Convective-scale Warn-on-Forecast:
The Severe Weather Forecast Improvements
Project Plan

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Executive Summary

Increasing lead time and accuracy for hazardous weather and water warnings and forecasts in order to reduce loss of life, injury, and damage to the economy, is one of the main objectives of the weather and water strategic mission goal for the National Oceanic and Atmospheric Administration (NOAA). Trends in yearly-averaged tornado warning lead time suggest that the present weather warning process, largely based upon a *warn-on-detection* approach using National Weather Service (NWS) Doppler radars, is reaching a plateau and further increases in lead time will be difficult to obtain. A new approach is needed to extend warning lead time in which probabilistic hazard guidance is provided by an ensemble of forecasts from convection-resolving numerical weather prediction models. This convective-scale probabilistic hazardous weather forecast system is called *warn-on-forecast*.

This plan outlines the development of a frequently updated numerical model-based probabilistic convective-scale analysis and ensemble forecast system to support severe weather warning operations within NOAA. Such a warn-on-forecast system will 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. However, developing a skillful convective-scale warn-on-forecast system requires research in a number of areas throughout the next decade. These research areas include the quality control of Doppler radar observations, methods to accurately incorporate radar observations into convection-resolving numerical weather prediction models, improved understanding of the physical processes that produce severe and hazardous weather, improved physical process representation in convection-resolving models, improved ensemble methods for convection-resolving models, and an improved understanding of how society uses severe weather warning information. Continued testing of the evolving research applications in a quasi-operational testbed environment is critical to ensuring that any warn-on-forecast system provides clear operational utility and well-designed output that can be used effectively by NWS forecasters.

The warn-on-forecast project represents a collaborative effort across several NOAA units and academia. The project is led by the National Severe Storms Laboratory, with substantial NOAA contributions from the Earth System Research Laboratory, the Storm Prediction Center, and the Norman NWS Forecast Office. Academic collaborators are the Center for Analysis and Storms and the Cooperative Institute for Mesoscale Meteorological Studies at the University of Oklahoma.

1. Introduction

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, and most warnings are a natural outcome of the information that has preceded them. 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).

One of the smallest, shortest-lived and most dangerous 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 through knowledge of the storm environment and its expected evolution and other environmental cues. This warning paradigm is referred to as warn-on-detection and is primarily founded upon Doppler radar observations of the parent thunderstorm, yielding warning lead times that 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 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. Proxy tornado observations typically used in NWS warning operations include radar detection of tornado vortex signatures, thunderstorm rotation, 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. 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.

The warnings of convective-scale weather phenomena (severe thunderstorms, tornadoes, and flash floods) are unique in the NWS since they have little reliance upon direct numerical model forecast guidance. Instead, numerical weather prediction model forecasts are primarily used to help issue severe thunderstorm and tornado watches indicating that future environmental conditions are supportive of these types of storms. Since tornado warnings are largely based upon detection or perceived threat, little uncertainty information is provided.

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. Although the need for NWS warnings that call for immediate public action will never disappear, many of these users also can effectively utilize 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 (WoF) paradigm - in which numerical model forecasts play a substantially larger role in warning operations - is needed.

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, fast scanning phased array radars), while 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 and probabilistic forecast guidance for severe thunderstorms, heavy rainfall, and tornadoes.

To be successful, the WoF effort requires three integrated components. First, to improve the understanding of the small-scale precipitation (microphysical) processes occurring within thunderstorms, a field experiment called the Verification of the Origins of Rotation in Tornadoes Experiment 2 (VORTEX2) will be conducted. NOAA will leverage National Science Foundation funding of $10M between 2009-2010 to assist in this experiment. VORTEX2 will use a mix of new operational observation systems (e.g., dual-polarized radar) and prototype future systems (e.g., phased array radar (PAR), gap-filling radar, mobile mesonet surface observations, unmanned aircraft systems) to observe thunderstorm evolution as never before. The intended outcome is to learn the mechanics of how tornadoes form, or “tornadogenesis”. Observations from VORTEX2 are critical to assess the skill of the WoF system by providing high-resolution thunderstorm analyses for verification.

