Exploring Applications of Storm-Scale Probabilistic Warn-on-Forecast Guidance in Weather Forecasting

Katie A. Wilson[1,2(✉)], Jessica J. Choate[1,2], Adam J. Clark[2], Burkely T. Gallo[1,3], Pamela L. Heinselman[2], Kent H. Knopfmeier[1,2], Brett Roberts[1,2,3], Patrick S. Skinner[1,2], and Nusrat Yussouf[1,2]

[1] Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman, OK 73072, USA
Katie.Wilson@noaa.gov

[2] NOAA/OAR National Severe Storms Laboratory, Norman, OK 73072, USA

[3] NOAA Storm Prediction Center, Norman, OK 73072, USA

Abstract. The National Oceanic and Atmospheric Administration National Weather Service is responsible for issuing watches, warnings, and other forecast products related to hazardous weather. These products are intended to reach end users including government organizations, the media, emergency managers, and the public, such that decisions can be made to protect life, property, and the national economy. However, discontinuities currently exist in the guidance available to forecasters and in the products that are issued. Therefore, the NOAA Warn-on-Forecast program is developing and testing a convection-allowing ensemble analysis and prediction system. This system provides 0–6 h probabilistic forecast guidance for individual thunderstorms between the Watch and Warning timeframe. In addition to focusing research efforts on the development and testing of the Warn-on-Forecast system, a group of scientists are working closely with the weather forecasting community to establish ways in which Warn-on-Forecast guidance can be most useful during real-time operations. Two primary research questions being explored are: (1) How do meteorologists perceive, interpret, and understand Warn-on-Forecast guidance? (2) How can Warn-on-Forecast guidance be applied in the operational environment to enhance the forecast process? Research undertaken to address these two questions will be discussed.

Keywords: Probability · Forecast · Thunderstorm

1 Introduction

In the United States, the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) is tasked with providing timely weather, water, and climate information that will protect life and property and enhance the national economy [1]. Most weather forecast information originates with the National Centers for Environmental Prediction, which is comprised of nine separate centers. Each center monitors and provides environmental predictions for various weather phenomena

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across the United States. Additionally, many of these centers issue products to alert others to the possibility of impending hazardous weather. For example, as well as providing Convective Outlooks, the Storm Prediction Center assesses a variety of forecast guidance (e.g., the Global Forecast System model, High-Resolution Rapid Refresh model, and High-Resolution Ensemble Forecast system) to issue tornado and severe thunderstorm Watches. These products are issued typically hours ahead of when hazardous weather is expected to occur and for a broader area than what is usually impacted.

In addition to the national centers, 122 local Weather Forecast Offices (WFOs) provide localized short-term forecasts, advisories, warnings, and statements for their designated county warning area. In the case of a severe thunderstorm or tornado event, the local WFO is responsible for issuing warnings to alert their local community of the impending threat. Forecasters at local WFOs depend heavily on observations (e.g., radar and storm spotter reports) to make warning decisions about the real-time weather scenario. Warnings are typically issued minutes prior to when severe weather occurs, are valid for less than one hour [2], and cover a more specific area than what a Watch may have encompassed earlier in the day.

It is common for many hours with little or no official hazard guidance to occur between the issuance of a Watch and Warning. However, many important weather-related decisions are made by members of the general public and community officials during these hours. Therefore, a need exists for regularly updated information about the evolving weather scenario during the several hours that precede hazardous weather. Furthermore, enhancements to the current deterministic (yes/no) warning system are required to effectively communicate the evolving uncertainty of a weather event such that users of this information can make weather-related decisions according to their specific risk thresholds [3].

The need for a more continuous flow of probabilistic weather information across a broad range of temporal and spatial scales has been discussed at length over the past several years during the framing of NOAA's Forecasting a Continuum of Environmental Threats (FACETs) paradigm [4]. The FACETs paradigm describes seven stages of the forecast process that together encompass physical, social, and behavioral scientific challenges (Fig. 1). Although this paradigm is designed to address a wide variety of environmental threats, many of these challenges are first being explored within the context of severe weather. Furthermore, to date, much of the FACETS-related research effort has focused on demonstrating, testing, and evaluating methods and ideas at the warning scale. For example, during a series of studies at the NOAA Hazardous Weather Testbed in Norman, Oklahoma, a team of researchers have investigated NWS forecasters' use of probabilistic hazard information (PHI) within a new web-based prototype warning system for communicating the threat of severe weather [5]. Integrated warning teams have also been used to learn about applications of forecasters' PHI-driven guidance (in place of traditional deterministic warnings) to emergency managers' and broadcast meteorologists' decision making [5–7]. While this work will continue to evolve, efforts to explore the application of the FACETs paradigm at larger temporal and spatial scales is necessary. With respect to the NOAA Warn-on-Forecast program, these efforts are already underway.

