CONVECTIVE-SCALE WARN-ON-FORECAST SYSTEM

A Vision for 2020

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Warnings about convective-scale hazards are currently based on observations, but the time has come to develop warning methods in which numerical model forecasts play a much larger role.

The National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS) issues warnings when there is a threat to life and property from weather events. A warning is an urgent call for the public to take action when a hazardous weather or hydrologic event is occurring, is imminent, or has a high probability of occurring. Warnings are the culmination of a sequence of actions taken by NWS forecasters that act to alert the public to a heightened probability of high-impact weather minutes, hours, or even days in advance. Improvements in the accuracy and timeliness of warnings over the past few decades, along with better societal response, have helped to reduce fatalities from hazardous weather events in the United States (Brooks and Doswell 2002; Pielke and Carbone 2002; Simmons and Sutter 2005). In the following discussion, we define high-impact weather to include hazardous weather and hydrologic events for simplicity.

Public confidence in NWS warnings is in large part the result of the flow of information on the evolving weather situation prior to the warning being issued. This information flow often begins days in advance of a high-impact event through the use of outlooks, other tailored forecast products, and direct communication with community leaders. As the time to an event decreases, and the risk of an event increases, watches are used to alert the public to the developing conditions that might spawn a high-impact event. Thus, most warnings issued are a natural outcome of the information that has preceded them (Fig. 1), and ideally the public is ready to respond appropriately and effectively to the hazard.

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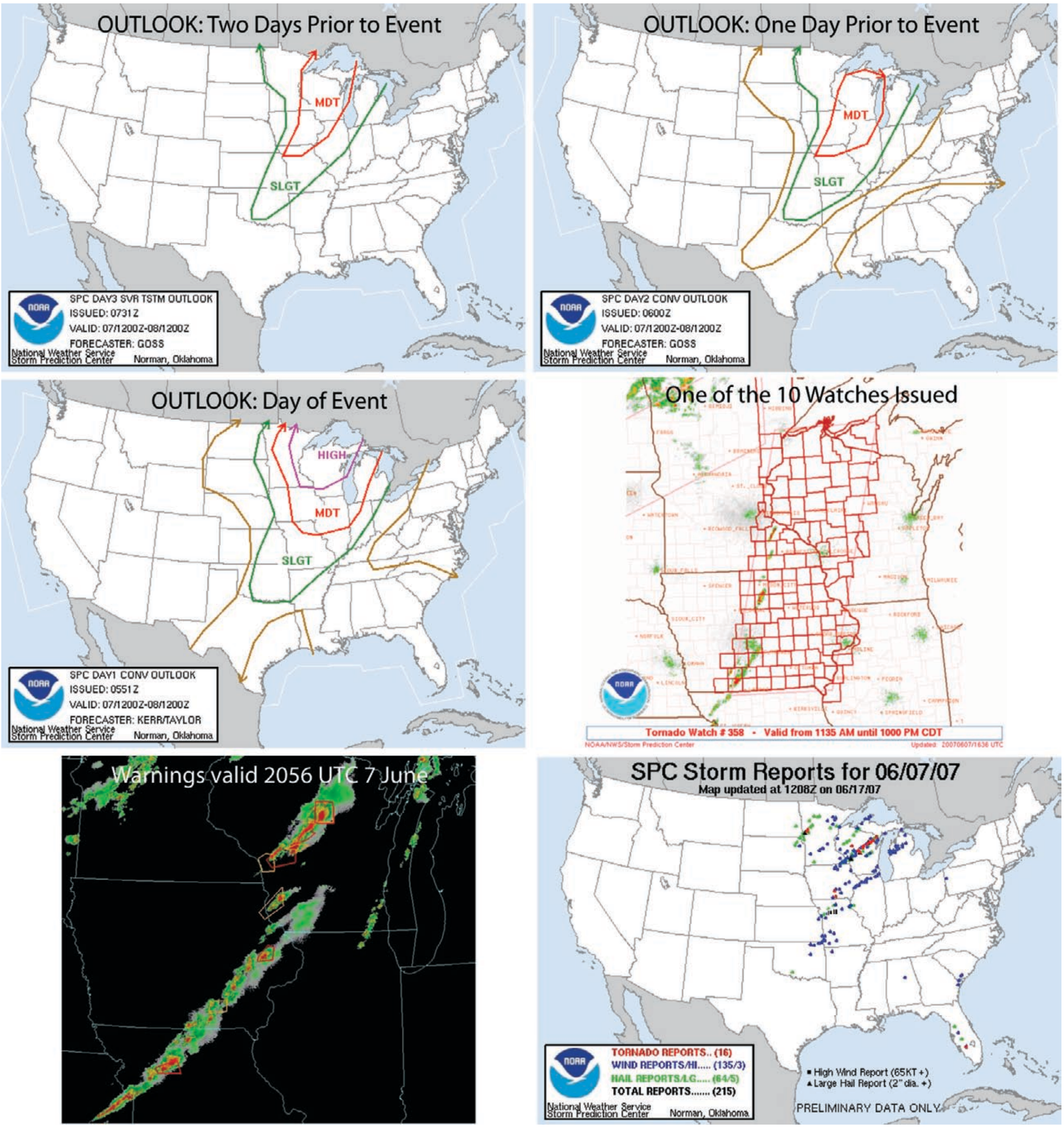


Fig. 1. Sequence of NWS products valid on 7 Jun 2007 starting from two days prior to a high-impact weather event through the day of the event. Three outlooks are shown, along with 1 of 10 severe weather watches. Also shown are a composite reflectivity field overlaid with actual warning polygons valid at 2056 UTC and a plot showing the distribution of severe weather reports. Note how the event is recognized several days in advance, with probabilities increasing on the day of the event (the threat changing from moderate to high). Watches are issued in advance of the high-impact weather, and 215 instances of severe weather are reported in the upper Midwest.

