Probabilistic Guidance for Severe Weather Threats

A collaborative experiment for the NOAA Hazardous Weather Testbed's Experimental Warning Program

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1. Introduction

The National Weather Service (NWS) has recently transitioned to "storm-based" warnings (formerly known as "polygon" warnings) from "county" warnings to better serve the public by providing more specific information about hazardous weather threats. These storm-based warnings have the same general structure as county warnings, except that the threat area is assigned by a polygon that, in theory, is not restricted by county boundaries and should highlight a smaller area. However, the science and verification methods to support new warning practices are not fully developed, and it is imperative that applied researchers, alongside expert forecasters, take a leading role in the development of warning decision-making tools and techniques based on sound science, as well as enhanced severe storm verification methods, that support improvements to NWS Tornado and Severe Thunderstorm warnings.

The WRDD/SWAT group at NSSL has a long history of collaboration with local NWS forecast offices (NWSFOs) across the United States and has conducted proof-of-concept tests for WDSS and WDSS-II systems at over 20 offices since the mid-1990s. The 2008 Hazardous Weather Testbed / Experimental Warning Program (HWT/EWP) spring experiment is the second year of a new era of collaboration between NSSL and local NWSFOs as we work on warning-scale (0-2 hour) nowcasting challenges for convective weather hazards. During 2007, our objectives were to begin the collaborative process between forecasters and researchers on this challenging task. The goal of this first full year of the project in Spring 2008 is to continue the development of new warning techniques that build upon "storm-based" warnings. These experimental warnings will have the following characteristics:

- More specific in time (when will the storm affect a location and when will it end?);
- More specific in space (covering less area; threat area advects with storm);
- More specific intensity estimates;
- Defines the types and intensity of threats (wind, tornado, hail, lightning);
- Defines the temporal, spatial, and intensity uncertainties of the threats through the use of probabilities that may be communicated to advance users, allowing for longer lead times for threats (albeit with greater uncertainty);
- Update continuously in real-time each minute to reflect changes in storm motion and evolution.

Visiting forecasters will use WDSSII applications and display tools to identify threat areas for each convective hazard type in real-time for events across the conterminous United States. These continuously updating threat areas will be compared to storm-based and county-based warnings to evaluate lead time at different points, area-under-warning and time-under-warning, and correct warnings and non-warnings on a high-resolution (~ 1 km^2) grid.

The HWT/EWP will have teams of about four “forecaster/evaluators” available each week during May and early June 2008. The evaluators are collaborating meteorologists from NWSFOs, international weather agencies, and the Warning Decision Training Branch who have expertise in the area of warning decision-making. Forecasters will draw threat area polygons and interact with experimental software that projects the future locations of storm threats. Using the techniques developed in the Severe Hail Verification Experiment in 2006 and 2007, a team of students will collect high-resolution verification data for hail, severe wind, and tornado events in the identified threat areas, as it is impossible to conduct this research without detailed validation data.

The long-term goal of this project is to develop a methodology and applications for probabilistic warning guidance of tornadoes, damaging winds, and large hail that may be updated continuously as threats evolve. Using integrated multi-radar, multi-sensor data sources and extrapolation forecast techniques (“Warn-On-Integrated-Detection”), we will develop a framework that may also be applied to future technological and scientific advances such as Phased Array Radar and that bridge the gap to “Warn-on-Forecast” techniques. Results will be directly applicable to the Next Generation Warning Tool being developed for the NWS’s AWIPS workstation.

2. Background for the Probabilistic Warning Guidance Experiment

2.a Probabilistic Warning Guidance: Why?

New technologies and advancements in the science of meteorology allow Tornado Warnings and Severe Thunderstorm Warnings to be much more specific in time and space than warnings the NWS currently disseminates. Additionally, more information can be conveyed to more advanced public and private sector users about forecaster uncertainty concerning the likelihood of severe weather at a given location by using high temporal- and spatial-resolution probabilistic warning grids for multiple types of hazards (tornadoes, damaging winds, hail, flash floods, and lightning). These advancements will result in a higher level of service to all users through better communication about the threat in time, space, and the level of uncertainty. Overall, this **reduces false alarms and false alarm area** (reducing the number of people who perceive a warning as a false alarm) while maintaining a **high probability of detection** and **providing longer lead times for tornado and other severe weather threats** to a wide variety of users.