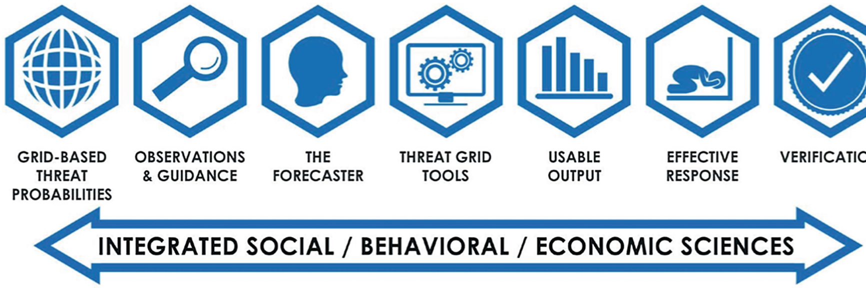

Fig. 1. The seven components of the FACETs forecast process [4].

2 Warn-on-Forecast

The NOAA Warn-on-Forecast program is tasked with developing and testing a convective-scale ensemble analysis and forecast system that can provide probabilistic short-term guidance for individual thunderstorm hazards [8, 9]. While many sources of observations and guidance already exist within the NWS (e.g., radar, satellite, surface observations, models), advancements in numerical weather prediction have led to an increasing availability of real-time high-resolution forecast models capable of partially resolving convective storms known as convection-allowing models (CAMs) [10, 11]. More specifically, the NOAA Warn-on-Forecast program has led the development of a prototype CAM system. This system is currently in a testing phase and continues to evolve.

Unlike other CAMs, the Warn-on-Forecast system provides on-demand, rapidly-updating, short-term probabilistic forecast guidance for a variety of weather threats associated with individual convective storms. Technical descriptions and demonstrations of this system are available in several recent publications [12–15]. Warn-on-Forecast guidance is generated in an on-demand basis for a regional forecast domain (approximately 900 km $\times$ 900 km with 3-km horizontal grid spacing) within the Watch-to-Warning timeframe (0–6 h). Guidance from national centers is used to identify the most appropriate forecast domain, such as the Day 1 Convective Outlook from the Storm Prediction Center and the Day 1 Excessive Rainfall Outlook from the Weather Prediction Center (Fig. 2).

When run in experimental real-time settings, the Warn-on-Forecast system has provided 3-h probabilistic forecasts every 30 min (for severe hazards) or 6-h probabilistic forecasts every hour (for heavy rainfall and flash flooding). Guidance products from these forecasts are produced every 5-min during the forecast period, which enables detailed observation of the predicted storm evolution. A wide range of forecast products have been developed for operational use. These products include both environmental and storm-specific products. While the environmental products are similar to output from other CAMs, the storm-specific products provide probabilistic predictions of different hazards within individual thunderstorms. For example, guidance on the rainfall intensity and rotational characteristics of thunderstorms is provided using simulated radar reflectivity and updraft helicity [16], respectively. The distribution of

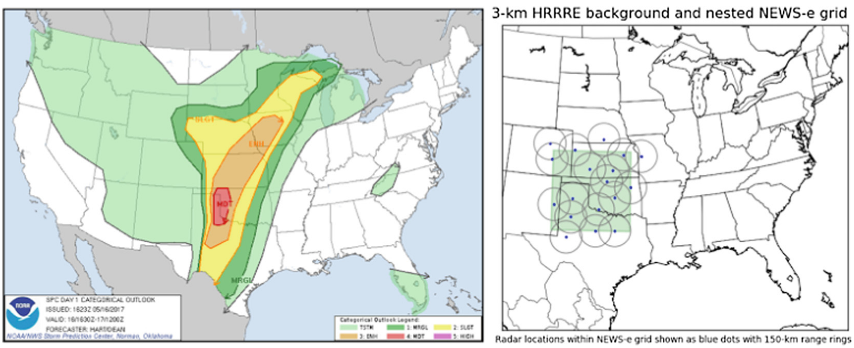

Fig. 2. The Storm Prediction Center Day 1 Convective Outlook for 16 May 2017 provided guidance for the placement of the Warn-on-Forecast domain, which is indicated by green shading in the right panel. (Color figure online)

forecast solutions provided by the 18-member ensemble allows for the generation of probabilistic products tailored to specific forecast problems. For example, the likelihood and severity of a predicted hazard may be assessed using probability of exceedance or percentile products. Additionally, ensemble guidance may be viewed similarly to deterministic forecasts using products such as the probability matched mean [17, 18], or paintball plots [19]. More recently, verification products using radar-derived proxies for severe thunderstorm hazards have been added for real-time assessment of forecast performance.

A Warn-on-Forecast web interface was created to view the forecast products (Fig. 3). This website has been through many iterations of improvement based on users' feedback and is designed to enable users to rapidly access and interrogate real-time guidance. The core web interface capabilities include: viewing both real-time and archived forecasts, navigating different forecast times, viewing a variety of ensemble forecast products, scrolling through the 5-min increments of each forecast product, and accessing individual ensemble member forecasts. The web viewer is used both in research and by operational meteorologists who may wish to access the guidance in real time and apply it experimentally to their forecast process.