Because warnings are calls for the public to take protective action, the time scale of a warning depends upon the weather event. One of the largest and longest-lived hazardous weather events is the hurricane, which evolves over many days. A hurricane warning is issued when winds associated with a tropical disturbance are expected to exceed 74 mph (119 km h^{-1}) in a specified coastal area within the next 24 h or less. However, guidance with sufficient accuracy to support coordinated societal action is provided days in advance of landfall because of the ability of NWS forecasters to use the output from numerical weather prediction models to predict hurricane tracks. Public confidence in hurricane guidance and warning products induces protective action among the majority of affected residents. The NWS also provides information on hurricane forecast uncertainties, which helps the public to understand the potential for forecast amendments and alternative forecast hurricane track and intensity scenarios.

At the other end of the warning spectrum, one of the smallest and shortest-lived hazardous weather events is the tornado, which evolves over a few minutes. Tornado warnings are issued when a tornado is indicated by radar, seen by spotters, or otherwise deemed imminent by the NWS forecaster through knowledge of the storm environment and its expected evolution and other environmental cues. This warning paradigm is often referred to as warn on detection. In contrast to hurricane warnings, current numerical weather prediction model output has little direct effect on the issuance of tornado warnings. Numerical weather prediction model forecasts are primarily used to help issue severe thunderstorm and tornado watches that indicate that future environmental conditions are supportive of these types of storms. Current warning strategies instead focus primarily on Doppler radar observations of the parent thunderstorm, yielding tornado warning lead times that presently average 13 min nationally. Despite this comparatively short lead time, the national mean false-alarm rate for tornadoes is near 75%. The high number of false alarms results in part from the lack of any technology, other than the eyes of trained observers, to uniquely detect tornadoes and in part from our lack of understanding of tornadogenesis. Warning forecasters often act based upon the principle that it is better to warn the public for marginal events than to have a potentially devastating tornado strike without warning. Because tornado warnings are based upon detection, little uncertainty information is provided.

The preceding discussion highlights a clear difference between the tools used by a forecaster in a potential hurricane situation and those used by the same forecaster in a potential tornado situation. Hurricane warnings are issued based in large part upon numerical model forecasts of the track of an observed tropical disturbance, whereas tornado warnings are issued based upon either visual confirmation of an existing tornado, the observational detection of a proxy for a tornado, or environmental cues that indicate tornado development is likely given that a thunderstorm already exists. Zero lead time is provided for the area initially affected when visual confirmation is used to issue a tornado warning. Tornado proxies and environmental cues, on the other hand, give positive lead time but are actually only indicators of an enhanced tornado risk for a specific storm. Proxies that are used in NWS tornado warning operations include radar detection of tornado vortex signatures, thunderstorm rotation (mesocyclones), or characteristic three-dimensional reflectivity structure. Once the NWS completes the upgrade of the existing operational Doppler radar network to dual-polarization capability, forecasters will have an increased capability to use direct radar observations of the tornado debris field to assist in tornado warning operations. However, the correct interpretation of a tornado proxy indicator still depends upon the skill and experience of the warning forecaster. The warnings of convective-scale weather phenomena (severe thunderstorms, tornadoes, and flash floods) are unique in the NWS, having little reliance on direct numerical forecast guidance.

Increasing severe thunderstorm, flash flood, and tornado warning lead times is a key NOAA strategic mission goal designed to reduce the loss of life, injury, and economic costs of high-impact weather by providing more trusted weather and water information in support of organized public mitigation activities. Longer lead times are needed because many hospitals and nursing homes require 30 min or more to move patients to safe locations, large venue operators such as sports stadiums require at least 30 min to move thousands of people from exposed locations to safety, and towns may need more than 30 min to evacuate residents from low-lying areas threatened by flash flooding. Although the need for NWS warnings that call for immediate public action will never disappear, many of these users also can effectively use uncertainty or probabilistic information in their decision-making process. Thus, the longer lead times needed by various decision makers can be provided through an additional layer of warning information containing probabilistic hazard information. This enhancement of warning information requires a new paradigm beyond warn on detection. The combination of recent scientific advances and increased public demand indicates that rapid progress toward a convective-scale warn-on-forecast paradigm, in which numerical model forecasts play a substantially larger role in warning operations, is needed.