The current NWS warning system has several limitations that may be addressed by applying new technology and new scientific understanding of convective storm behaviors. The recent (October 2007) change from county-based to storm-based warnings has addressed some of these issues in theory, but often not in practice. For instance, there are major inconsistencies between NWSFOs (and even between individual forecasters at the same NWSFO) on deciding the size of the polygon that should be drawn for different threats. Additionally, the polygons are frequently modified (or "clipped") to avoid including small sections of counties that might trigger an alert for the Emergency Broadcast System of an entire county when only one small section might be affected by the storm. The length of the polygon along the path of the storm is usually cut off by the issuing forecaster at the county line of the next county. As a severe storm moves across a county (and polygon) and is about to enter a new county, a warning (and polygon) may be issued for the new county. This results in uneven lead times for residents of the county: the people in the new county nearest the storm usually receive a very short lead time, whereas the people on the far side of the new county from the storm have a much longer lead time before the storm affects them (Figure 1).

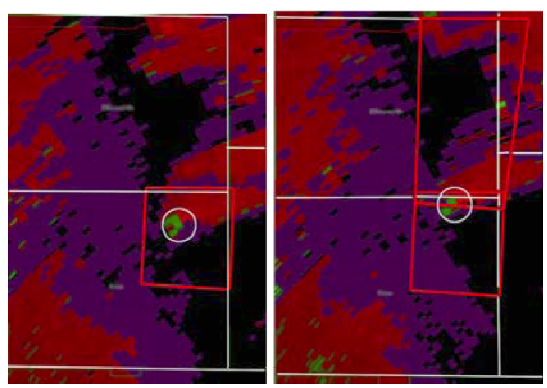

Figure 1, Left: a tornado warning polygon (red box) for a mesocyclone (white circle over red/green Doppler velocity couplet) moving rapidly northward. Right: A new warning polygon (upper red box) for the northern county is issued just as the threat area enters the county. The polygon information is not usually conveyed to the general public by the media or by NOAA all-hazards radio, and so even though the threat is only for the eastern portion of these counties, users in the entire county may be seeking shelter.

Better verification of severe weather events is needed to conduct scientific research that reduces the spatial and temporal scale of hazardous weather warnings as well as to provide a measurement of uncertainty in the warnings.

At present, warning validation data are collected by the same team of forecasters who issue the warnings either during or soon after warning operations. The validation data they collect is usually on the same temporal and spatial scale as the warnings they issue – roughly hourly and 1 county (very roughly 1000 km^2 to 3000 km^2). Because of the current mechanism in the way the verification data are collected, many temporal and spatial errors appear in the resulting publication, *Storm Data*, the official record of severe weather events for the United States (Trapp et. al 2006; Witt et. al 1998). However, the Severe Hail Verification Experiment, conducted during the Spring/Summer of 2006 and 2007 (Smith et. al 2006; Ortega et. al 2006) showed that it is possible to collect very high-resolution validation data with a time and space scale on the order of 1-5 minutes and 1-10 km^2 by combining geographic information with real-time high-resolution radar data over the CONtinental United States (CONUS; see Figure 2). These improved validation data are not only required for ongoing and future research (to verify high-resolution digital warning grids), but also have the capability to validate county-based and polygon-based warnings currently issued by NWS offices, thus reducing the perceived false alarm rate for storms that are, in fact, severe but unverifiable using present verification methods.

