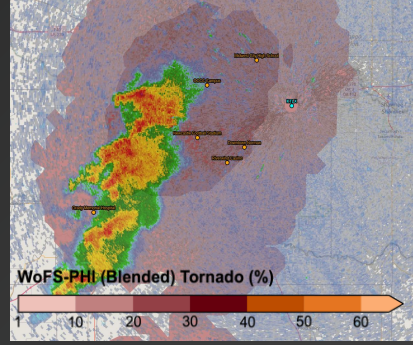
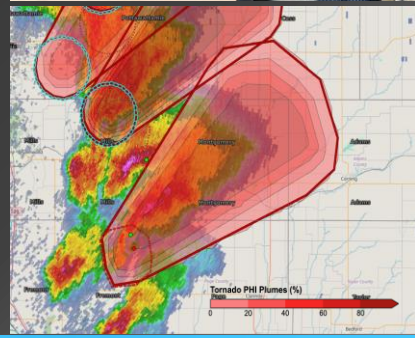
Improving the watch-to-warning space with Probabilistic Hazard Information and the Warn-on-Forecast System

Presenting: Drs. Eric Loken and Kristin Calhoun

With contributions from: Miranda Silcott, Thea Sandmael, Adrian Campbell, Rebecca Steeves, Claire Satrio, Ryan Martz, David Hogg, T. Galarneau, P. Skinner, J. Monroe, J. Madden, P. Burke, K. Berry, T. Lyza

NOAA/National Severe Storms Laboratory & University of Oklahoma/CIWRO

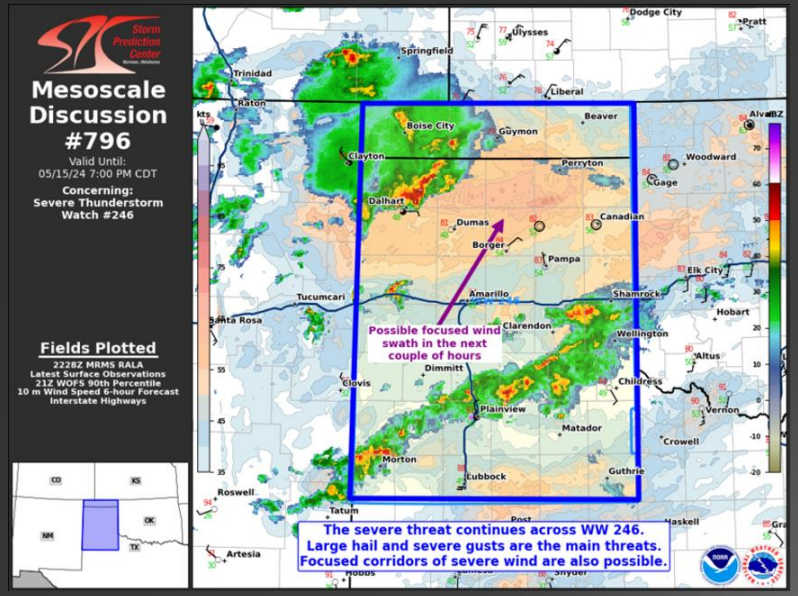




How to best handle the watch-to-warning space is not well understood

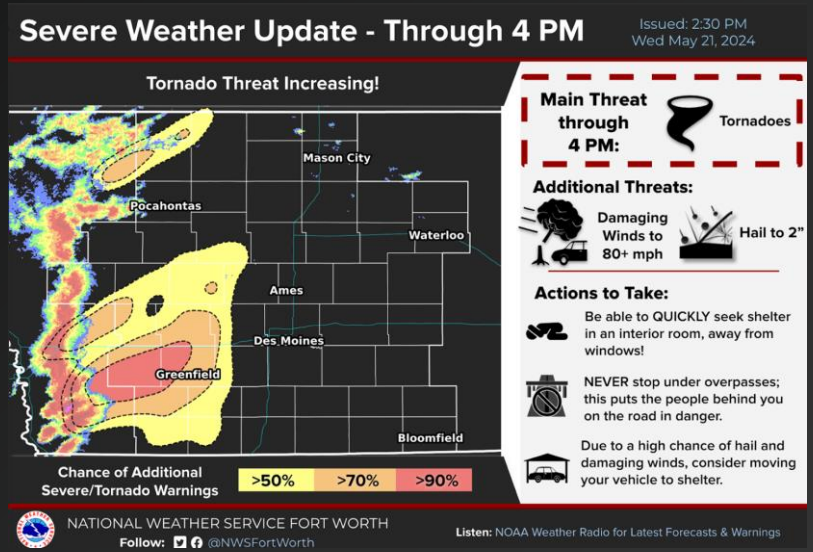
How to best handle the watch-to-warning space is not well understood

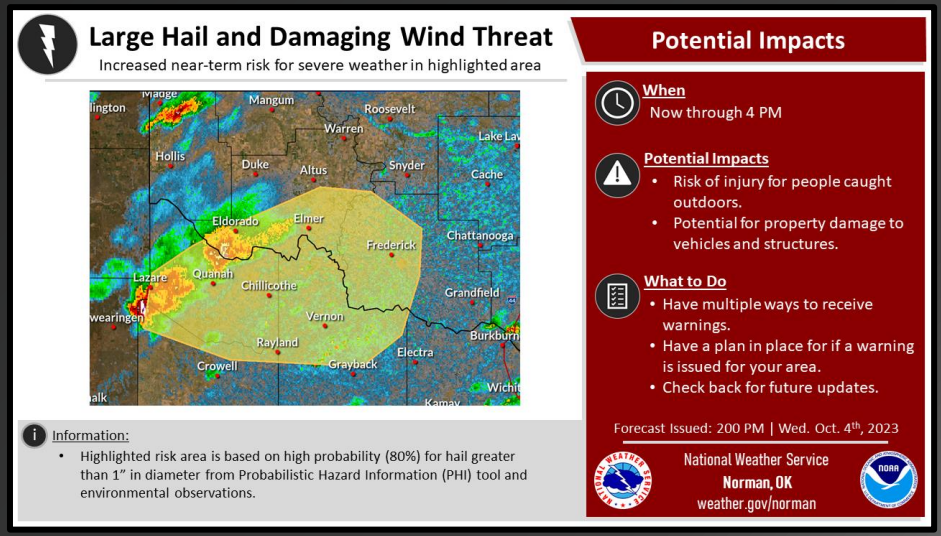
How to best message the threat?



How to best handle the watch-to-warning space is not well understood

Can/should we incorporate probabilities? How?