In addition to the creation of a web viewer, a web-based forecast drawing tool was developed so that users can both view and interact with data from CAM ensemble forecast systems (Fig. 4). This tool was designed to support the transition of CAM ensemble systems from experimental to operational status [19], and has been used heavily in the NOAA Hazardous Weather Testbed Spring Forecast Experiment [20, 21]. The drawing tool allows forecasters and other research participants to draw polygons representing hazard probability thresholds over the model data and issue experimental forecasts. These experimental forecasts are prototypes representing the types of products which may be issued by the NWS Storm Prediction Center in the coming years. The tool also allows users to view, compare, and verify forecasts from multiple CAMs and CAM ensembles, including the prototype Warn-on-Forecast ensemble system.

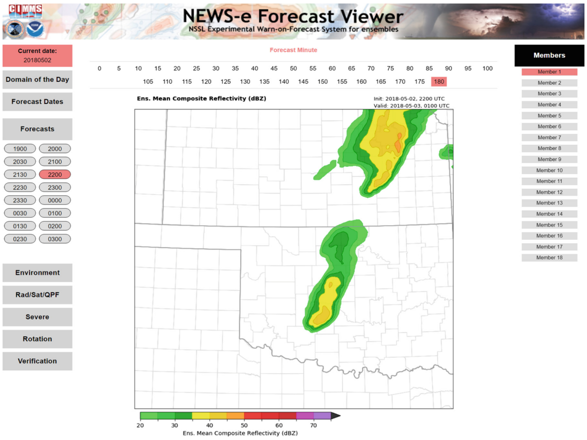

Fig. 3. The Warn-on-Forecast web viewer, which can be accessed at wof.nssl.noaa.gov.

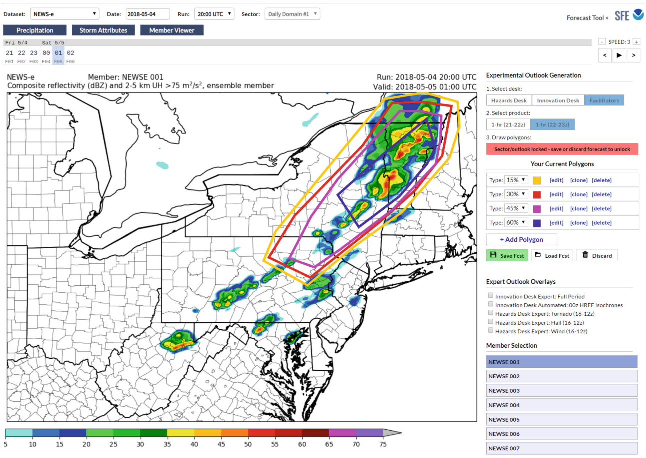

Fig. 4. Web-based forecast drawing tool for viewing and interacting with CAM ensemble forecast systems.

3 Perceptions and Interpretations of Warn-on-Forecast Probabilistic Guidance

3.1 Meteorologist Survey

In addition to investing research efforts into the development of a Warn-on-Forecast CAM ensemble system and suitable viewing tools, studies have been crafted to explore users' perceptions and interpretations of Warn-on-Forecast guidance. This area of research is also an identified challenge in the FACETs paradigm, such that social and behavioral understanding of how weather forecasters interpret and use probabilistic guidance must be investigated [4]. Plenty of research exists for examining how the general public make sense of and use probabilistic information [22–24], but not as much attention has been given to the assumed expert user, the meteorologist. Despite this lack of research, numerous reports and research studies have identified the potential benefits of incorporating uncertainty information into the forecast process and recommend moving towards a probabilistic operational framework [25–27].

To begin developing a social and behavioral understanding of how meteorologists perceive and interpret Warn-on-Forecast guidance, a survey was issued to participating meteorologists and atmospheric scientists during the 2017 NOAA Hazardous Weather Testbed Spring Forecasting Experiment [28]. This survey presented 62 participants with a series of multiple-choice and open-ended questions designed to measure how they perceive and interpret storm-scale ensemble-based forecast guidance. Many of the questions required the respondents to view, understand, and extract relevant information from graphics. In particular, these questions tested meteorologists' understanding of probability and percentile concepts.

Overall, respondents' answers were encouraging, with correct answers provided between 60%–96% of the time for different questions. However, respondents' depths of understanding and abilities to think beyond a deterministic mindset varied drastically in some questions. For example, the first question presented the respondents with a forecast representing the probability of accumulated rainfall exceeding 0.01 in. (Fig. 5). Respondents were asked to describe what type of weather event this graphic depicted. Many of the respondents correctly inferred that the graphic depicts a widespread area, with some isolated regions having a greater than 90% probability of exceeding 0.01 in. of rainfall between 0000 UTC and 0130 UTC. However, approximately one third of the participants incorrectly tried to infer the severity of the rainfall event. Other respondents tried to explain the forcing mechanisms responsible for the rainfall or the storm mode, neither of which can be confirmed using this graphic.