The second integrated WoF component is the improvement of existing high-resolution forecast models and data assimilation systems. New knowledge of thunderstorm precipitation processes and tornado formation and dissipation must be incorporated into the forecast models through new or improved physical process parameterization schemes as the second integrated component of WoF development. The unique high-resolution in-storm observations obtained from radar, both the operational WSR-88D and the high-resolution prototype PAR, must be assimilated every 1 to 5 minutes into numerical models in near real time along with other high-frequency observations (e.g., aircraft, profiler, surface, satellite). Techniques to accurately assimilate observations this quickly into models are under development, but will require testing, evaluation, and improvements in computational efficiency. Federal and university partnerships will be established to address these issues. The WoF design will include nesting within the hourly updated 3-km radar-assimilating High-Resolution Rapid Refresh (HRRR) numerical model planned by the Office of Oceanic and Atmospheric Research (OAR) and the National Centers for Environmental Prediction (NCEP).

The third integrated WoF component is real time testing of the developing WoF system and WoF concepts in the NOAA Hazardous Weather Testbed (HWT). While any initial WoF system will be far from optimal, this type of quasi-operational testing is the best way to discover potential pitfalls, examine system performance for a wide variety of convective weather events, and obtain forecaster input on system design. For example, to gain a better understanding of how probabilistic information can be used in warning operations, HWT activities will integrate real-time observations taken during the VORTEX2 field program during 2009 and 2010 with various techniques to produce probabilistic forecasts of thunderstorm-produced hazards. Physically located in the National Weather Center building between the NWS Norman Forecast

Office, the NWS NCEP Storm Prediction Center, and the NOAA Research National Severe Storms Laboratory, the HWT is improving the Nation's hazardous weather warning services by bringing together forecasters, researchers, trainers, developers, and user groups to test and evaluate new techniques, applications, observing platforms and technologies. The HWT is the natural testing ground for assessing the benefits of WoF and obtaining forecaster feedback on system design prior to any operational implementation. This work will also support the development and testing of new products for external customers, including emergency managers and the private sector.

This plan outlines the development of a frequently updated numerical model-based probabilistic convective-scale analysis and forecast system to support warning operations within NOAA. Such a warn-on-forecast system will 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 will provide increased lead times for high impact weather events in support of critical NOAA strategic mission goals. Another 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 other national centers, 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 are being brought together to address the warn-on-forecast challenge.

2. Statement of Need and Economic Benefits

The Office of Oceanic and Atmospheric Research (OAR) continually provides new science and technology to the NWS, helping NWS improve the weather forecasts and storm warnings it issues as directed by the NWS Organic Act. The significant improvements in warning lead times improvements brought about by OAR's Next-Generation Radar (NEXRAD) research in the '90s appear to have leveled off at 13-15 minutes. In 2002, the NWS developed its visionary Science, Technology and Infusion Plan (STIP), which articulated a goal of 30-minute tornado lead times. This research plan is intended to demonstrate the STIP vision of a 30-minute lead-time forecast. Further, a key driver for this research is the National Research Council report: *Completing the Forecast,* in which the National Academies of Sciences recommends new products which convey the degree of certainty of the severe weather forecast to allow users to take appropriate risk-mitigation actions.

The density of urban communities surrounded by sprawling suburbs makes it imperative that the public and emergency managers have increased tornado and severe-weather lead time to save lives and mitigate property damage. Impacts from severe storms in the US cost hundreds of millions of dollars as well as 150 to 250 lives per year. On average, flash floods created by severe storms kill over 130 people per year, while tornadoes kill more than 50 people per year. The 5 February, 2008, tornado outbreak in the Southeast U.S. alone killed nearly 60 people.

3. Warn-on-Forecast Major Tasks Overview

The main research tasks that need to be addressed in order to make progress with the development of a warn-on-forecast system are outlined. While each task is important, the timing of the tasks is different owing to funding limitations and task dependencies. However, each task contributes to the success of the project. The potential risks associated with each task also are briefly summarized.

While the WoF project depends upon a variety of observations to define the large-scale, mesoscale, and convective-scale features and requires the use of data assimilation techniques that can assimilate data on a variety of spatial scales, the project is focused upon convective-scale data assimilation. This focus implies that radar data are the most important data set for the project, as radar data provide the most complete set of in-storm observations from presently available sensors. The accurate and rapid assimilation of radar observations into convection-resolving numerical models is thereby a key to project success. The central role that radar plays in the project helps to limit project scope and it is assumed that improvements to large-scale and mesoscale data assimilation will be provided by other NOAA and academic units as they fulfill their missions and strategic goals.

