Convective-scale Warn on Forecast: A Vision for 2020

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Abstract

The National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS) issues warnings for severe thunderstorms, tornadoes, and flash floods since these phenomena are a threat to life and property. These warnings are presently based upon either visual confirmation of the phenomena or the observational detection of proxy signatures that are largely based upon radar observations. Convective-scale weather warnings are unique in the NWS by having the least reliance on direct numerical forecast guidance. Since increasing severe thunderstorm, tornado, and flash flood warning lead times is a key NOAA strategic mission goal designed to reduce the loss of life, injury, and economic costs of these high impact weather phenomena, a new warning paradigm is needed in which numerical model forecasts play a larger role in convective-scale warnings. This new paradigm shifts the warning process from warn on detection to warn on forecast and has the potential to double or triple warning lead times.

A warn on forecast system is envisioned as a probabilistic convective-scale ensemble analysis and forecast system that assimilates in-storm observations into high-resolution convection-resolving model ensemble. The building blocks needed for such a system are presently available and initial research results clearly illustrate the value of radar observations to accurate analyses of convective weather systems and improved forecasts. While a number of scientific and cultural challenges still need to be overcome, the potential benefits are significant. A probabilistic convective-scale warn on forecast system is a vision worth pursuing.

Article

A convective-scale, ensemble-based warn on forecast system represents a grand challenge for the meteorological community whose time has come.

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 as 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 warnings is due in large part to 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.

Since 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. 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 amongst the majority of impacted citizens. The NWS also provides information on hurricane forecast uncertainties, which helps the public to understand the potential for forecast amendments and alternative forecast 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 a NWS forecaster. This warning paradigm is often referred to as warn on detection. In contrast to hurricane warnings, numerical weather prediction model output has little direct impact on the issuance of tornado warnings (although numerical weather prediction output is used to help issue severe thunderstorm and tornado watches indicating that environmental conditions are supportive of these types of storms). Current warning strategies instead focus on observations of the parent thunderstorm, yielding tornado warning lead times that presently average 13 minutes. Despite this comparatively short lead-time, the national mean false alarm rate for tornadoes is near 75%. The high number of false alarms results from the lack of any technology, other than the eyes of trained observers, to uniquely detect tornadoes. 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. Since 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 or the observational detection of a proxy for a tornado. Zero lead-time is provided for the area initially impacted when visual confirmation is used to issue a tornado warning. Tornado proxies, 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. The correct interpretation of a tornado proxy indicator depends upon the skill and experience of the warning forecaster. Numerical model output has little current role in the tornado warning decision. The warnings of convective-scale weather phenomena (severe thunderstorms, tornadoes, and flash floods) are unique in the NWS since they have the least reliance upon direct numerical model 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. Emergency managers responsible for notifying volunteer storm spotters require 45 to 60 minutes to get their spotters in position, hospitals and nursing homes require 30 minutes or more to move patients into hallways and safe locations, and large venue operators such as sports stadiums require at least 30 minutes to move thousands of people from exposed locations to safety. Many of these users can effectively utilize uncertainty or probabilistic information in their decision making process, although the need for deterministic warnings that call for immediate public action will never disappear. To respond to evolving public needs, the high impact weather-warning program must additionally provide sufficiently long and sufficiently accurate probabilistic warnings to support the needs of various decision makers. These extended warnings require a new paradigm beyond warn on detection. The combination of recent scientific advances and increased public demand indicates that the time is right to make rapid progress towards a convective-scale warn on forecast paradigm in which numerical model forecasts play a substantially larger role in warning operations.

A ROADMAP FORWARD. The concept of numerically predicting thunderstorms was proposed nearly two decades ago (Lilly 1990). More recent demonstrations of the utility of convective-scale numerical weather prediction (Xue et al. 1996; Done et al. 2004; Kain et al. 2006; Smith et al. 2008), combined with improved ensemble-based data assimilation methods (e.g., Anderson and Collins 2007) 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 already are predicted by real-time experimental convective-scale model forecasts (Fig. 2), although these forecast 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 forecasters 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 on-going convection to obtain the necessary one-to-one correspondence between model-predicted and observed thunderstorms.

