. 1993; Sherman-Morris 2010). Why this is the case may be explained through socialization, as well as the fact that women tend to be caregivers (Perry 1983). Additionally, the higher one's socioeconomic class, the more likely one is to believe a warning (Sorensen 1982; Perry 1987). Finally, a society's culture may also play a role in warning response. Finding the Japanese more likely than U.S. residents to respond to volcano warnings, Perry and Hirose (1991, p. 112) explain that Japanese live within a "collectivist culture in which citizens have higher expectations that authorities will provide care in the event of disasters or other disruptions in social life." Perry and Hirose suggest that the Japanese population has greater trust in government, and thus greater response rates, than Western societies, and that response to warnings among the Japanese might reflect the broader cultural rules of obedience and authority common in Asian societies.

Confirmation. A common feature of the warning process (Mileti 1999), confirmation serves to clarify and specify warning information, but at the cost of delaying sheltering. Confirmation has been found to take place among neighbors, rather than through formal channels (Kirschenbaum 1992), with information from media sources more likely the subject of confirmation (Frazier 1979). Confirmation may also be something as simple as visual confirmation of the storm. Whether beneficial or detrimental, confirmation remains a certain feature of the warning process.

Personalization of risk. Risk personalization deals with whether community members believe severe weather will affect them personally. In other words, one can believe that a threat exists *somewhere*, but the threat is not immediate and therefore action is unnecessary. For example, residents may decide that the mountains or rivers surrounding their community protect them from tornadoes, even if they believe local reports that storms may produce tornadoes (Donner et al. 2012).

The psychological elements of risk personalization are well understood. Warning consistency yields greater personalization of risk (McDavid and Marai 1968; Lindell and Perry 1983). Warning specificity (Perry et al. 1981) and sender credibility (Perry 1979; Rogers and Nehnevajsa 1987) contribute to personalization. Geographical proximity to a threat appears to be the most important in the literature (Flynn 1979; Perry and Lindell 1986; Rogers and Nehnevajsa 1987). With some notable dissent (Mileti and Darlington 1995), most research agrees that past hazards experience leads to a greater likelihood of personalization (Perry 1979; Hansson et al. 1982; Saarinen et al. 1984; Rogers and Nehnevajsa 1987).

Demographics also play a role. As with belief, women are more likely to personalize a threat (Flynn 1979; Hodge et al. 1981). Socioeconomic status also may play a role in risk personalization (Flynn 1979; Mileti et al. 1981).

Action necessary and feasible. Believing that one is personally at risk sets off a process of determining whether one must and is able to do something to protect oneself. Little research has been conducted in this area of the model. This stage is unique from resource availability, in that resources may be available but the potential victim either does not know about them or does not think them useful for protection.

Protection from severe weather often takes the form of sheltering. Sheltering may be broadly defined as either "in home" or "public." With in-home sheltering, refuge is typically sought in hallways, closets, underground basements, or, ideally, personal shelters. Those under warning may also choose to seek public shelters, which are typically set up and maintained by local government. Public shelters may be stand-alone shelters, in that their only use is as a shelter, or schools, town halls, or other municipal structures may become "shelters" during storms. Education, possibly through increased income, is most consistently associated with the availability of resources such as shelters (Edwards 1993; Balluz et al. 2000); see "Public response challenges" for more information.

NEXT STEPS. All other things being equal, as the U.S. population density increases, tornado fatalities may be expected to increase, calling for a review of the prediction, detection, and communication processes through which tornadoes are warned. Urban populations continue to rise in hazard prone regions, thereby placing greater numbers of people at risk (Brooks and Doswell 2001; Ashley 2007). In addition, the overall population is aging, with increasing numbers living alone (Gusmano and Rodwin 2006). Greater diversity among the population introduces additional challenges, such as warning dissemination to non-English-speaking populations (Donner and Rodríguez 2008). As described herein, a number

PUBLIC RESPONSE CHALLENGES

Although the determinants of shelter seeking are well documented in the literature, little is known about the sheltering process itself. Personal shelters are ideal, in that sheltering is immediate; traveling to a public shelter may be dangerous, especially in the context of tornadoes that are rapid and violent on onset. For those in mobile homes or similar vulnerable structures without shelters, evacuation may be the only option; mobile homes comprised 7.6% of U.S. housing stock in 2000, but 43.2% of all tornado fatalities between 1985 and 2007 occurred in mobile homes (Sutter and Simmons 2010). In addition to distance, other more "human" factors may shape the use of shelters. Cola (1996) found that people were less likely to use shelters thought uncomfortable. Pet owners also may be less likely to seek shelter (Heath 1999; Pfister 2002). More research is needed to understand shelter use and its relationship to lead time and social factors. Additional work needs to explore the associated needs, optimal locations, and operation of public tornado shelters.