THE TIME IS RIGHT. The concept of numerically predicting thunderstorms was proposed nearly two decades ago (Lilly 1990; Droegemeier 1997). More recent demonstrations of the utility of convective-scale numerical weather prediction (Xue et al. 1996, 2007b, 2008; Done et al. 2004; Kain et al. 2006; Kong et al. 2007b; Smith et al. 2008; Weisman et al. 2008) and the continued rapid increase in affordable computational resources suggest that numerical forecasts can become an important component of convective-scale warning operations in the future. The general lifetime and gross evolution of thunderstorms are already predicted by real-time experimental convective-scale model forecasts (Fig. 2), although these forecasts do not produce a one-to-one correspondence between forecast and observed storms. This result suggests that high-resolution numerical weather prediction models can potentially provide warning information on the future evolution of storms and their internal structure, thereby increasing convective-scale warning lead times. However, it is essential that the model be started with a very accurate representation of ongoing convection to obtain the necessary one-to-one correspondence between model-predicted and observed thunderstorms.

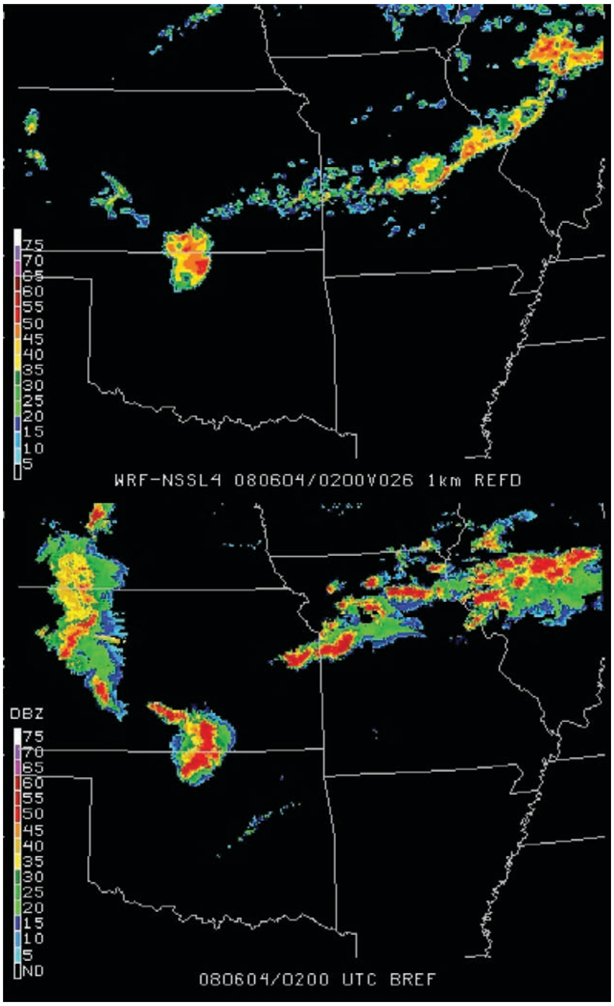
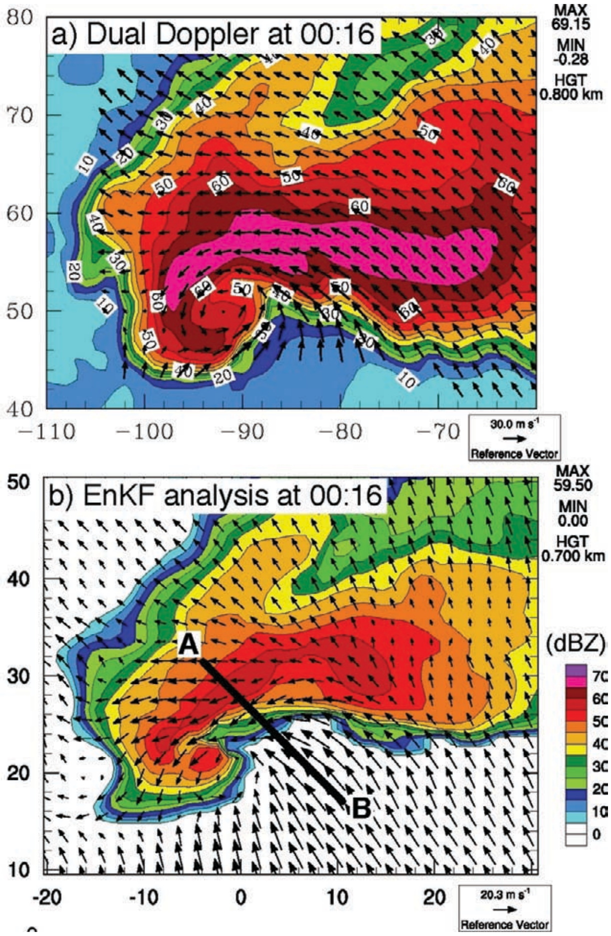


Fig. 2. Reflectivity fields (dBZ) valid at 0200 UTC 4 Jun 2008 from (top) a 26-h real-time, experimental 4-km Weather Research and Forecast (WRF) model forecast, and (bottom) national composite radar observations. Although the forecast reflectivity field is not perfect, the general evolution of the forecast convective region in north-central Oklahoma parallels the evolution seen from the observations. This suggests that convective-scale models are able to evolve predicted thunderstorms reasonably well. (Model forecast produced by the National Severe Storms Laboratory.)