Recent results using explicit convective-scale modeling also indicate that rapidly evolving convective events 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). 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 convection-resolving numerical weather prediction models is crucial for developing a probabilistic convective-scale analysis and forecast system. Further benefits may be found by combining this convection-resolving ensemble system with ensemble-based data assimilation methods that may be able to most effectively assimilate radar observations.

We envision a 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 radars such as the WSR-88D and its successors (e.g., fast scanning phased array radars), while the weather prediction models will have explicit microphysics more sophisticated than those presently used in operational models. New observations from the Geostationary Operational Environmental Satellite R-Series (GOES-R) may also be useful in obtaining more accurate representations of environmental conditions. This ensemble system will provide the warning forecaster both improved analyses of convective thunderstorms and probabilistic forecast warning guidance for severe thunderstorms and tornadoes (Fig. 3). The knowledge gained during the development of this system will also lead to improvements in microphysical parameterization schemes, ensemble data assimilation methods, and greater use of radar observations in numerical weather prediction. Dual polarized radar observations in particular should be very valuable in the development of improved of microphysical parameterizations and in the assimilation of microphysical information (Jung et al. 2008). The techniques developed for warn on forecast also may aid researchers working to improve hurricane intensity and track forecasting, since model grid spacing as small as 1 km is likely needed for accurate hurricane forecasts (Davis et al. 2008).

THE TIME IS RIGHT. There are many scientific, technical, and sociological challenges that need to be overcome before an operational warn on forecast system can be implemented. While significant developments are occurring in many areas, one of the most challenging aspects of convective-scale numerical weather prediction is starting the model with an accurate depiction of on-going convection. The routine observations used for starting operational numerical weather prediction models are tens to hundreds of km apart (Benjamin et al. 2004). These observations may be suitable for defining the convective storm environment on synoptic- or meso-scales, but clearly are inadequate for defining the convective-scale features themselves. However, the advent of the national network of Doppler radars (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) provides an opportunity to insert Doppler radar data observations of reflectivity and radial velocity into convective-scale forecast models. Using simulated Doppler radar observations, Snyder and Zhang (2003) show that synthetic observations from a simulated thunderstorm can be inserted into a convective-scale numerical model using an ensemble Kalman filter data assimilation method. Since then, 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 (Dowell et al. 2004; Weygandt et al. 2008) to produce realistic thunderstorm structures within convective-scale numerical models (Fig. 4). One particularly interesting example is a retrospective simulation of a supercell thunderstorm initialized using radar data in which an embedded tornado is successfully predicted more than 30 minutes in advance of the observed occurrence (Fig. 5) (Xue et al. 2007).

Daily experiments also are presently underway to evaluate the assimilation of hourly radar reflectivity data into a 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 (Fig. 6). Similar experimental results highlighting the benefits of radar reflectivity assimilation to quantitative precipitation forecasts are found when using a convection-resolving ensemble forecast system (Kong et al. 2008).

CHALLENGES TO BE OVERCOME. While the vision of a probabilistic convective-scale analysis and forecast system is clear, a number of challenges must be met. First and foremost is the need for very rapid data quality control. Today's operational Doppler radars scan the atmosphere every 5 minutes or less, but there are often such problems as 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. The deployment of gap-filling radars also 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), while 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, improvements are also needed in the data assimilation methods. In particular, the computational time of ensemble-based methods needs to be reduced (Gao and Xue 2008) and new filter methodologies need to be developed for use when the number of observations is larger than the number of model grid points (Lewis et al. 2006). Finally, model errors within the microphysical parameterization need to be reduced, since thunderstorm simulations are particularly sensitive to changes in the intercept and graupel density parameters within single-moment bulk microphysics schemes (Gilmore et al. 2004; Tong and Xue 2008). More sophisticated multi-moment bulk or bin microphysics schemes likely are needed to reduce the model sensitivity to the treatment of microphysics. Model errors produced by the parameterization of other processes, such as radiation and turbulence, may also be important to identify and to reduce.