Being able to recognize what information Warn-on-Forecast products provide and how they can be used to draw conclusions is a skill that was not consistently applied among the 62 respondents. The survey findings [28] include instances when respondents were unable to report on the uncertainty aspect within a question when it was called for, and by comparison, inferred uncertainty when the graphic did not support it. Respondents also demonstrated an inconsistent application of knowledge, such that conceptual understanding of Warn-on-Forecast products varied depending on familiarity with the meteorological variable being presented. This finding demonstrates the importance in ensuring the user understands how products are calculated. Additionally, respondents displayed a tendency to focus on the worst-case scenario when presented with a combination of probabilistic and percentile representations of meteorological variables. These findings provide a base level understanding of the current strengths and gaps in meteorologists' knowledge of storm-scale ensemble guidance, and will form the basis for training recommendations that will soon be tried and tested among other meteorologists.

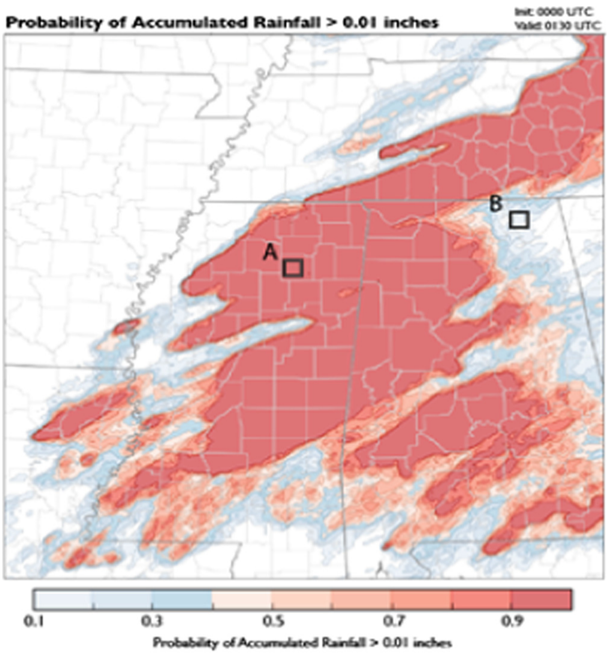

Fig. 5. Probability of accumulated rainfall exceeding 0.01 in. [28].

3.2 Spring Forecast Experiment

The NOAA Hazardous Weather Testbed Spring Forecast Experiment provides opportunities to present new data and products in front of operational and research meteorologists. These participants provide invaluable testing, evaluation, and feedback that help to improve and guide future research and development [10, 20, 21]. During the five-week 2018 Spring Forecasting Experiment, all attendees were provided with a one-hour training session on their first day that introduced Warn-on-Forecast and gave an overview of the task they would participate in during the rest of the week. This task assigned participants to one of two groups. Each group had approximately four participants and efforts were made to balance forecasting expertise between them. During each afternoon, the two groups each worked with a facilitator to view Warn-on-Forecast guidance, and collectively issue severe weather outlooks for two, 1-h periods, then update the outlooks when new Warn-on-Forecast guidance became available. These outlooks identified areas with contours of varying probability for experiencing severe weather during the valid 1-h period. An example of a 1-h severe weather outlook is shown in Fig. 4. Survey questions were designed to learn about forecasters' use, understanding, and attitudes about Warn-on-Forecast guidance while participating in this activity.

Participants' use of Warn-on-Forecast guidance was analyzed by tracking each group's product usage. The data collected provided information on the most popular products used to create outlooks each day. The most used product, regardless of which group participants were assigned to or what day they were forecasting for, was paintball plots. This product plots the location of all ensemble members (in different colors) that exceed a threshold value for a particular variable. Paintball plots allow for the visualization of model uncertainty, such that users can assess the location and extent of overlap of the 18 ensemble members. This deterministic assessment differs to viewing overall probabilistic information. The next four preferred products, in order of most to least requested, were for assessment of: hail (probabilistic), composite reflectivity (probabilistic), environment (deterministic), and individual member viewers (deterministic).

All 1-h severe weather outlooks were verified the next morning using the local storm report driven practically perfect method [29]. The reliability diagrams (Fig. 6), while only measuring one aspect of forecast quality, show that Group 1 performed slightly better than Group 2 (although overall both groups provided skillful forecasts). One explanation for this result is that Group 2's forecast outlooks covered a broader area than Group 1's forecast outlooks. Therefore, while Group 2 forecasted for more areas impacted by severe weather than Group 1, their forecasts also encompassed a larger false alarm area. Furthermore, when comparing all preliminary and updated outlooks for both groups combined, the preliminary outlooks verified slightly better. This finding was unexpected, since the updated outlooks used more recent Warn-on-Forecast guidance and participants' satisfaction ratings of their team's outlook tended to improve slightly for the updated outlook compared to the preliminary outlook. As can be seen in Fig. 6b, this slight degradation in reliability occurred for higher probability thresholds, and therefore it is possible that participants were operating with higher levels of confidence. Further research needs to assess what and why modifications are made to the outlook after receiving the latest Warn-on-Forecast guidance, and in what instances they benefit the outlook.