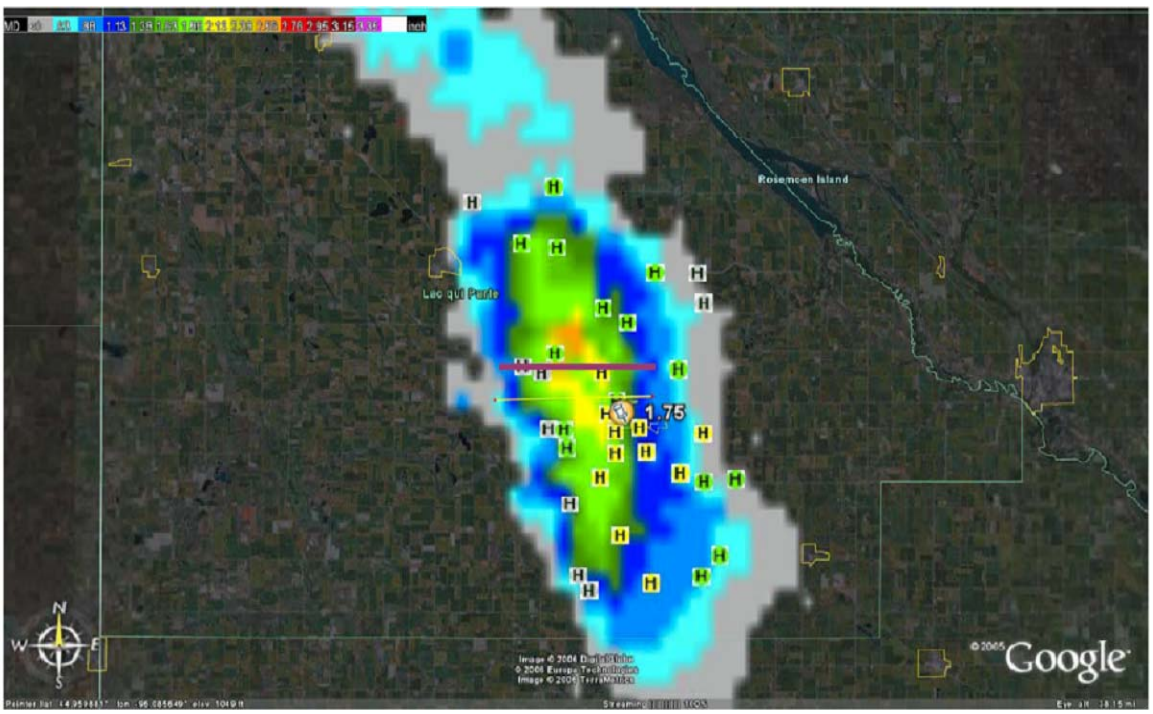

Figure 2: The NSSL Hail Swath algorithm showing radar-estimated maximum hail size during a 180 minute period for a storm that occurred in Lac qui Parie County, MN on July 27, 2006. The grey icons (no hail), green icons (hail up to 1” – 2.54 cm) and yellow icons (hail >1” to 2” – 2.54 cm to 5.08 cm) represent data points collected during the Severe Hail Verification Experiment. The single “push pin” icon represents two collocated data points collected in the county by the National Weather Service as part of warning verifications efforts and published on the Storm Prediction Center web site at http://www.spc.noaa.gov/climo. The purple line is 10 km long in the scale of the map.

Additionally, very little research addresses the specific needs of lead time and warning accuracy for different user types. For instance, if a tornado threat exists:

- A healthy individual in a well-built home may only need a few minutes of lead time to take cover;
- A family with small children or an elderly person who has mobility limitations may need a few minutes more;
- A person or family in a manufactured home or recreational vehicle may need 20-30 minutes to evacuate their location and find more substantial shelter;
- A "community gatekeeper" responsible for the safety of large groups of people (schools, hospitals, youth sporting events, etc) may need 45 minutes, an hour, or more to evacuate people or move them to places of safety.