Special observations from the Verification of the Origin 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 2011 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.

In parallel with the development and testing of a probabilistic convective-scale analysis and forecast system, questions regarding the operational use of the additional probabilistic information in warning operations also must be addressed (Laksmanan et al. 2007b). Current convective-scale warnings are deterministic and it is unclear how NWS forecasters, much less weathercasters and the public, can make the best use of probabilistic 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) hosted by the NOAA Storm Prediction Center and National Severe Storms Laboratory have already begun to address some of these warn on forecast challenges (Kain et al. 2003, 2006). In 2007 and 2008, the HWT experimental forecast program examined output from an experimental ten-member storm-scale ensemble forecast system and evaluated the probabilistic guidance derived for high-impact convective weather events. These experiences with storm-scale ensembles will help guide future experiments to assess any convective-scale warn on forecast system and develop best practices for its use in operations. The standard methods by which warnings are presently issued also may need to be changed as our understanding of how the public responds and reacts to warnings is improved. Fundamental research is needed on how to best communicate this information to decision makers and the public (Morss et al. 2005).

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 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 data likely will overwhelm the forecaster and cause the human to be a bottleneck in the warning process. The human expert's role in the process will then change to one of guiding and monitoring the process (i.e., the expert's role will be in front of, or over, the process instead of at the back end of the process). The warning forecaster will oversee the collection of data, the preparation of the analysis, the verification of recent forecasts and the plausibility of the proposed forecast while controlling the warning process with something of a "dead man switch" which will allow human intervention prior to warning issuance if problems are detected.

The computational and data communication resources required for an operational warn on forecast system also need thoughtful evaluation during the coming years. New emphasis is needed on the short-range (0-12 h) numerical weather prediction problem and the ability to rapidly produce frequent updates to analyses and ensemble forecasts using all available data sources. Methods to make the best use of probabilistic forecast guidance in both warning and forecast operations need to be explored, tested within the HWT, and refined for use by all NWS forecasters.

While the challenges to the development of a warn on forecast system are large, the potential payoff is enormous. Imagine the benefits from reliable 15-60 minute convective-scale probabilistic forecasts of tornadoes, hail, flash floods, and damaging winds in terms of lives saved and injuries reduced. 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 hour or two. Benefits also are 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. 3). Such a 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 and universities, as well as lead to improvements in numerical weather prediction and data assimilation for the meteorology community. Various centers with expertise in data quality control, data assimilation, ensemble methods, 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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Figure Captions

Figure 1. Sequence of NWS products valid on 7 June 2007 starting from two days prior to a high impact weather event through the day of the event. Three outlooks are shown, along with one 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.

Figure 2. Reflectivity fields (dBZ) valid at 0200 UTC 4 June 2008 from (a) a 26 h real-time, experimental 4 km Weather Research and Forecast (WRF) model forecast, and (b) national composite radar observations. While 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.

Figure 3. Schematic showing the information that could be provided by a convective-scale warn on forecast system. Developing thunderstorms are observed by radar and assimilated into a numerical weather prediction model ensemble forecast system. Probabilistic predictions of the future evolution of these storms with

significant lead-time are produced, yielding a probability field for tornado path over time and the most likely location for the storm at any given time. Forecasters use the probabilistic information produced by the ensemble to make warning decisions, yielding longer warning lead times than possible based upon observations alone.

Figure 4. 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) an dual-Doppler analysis and (b) an ensemble Kalman filter analysis that assimilates reflectivity and radial velocity observations. The good agreement between the dual-Doppler analysis based on observations and ensemble Kalman filter analysis indicates that the filter is successful at inserting this thunderstorm into the numerical model. Figure courtesy of Kristin Kuhlman, Louis Wicker, and David Dowell.

Figure 5. Low-level reflectivity field of a tornadic supercell thunderstorm over southern Oklahoma City valid at 2213 UTC 8 May 2003 from (a) a thirty three-minute model prediction using a grid of 50-meter 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. From Xue et al. (2007).