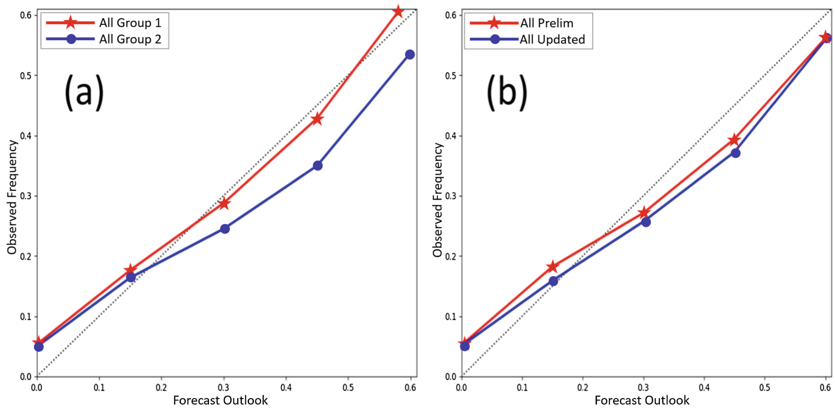

Fig. 6. Reliability diagrams for (a) Group 1 and Group 2 outlooks and (b) combined Group 1 and Group 2 preliminary and updated outlooks.

3.3 Hydrometeorology Testbed

The potential applications of Warn-on-Forecast guidance for the prediction of heavy rainfall and flash flooding events is also being explored within the NOAA Hazardous Weather Testbed [30]. For the first time in 2018, nine NWS forecasters evaluated probabilistic flash flood products to examine how the inclusion of 3-h Warn-on-Forecast quantitative precipitation forecasts (QPFs) affected forecasters' understanding of a possible flash flooding event. Forecasters reported on their perceptions of the flash flooding risk, where they chose to prioritize attention, and what they expected their subsequent action would be if in real-time operations (e.g., issuing a warning or statement).

Early analysis of forecasters' feedback from one scenario indicated that access to Warn-on-Forecast QPF driven guidance increased the area forecasters attended to from 2.8 counties per hour to 5.2 counties per hour. The additional areas attended to were mostly associated with the first 2 h of the 3-h Warn-on-Forecast QPF driven guidance. This heightened awareness of potential downstream impacts resulted in most participants keying into the region that later experienced flash flooding several hours earlier than when Warn-on-Forecast was not used. Furthermore, when comparing participants' expected actions, several warning decisions were made 2–3 h earlier and a handful of participants began communicating the potential threat to officials a few hours earlier also.

The findings from the early analysis of the 2018 study suggest that the use of Warn-on-Forecast QPFs in hydrologic modeling will be beneficial to the forecast process. To further explore these benefits, a follow-on study in the 2019 hydrometeorology testbed will evaluate use of Warn-on-Forecast for flash flood prediction in simulated real-time operations, such that forecasters will view data and issue products like they would in the real world, and their actions will be compared to the decisions that forecasters made during the actual event.

4 Operational Applications

In addition to investigating uses of Warn-on-Forecast in controlled settings such as the NOAA Hazardous Weather Testbed, experimental demonstrations within operational settings have also been conducted. These demonstrations are made possible through collaborative efforts with NWS offices, such that forecasters integrate the probabilistic Warn-on-Forecast guidance into real-time decision making and later provide feedback on whether the guidance was useful and why, in what way it was applied, and how it can be improved for future uses. Below are some examples of these operational demonstrations with NWS National Centers and local forecast offices.

4.1 National Centers

The NOAA NWS's Weather Prediction Center is responsible for providing forecasts and guidance for high-impact precipitation events. In particular, the Met Watch desk at the Weather Prediction Center monitors the potential for heavy rainfall and flash flood events, and issues Mesoscale Precipitation Discussions (MPDs) that indicate the likelihood of flash flooding should the threat exist over approximately two county warning areas during a 1–6-h period. The regional and short-term aspects of this forecast product make Warn-on-Forecast a potentially useful source of guidance for Met Watch responsibilities. Therefore, following a collaborative visit in which scientists learned about Met Watch forecasters' workflow, provided training on the Warn-on-Forecast concept, and introduced the web viewer, Met Watch forecasters agreed to use Warn-on-Forecast guidance experimentally in real time and provide feedback using a survey designed by both the scientists and the lead Met Watch forecaster.