Task 1. Rapid radar data quality control. Reliable and rapid radar data quality control is a significant concern. Today's operational Doppler radars scan the atmosphere every 5 to 10 minutes 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 radar 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. Significant efforts should also be made to utilize 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 success of this task depends upon successful progress with the collection of a portfolio of human quality controlled observations from severe weather event cases as described in Task 3 below. Any errors in the human-produced quality controlled observations will negatively impact the development of an accurate radar data quality control system. However, the upgrade of the NWS Doppler radar network to dual polarization over the next few years, in conjunction with the planned transition of a staggered pulse repetition time to the NWS Doppler radar system, will greatly assist in improving radar data quality control. Thus, this research task is determined to be a low risk endeavor.

Task 2. Data assimilation development. One of the most daunting aspects of convective-scale numerical weather prediction is starting the model with an accurate depiction of the atmosphere that includes the representation of ongoing deep convective clouds and thunderstorms. A fundamental question to be answered is whether digital filter, variational, ensemble-based or a hybrid of these data assimilation methods yields the best convective-scale analyses and forecasts. The value of cycling to convection-resolving data assimilation also needs to be determined. Regardless of the answers to these questions, the computational time of assimilation methods will need to be reduced (e.g., Anderson and Collins 2007; Gao and Xue 2008). New assimilation methodologies for use when the number of observations is larger than the number of model grid points also should be evaluated (Lewis et al. 2006), since the observations from radar likely will exceed the number of model grid points in WoF. Comparisons of WoF analyses with the human-produced quality controlled observational data sets (Task 3) and with dual-Doppler derived analyses from VORTEX2 (Task 5) will be needed to help determine which data assimilation methods perform best for the computational cost.

The success of this task depends upon successful progress with the collection of a portfolio of human quality controlled observations from severe weather event cases as described in Task 3 below, along with dual-Doppler analyses described in Task 5. This task also depends upon rapid and accurate radar data quality control (Task 1) for successful implementation of a quasi-real-time test WoF system.

Several of the candidate data assimilation methods require multiple radar observation volumes to successfully insert the convective storms into the convection-resolving numerical models. Using current NWS Doppler radars, this translates into needing roughly 40 min of in-storm radar observations prior to the storm being accurately inserted into the numerical model. This is too long of an assimilation time period and presents a moderate risk to project success. Data assimilation methodologies that do not rely on such a long assimilation period, such as digital filter, hybrid, cycling, or running-in-place, perhaps combined with upgrades to the NWS Doppler radar network to fast-scanning phased array radars should be explored carefully and benefits and costs determined relative to other assimilation approaches.

The importance of accurate background forecasts for convective-scale data assimilation also needs to be explored more fully. A recurring problem in convective-scale data assimilation is the presence of regions of deep convection in the model forecasts that are not observed. Deep convection acts to strongly influence the environment surrounding it, and so these regions of the model forecast are hard to correct in the presence of new observations. Research is needed on how to overcome these challenges, thereby allowing us to create accurate convective-scale analyses for use in starting the numerical forecasts for WoF. This situation also represents a moderate risk to project success.

Task 3. Case Studies for Evaluation. To develop a successful WoF system, the different system components must be tested across a variety of hazardous weather events. This situation requires the system to be run on historical weather events during the early stages of the project, transitioning to real-time events once quasi-real-time testing begins. Events from across the United States, representing different types of severe weather conditions and environments, must be evaluated. Quality controlled observations from tornadic supercell thunderstorms, non-supercell tornadic thunderstorms, non-tornadic supercell thunderstorms, hail storms, flash floods, mesoscale convective systems, and complex storm interactions events are needed in order to fully investigate the capabilities and limitations of the WoF system and outline any additional observational requirements. The development of this portfolio of severe weather event cases will require the manual editing of NWS Doppler radar data to remove known problems with the raw observations; this manual quality control process represents a significant commitment of human resources. However, the development of this portfolio is critical to testing improvements in radar data quality control, evaluating data assimilation methods, and testing improvements to numerical model parameterizations. Thus, this research area is a critical piece of the WoF project. Once a quasi-real-time WoF system is in place, daily testing of severe weather events can proceed and the number of cases examined will dramatically increase. At this point, the evaluation process begins to interact strongly with the activities of the Hazardous Weather Testbed (Task 4).