Different end-users of NWS warning products have varying needs for lead time and accuracy. The false alarm rate becomes larger as the required lead time increases due to uncertainties involved with storm evolution. Many users who need longer lead times, however, will be able to utilize the uncertainty information in a probabilistic warning to plan the best course of action. Probabilistic information will provide information that will allow different sectors of users to determine their individual risk if preventative action is not initiated. For example, users who require longer lead time may take action with lower probabilities, as their assessed risk might be higher than an average user. That is, if the costs associated with a missed event are higher than those associated with a false alarm, the user's decision threshold may have a higher Probability Of Detection (POD) but the Probability Of False Detection (POFD) will increase as well (Figure 3; Brooks 2004).

An effective way must be developed to communicate digital high-temporal-and-spatial resolution probabilistic warning data to the public, in high detail for more sophisticated users and in simple detail for less-sophisticated users, and for advanced users (e.g., those who may be responsible for the safety of a large number of people) as well as for individuals. The effective use of Geographic Information Systems (GIS) is essential to the successful implementation of any improvements to the NWS severe weather hazards dissemination system, as digital high-resolution grids of weather information are ineffective without the ability to integrate them with geographic information.

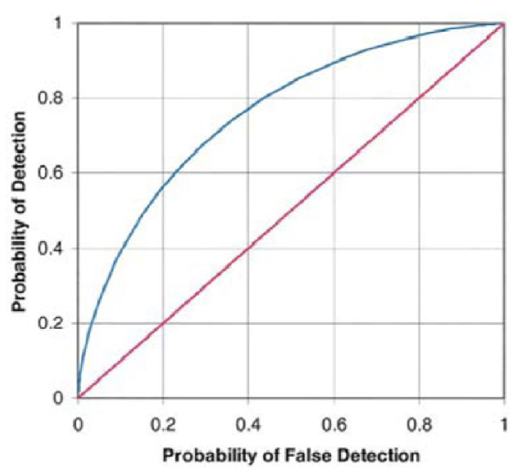

Figure 3: An example of a relative operating characteristic curve from Brooks (2004). The curved blue line is the plot of POD vs. POFD for each decision threshold, and the 45° angle red line represents no skill.

2.b. Uncertainties in Warning Decision-Making

Several types of uncertainties must be considered when generating a probabilistic grid for a threat, whether by a forecaster or by an objective algorithm. The probability estimates must consider:

- Uncertainty in the *existence* of a threat, e.g.,
  - A strong circulation signature in the Doppler velocity field on radar indicates a tornado may exist or may soon exist, but also may not indicate a tornado;
  - If a member of the public reports a tornado, uncertainty associated with whether or not the public were truly able to distinguish a tornado from some other sky object that resembles a tornado;
  - If a trained spotter reports or a live media video feed shows a tornado, then the confidence that one exists is very high, near 100%;
- Uncertainty in the *location* of a threat, e.g.,
  - Hail cores may be easily identified aloft via radar, but the actual path the hail travels to reach the ground is highly variable;
  - A Tornadic Vortex Signature (TVS) on radar may be centered at one location, but because the radar is sampling at some elevation above the ground, an associated tornado may be displaced from the TVS location;
  - A Quasi-Linear Convective System (QLCS) can produce rapid spin ups long its leading gust front, and the TVS signatures may not yet exist at the time of the warning;
- Uncertainty in the *motion* of a threat, e.g.,
  - A supercell thunderstorm may continue on a constant-speed straight path or slow down make a right turn at some time in its life cycle;
  - Most storms have at least slight deviations in speed and direction of travel and propagation during their life cycle;
  - Under weak steering flow, storm motions can be dictated by interactions with outflows from other storms, which can be very difficult to predict with certainty;
  - Storms can merge or split;
- Uncertainty in the *intensity* of a threat, e.g.,
  - Very high radar reflectivity values may indicate large hail, copious small hail, or copious rain;
- Uncertainty in storm *evolution*, e.g.,
  - A storm that crosses an atmospheric boundary into moisture-laden air may intensify, but the boundary may escape detection (i.e., it is not sampled by radar or by surface observations at an adequate resolution);
- Uncertainty in *data quality*, e.g.
  - Radar range and velocity dealiasing errors, terrain, and non-precipitation returns may mask the existence of a threat;
  - Bad surface observations or other environmental data errors such as a poor objective analysis scheme for upper-air data may make storm evolution difficult to correctly anticipate.