The ability to accurately depict ongoing convection within a numerical model requires in-storm observations. The advent of the national network of Doppler radars [Weather Surveillance Radar-1988 Dopplers (WSR-88Ds); Crum and Alberty 1993; Crum et al. 1998] in the early 1990s and the more recent ability to transmit, composite, and merge all the radar data in near-real time (Kelleher et al. 2007; Langston et al. 2007) allow for the assimilation of in-storm Doppler radar reflectivity and radial velocity observations into convective-scale forecast models. Snyder and Zhang (2003) demonstrate that synthetic Doppler radar observations from a simulated thunderstorm can be inserted successfully into a convective-scale numerical model using an ensemble Kalman filter data assimilation method. Several other studies have assimilated simulated (Zhang et al. 2004; Tong and Xue 2005; Caya et al. 2005; Xue et al. 2006; Jung et al. 2008) or real radar observations (Xue et al. 2003; Dowell et al. 2004; Hu et al. 2006; Smith et al. 2008; Weygandt et al. 2008; Dowell and Wicker 2009; Aksoy et al. 2009) to accurately initialize supercell thunderstorms (Fig. 3), mesoscale convective systems, and multicell thunderstorms within convective-scale numerical models. One particularly interesting example is a retrospective simulation of a supercell thunderstorm initialized using radar data in which a tornado is successfully predicted 30 min after the beginning of the model run and in good agreement with observations (Fig. 4; Xue et al. 2007a). Although this simulation required several days of supercomputer time to complete, the ability to predict the development of a tornado is a very promising outcome.

The value of assimilating radar observations is also seen in daily forecasts from the 3-km version of the High-Resolution Rapid Refresh (HRRR) model (Smith et al. 2008; Weygandt et al. 2008). Initial results indicate that radar reflectivity data assimilation using a diabatic digital filter (Weygandt et al. 2008) improves both the analysis of present convective activity and the short-range (0–6 h) convective weather forecasts in comparison with forecasts without radar data assimilation (Fig. 5).

Fig. 3. Reflectivity and horizontal winds at ~750 m above ground level from a supercell thunderstorm at 0016 UTC 30 May 2004 over central Oklahoma from (a) a dual-Doppler analysis and (b) an ensemble Kalman filter analysis that assimilates reflectivity and radial velocity observations from only a single radar. The good agreement between the dual-Doppler and ensemble Kalman filter analyses indicates that the filter is successful at inserting this thunderstorm into the numerical model and can generate the two-dimensional wind field with some fidelity. (Figure courtesy of Kristin Kuhlman, Louis Wicker, Ted Mansell, and David Dowell.)



Additional results from explicit convection-resolving models, however, indicate that rapidly evolving convective events and tornado predictions are highly sensitive to both environmental conditions (Elmore et al. 2002; Martin and Xue 2006) and internal storm processes (Gilmore et al. 2004; Tong and Xue 2008; Snook and Xue 2008). These sensitivities indicate that a probabilistic forecasting approach is absolutely necessary for predictions on the convective scale, as the uncertainties associated with high-impact weather are large. Thus, constructing an ensemble system that uses high-resolution, explicit convective-scale numerical weather prediction models is crucial for developing a probabilistic convective-scale analysis and forecast system.

We envision a warn-on-forecast system that assimilates observations of convective storms and their environments into an ensemble of convective-scale numerical weather prediction models. The data assimilation will emphasize in-storm observations from ground-based Doppler radars, such as the WSR-88D and its successors (e.g., polarized radars and fast-scanning phased-array radars), whereas