The testing, evaluation, and improvement of a warn-on-forecast system will also greatly benefit from the collection of high-resolution verification data for all cases examined. 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. We must also begin to examine the probabilistic quantitative precipitation forecasts (PQPFs) produced by a WoF system in comparison with gauge and streamflow observations to specify the potential improvements in hydrological applications that can be provided. Precipitation data sets provided by the National Mosaic and Multi-sensor Quantitative Precipitation Estimation (NMQ) program will be very valuable to these comparisons.

The success of this research task depends upon the ability of the WoF project to obtain the support of scientists with the background and skills to manually edit NWS Doppler radar data with high proficiency. This is seen as a low risk, as these scientists are on staff at CIMMS and NSSL.

Task 4. Hazardous Weather Testbed. Questions regarding the operational use of the additional probabilistic hazard information a WoF system would provide to warning operations must 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 ten-member storm-scale ensemble forecast system (Kong et al. 2007) 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 needed. 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 in the Social Science Woven into Meteorology (SSWIM) group, and refined for use by all NWS forecasters. National Weather Service evaluation of the WoF system in the HWT will occur through support from the Service Proving Ground at the Storm Prediction Center and the National Weather Service Forecast Office in Norman.

The success of this research task depends upon the successful continued collaborations between the SPC, Norman NWS Forecast Office, CAPS, CIMMS, and NSSL. As this collaboration already has a long and successful history, this task is viewed as low risk. Uncertainties in how to best use probabilistic forecast guidance in warning and forecast operations are also low risk, as current experiences in using probabilistic forecast information have been positive, although being able to provide the probabilistic information in an easy-to-use format will require inventiveness.

Task 5. VORTEX2 data collection and analysis. The collection of 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 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 non-tornadic thunderstorms. Past experience shows that improvements in our understanding of severe weather processes lead to improvements in convective-scale warnings.

Another import aspect of VORTEX2 is the validation of WoF forecasts generated using conventional data (e.g., WSR-88D radar, surface, and upper air data) versus the analyses generated from the high-resolution VORTEX2 radars, mobile mesonets, etc., from tornadic or non-tornadic storms. Data from VORTEX2 also can be used to estimate the potential benefit to WoF from dual-polarization and fast-scanning radars.

The risks to this research area are that the atmosphere will not cooperate and the special observations collected during VORTEX2 will not be sufficient in number to successfully test the hypotheses for tornadogenesis. This is a moderate risk, since the first year of VORTEX2 produced only a handful of good cases and only one tornadic supercell thunderstorm was sampled.

Task 6. Interface with RR/HRRR. The WoF system will require initial and boundary conditions from the Rapid Refresh/High-Resolution Rapid Refresh (RR/HRRR) to run quickly enough for use in NWS operations. However, the boundary conditions will require more frequent updating than is possible using the present hourly output frequency of RR/HRRR. Options in development include providing a HRRR-to-1km-nest (and finer) capability for full 2-way nesting, and providing separate lateral boundary conditions. For option 1, ESRL will develop a subnesting capability to allow WoF partners, especially NSSL, to run regional HRRR-with-subnesting. This will mimic the HRRR-subnesting now planned for the FAA, with 2-way 1-km nests planned over key hubs. For option 2, the Global Systems Division (GSD) of ESRL will provide 15-minute model output during the 0 to 3 h forecast time window across the United States for WoF development and testing. This output will provide improved environmental information to the WoF system, limiting errors due to coarse time sampling of model boundaries in limited area forecast domains. The WoF project team will also collaborate on issues relating to the frequent updating of convective-scale models during ongoing convection, examine methods for creating convective-scale ensembles, ensemble post-processing, and verification methods.

The risks to this research area are low, as the RR/HRRR are already available on a routine basis and are known to be stable forecast systems.

Task 7. Computational capabilities. The computational demands of a WoF system are large, as small grid spacing (250 m or less) will be needed to accurately define convective features (Bryan et al. 2003). 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 and affordable within the next 10 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 careful evaluation. WoF system development and testing will require regular yearly investments in local computational infrastructure in terms of computer speed, computer maintenance, disk storage, and communications.

Access to high performance computing and data communication systems is critical to nearly all aspects of the WoF project. Changes in computer architecture influence the timeliness of research results and can create unforeseen difficulties in code modifications to maximize system performance. The costs of high performance computing may limit our ability to conduct research, test quasi-real-time WoF systems, and develop a system deemed affordable by the NWS. A failure of computer performance to follow Moore's Law[1] over the next decade also risks our ability to develop a quasi-real-time WoF system.