Feedback from five Met Watch forecasters provided over 24 different weather events gave insight into when Warn-on-Forecast both did and did not positively impact their forecast process. In total, forecasters reported Warn-on-Forecast as benefiting their forecast process for 15 of the 24 events, of which MPDs were issued for nine events. Qualitative feedback described Warn-on-Forecast as being useful for determining the placement, timing, and persistence of heavy rainfall. This information supported forecasters' conceptual models and provided confidence in deciding the spatial extent, duration, and wording of MPDs. For example, on 20 July 2018, a Met Watch forecaster observed an organized convective event in the Upper Ohio Valley (Fig. 7). The Warn-on-Forecast guidance brought attention to where backbuilding and repeated convection would occur, and provided confidence that the wording "flash flooding likely" was justified. The forecaster also viewed that the early model runs were verifying well against observations, which encouraged him to weight the Warn-on-Forecast guidance more heavily in his decision-making process. In the six instances in which Warn-on-Forecast was useful but MPDs were not issued, forecasters reported that the guidance confirmed the lack of convective coverage and provided confidence that an MPD was not needed.

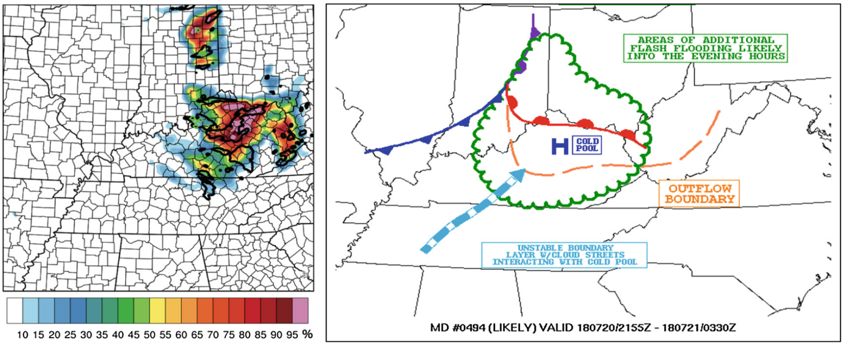

Fig. 7. (Left) Warn-on-Forecast 6-h rainfall probabilities >1 in. verified with the National Center for Environmental Prediction Stage IV 6-h rainfall probability >1 in. (black contours). (Right) The MPD issued on 20 July 2018, indicating the area where flash flooding is likely. Later in the evening, numerous flash flood warnings were issued in this area and local storm reports were received.

Warn-on-Forecast was not found to benefit the forecast process for nine of the 24 events reported. Of these events, MPDs were issued for seven events. Forecasters' feedback described both model limitations and logistical limitations as reasons why. For example, in some instances the Warn-on-Forecast guidance was slow to initiate organized convection or it did not match observations. Therefore, the guidance did not aid the forecast process and observations were relied on to make real-time decisions. In other instances, the guidance was either unexpectedly unavailable or the forecaster coming on shift did not have adequate time to assess all model guidance before issuing urgent MPDs. For the two events in which the guidance was not helpful nor did forecasters issue MPDs, they simply reported that there was not sufficient convection in the area to be concerned about flash flooding.

The Warn-on-Forecast group is also beginning to work with the NOAA Storm Prediction Center to explore utility of this guidance for severe convective weather prediction. Similarly to the MPDs issued by the Weather Prediction Center, the Storm Prediction center issues Mesoscale Discussions (MDs) on severe thunderstorm hazards and winter precipitation. These MDs often cover a similar or smaller area than a Watch, and include information about current observational trends and short-term guidance such as that provided by the Warn-on-Forecast system. Currently, the Warn-on-Forecast system has been used informally when available within the Storm Prediction Center, and its guidance was used in the issuance of an MD related to the tornado threat from Hurricane Florence. Moving forward, the guidance will be used in simulated real-time forecaster training activities, to give all Storm Prediction Center forecasters increased familiarity with the system and the effects of the rapid update cycles. Efforts are also underway to engage scientists and Storm Prediction Center forecasters more closely, including shadowing activities and co-development of guidance for the time period within the Watch to Warning scales. Finally, the system will be available in real-time to forecasters during the peak spring severe convection season, to help them refine their probabilistic forecasts and identify corridors of heightened risk.

4.2 Local NWS Forecast Offices

Given the co-location of federal, university, and operational partners at the National Weather Center, scientists have worked closely with the Norman WFO to experimentally explore applications of Warn-on-Forecast guidance within the Watch-to-Warning timeframe. On 16 May 2017, the Norman WFO used this guidance to assess the increasing tornado threat. After viewing notably high values of 2–5 km updraft helicity (a measure of mesocyclone intensity), the Norman WFO decided to issue a Significant Weather Advisory to indicate a "high probability that tornado warnings will be issued." Sharing expectations for later warning activity is very unusual, and represents the potential enhancements in weather threat communication that Warn-on-Forecast could provide to the traditional Watch and Warning products (Fig. 8).