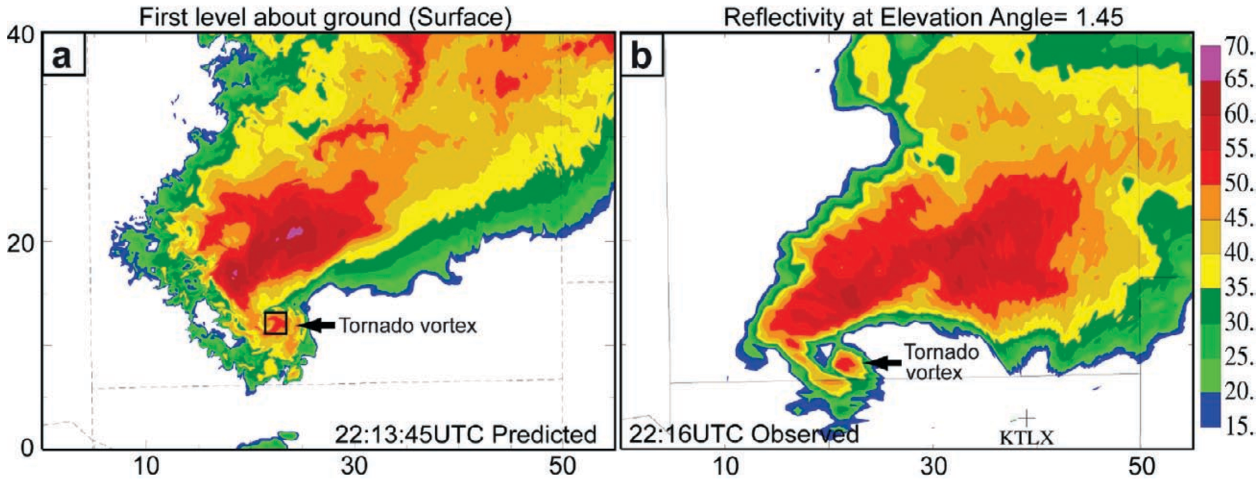


Fig. 4. Low-level reflectivity field of a tornadic supercell thunderstorm over southern Oklahoma City valid at 2213 UTC 8 May 2003 from (a) a 33-min model prediction using a grid of 50-m grid spacing, and (b) radar observations at a similar time. The thunderstorm was initialized at 2140 UTC using data from the Oklahoma City radar over a period of time. The axis labels show domain size in km (Xue et al. 2007a).

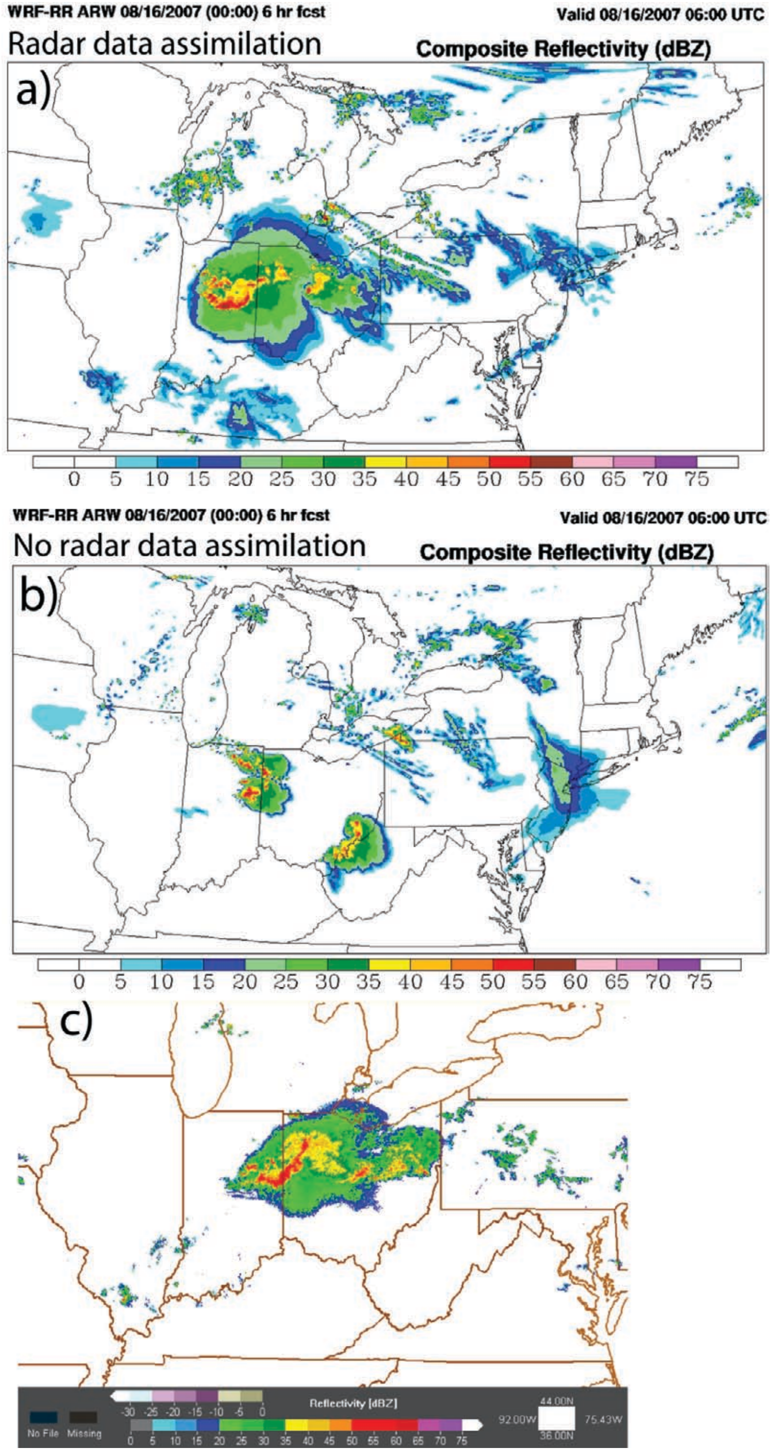


Fig. 5. HRRR 6-h forecasts of composite reflectivity initialized (a) with and (b) without radar reflectivity assimilation (as described by Benjamin et al. 2008 and Weygandt et al. 2008). Also shown is the (c) observed reflectivity at the forecast valid time of 0600 UTC 16 Aug 2007 (Smith et al. 2008).

the weather prediction models will have explicit microphysics more sophisticated than those presently used in operational models. This ensemble system will provide the warning forecaster with both more complete three-dimensional analyses of convective thunderstorms (Fig. 3) and probabilistic forecast guidance for severe thunderstorms, heavy rainfall, and tornadoes (Fig. 6). All the pieces needed for a warn-on-forecast system are available and are in various stages of assembly at several institutions. However, the challenges to the successful implementation of this system are large and will require collaborative efforts among all interested parties to make rapid progress.