Task 8. Numerical model parameterization improvements. 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 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 the planetary boundary layer, radiation and turbulence, also are important to identify and to reduce. Many parameterization improvements are needed as model grid spacing moves below 3 km and more and more atmospheric motions and processes are resolved. The importance of observations from VORTEX2 to collect the data sets needed to improve these parameterization schemes and understand their interactions cannot 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

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[1] http://en.wikipedia.org/wiki/Moore's_law

or less is needed to accurately simulate deep convection, while horizontal grid spacing at or below 50 m likely is needed to simulate tornadoes (Xue et al. 2007). The optimal grid spacing for WoF must be defined through sensitivity tests and comparisons against observations of actual events.

Many scientists in the larger meteorology community are engaged in improvements to physical process parameterization schemes. Thus, the WoF project will benefit from research conducted elsewhere. However, the sensitivity of convective-scale forecasts to parameterization scheme changes is well known and may lead to a level of parameterization scheme improvement not required by modeling systems with larger grid spacing. Thus, this issue is also viewed as a moderate risk to the program.

Task 9. Environmental sensitivity evaluation. 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, non-supercell tornadic thunderstorms, non-tornadic supercell thunderstorms, hail storms, flash floods, mesoscale convective systems, and complex storm interactions in order 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. The uncertainties associated with environmental sensitivity remain largely undefined, but the success of deterministic and early convection-resolving ensemble forecasts suggests that this challenge is surmountable and represents a low risk to very short-range forecasts of 30 min or less.

4. Project Priorities and Goals

The research that needs to be conducted to support a viable warn-on-forecast system is substantial, as indicated by the discussion of the major tasks in Section 3. Therefore, short-term priorities must be set to establish the project foundation as well as medium and long-term priorities and goals to help define the overall project objectives.

a. Short-term priorities and goals

The following items represent the highest priority research areas in the 2010-2012 fiscal years.

- Create a database of quality-controlled severe weather events (the warn-on-forecast database). The severe weather events in this database will include at a minimum tornadic supercell thunderstorms, non-tornadic supercell thunderstorms, tornadic non-supercell thunderstorms, multicell thunderstorms, hailstorms, convective lines, quasi-linear squall line tornadoes, flash flood producing convection, and complex storm interactions. The radar data in each case will be both the raw data and human quality-controlled, and the data sets will also contain all surface, upper-air, profiler, and satellite observations as well as RUC analyses and NAM forecasts. The goal is to have 10 events in this database by the end of 2012.

- Development of improved automated radar quality control software. A working group will be formed to document the current algorithms used for the quality control of reflectivity and velocity observations from WSR-88Ds in both operations and research. The group will then identify areas in which progress can be made in improving radar quality control. Resulting software will be tested against the human quality-controlled radar observations in the warn-on-forecast database. The goal is to have improved automated radar quality-control software running in the HWT for testing and evaluation by spring 2012.

- Determine which data assimilation methods are most accurate and cost-effective when applied to radar data at convection-resolving scales. Once several methods are available using the same modeling system, then use the warn-on-forecast database to assimilate quality-controlled radar data and verify the resulting analyses and forecasts. The goal is to be able to evaluate an ensemble Kalman filter, an ensemble transform Kalman filter, a hybrid three-dimensional variational assimilation scheme and a digital filter initialization (DFI-radar) scheme by the end of 2012.

- Develop an HRRR-subnesting capability to allow testing of WoF grids with 1km and higher resolution nests using 2-way nesting inside the HRRR by 2012.

- Develop capability to obtain RR/HRRR forecasts at 15-minute output intervals for the first three forecast hours by 2011. Rerun a few selected warn-on-forecast database severe weather cases to obtain this output frequency to help in data assimilation testing and evaluation.

- Explore the predictability of severe thunderstorms using a numerical modeling approach. The predictability of thunderstorms is largely unknown and represents an important research area. If we can only predict thunderstorm evolution out to 30 minutes, then hoping to extend warning lead times beyond 30 minutes is unreasonable. We need to better understand thunderstorm predictability to define reasonable project expectations. Goal is to have initial results from a thunderstorm predictability study by the end of 2012.