Uncertainties in data quality usually play into other uncertainties listed above. Although some of these variables are easier to quantify than others, they all are typically taken into account during the warning decision-making process.

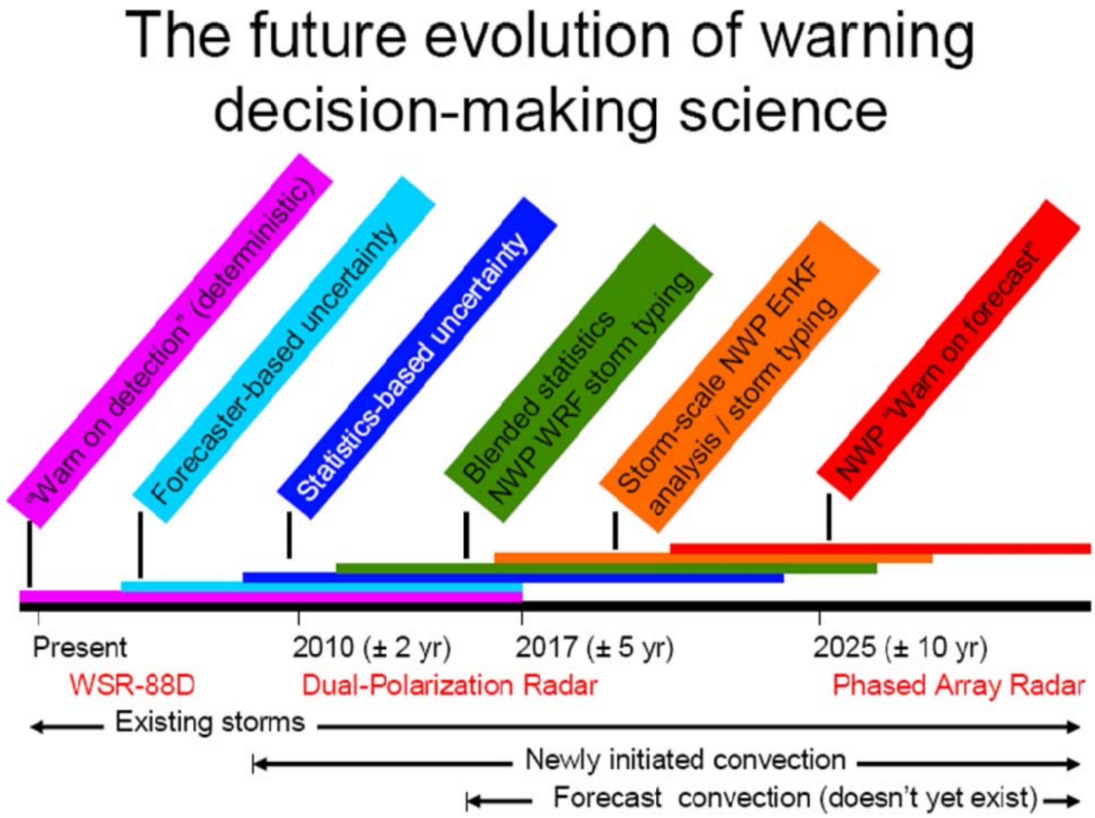

Figure 4: A vision for the development of probabilistic warning guidance techniques based on climatology and mesoscale and storm-scale NWP. The timeline is for illustrative purposes only.