The knowledge gained during the development of a warn-on-forecast system is expected to lead to improvements in numerical model parameterization schemes and ensemble data assimilation methods and to greater use of radar observations in numerical weather prediction. Dual-polarized radar observations in particular should be very valuable in the development of improved microphysical parameterizations, radar data quality control, and the assimilation of microphysical information (Jung et al. 2008). The techniques developed for a warn-on-forecast system may also aid researchers working to improve hurricane intensity and track forecasting because model grid spacing as small as 1 km is likely needed for accurate hurricane forecasts (Davis et al. 2008).

A ROAD MAP FORWARD.

Rapid progress in the development of a warn-on-forecast system can be made within the next decade as two activities occur in parallel. First, a basic warn-on-forecast system that uses WSR-88D radar observations to create quasi-real-time three-dimensional analyses needs to be completed and tested as soon as possible. Although this initial system will be far from optimal, this type of quasi-operational testing is the best way to discover potential pitfalls, examine

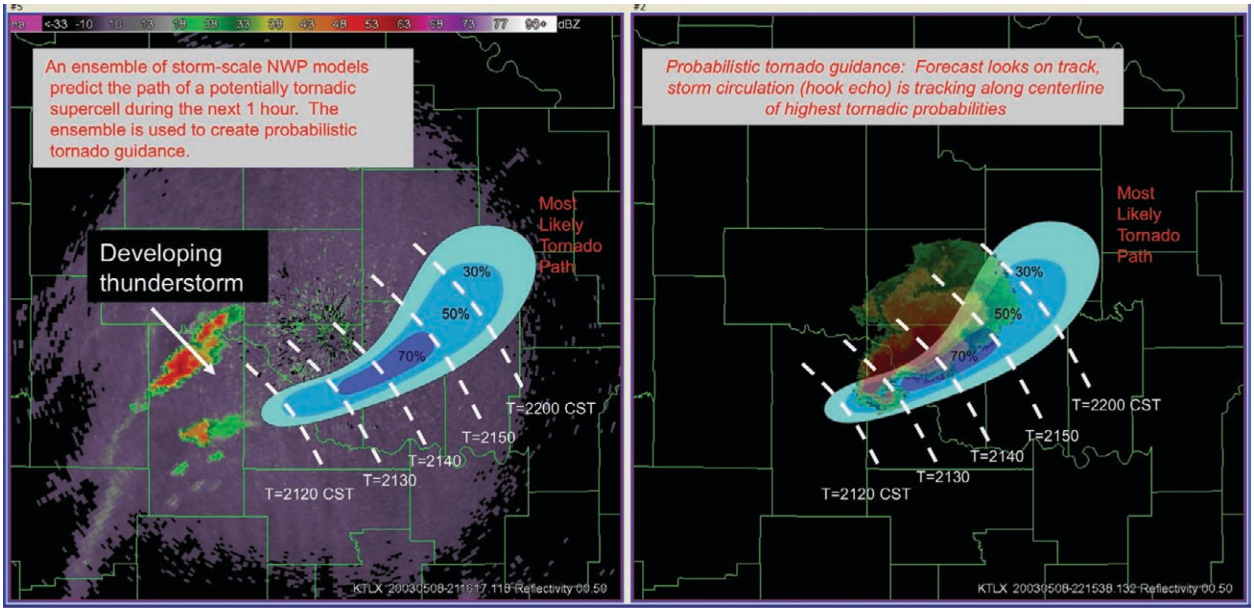


Fig. 6. A conceptual illustration of a convective-scale warn-on-forecast system. Developing thunderstorms are observed by (left) radar and assimilated into a convection-resolving numerical weather prediction model ensemble forecast system. Probabilistic predictions of the future evolution of these storms are produced, yielding a tornado probability field valid over the following 90 min (blue). If the warn-on-forecast system is accuruate, then the (right) observed storm 45 min later produces a mesocyclone and hook echo that are along the axis of highest tornado probability. This type of predicted probabilistic hazard information would be updated frequently (not shown), perhaps with each volume scan of radar observations, and used to make warning decisions. Longer warning lead times are provided than are possible based upon observations alone.

system performance for a wide variety of convective weather events, and obtain forecaster input on system design. Recent real-time experiments and post-real-time case studies that use radar data assimilation have produced useful ensemble thunderstorm forecasts with horizontal grid spacing of 1–4 km (Kong et al. 2007a, 2008; Gao et al. 2008; Xue et al. 2009), suggesting that an evaluation of a 1–4 km grid spacing warn-on-forecast system can provide useful results and be used to help inform choices relating to system development. Second, research studies need to be undertaken to address the many scientific, technical, and sociological challenges that remain before a warn-on-forecast system can be implemented in operations.