- Document current NWS forecaster practices for determining and generating severe weather watches and warnings. Identify gaps in extending watch and warning capabilities.

b. Medium-term priorities and goals

The following items represent the highest priority research areas in the 2013-2015 fiscal years. These priorities and goals will need to be reassessed yearly and may be changed as the project evolves.

- Improve our understanding of the physical processes that produce tornadogenesis using special observations from VORTEX2. Goal is to have several VORTEX2-related formal publications by the end of 2015.

- Conduct a bake-off in the HWT of warn-on-forecast analysis systems starting in 2013. Goal is to define which three-dimensional analysis fields are most useful to warning operations by 2015.

- Determine if a warn-on-forecast system can be produced on a national scale or must be done over smaller regional domains by 2015.

- Expand the number of severe weather events in the warn-on-forecast database to over 20.

- Determine the data assimilation technique, including an evaluation of cycling for convection-resolving data assimilation, that is most suitable for a warn-on-forecast system by the end of 2015. This recommendation should be based upon analysis and forecast accuracy as well as computational efficiency.

- Develop an improved understanding of how the public uses severe weather warning information to make decisions.

- Develop an improved understanding of how probabilistic information can be used to inform warning decisions by the end of 2015. To help obtain this improved understanding, develop a displaced real-time evaluation of warn-on-forecast techniques and capabilities for use in the HWT.

- Develop an automated radar quality-control algorithm that uses dual-polarization radar data in addition to the reflectivity and velocity data by the end of 2015.

- Develop an improved understanding of thunderstorm predictability by the end of 2015 and determine if the observational data stream is sufficient to define the environmental conditions to the needed degree of accuracy to predict thunderstorm evolution accurately out to 1 hour.

c. Long-term priorities and goals

The following items represent the highest priority research areas in the 2016-2020 fiscal years. These priorities and goals will need to be reassessed every few years and may be changed as the project evolves.

- Develop a quasi-operational warn-on-forecast system by 2016 for testing within the HWT.

- Finalize an improved automated radar quality-control algorithm for transfer to the NWS in 2017 that includes the use of staggered PRTs for velocity observations.

- Recommend the output format for warn-on-forecast probabilities to be provided to NWS forecasters by 2017.

- Complete initial study of how the public can best use warn-on-forecast probabilistic hazard information by 2018.

- Incorporate improved physical process parameterization schemes into the warn-on-forecast system numerical model as needed by 2018.

- Evaluate the 1-way and 2-way nesting of very high-resolution model grids within the HRRR for warn-on-forecast support and assess computational requirements.

5. Project Schedule

The WoF program as defined in the NOAA funding request contains a number of items that help define the project schedule and milestones, deliverables, and project scope. These items are important to consider in creating the project plan and are repeated here for completeness and were used to help determine priorities and goals as outlined in Section 4. The funding request also includes NWS measures of success, namely tornado warning lead times.

Schedule and Milestones:

- Complete field phase of VORTEX2 field experiment (2010).

- Complete documented plan to assemble and test a WoF system (i.e., this document) (2010).

- Complete plan and establish an evaluation approach to develop and assess new end user products and services using HWT and SSWIM with the NWS (2011).

- Collect and evaluate VORTEX2 observations for keys to understanding the physical processes that lead to tornadogenesis. Identify potential model physical process schemes for incorporation of processes correctly into storm-scale forecast models (2012).

- Complete study and prepare report assessing the relative value of different data sources and modeling techniques for use in WoF, including the impact of spatial and temporal scanning strategies (e.g., PAR vs. 88D), dual polarimetric radar data, and impact of surface and satellite observations. Data from VORTEX2 will assist this process. Use knowledge gained to advise NOAA on optimum observing systems and strategies (2012).

- Complete study assessing ways of providing severe weather forecast uncertainty. Perform case studies with WoF-HRRR nesting design, including new data assimilation techniques at HRRR and WoF scales. Work with NOAA operations to define requirements for new warning products derived from WoF research (2013).

- Complete specification of basic components of a complete WoF system, including data conversion and quality control, ensemble initialization, storm-scale forecast model, data assimilation system, display, and diagnostic software, along with all needed computer communication packages (2013).

- Complete an operational demonstration with the NWS operations of a WoF system during the severe weather season with WoF nested inside HRRR (2014).

- Complete report documenting major findings from VORTEX2. Develop plan for WoF modeling component using the High-Resolution Rapid Refresh (HRRR) to provide initial 3-km fields, comparing 0.25 – 1.0 km WoF with 3-km HRRR forecasts (2014).