The Norman WFO continued to use Warn-on-Forecast experimentally during the 2018 severe weather season, and further demonstrated enhanced messaging between the Watch and Warning products on 2 May 2018, when a forecaster disseminated five graphics to their official social media accounts as the event evolved (Fig. 9) [31]. These graphics provided greater specificity in the timing, location, and type of weather

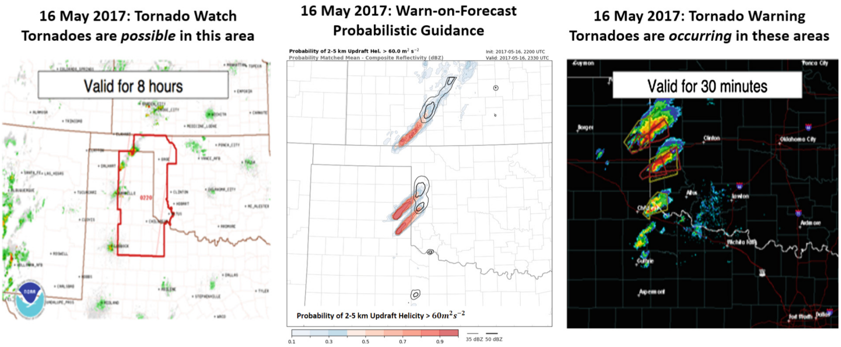

Fig. 8. Warn-on-Forecast guidance was provided for the temporal and spatial scales that span between the Watch and Warning products issued on 16 May 2017.

hazards expected than what the Watch provided, and were primarily based on the ensemble 90th percentile value of 2–5 km updraft helicity product. During this event, the forecaster was focused initially on the severe weather threat. As storms evolved and the Warn-on-Forecast guidance suggested an increasing likelihood of tornadoes, the forecaster switched the focus of the graphics to emphasize the tornado threat. In the final graphic, the storm system had grown upscale from supercellular storms into a mesoscale convective system, and the forecaster communicated the continued threat for possible hail, wind, and brief tornadoes. These graphics were issued spontaneously and were not based on learned best practices. Therefore, many questions remain regarding what the most effective methods are for translating and disseminating Warn-on-Forecast guidance to the general public as well as to official community members.

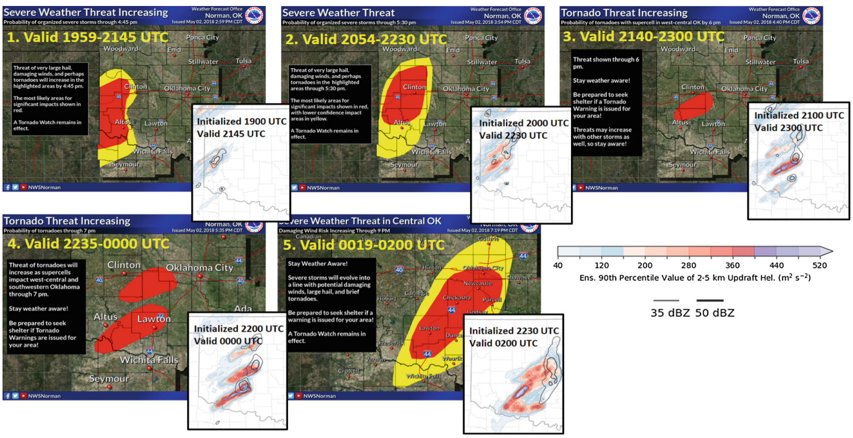

Fig. 9. Graphics issued by the Norman WFO during 2 May 2018 weather event in Oklahoma. The inset boxes show the Warn-on-Forecast product primarily used to create these graphics: the ensemble 90th percentile value of 2–5 km updraft helicity.

In addition to working with the Norman WFO, scientists have collaborated with the Topeka WFO to learn about their experimental use of Warn-on-Forecast guidance during real-time operations. On 1 May 2018, forecasters from this office reported that Warn-on-Forecast guidance provided "critical information to refine the spatiotemporal precision of forecast information pertaining to severe thunderstorm and tornado threats across the NWS Topeka county warning area." This guidance influenced forecasters to provide high-confidence messaging of severe and tornado threats in Enhanced Short-term Weather Outlooks. As can be seen in the ensemble 90th percentile values of 2–5 km updraft helicity (Fig. 10), Warn-on-Forecast identified a location favorable for tornado development, and as the model runs approached valid time, the guidance homed in on the location where an EF-3 tornado occurred. Furthermore, forecasters from the Topeka WFO reported that not only did Warn-on-Forecast guidance alert them to the most intense storms, but it also accurately predicted the weakening of other storms. Together, this information aided forecasters in assessing expectations for how this event would evolve.