Figure 6. High-Resolution Rapid Refresh (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 August 2007. From Smith et al. (2008).

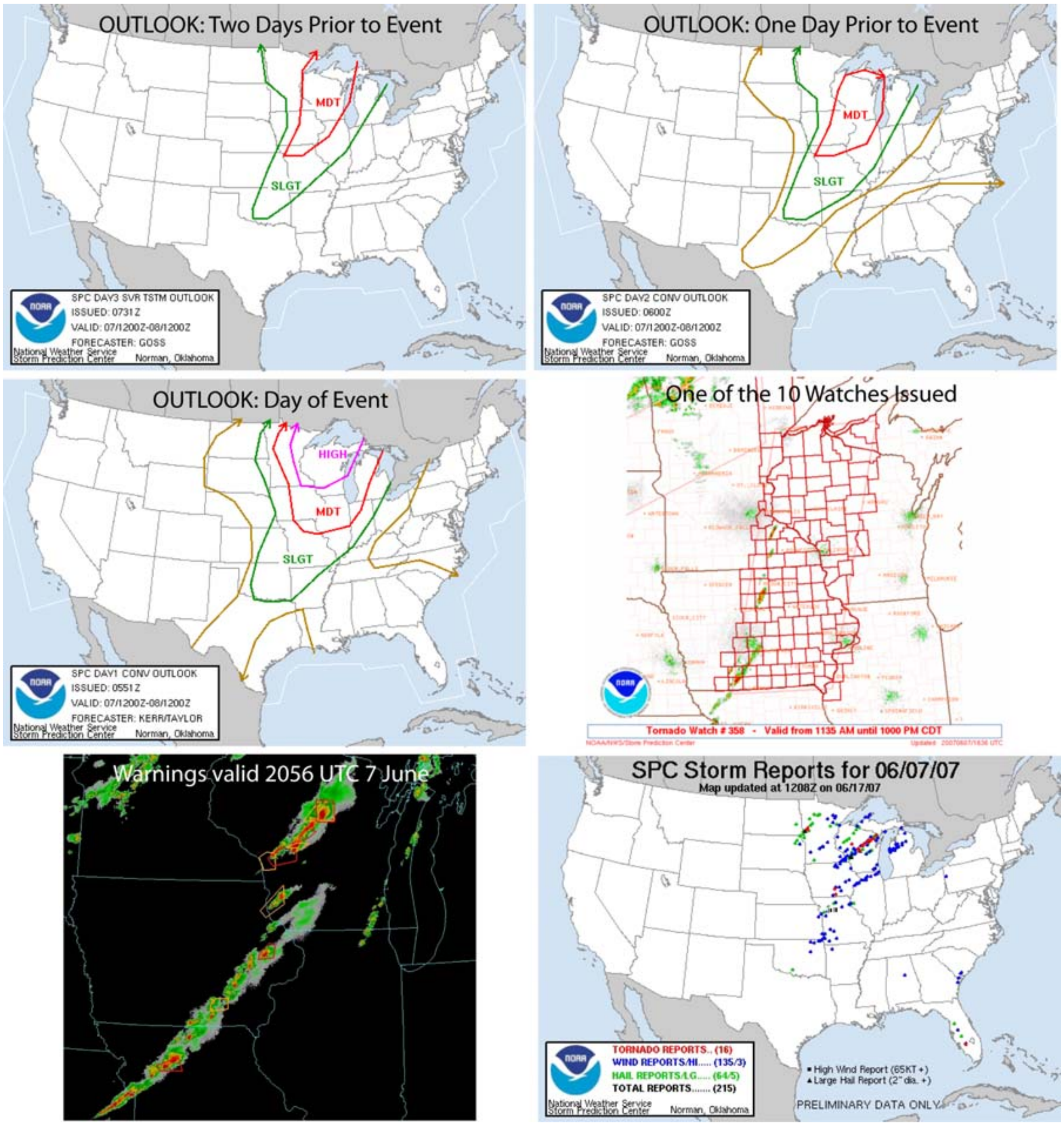


Figure 1. Sequence of NWS products valid on 7 June 2007 starting from two days prior to a high impact weather event through the day of the event. Three outlooks are shown, along with one of 10 severe weather watches. Also shown are a composite reflectivity field overlaid with actual warning polygons 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.