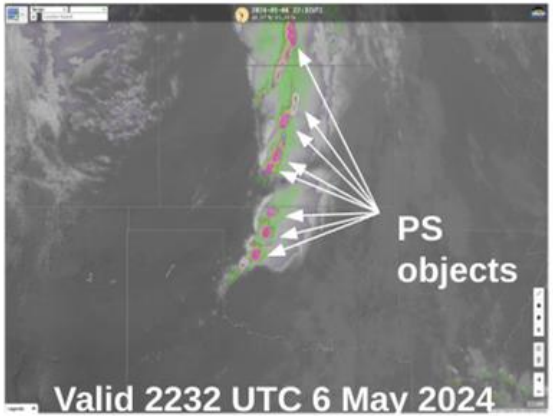




How to best handle the watch-to-warning space is not well understood

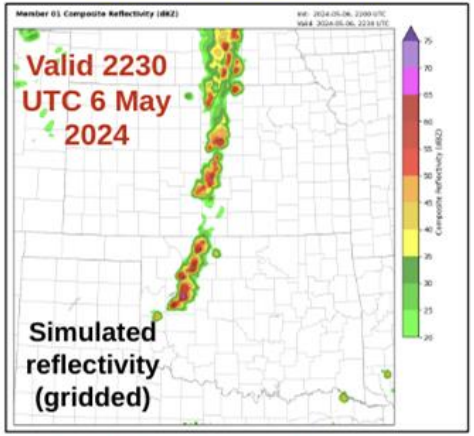
How to account for uncertainty in both observation and model data?

ProbSevere (PS)



https://cimss.ssec.wisc.edu/severe_conv/

Warn-on-Forecast System (WoFS)

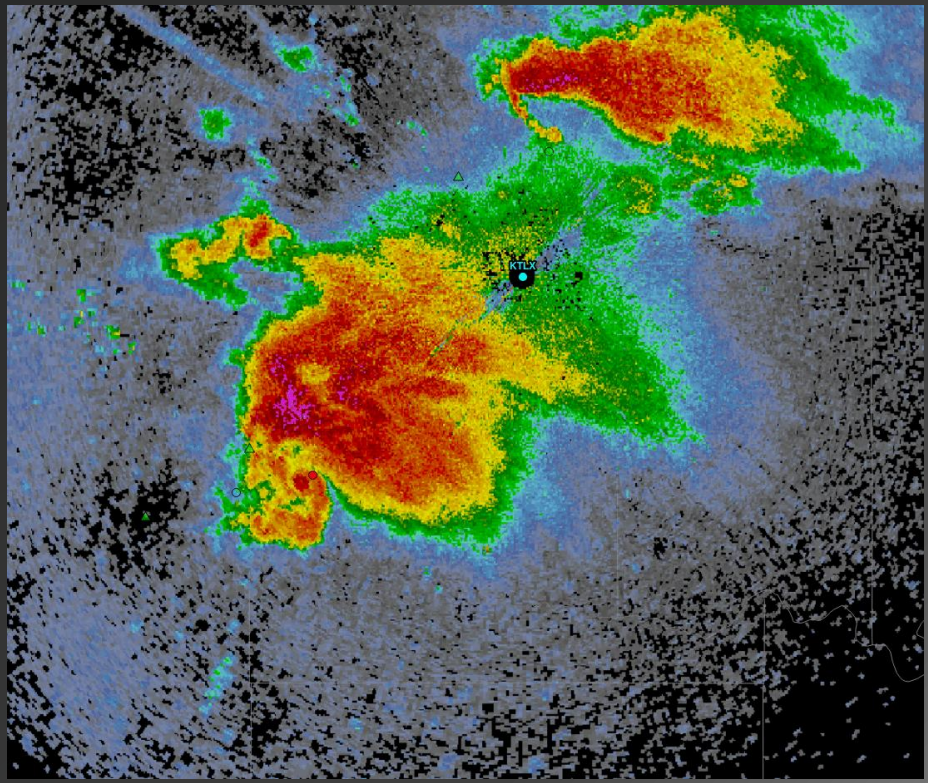


https://cbwofs.nssl.noaa.gov/

Probabilistic Hazard Information (PHI)

Storm-based product that conveys motion, timing, and likelihood of severe weather hazards

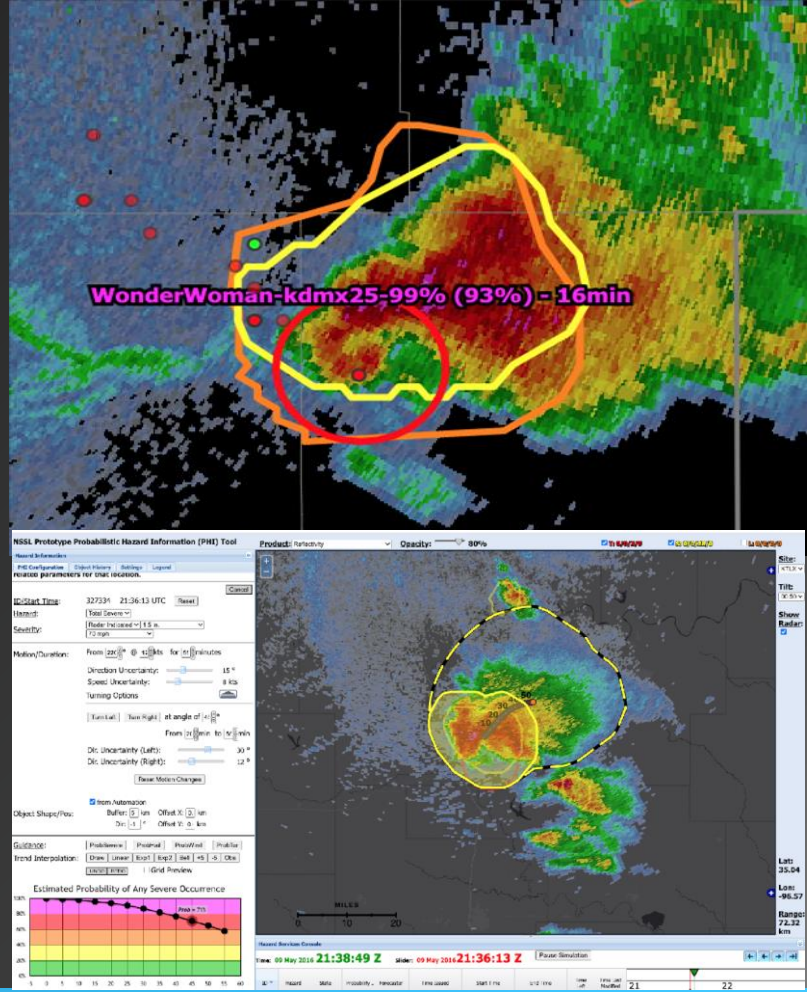
- Defines the temporal, spatial, and intensity uncertainties of threats.
- More specific regarding time (when storm will affect location, when it will end);
- More specific regarding space (smaller aerial coverage moves with storm);
- Allows for longer lead-times, though with higher uncertainty;
- Updates continuously in real-time to reflect changes in storm motion and evolution.
- Does not replace the warning!



Observational machine learning guidance provides:

- Storm object -> size, location
- Storm motion -> speed, direction
- Hazard-based Probability
  - Severe (ProbSevere V3, hail/wind)
  - Tornado (TORP – Sandmæl et al 2023)
  - Lightning (MRMS CG ProbLightning)

- **Speeds up object creation & issuance**
- **Calibrates the probabilities across forecasters**



Automated Severe PHI

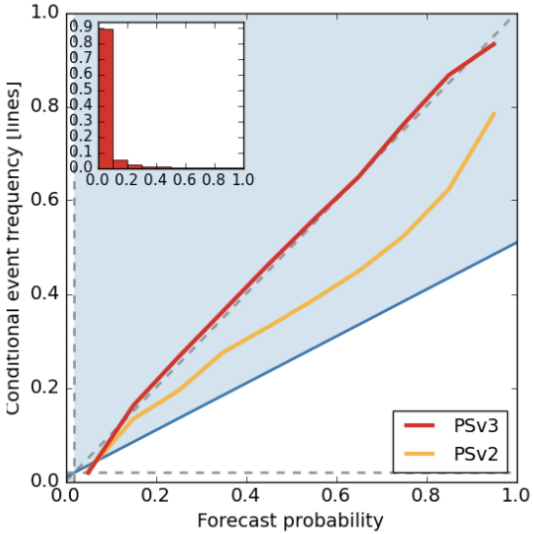
Created using ProbSevere v3 as the basis for storm probabilities.