- Complete a report documenting the readiness of WoF technology and utility of transitioning WoF functionality to operations (2015).

- Assess the use of frequently updated national scale and local ensembles for probabilistic forecasts in the WoF context. Determine methods for best communicating uncertainty in warnings to both forecasters and non-NOAA customers with help from SSWIM. HWT will play a key role in this assessment (2015).

- Address fundamental science questions that may limit WoF utility, including effects of model error on thunderstorm evolution, needed accuracy of storm environmental conditions, and errors in conversions from model data to observational data. VORTEX2 data will assist this evaluation (2018).

- Go/No Go decision for WoF. Provide NOAA management with information needed to decide whether to make WoF operational. Total cost to Go/No Go decision ($20.7M) (2018).

- Conduct real-time tests of WoF system in HWT in collaboration with NWS forecasters and collect data needed to verify WoF predictions. Collaborate with NWS forecasters to evaluate WoF and develop new display capabilities for use in warning operations. Evaluate WoF predictions using rigorous verification measures and use knowledge gained to further improve WoF system (2020).

Deliverables:

- Complete documented plan to assemble and test a WoF system (i.e., this document) (2010).

- Complete field phase of VORTEX2 (2010).

- Complete plan and establish an evaluation approach to develop and assess new end user products and services using HWT and SSWIM with the NWS (2011).

- Report documenting the relative value of different data sources, new data assimilation and modeling techniques appropriate for use in WoF, and a design to optimize WoF via nesting inside the HRRR. Report assessing the ways of providing severe weather forecast uncertainty (2013).

- Report documenting the major components of a WoF system, with operational demonstration of some WoF components in the pseudo-operational environment of the HWT (2013).

- Report documenting major findings of the VORTEX2 field phase (2014).

- Report documenting the assessment of operational readiness of WoF technology, with computer code and documentation suitable for transitioning to operations (2015).

Performance Metrics:

Tornado warning lead time (minutes)	**FY 2009 Target**	**FY 2010 Target**	**FY 2011 Target**	**FY 2012 Target**	**FY 2013 Target**	**FY 2014 Target**
With WoF*					**20**	**30**
Without WoF	**12**	**12**	**12**	**12**	**13**	**13**

* Note that the "with WoF" targets are experimental/demonstration targets.

6. Project Procedures

The warn-on-forecast project team is geographically and organizationally diverse, residing in two states and representing at least seven different organizational units. This diversity elevates the importance of project procedures that act to unify the project team and help the team maintain focus upon long-term goals. It is also expected that the WoF project will be highly visible within NOAA, leading to a need to provide a single source for project information. To accomplish these goals of team unity, team focus, and project information, the organizations involved have agreed upon the follow guidelines for team organization.

The WoF project is managed by a project leader selected by NSSL. The WoF project leader is supported by a science advisory board consisting of senior personnel from both the research and operational organizations invested heavily in the project (Table 1). The role of the project leader is to oversee all parts of the project and to ensure that each organization contributes to the success of the project and the team. Working groups will be formed as needed to address each of the major tasks outlined in Section 3 and according to the funding schedule. Each working group will select a group leader to interact more closely with project management and be a focal point for information dissemination.

The project leader will require yearly three-page work plans from each working group that obtains funding. These work plans are due on 31 January of each year. These plans will briefly outline current working group status, discuss the remaining challenges, list goals and deliverables for the coming year, and provide a detailed budget. It is expected that these goals and deliverables will be closely tied to the project plan. The project leader will provide the working group plans to the science advisory board and will call a board meeting to review the plans. The project leader and the board are responsible for making sure that the individual working group plans conform to the project plan, address the known project needs, maximize collaboration and information/code sharing among team members, and advance the science and operational needs of the WoF project. While consensus among board members is desired, if disagreement arises the project leader has final oversight authority and can work directly with the working group to adjust goals and deliverables to fit the project needs for that year.

WoF Project Leader
David Stensrud, NSSL

WoF Science Advisory Board
Stan Benjamin, ESRL/GSD
Mike Foster, MIC Norman NWSFO
Kevin Kelleher, NSSL Deputy Director
Steven Koch, ESRL/GSD Director
Russ Schneider, NCEP/SPC
Louis Wicker, NSSL
Ming Xue, CAPS Director

Table 1. Warn-on-Forecast Project Leader and Science Advisory Board members.