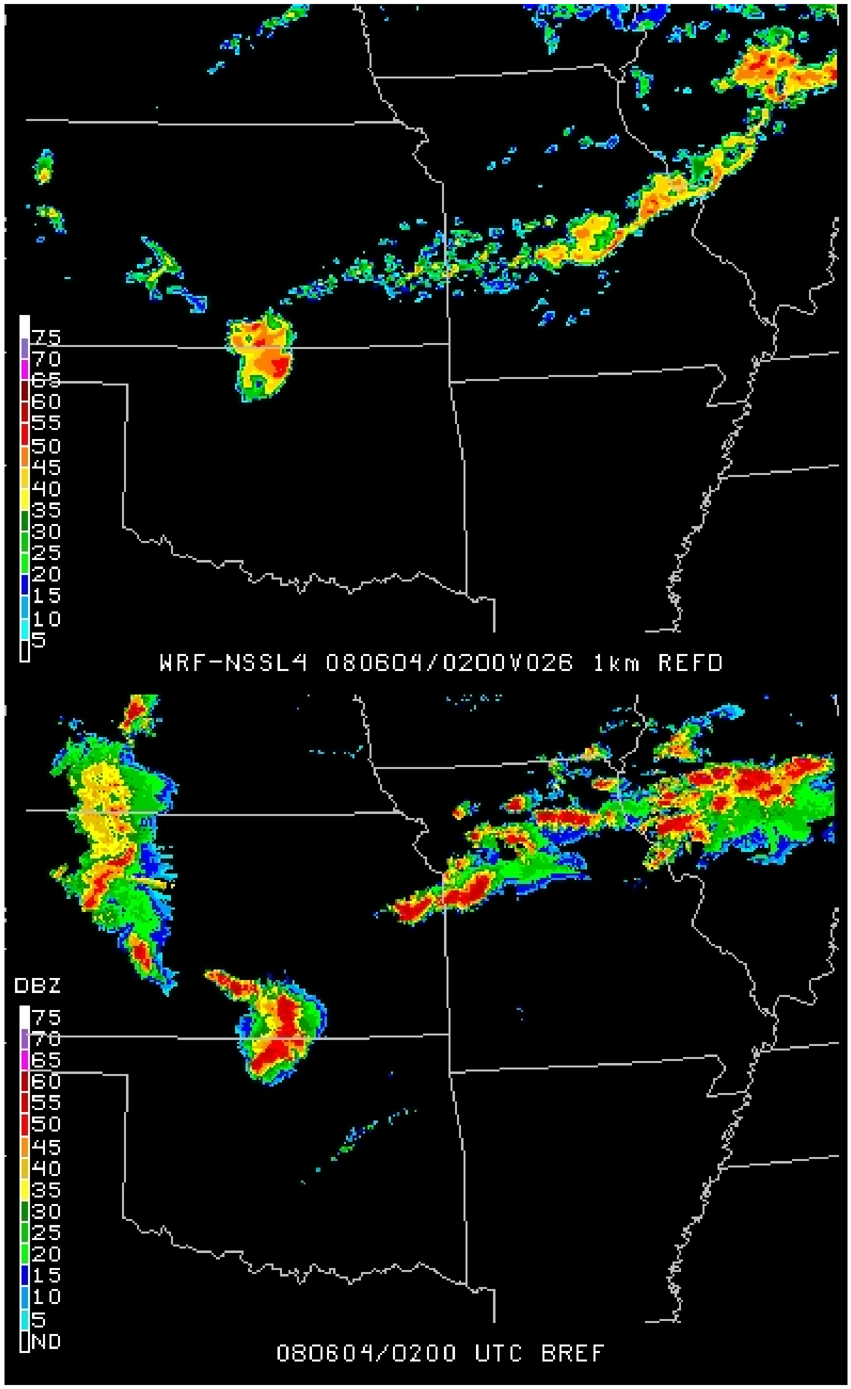


Figure 2. Reflectivity fields (dBZ) valid at 0200 UTC 4 June 2008 from (a) a 26 h real-time, experimental 4 km Weather Research and Forecast (WRF) model forecast, and (b) national composite radar observations. While the forecast reflectivity field is not perfect, the general evolution of the forecast 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.