PSV3 is a Machine Learning Model using Gradient-Boosted Decision Trees. It provides individual probabilities for different hazards. However, PHI plumes use the “all Severe” Probability only.

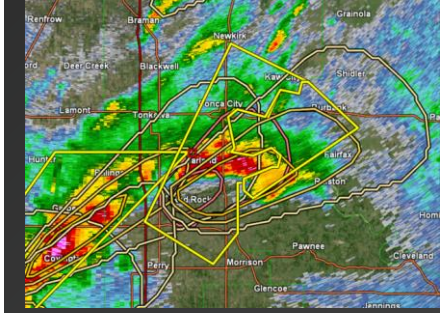
Blends data from: HRRR, GLM, GOES ABI, MRMS

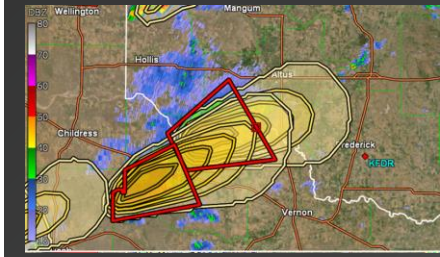
The PHI plume duration is **1 hr** based on the automated storm motion (e.g., faster storms will have longer plumes)

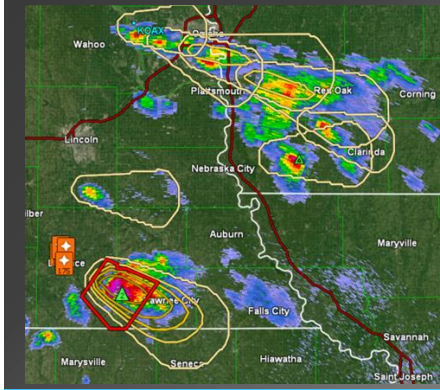
The peak probability is equal to “all severe” of PSv3; a gaussian filter is used to decrease probabilities to the outer edge of the plume with contours (fill) every 20%.



Reliability Diagram for ProbSevere v3 (PSv3, red) and PSv2 (yellow). Taken from the PSv3 training by Cintineo et al.







What does QC do?

Stabilizes the storm shape and motion to minimize variation across time steps using a confidence interval and Kalman filter, respectively.

Applies a probability threshold to only display storms with >2% to minimize clutter.

Limitations: Track breakages of storms due to splits/mergers. Linear systems will often break apart into multiple plumes.

Automated Tornado PHI

Created using the Tornado Probability algorithm (TORP).

TORP is a Machine Learning Probability based on a Random Forest from single radar properties extracted from a 2.5 km radius centered on a local AzShear Max.

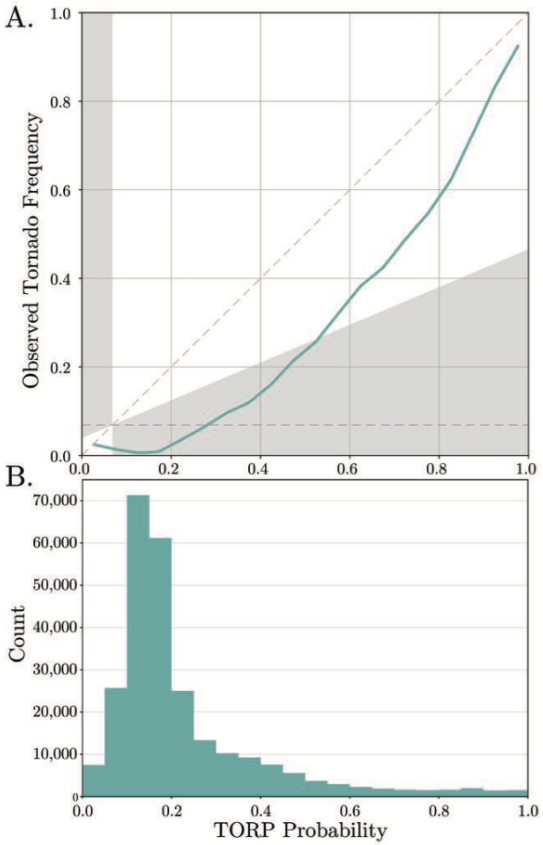
A circle (7.5 km radius) is placed at a TORP AzShear Max detection. The TORP probability provides the peak probability and a gaussian filter is applied to decrease probabilities to the outer edge of the plume.

The plume duration is **30 min** based on the automated storm motion.

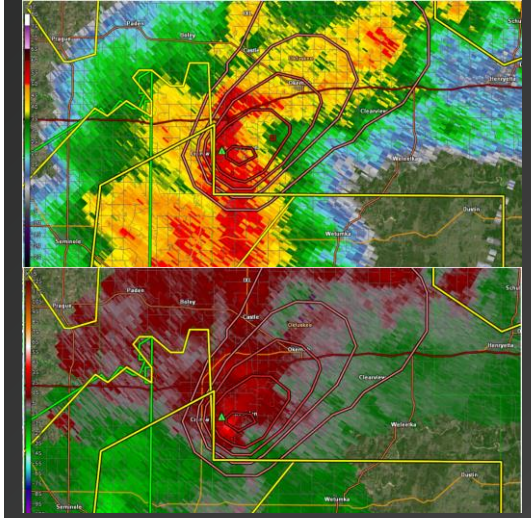
What does QC do?
Stabilizes the storm motion to minimize variation across time steps using a Kalman filter. Uses an input from 0-6 km Mean Storm Motion from Near Storm Environment data (RAP, if available).

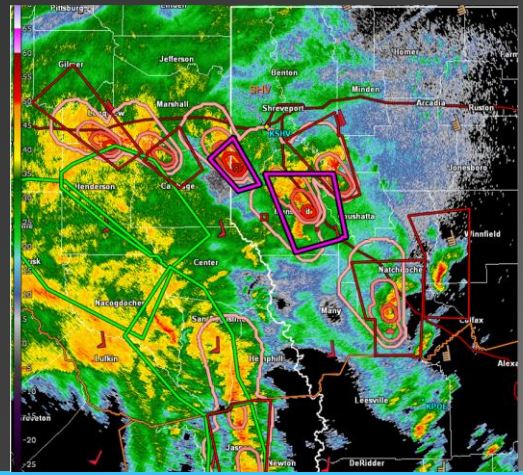
Applies a probability threshold to only display storms with >30% to minimize clutter.

Limitations: Side lobe contamination will often trigger bad detections with >30% probability.



TORP Reliability diagram and frequency count from 2017-2018. Fig 8 from Sandmæl et al (2023).