One of the most daunting aspects of convective-scale numerical weather prediction is starting the model with an accurate depiction of the atmosphere. The routine observations used for starting operational numerical weather prediction models are tens to hundreds of kilometers apart (Benjamin et al. 2004). High-resolution observations from the Geostationary Operational Environmental Satellite-R (GOES-R) program, particularly those relating to the horizontal gradients in environmental conditions (Schmit et al. 2002), may be very useful in obtaining more accurate representations of environmental conditions when assimilated in conjunction with other observations. However, although these observations may be suitable for defining the synoptic-scale environment, and contain some mesoscale information, the storm environment is known to play an important role in determining thunderstorm behavior (Weisman and Klemp 1984; Rasmussen and Blanchard 1998; Thompson et al. 2003; Sun and Zhang 2008). It is uncertain how accurate the storm environment must be defined within convective-scale numerical models to yield skillful predictions of storm behavior. Studies examining the sensitivity of convective-scale forecasts initialized with radar observations to uncertainties in the storm environment are needed for cases of tornadic supercell thunderstorms, nonsupercell tornadic thunderstorms, nontornadic supercell thunderstorms, hail storms, flash floods, mesoscale convective systems, and complex storm interactions to fully investigate the capabilities and limitations of convective-scale numerical models and outline any additional observational requirements. Improved understanding of the predictability of thunderstorms and mesoscale convective systems (e.g., Wandishin et al. 2008), along with their embedded features and associated weather hazards, is also needed.

Reliable and rapid data quality control is another significant convern that merits attention. Today's operational Doppler radars scan the atmosphere every 5–10 min or less, but there are often problems with aliased velocity data (Gong and Xu 2003), anomalous propagation, biological target contamination (Liu et al. 2005; Zhang et al. 2005), and ground clutter, which can severely limit the use of the observations. Robust and rapid quality-control methods to correct these radar data problems (Friedrich et al. 2006; Lakshmanan et al. 2007a), as well as quality control of observations from other sensors, are needed before these data can be ingested into operational high-resolution models. Although initial radar quality control procedures (Zhang et al. 2005) have enabled the initial operational assimilation of radar reflectivity data (Benjamin et al. 2008), these methods need to be improved and extended to quality control radar velocity data as well. Significant efforts should also be made to use clear-air radial velocity observations, while the valuable information contained in polarimetric radar measurements on the nature of radar targets should be exploited for improved data quality control. The deployment of gap-filling radars can help improve the in-storm observations by significantly improving radar data coverage in the low-levels of the atmosphere and in mountainous regions (e.g., Xue et al. 2006), whereas fast-scanning phased-array radars can help provide much more frequent in-storm observations (Zrnić et al. 2007).

Once the data from all sources are of sufficient quality to define the environment and storm structures, improvements are also needed in data assimilation methods. A fundamental question to be answered is whether a variational method, ensemble-based method or a hybrid of these two data assimilation methods yields the best convective-scale analyses and forecasts. Regardless of the answer to this question, the computational time of variational and ensemble-based methods will need to be reduced (e.g., Anderson and Collins 20007; Gao and Xue 2008). New assimilation methodologies for use when the number of observations is larger than the number of model grid points should also be evaluated (Lewis et al. 2006).

Model error acts to limit the increase in warning lead time that a warn-on-forecast system can provide. Thunderstorm simulations are known to be particularly sensitive to the tunable parameters within single-moment bulk microphysics schemes (Gilmore et al. 2004; Tong and Xue 2008). More sophisticated multimoment bulk or bin microphysics schemes are likely needed to reduce the model sensitivity to the treatment of microphysics. Model errors produced by the parameterization of other processes—such as the planetary boundary layer, radiation, and turbulence—also are important to identify and reduce. The importance of field experiments to collect the datasets needed to improve these parameterization schemes and understand their interactions should not be underestimated.

Model grid spacing also influences model error, as it defines the physical processes that can be resolved properly. Bryan et al. (2003) indicate that grid spacing of 100 m or less is needed to accurately simulate deep convection, whereas horizontal grid spacing at or below 50 m is likely needed to simulate tornadoes (Xue et al. 2007a). The computational demands associated with such small grid spacing are significant, but the continued rapid increase in computing power suggests that the needed resources will be available within the next 20 years. Real-time convective-scale ensemble forecasts using horizontal grid spacing on the order of 250 m should be possible within the next decade. In tandem with the computational requirements, the data communication resources required for an operational warn-on-forecast system that provides updates to both analyses and probabilistic forecasts every few minutes also deserves thoughtful evaluation.

Special observations from the Verification of the Origins of Rotation in Tornadoes Experiment 2 (VORTEX2), planned for 2009 and 2010, and the scheduled upgrade of the national network of Doppler radars to dual polarization by 2013 should prove useful in developing, testing, and evaluating improved microphysical parameterizations. In addition, the unique VORTEX2 observations should help researchers isolate the key ingredients essential for tornadogenesis within supercell thunderstorms. Improved understanding of the physical processes that lead to tornadogenesis is critical to evaluating storm-resolving predictions of tornadic storms, although the VORTEX2 observations will also broaden and improve understanding of severe nontornadic thunderstorms. Past experience shows that improvements in our understanding of severe weather processes lead to improvements in convective-scale warnings.