2.c. Vision for the development of a probabilistic "warn on forecast" technique

In 2008, the NWS typically takes a **"Warn on Detection"** approach to issuing warnings, although some NWS offices and forecasters provide additional warning update information to higher level users. The characteristics of a "Warn on Detection" approach are:

- Forecaster identifies threat area (T=0)
- Forecaster projects future motion of threat via extrapolation
- Forecaster may anticipate future evolution
- Threat area is defined by non-translating polygon
- Warnings are deterministic

A first step in the research plan towards developing probabilistic guidance for severe weather threats is to add a mechanism by which forecasters can convey the uncertainty they evaluate when issuing a deterministic warning. The **forecaster estimates the uncertainty** and assigns a probability to it based on their knowledge of past events:

• Forecaster identifies threat area (T=0)

– Assign a probability of threat occurrence to the threat area
– This could initially be deterministic (P = 100%)

• Motion estimate (and error estimates) are either:
  – Made by the forecaster or
  – Computed by an algorithm

• Forecaster may anticipate future evolution by providing a growth and decay curve

• Forecaster updates threat area is every 10-15 minutes with a translating polygon or "threat grid"

The second phase in the development of scientifically sound probabilistic warning guidance tools requires the development of a large, high-resolution dataset of storm types, storm environments, and severe weather validation data. This dataset will enable **statistical estimates of uncertainty** associated with severe weather events based on the climatology of those events:

• Threat area (at T=0) identified by forecaster or automated algorithm
  – Probability of threat assigned to area; probabilities can vary across this area

• Motion estimates and error distribution are automated (forecaster may edit)
  – Statistical or based on a mesoscale ensemble

• Threat growth/decay curves are determined by:
  – Identifying most likely storm type(s)
  – Applying a curve based on a statistical database of historical storms with similar characteristics

• Updated every 10-15 minutes

In the third phase of the project, **mesoscale model ensemble forecasts may be blended with the statistical uncertainty estimates** that are based on climatology:

• Threat growth/decay curves are determined by:
  – Identifying most likely storm types given the storm types in a mesoscale model ensemble

• Longer lead-times
  – Threat areas may be defined (albeit with at lower probability) for storms that do not yet exist
  – Projections of severity from new areas of convective initiation

The next step in the process is to i**ncorporate uncertainty based on storm-scale data assimilation**:

• Analysis data are from EnKF

• Threat growth/decay curves are determined by identifying storm types in a storm-scale model
  – Not yet real-time, but possibly a better estimate of storm type than mesoscale models

- Possible better handling of convective initiation areas

All of the previous steps lay the groundwork for the understanding and interpretation of **storm-scale ensembles and “Warn on Forecast” techniques**:

- Storm-scale model ensembles run every 5-10 minutes to predict future behavior of storms out to 2 hours or more.
- Forecasters interpret:
  - – Analysis
  - – Ensemble forecast in light of the additional information they have available (spotter reports, knowledge of model behaviors compared to reality, etc.)
- Forecasters are still integral to the warning process, but will use different integrated data sets than at present.

3. Probabilistic Warning Guidance Experiment guidelines for Spring 2008

3.a. Goals

The focus of the experiment will be on the *identification of threat areas* and *validating storm behaviors*. Because of the CONUS scale of data available at the Hazardous Weather Testbed, operations can occur on any day with a severe weather threat within the CONUS, minimizing "down days" when severe weather cannot be sampled and providing diversity in storm environment and topography. The facilities at the HWT will allow us to access local data from anywhere in the CONUS. If there are "down days," we may play back archived cases for forecasters to examine. The goals of the experiment are to determine:

a. How well can we identify hazardous weather threats for both human-generated probabilistic warnings and probabilistic algorithm guidance at a small scale (on the order of 10 km)?
b. Can we improve lead time and "time under warning" at specific points via both the downstream advection of warning grids and earlier identification of threats that might not yet warrant a warning under existing NWS warning criteria?
c. Can these ideas improve service to the public?

Forecasters will focus on regions of the CONUS where high-resolution storm verification