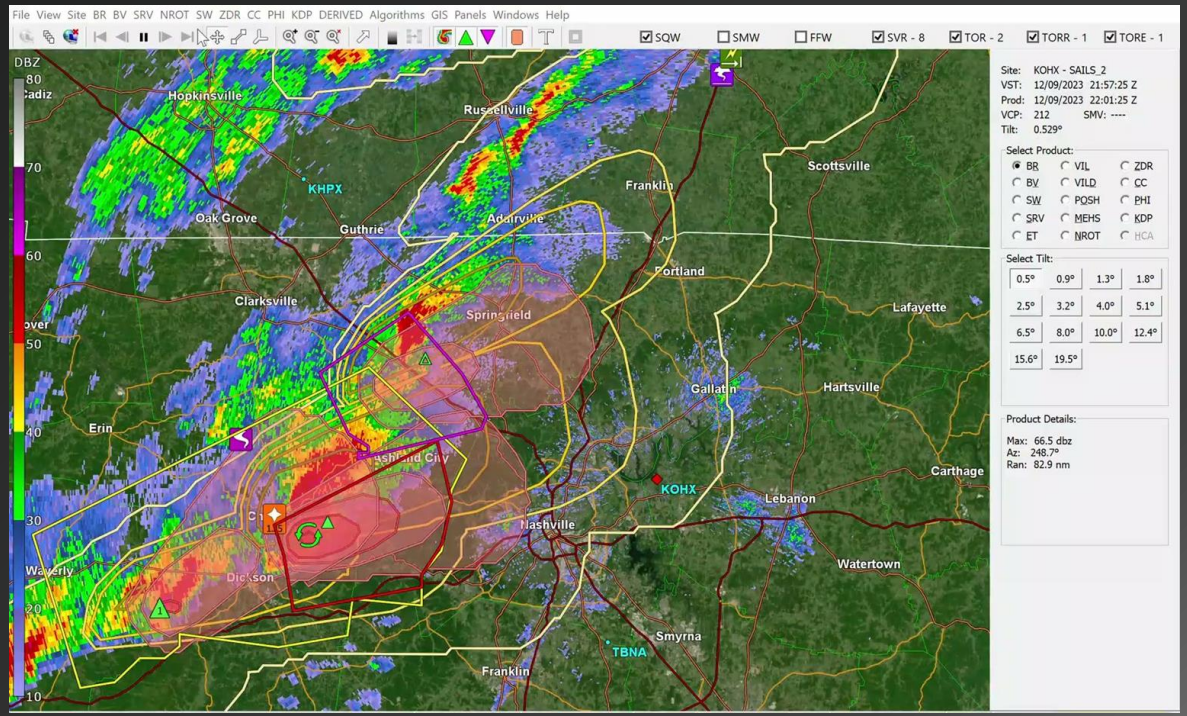




Probabilistic Hazard Information (PHI)

Fully automated system now available in GR. With archive capabilities and on-demand verification coming this spring.

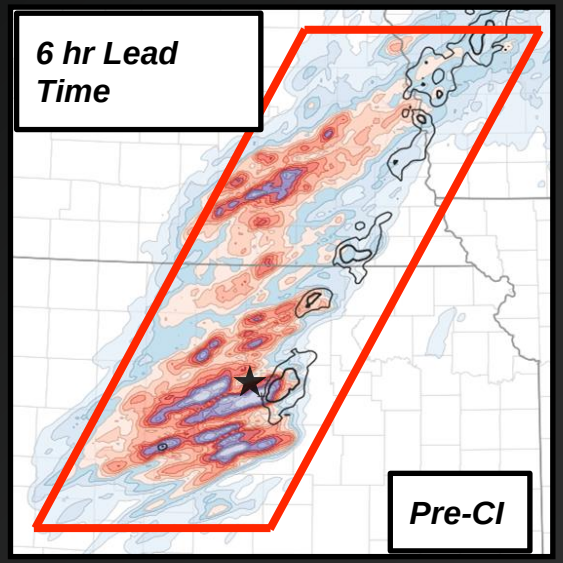
https://phi.nssl.noaa.gov/

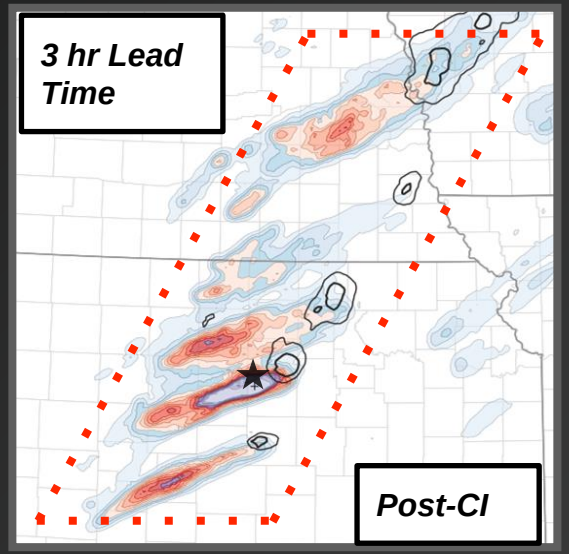


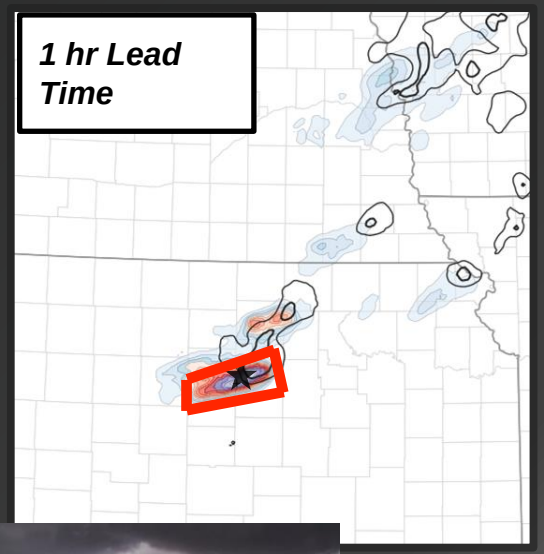
OHX, 9 Dec 2023

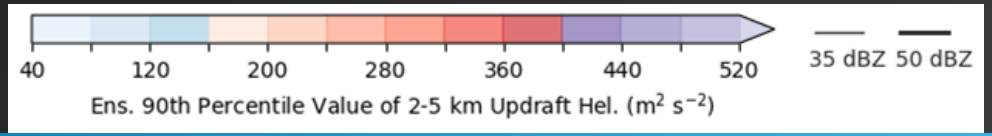
WoFS is designed to predict individual thunderstorms between watch and warning scales