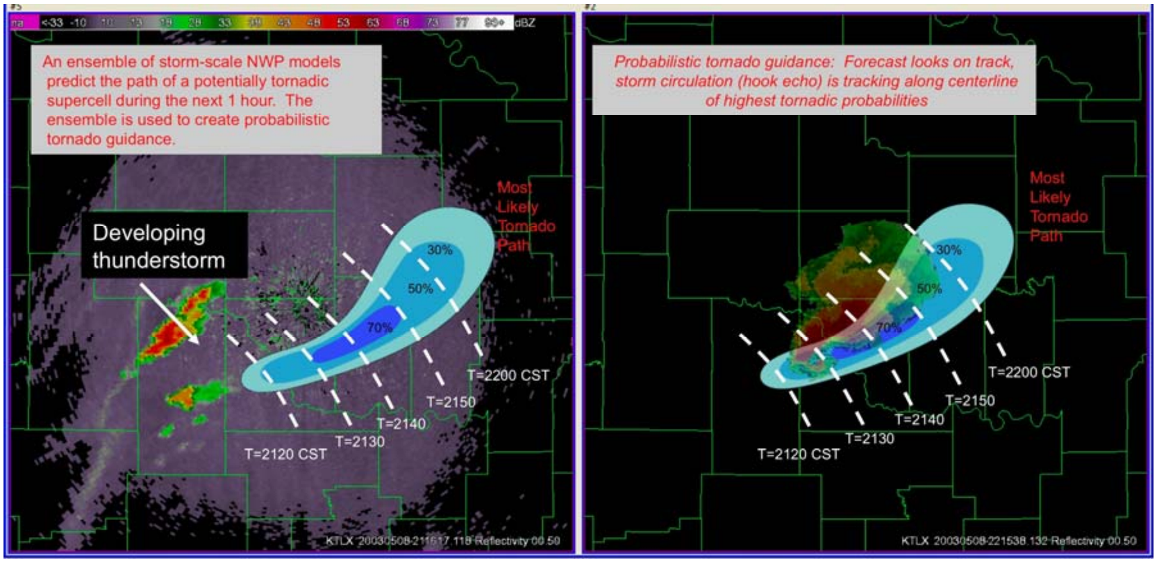