There is also the real inability by some to take shelter because of disability. In the Joplin, Missouri, tornado, three mentally handicapped men died when their home was hit. Also in Joplin, 12 residents and a nursing assistant died at the Greenbriar nursing home, and another 8 patients died when St. John's Regional Medical Center was hit. Both facilities had been warned and had begun taking storm precautions, but neither had enough lead time to evacuate. In Shoal Creek, Alabama, seven people were killed when an assisted living facility was hit. Additional research is needed to explore the lead time requirements for those who must evacuate (e.g., from trailer homes) or need help sheltering (e.g., those with special needs). Indeed, the public at large requires a continuum of lead times, where for some a warning lead time of well over 30 min could be essential, whereas for others, a large lead time could lead to apathy and greater danger.

of challenges limit the effectiveness of the current warning system (Table 1). Based upon the preceding literature review and these associated challenges, the warning process can be fundamentally improved with a greater emphasis and understanding of **acceptable risk**, **preparation**, and **personalization**.

A fundamental question society must ask is, "How much risk are we willing to tolerate?" The answer to this dilemma will set the limit on how much money should be expended toward further research and warning infrastructure. In other words, the public must define its acceptable risks, and its willingness to provide additional resources or reduce existing services or quality to match those risks (Stallings 1990). The public's level of acceptable risk likely varies across the country as a function of the nature and extent of the risk. This variability calls for an emphasis on local-to-regional decision making, such that any top-down, one-size-fits-all strategy will likely be less than optimal. A dense observing spotter and warning dissemination network in the plains may vary in function and form from one in the Southeast, whereas neither system may be cost effective in the West or New England.

A second essential subject often overlooked in discussions of the tornado warning process is preparation, both at the organizational and personal levels. Preparation at the organizational level may include the development of public policy regarding the use and availability of public shelters and warning systems, the availability of multilingual warnings, requirements or guidelines for shelters in mobile home parks, building codes, and sheltering procedures. Private preparations may include developing a family disaster plan, copying and storing critical insurance papers and photos in safety deposit boxes, or purchasing a safe room or shelter. Proper preparation at the organizational level can often facilitate the speed and ease of personal decision making during a moment of crisis.

Preparation should focus on maximizing personal safety, minimizing economic loss, and easing recovery efforts. While this article has focused on public safety, total damage estimates from tornadoes between 1950 and 2011 range from $300 billion to $450 billion (U.S. dollars; Simmons et al. 2013). A greater focus on personal mitigation could reduce tornado damage. Sutter et al. (2009) found that low-cost home mitigation could reduce tornado damage by as much as 30%.

Finally, the one common ingredient to a successful end-to-end tornado warning program is the personalization of the warning; to be successful, warnings must evoke a sense of specific and immediate risk. Even days prior to an event, the efforts of the SPC and others are spent narrowing the area of a potential threat; local WFOs narrow the threat further in time and space, issuing warnings over specific regions in time. The most effective warnings are those that communicate clearly to individuals the specific information they need to know with enough time to react. The goals of ensemble NWP, warn on forecast, phased array and gap-fill radars, and storm-based warnings are to provide more detailed data on when and where tornadoes will strike. Many new and innovative warning dissemination tools, many developed and sold by the private sector, convey this detailed information to individuals, through the use of local media, outdoor warning sirens, NOAA Weather Radio, the Internet, smart phones, and pagers. Similarly, preparation for tornadoes needs to be personalized, and specific mitigation information provided at a household

Table 1. List of tornado warning system challenges.

Integrated Warning System	Challenges
Prediction	Need higher spatial and temporal observation sampling
	Ability to process and assimilate large volumes of data
	Faster computer processing
	Improve prediction of inherently less-predictable systems
	Improve differentiation between tornadic and nontornadic cells
	Greater accuracy at longer time scales
	Ability to apply ensemble prediction at high resolutions
Detection	Radar temporal sampling
	Radar spatial gaps, primarily at low levels
	Erroneous, sporadic, or unreliable spotter reports
	Poor or incomplete conceptual models
Warning decision	Balancing POD with FAR
	Data overload
Warning dissemination	Cost of dissemination systems
	Maintenance of old systems, adoption of new sensors
	Reception of warning during night and in rural areas
	Consistent use of warning systems and false alarms
	Effective communication of warnings
	Multilingual warnings
	Access of poor to private sector warning methods; e.g., personal digital assistants (PDAs)
Public response	Inability to shelter because of handicap or age
	Mobile homes
	Cost of sheltering
	Cost of purchasing in-home shelters
	Safety of in-home sheltering vs evacuation
	Impact of warning lead times, false alarms ("cry wolf effect")
	Response of public facilities (e.g., large venues, schools)
	Demographic and cultural factors
	Mitigation and preparation
	Personalization of risk

level could see potential dividends in reducing home damage and personal injury.

Social and cultural factors may inhibit personalization of warnings. Long lead times and high false alarm rates tend to depersonalize risk. A continuing program of research and education remains key to systematically improving public response to warnings.

A highly integrated and efficient tornado warning system does not *necessarily* ensure that no fatalities will ever occur, but it does set a priori standards of warning capability as a function of the community-defined level of acceptable risk, resources, and will. The effectiveness of the best tornado warning system is dependent largely upon the comprehensiveness and manner of preparedness at the organizational and personal levels. This review has demonstrated the value of research and investment at all stages of the warning process for improving the personalization of the warning. In an era of austerity, additional investments will need to be strategically focused to further prepare and personalize the tornado threat.

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