WATCH → WARNING



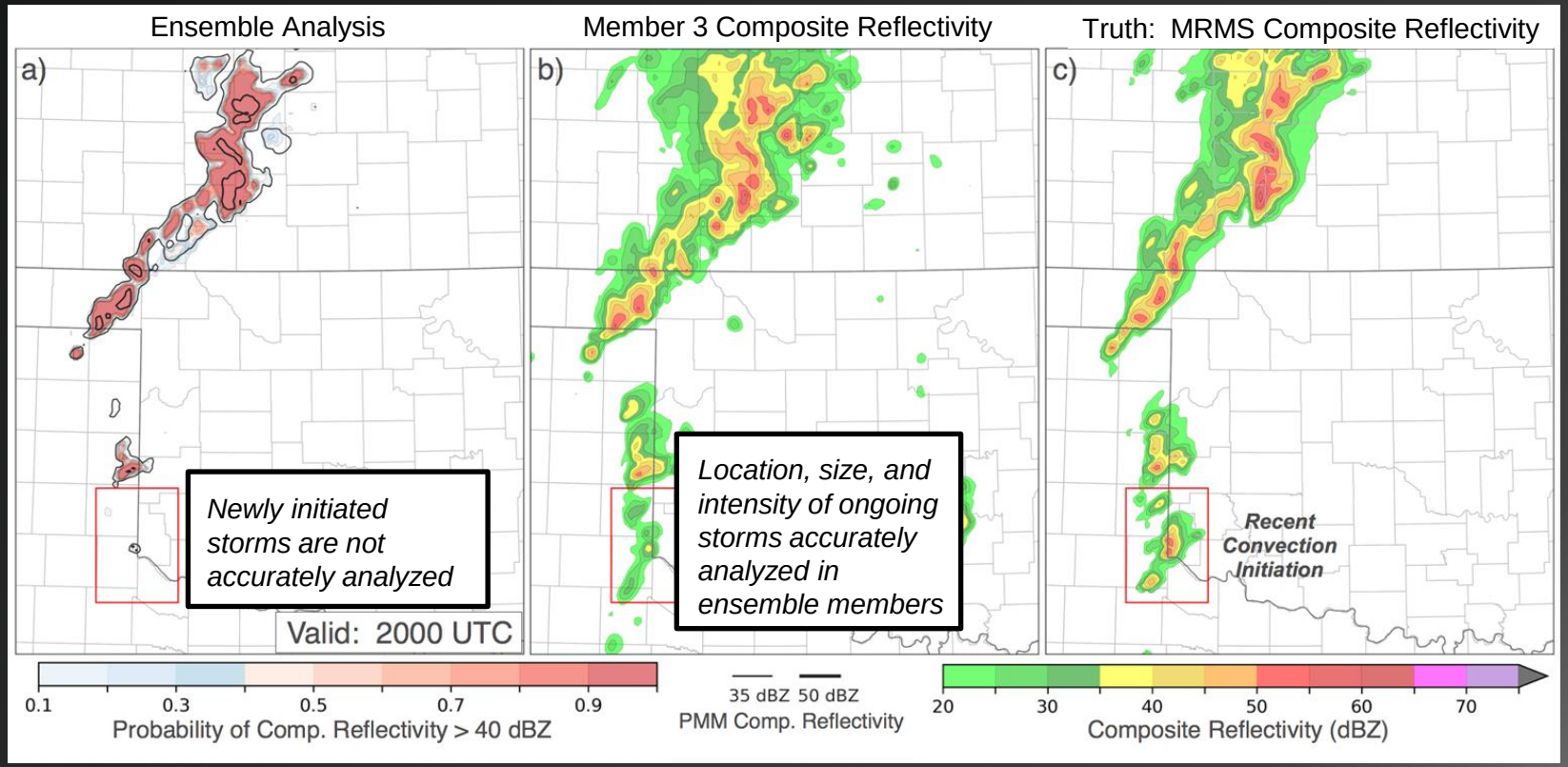






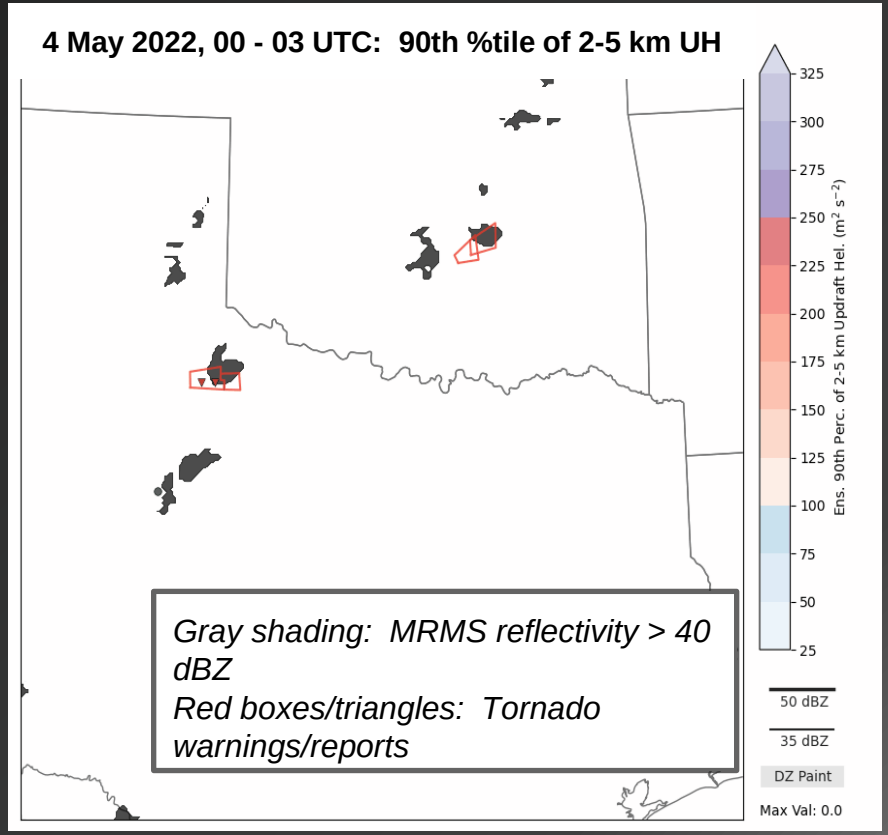
☆- EF3 Tornado

Rapid (15-min) data assimilation allows WoFS to analyze ongoing storms:



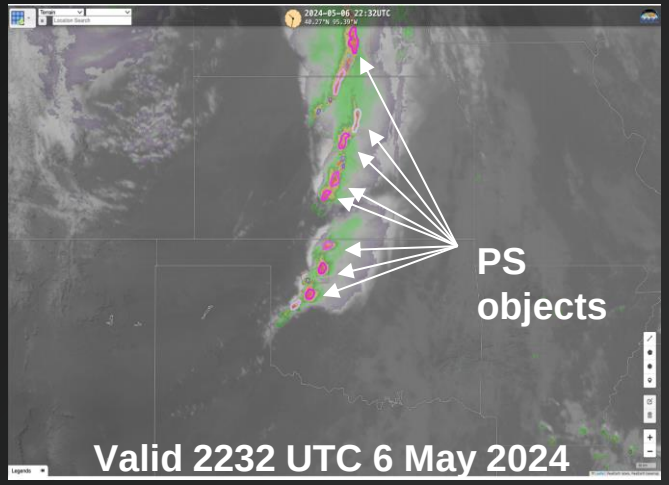
WoFS accuracy will vary from storm to storm

- **Good:**
  - WoFS accurately predicts intense 2-5 km updraft helicity along tracks of three tornadic supercells
  - Accurately predicts potential for extreme precipitation with training supercells in central OK
- **Bad:**
  - Large amounts of spurious convection predicted, particularly along warm front in southwest OK
  - WoFS fails to maintain tornado warned supercell moving into western OK