The testing, evaluation, and improvement of a warn-on-forecast system will also greatly benefit from the collection of high-resolution verification data. Damage surveys conducted by the NWS are one source of high-resolution verification data, but these extensive surveys cannot be provided for every severe weather event. One novel and inexpensive approach used to collect verification data is the Severe Hazards

Analysis and Verification Experiment (SHAVE), in which phone calls are made to businesses and homes immediately after the passage of a hail storm to collect observations of hail size, the time when hail began, and event duration (Ortega et al. 2009). This approach also has been extended to collect information on flash floods (Erlingis et al. 2009). These data will be extremely useful in verifying analyses and probabilistic forecasts from a warn-on-forecast system.

Questions regarding the operational use of additional probabilistic hazard information in warning operations must also be addressed (Lakshmanan et al. 2007b). Present-day convective-scale warnings are deterministic calls to action, and it is unclear how NWS forecasters, weathercasters, and the public can make the best use of probabilistic hazard information in addition to the present deterministic warnings in their decision processes. Collaborative research activities between researchers and operational forecasters within the NOAA Hazardous Weather Testbed (HWT) have already begun to address some of these warn-on-forecast challenges (Kain et al. 2003, 2006; Stumpf et al. 2008). In 2007 and 2008, the HWT experimental forecast program examined output from an experimental 10-member storm-scale ensemble forecast system (Kong et al. 2007b) and evaluated the probabilistic watch guidance derived for high-impact convective weather events. In 2008, the HWT experimental warning program explored the development of probabilistic hazard information for severe weather warnings (Kuhlman et al. 2008). These experiences with ensemble-based probabilistic guidance will help guide future experiments to assess any convective-scale warn-on-forecast system and help the NWS develop best practices for its use in operations.

Efforts to understand how the public uses and responds to warnings, to explore new warning dissemination methods and formats, and to educate the public on the additional warning guidance provided by a warn-on-forecast system are strongly desired. The standard methods by which warnings are presently issued to decision makers and the public may change as our understanding of how the public responds and reacts to warnings is improved through fundamental social science research (Morss et al. 2005; Kuhlman et al. 2009). Proposed methods to make the best use of probabilistic forecast guidance in both warning and forecast operations should be tested within the HWT, evaluated by social scientists, and refined for use by all NWS forecasters.

A significant cultural change will need to occur within NWS warning operations during a shift from warn on detection to warn on forecast. Today, the flow of data from remote observing systems, algorithms, statistical guidance, and direct observation converges on the human expert who assimilates all the data and makes the warn/no-warn decision. In this system, the human is the fastest and most robust component in the process. However, in the envisioned warn-on-forecast system, the sheer volume of observational data and ensemble forecast output will likely overwhelm the forecaster. We envision a warn-on-forecast system that updates the analyses and probabilistic hazard forecasts every few minutes as radar volume scans are completed to capture and predict the evolution of convective storms. The prediction component of the system may provide ensemble forecasts out to several hours. With all this information being provided, the human expert's role in a warn-on-forecast system may be one of examining the rapidly updated three-dimensional storm and environmental analyses, assessing the plausibility of the probabilistic hazard forecasts, assessing system performance as spotter information and other verification data become available, looking for errors in the system that lead to inaccurate probabilistic hazard information, and issuing warnings as needed. Thus, the human role in the warning process is elevated to a higher level and leaves much of the assimilation process to the computer.

Although there are many challenges to the development of a warn-on-forecast system, a reliable warn-on-forecast system would provide numerous benefits to society. Imagine the number of lives saved and injuries reduced from having reliable 15–60 min convective-scale probabilistic forecasts of tornadoes, hail, flash floods, and damaging winds. Imagine the economic benefits from applying cost–benefit analyses to yield improved air traffic, surface transportation, and electrical power generation and routing from reliable probabilistic information on the evolution of convective cells and lines over the next few hours. Benefits are also likely to be seen in fire weather, air quality, and coastal marine forecasts. A convective-scale warn-on-forecast is a vision worth pursuing.

DISCUSSION.

A vision for a frequently updated numerical model–based probabilistic convective-scale analysis and forecast system to support warning operations within NOAA has been outlined (Fig. 6). Such a warn-on-forecast system would fill a gap in present NWS warning operations in which only convective-scale warnings (severe thunderstorm, tornado, and flash flood) are based upon observational detection and do not contain a major numerical forecast component. It is envisioned that a convective-scale warn-on-forecast system would provide increased lead times for high-impact weather events in support of critical NOAA strategic mission goals. Another likely outcome is the use of ensemble precipitation forecasts to drive high-resolution distributed hydrologic models to produce explicit probabilistic flash-flood forecasts. Perhaps, most importantly, the development of a convective-scale probabilistic warn-on-forecast system represents a grand challenge that will strengthen the ties between NOAA research units, NOAA operational units, universities, and the National Center for Atmospheric Research (NCAR), as well as lead to improvements in numerical weather prediction and data assimilation for the meteorology community. Various groups with expertise in data quality control, data assimilation, ensemble methods, mesoscale and convective-scale modeling, and verification exist today and need to be brought together to address the warn-on-forecast challenge. It is an opportunity whose time has come.

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