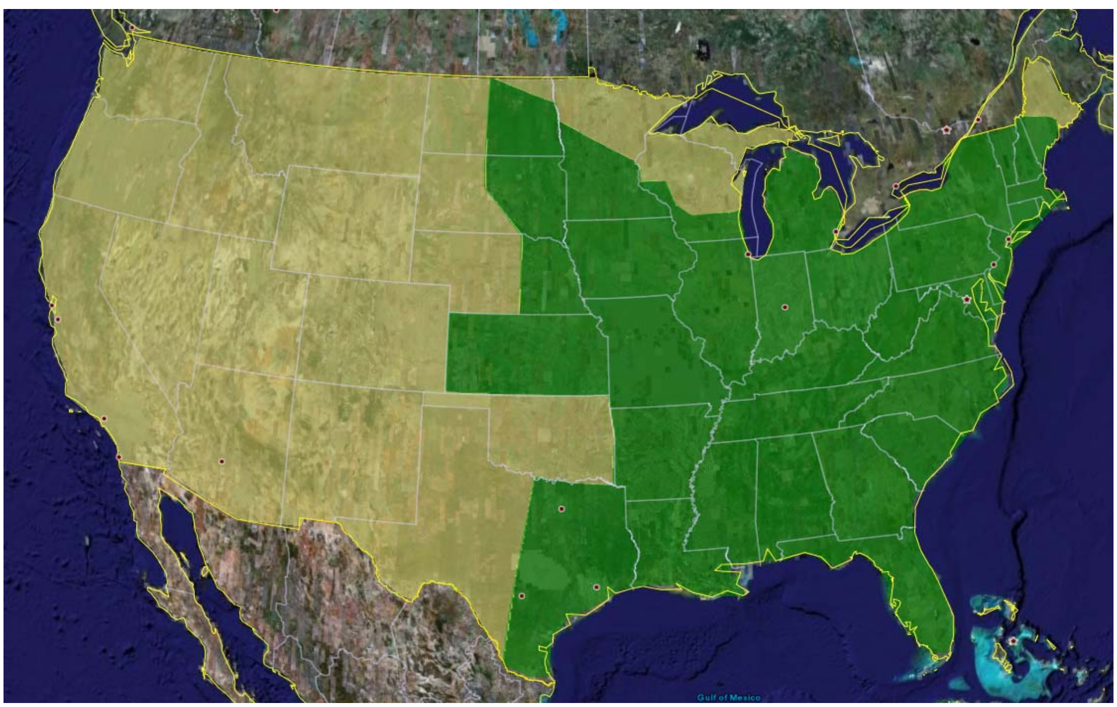

Figure 5: Areas of the CONUS where high-resolution verification data are most likely to be available are shown in green. The areas shown in yellow are likely to only have high-density data available around major cities.

Making a probabilistic warning for a hazard:

1) Identify the types of hazard:
    a. Winds exceeding 50 kts
    b. Hail exceeding ¾"
    c. Tornado
2) For each type of hazard for each storm, identify:
    a. the area of the threat at the current time
    b. Storm motion uncertainty
3) Assign probabilities value to the area or areas:
    a. At current time
    b. At Time T in the future (to give a trend for the threat)
4) Make automated probabilistic forecasts of the behavior of the area.
5) Continuously update the warning grid at 5-10 minute intervals to account for advection and growth / decay of the threat area.
6) Assign expiration time, if known, or cancel the threat if needed.
7) Verify the warnings.

Figure 6: The steps required to make a probabilistic warning.

is possible (Figure 5).

Forecasters, utilizing various operational and experimental data sources, will follow the steps described in Figure 6 to identify hazard areas and will draw a polygon or ellipse that highlights each hazard for a storm or storms. As a baseline (for future comparison), the forecaster will subjectively outline the area where they believe the hazard to be located. The hazard areas will be advected downstream utilizing the automated methods developed by Lakshmanan and Ortega (2007) to create the forecast threat probability grid, which updates every minute to give a swath that moves along with the storm. The forecast threat probability grid will advect until the threat is considered ended (either via an expiration time or manual cancellation). Forecasters will regularly update the threat areas to account for changes in the threat area and changes in storm evolution.

3.b. Operational Environment and Duties

Each Intense Operations Period (IOP) will last approximately three hours. Forecasters may work in teams of one to three, sharing the following tasks:

- identifying new, developing threat areas;
- assign probabilities of tornado, hail, and wind to the threat areas;
- maintaining and updating ongoing threat areas at least once every 15 minutes;
- maintaining situational awareness for the mesoscale environment;

The Cognizant Scientist role is to ensure that the experiment runs smoothly, specifically:

- Ensure the forecasters are following warning generation guidelines;
- Collaborate with SHAVE, which will attempt to verify the warnings with very high density reports;
- Note-taking for each warning update (via "live blogging" on the EWP blog).