WoFS-PHI: Blending WoFS and ProbSevere

ProbSevere (PS)

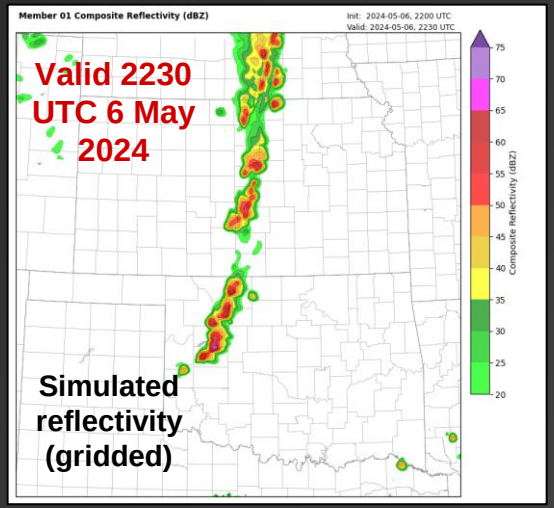


https://cimss.ssec.wisc.edu/severe_conv/

Strengths: Current storm location; update frequency

Weaknesses: Future storm development; no spatial forecast information

Warn-on-Forecast System (WoFS)

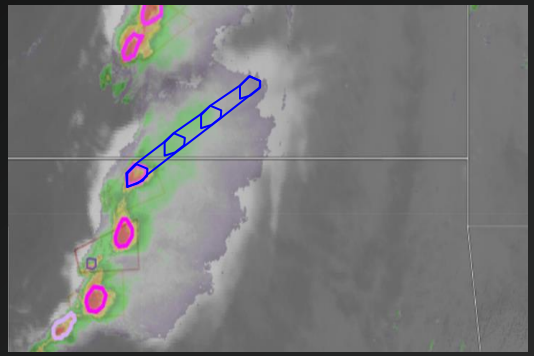


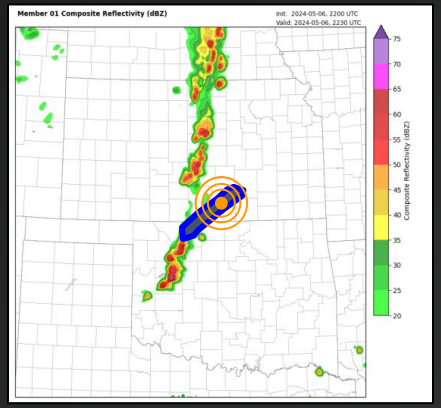
https://cbwofs.nssl.noaa.gov/

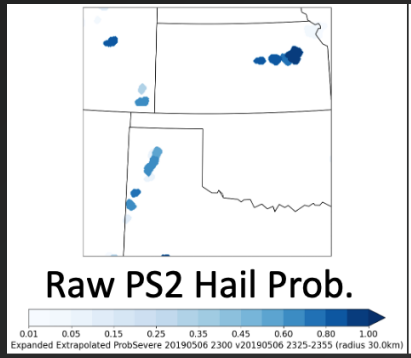
Strengths: Future storm evolution, spatial forecasts

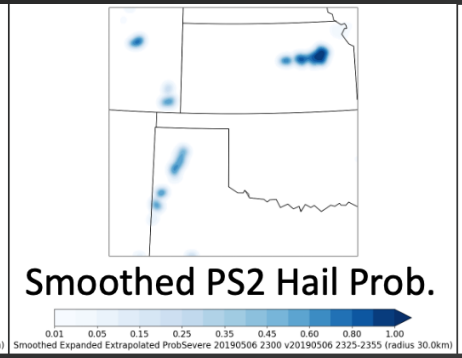
Weaknesses: Storm location (during spin-up), update frequency

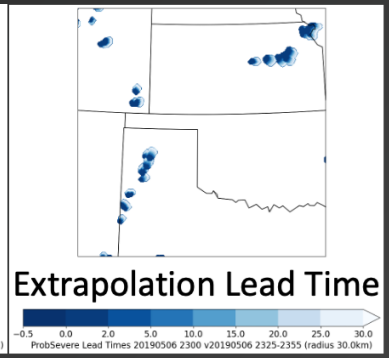
ProbSevere objects extrapolated, gridded to WoFS