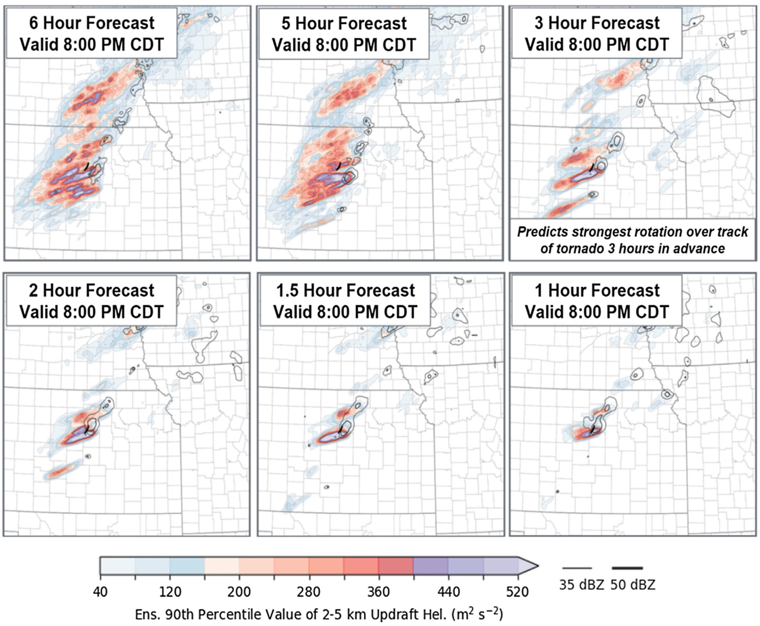

Fig. 10. Warn-on-Forecast ensemble 90th percentile value of 2–5 km updraft helicity for forecast hours preceding an EF-3 tornado in Culver, KS on 1 May 2018. The bold black line indicates the EF-3 tornado track.

4.3 Aviation

The short-term probabilistic forecast guidance provided by Warn-on-Forecast for individual storm hazards has potential to benefit the aviation community for air traffic planning. Assessment of numerous Warn-on-Forecast products can help determine the likelihood for storms growing upscale, their location, mode, and intensity, potential areas of dissipation, expected cloud top heights and cloud base heights, and the most likely types of weather hazards (e.g., hail, wind, or tornado). Use of this guidance may help determine feasible flight routes based on the extent of convection and potential gaps in coverage between storms.

An informal first demonstration of how Warn-on-Forecast guidance can aid decision making within the aviation community occurred on 12 May 2018. The Federal Aviation Administration (FAA) Air Traffic Control System Command Center used Warn-on-Forecast to guide decisions regarding possible severe weather in the northeast United States. The aviation meteorologist viewed paintball plots of 45-dBZ composite reflectivity to assess the expected location of storms, and reported that the guidance "pretty much nailed the solid line over MD/DE," and although the forecast members over MD/PA were not in as good consensus, they felt that "there was lots of value in seeing the spread." The meteorologist used this information to justify including this line of convection when issuing a Traffic Flow Management Convective Forecast (TCF) (Fig. 11).

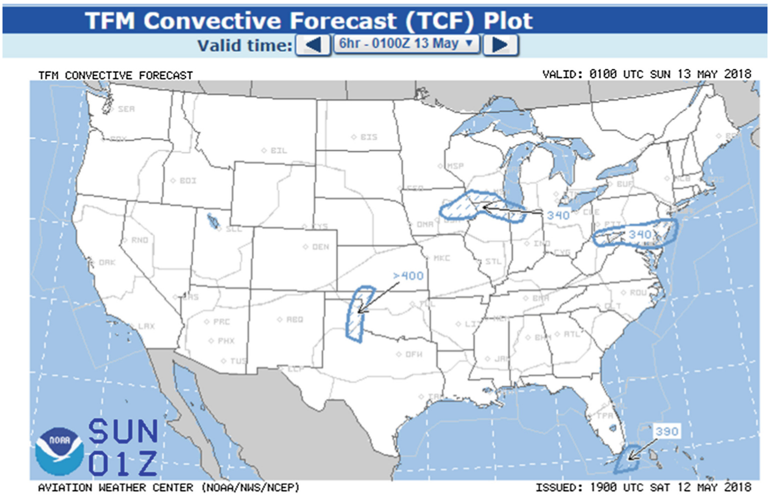

Fig. 11. The Traffic Flow Management Convective Forecast issued at 1900 UTC on 12 May 2018. Inclusion of the northeast corridor was justified by Warn-on-Forecast guidance.

5 Summary

The Warn-on-Forecast program is working to develop short-term probabilistic guidance for individual thunderstorms. No other guidance on this spatial and temporal scale currently exists. The goals of Warn-on-Forecast support the FACETs vision of providing a more continuous flow of probabilistic hazard information for various environmental threats, specifically between the temporal and spatial scales typical of a Watch and a Warning. Initial testing of the Warn-on-Forecast concept has been conducted in experimental conditions, through surveys, and in operational centers and local offices. This initial testing is crucial for obtaining early feedback on the strengths and limitations of the system, and is planned to continue in the coming years. In addition to exploring operational applications of Warn-on-Forecast, other research questions that need to be addressed include: how to visualize and interact with Warn-on-Forecast guidance in order to maximize forecaster experience; what types of real-time verification metrics are useful to the forecast process; how forecasters in National Centers and local WFOs should best work together to utilize the Warn-on-Forecast guidance; how forecasters can effectively communicate and disseminate Warn-on-Forecast guidance to stakeholders and the general public.

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