The working groups will provide the project leader with a status update on 31 July of each year and a final report outlining accomplishments and challenges by 15 January, two weeks prior to the due date for the next year's work plan. The status updates and yearly reports will be shared with the science advisory board. The working group leaders also are expected to provide regular updates to the WoF project leader on group activities and to raise any problems or concerns immediately. It is the responsibility of the project leader to elevate significant concerns to the level of the science advisory board. The project management team is then responsible for thoroughly discussing the concerns and searching for risk reduction strategies that move the project forward. It is critically important to share bad news as soon as possible in order to devise alternatives before small problems grow into large ones. The WoF project represents a substantial science, engineering, and societal advance and problems along the way are expected.

The project leader will schedule and organize a WoF project workshop in February of each year in Norman, Oklahoma. Funds will be provided by NSSL for up to three selected representatives from funded organizations outside of Norman to participate in the workshop. The workshop will be used as an instrument to present project results, discuss plans for the current year, revisit the project plan and revise as needed, continually assess project priorities and risks, allow open and frank discussions about any concerns or challenges to the program, and celebrate our successes. It also provides an opportunity for the science advisory board to meet in person. Any changes to the WoF project plan must be approved a majority vote from the science advisory board.

The project leader also will lead in the design of a WoF project website to be hosted at NSSL. This website will contain the approved project plan (this document), the working group work plans, status updates, year-end reports, a list of publications resulting from the project,

project meeting dates, and other material deemed relevant. The project leader will approach working group leaders occasionally for news items that can be placed on the website to highlight recent progress, articles published, and other newsworthy information that can be shared.

7. Team Member Expectations

The WoF Project represents a substantial investment in research and operations by NOAA with the hope of radically advancing the ability of the NWS to serve the weather warning needs of the US public. Thus, individuals who contribute to the WoF project are expected to maintain the highest professional and ethical standards. The success of the team is viewed as more important than the success of the individual. Individuals and working groups are expected to:

- report good results and bad results with equal candor
- be willing to share code and data sets to advance project goals
- maintain a collegial and positive attitude
- encourage collaborations where possible and helpful to build team unity
- be honest and open to considering alternative perspectives at all times
- remain focused upon project goals

8. Measures of success

Working group results will need to be compared against observations to quantify success and gauge improvements as the project matures. This situation requires that the observations used as truth be applied consistently across the project and that generally agreed upon success measures be defined.

<u>Observations</u>
The human quality-controlled radar data sets developed under Task 3, along with accompanying analyses and standard NWS observations, are the data that the project will use for evaluation. These data represent our best estimates of truth.

<u>Measures of success</u>
Measures that will be used to quantify working group success and gauge improvements include the following. While a number of these are standard statistical calculations often used in meteorology, success must also be defined from a broader perspective.

- Accuracy of analysis compared to the pre-defined truth (rmse, bias, mae, correlation).
- Forecast accuracy and reliability compared to the pre-defined truth (rmse, bias, mae, correlation, reliability, Brier Score, ranked probability score).
- Speed of calculation.
- Formal publications.
- Forecaster assessment of product value and usefulness.
- Percentage of data corrected.

- Collaborations produced as a result of interactions among working groups.
- Generation of external funding to support or enhance project goals.
- Timeliness of task completion.
- Budget tracking.

9. Summary

The warn-on-forecast program has the potential to dramatically increase and improve NWS warning services to the public by extending warning lead times to 30 minutes or more through the addition of probabilistic hazard information. This plan outlines the main research and operational challenges to making warn-on-forecast a reality and develops a path by which these challenges can be surmounted through targeted research and collaboration across NOAA and external partners. These areas include the quality control of Doppler radar observations, methods to accurately incorporate radar observations into convection-resolving numerical weather prediction models, improved understanding of the physical processes that produce severe and hazardous weather, improved physical process representation in convection-resolving models, improved ensemble methods for convection-resolving models, and an improved understanding of how society uses severe weather warning information. Continued testing of the evolving research applications in a quasi-operational testbed environment is critical to ensuring that any warn-on-forecast system provides clear operational utility and well-designed output that can be used effectively by NWS forecasters. The inclusion of social science research to this plan highlights the importance of understanding as soon as possible how both forecasters and the public view and use severe weather warning information. This research is important to develop a warn-on-forecast system that meets the public's demand for weather and water information.

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