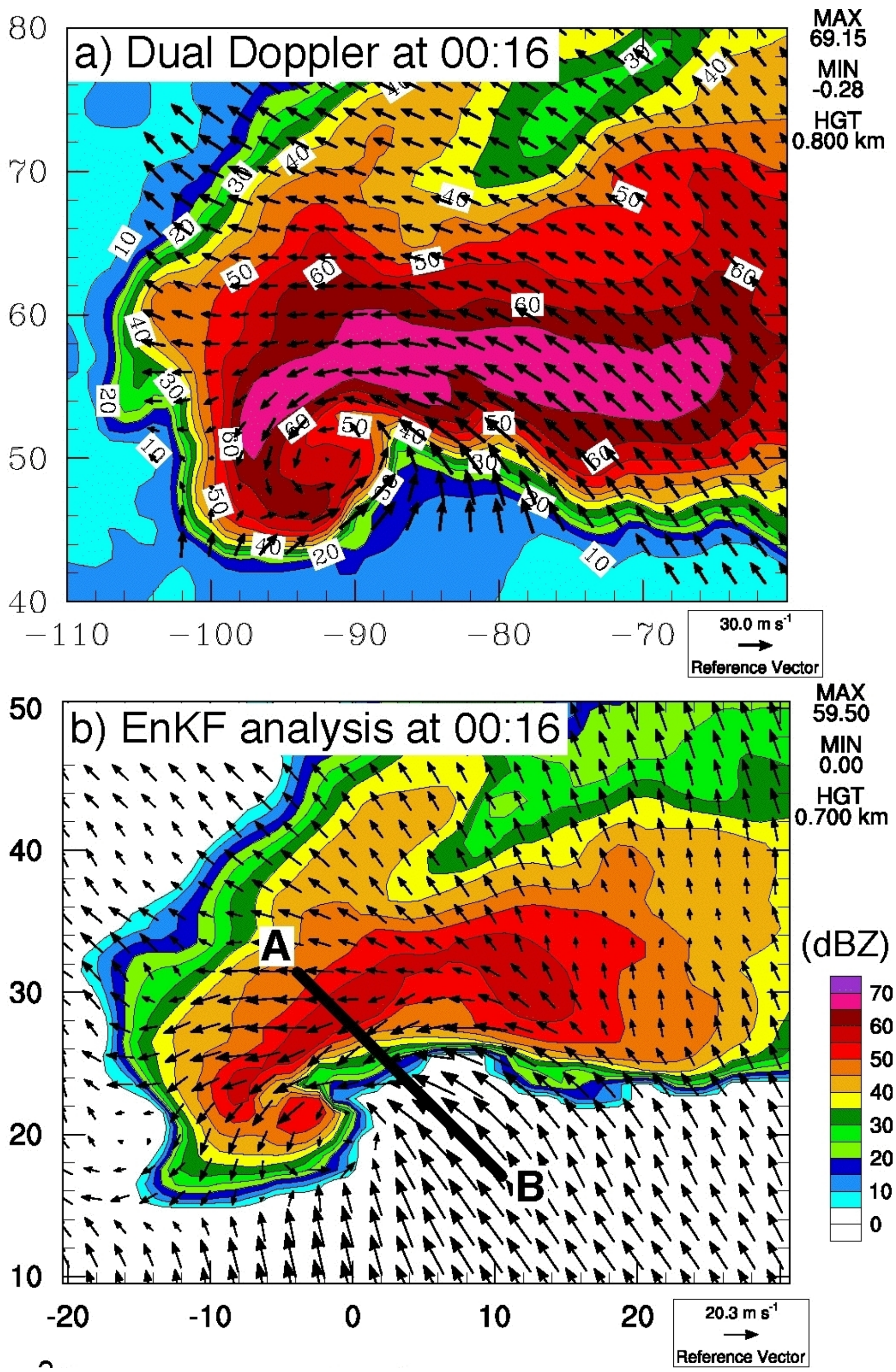