The tools that are at the disposal of the forecaster team include:

- WDSSII multi-sensor data fields (2-4 machines) & single radar base data analysis tools;

- A non-baseline AWIPS workstation;
- Web access;
- Enhanced Verification for SHAVE / spotternetwork.org;
- Situational Awareness Display – web streams from across the US, regional Mesoscale analysis graphics;
- Google Earth radar displays.

3.c. Guidance for drawing threat areas

You are to identify the area of the storm where the threat is possible, either at the current time or in the near future (up to 60 minutes). The probability of a threat is not necessarily tied to the intensity of the threat. As you initially define or update a threat area, please input whether or not you would have issued a warning for the specific threat under the current NWS guidelines for issuing warnings. You are encouraged to identify areas where you believe threats may be developing but that may not qualify for a warning yet under current NWS criteria. As you provide the initial conditions for the threat area, an automated process runs in the background and will update the projected storm threat area at future time intervals.

The following guidelines are for the Warning Contours interface.

There are three types of threats that the project is focusing on in 2008. For examples of how to draw polygon contours around each of these, please see the accompanying slideshow. Some initial guidelines are:

- Tornado
  - In a supercell (isolated or embedded in a quasi-linear system), please encircle the mesocyclone area with ~ 5km radius ellipse.
  - In a QLCS or Landspout situation, encircle the region of the threat with a similar ellipse or polygon.
- Hail > ¾”
  - Draw a polygon contour that encompasses the edge of the core aloft and the low-altitude 55 dBZ core.
- Wind > 50 kts
  - Damaging straight-line winds are difficult to identify with remote sensing instruments, and are also difficult to verify. However, we will attempt to identify threats from bow echoes, supercell rear-flank downdrafts, and microbursts from pulse storms as they present themselves.
  - Please draw these polygons relative to the scale of the wind threat.

In the polygon editor interface, you will need to adjust the following items:

Warning Length:

- Use the default length of 60 minutes, unless there is a good reason to choose another time. For instance:

- If it is expected to be long-tracked, you may with to issue a warning with a longer duration;
- If the storm is dying, you may wish to shorten the length.

Motion Direction / Speed:

- Use the storm motion tool to choose a motion by tracking the region of interest back in time 15 minutes or so (extrapolation);
- The storm motion / speed can optionally be set with the slide bar.

Motion Direction / Speed Uncertainty:

- What is the uncertainty in storm motion?
  - Could be larger for slowly evolving “pulse” storms than for storms in a strong flow regime;
  - Splitting supercells could have a large directional error.

Initial Probability

- What is the probability that the threat exists somewhere in the polygon at the current time? If the threat is developing, this is typically a non-zero number. If the threat is ongoing (e.g. a spotter is reporting a tornado on the ground), then the initial probability will be high.

Peak Probability and
Peak Probability Time

- These parameters are used to describe if the trend of the threat is increasing or decreasing in time.
- If you believe that the threat type is increasing (decreasing) from the initial time, then you should enter the time at which you believe the threat will peak (minimize) as well as the highest (lowest) probability. This is a linear trend.

Probabilities

- Always use “By Time” (default)

Buffer (miles)

- This is the radius around the forecaster-identified threat area that the probabilities drop to some negligible value.
- Leave this set at the default of 3 miles (~ 5 km), unless there is a good reason to modify the radius (and discuss it with the Cognizant Scientist).

Save Time:

- Simulation Time (time stamp at the top-left of the display),
- System Time, or
- Time of a specific product.

NWS Warning?

- If you were in an NWS operational setting, would you issue a Tornado Warning or a Severe Thunderstorm Warning for this storm at the time you drew the polygon?

Software documentation may be found with the accompanying slideshow.