Figure 3. Schematic showing the information that could be provided by a convective-scale warn on forecast system. Developing thunderstorms are observed by radar and assimilated into a numerical weather prediction model ensemble forecast system. Probabilistic predictions of the future evolution of these storms with significant lead-time are produced, yielding a probability field for tornado path over time and the most likely location for the storm at any given time. Forecasters use the probabilistic information produced by the ensemble to make warning decisions, yielding longer warning lead times than possible based upon observations alone.



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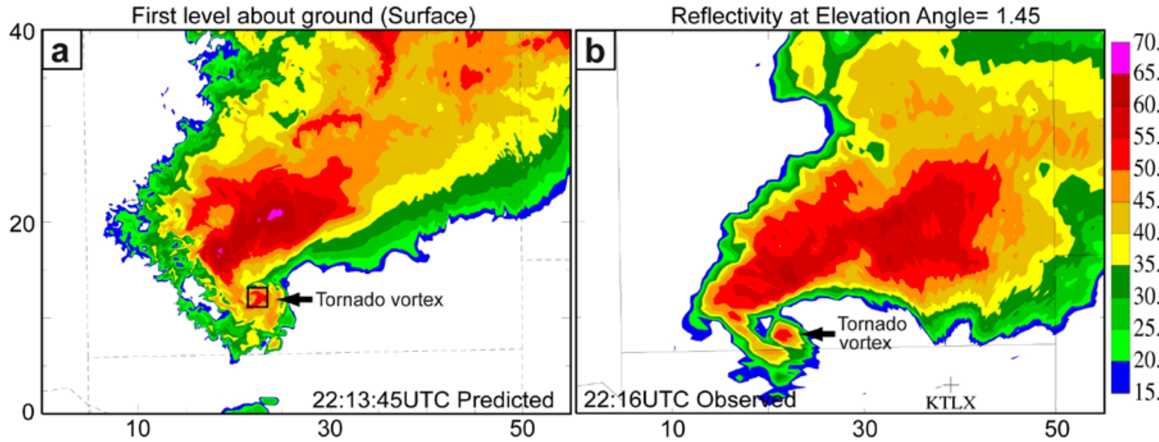

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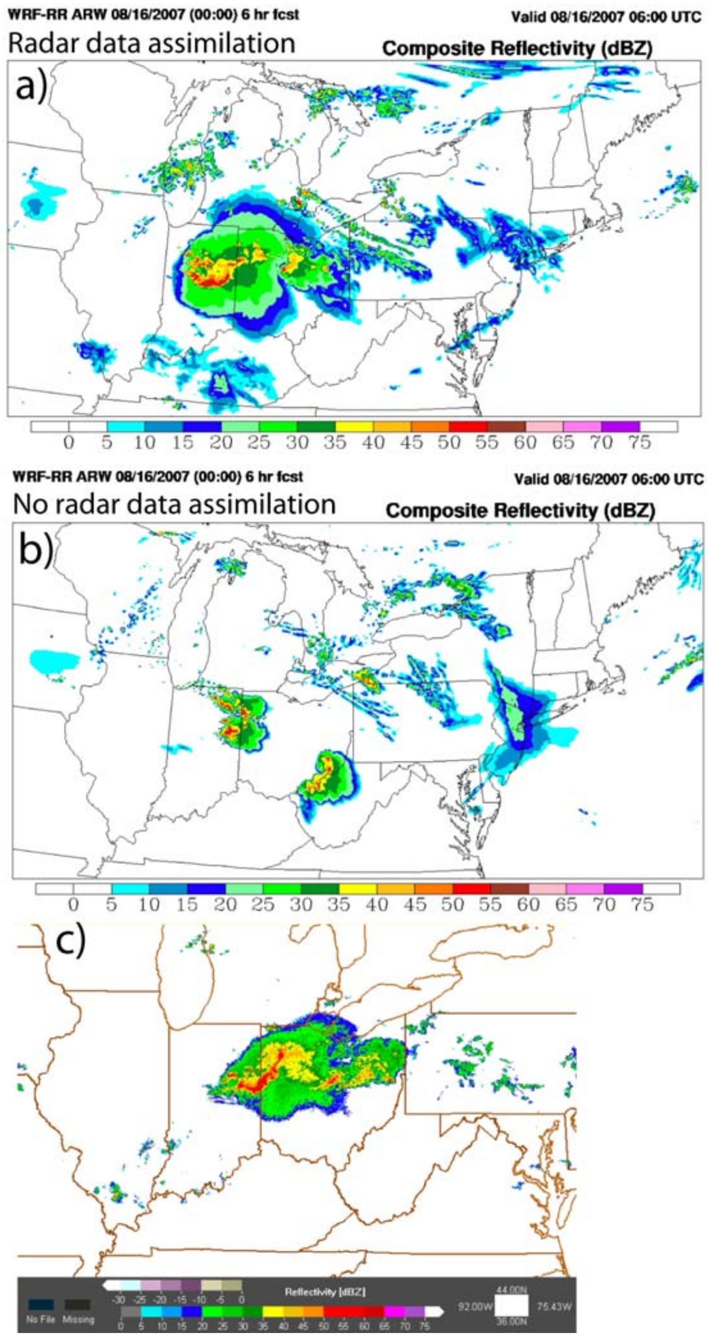

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