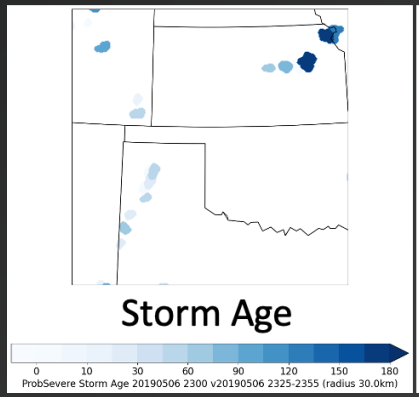


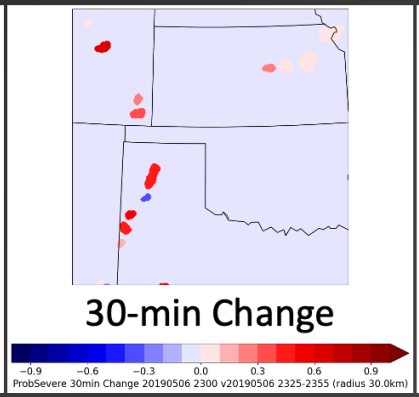


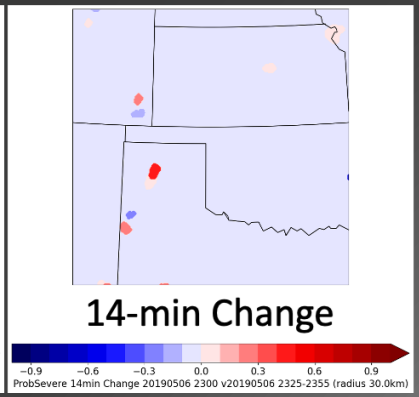




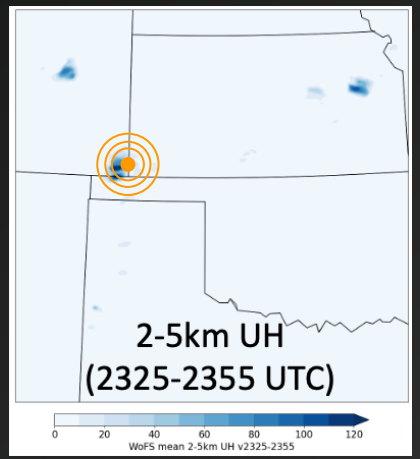


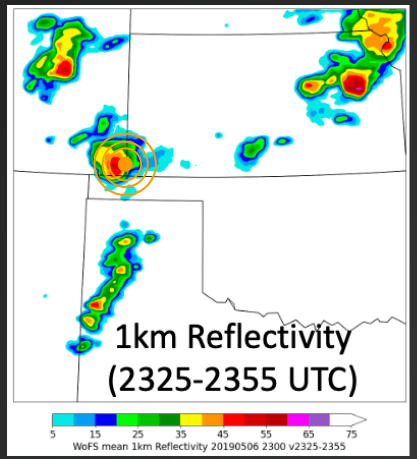






WoFS: Temporal aggregation -> ensemble mean -> predictors from multiple points

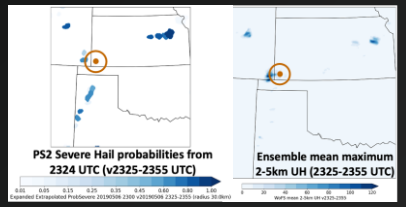




Ensemble mean of temporal maximum UH, reflectivity

Single-Point WoFS (Values taken from point of prediction only)	Multiple-Point WoFS (Values taken from within 0, 15, 30, 45, and 60km of point of prediction)
10-500m bulk wind shear	80m wind speed
10m wind components	1km Simulated reflectivity
2m temperature and dewpoint	0-2km vertical vorticity
0-1, 0-3, and 0-6 km wind shear components	0-2 and 2-5km updraft helicity
0-500m, 0-1km, and 0-3km storm relative helicity (SRH)	Updraft speed (1km and column-maximum)
Surface-based CAPE	Flash extent density (FED)
Significant Tornado Parameter (STP); Traditional and using 0-500m SRH	Downdraft speed
Supercell Composite Parameter (SCP)	Mean sea level and surface pressure
Cloud Top Temperature	Ensemble probability of reflectivity exceeding 40 dBZ
Surface-based LCL	Individual-member 2-5km updraft helicity
Predicted Hail	
Freezing Level	
Latitude & Longitude	
WoFS x and y grid points	
WoFS initialization time	

Random forests (RFs) are trained on spatial data using observed storm reports/warnings as targets



Spatial predictors from PSv2 and WoFS are input into hail-, wind-, and tornado-predicting RFs

Hail RF

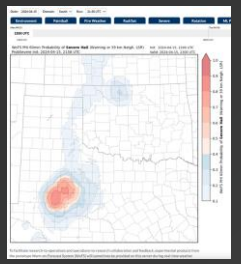
Wind RF

Tornado RF

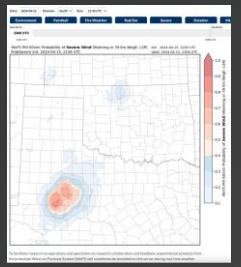
Map prob to Success Ratio

Map prob to Success Ratio

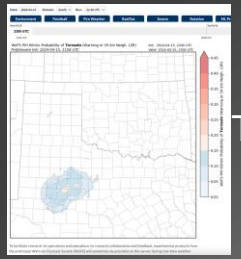
Map prob to Success Ratio



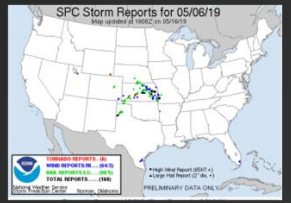
Hail



Wind



Tornado

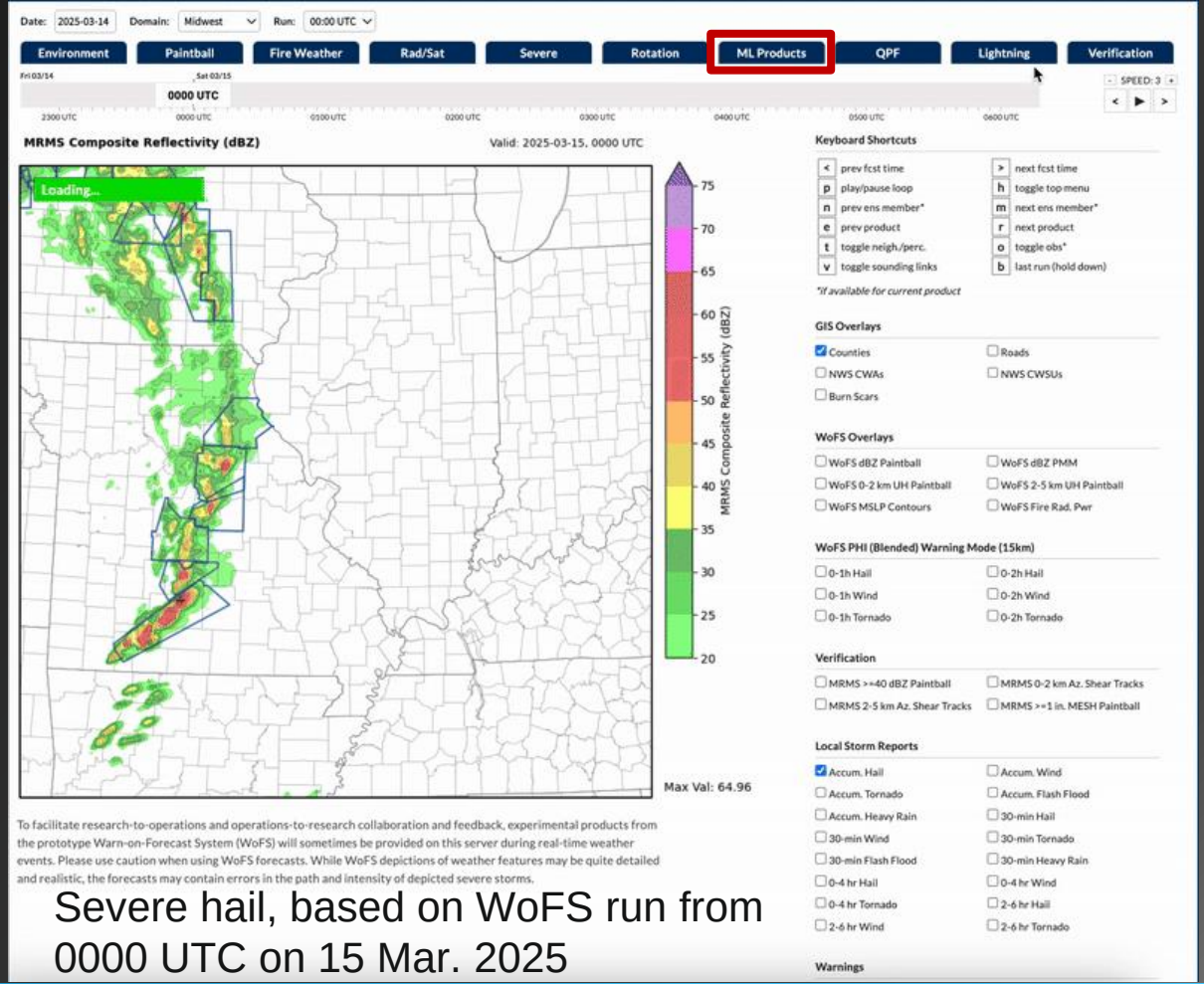


RFs trained on observed storm reports and/or hazard-specific severe warnings

WoFS-PHI probabilities

WoFS-PHI Forecast Mode:

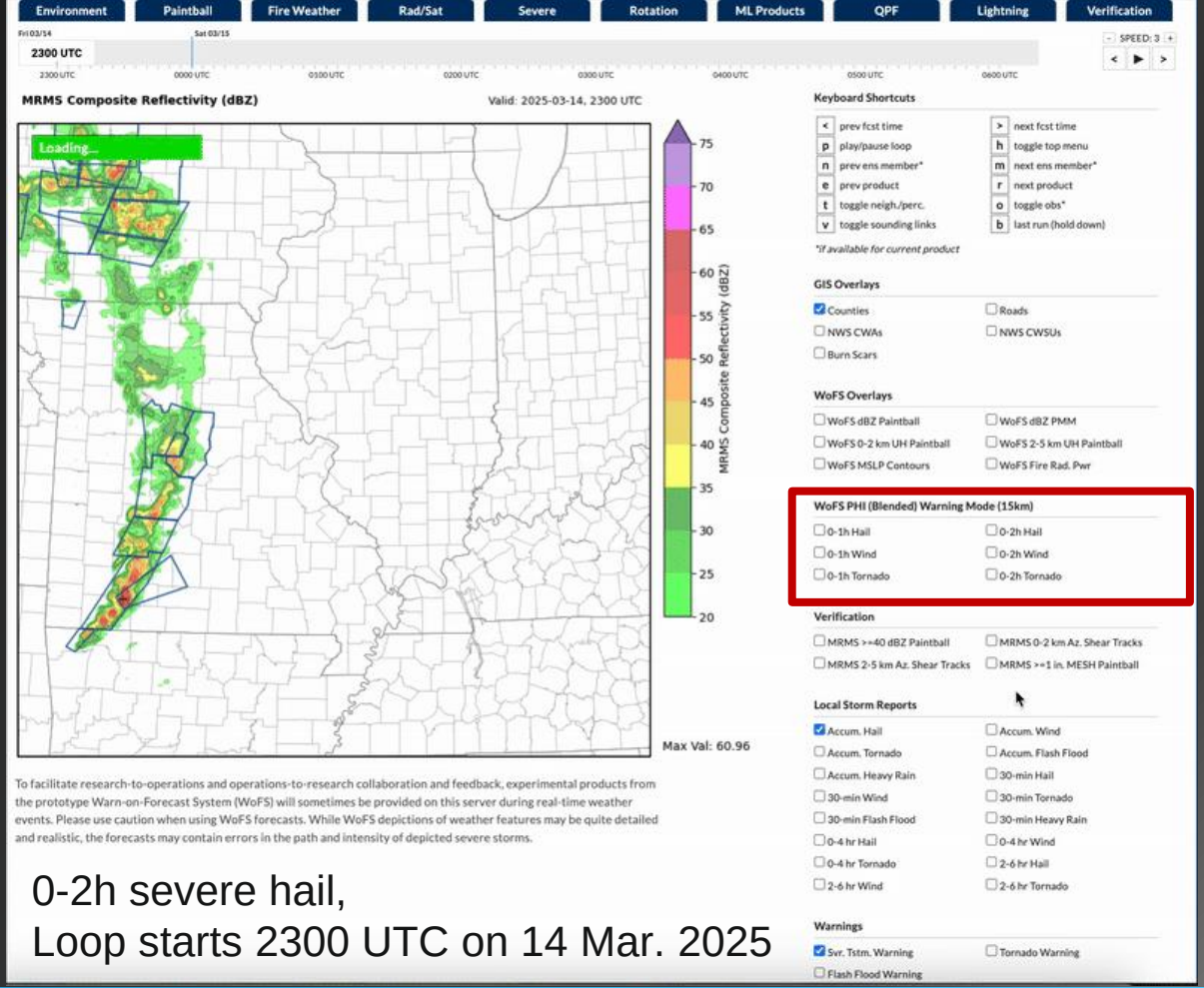
- Updates once per WoFS initialization
- Predicts for up to 4 h of lead time
- Located under “ML Products” tab



Severe hail, based on WoFS run from 0000 UTC on 15 Mar. 2025

WoFS-PHI Warning Mode:

- Updates every 5 min.
- Always predicts for next 1h or 2h
- Contour overlay (right side of viewer)



0-2h severe hail,
Loop starts 2300 UTC on 14 Mar. 2025

NOAA's Hazardous Weather Testbed (HWT)

Joint project of the National Weather Service (Storm Prediction Center & Norman Weather Forecast Office) & National Severe Storms Laboratory

Conceptual framework & physical space to foster collaboration between research & operations to test & evaluate emerging technologies & science for NWS operations.

2023-2024 HWT Watch-to-Warning Experiment

3 weeks annually, archive only, both SPC and WFO forecasters

Goals:

- Examine how to expand communication / products in the watch-to-warning gap working with both the SPC and Local WFOs
- Test multiple machine learning models blending obs and ensemble models (WoFS)

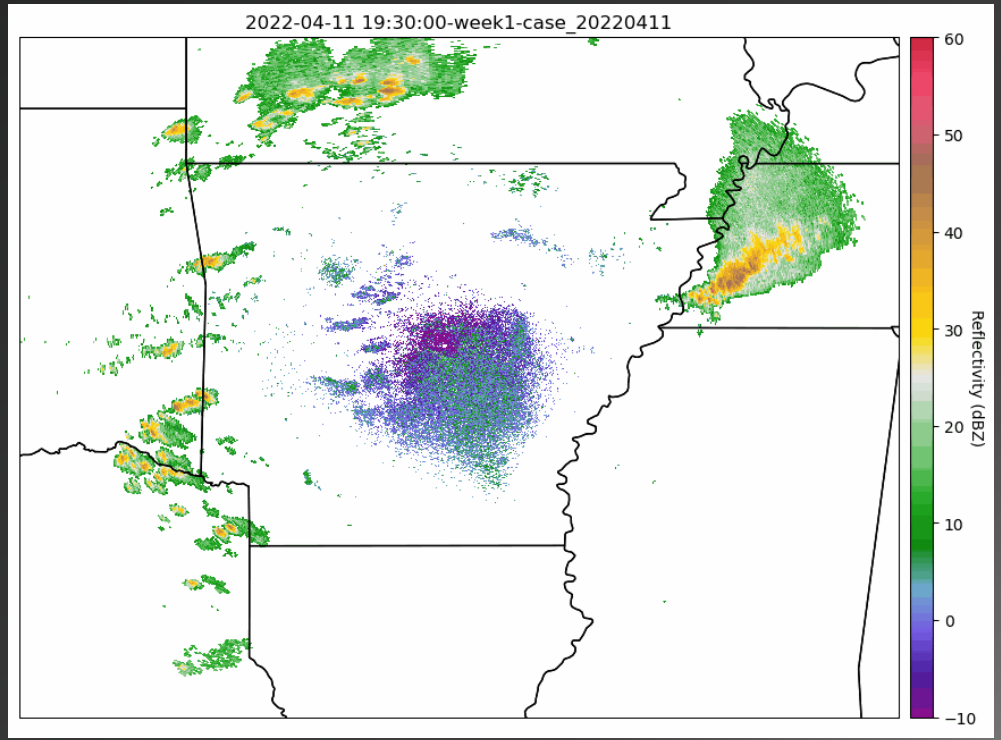
Archive Case Selection

4 cases with increasing progression of difficulty across the week → from single supercell storm, to mixed mode, high risk tornado outbreak, QLCS with warm sector supercells

2024 - Added Emergency Managers (Oklahoma) on final case

Watches from the Storm Prediction Center

- Specifically meant to provide 2 hours of lead time to the first report
- Smaller spatial coverage
- Counties added/removed by SPC forecasters at any time
- *In 2024: Added potential to color watch by probabilities associated with tornado / significant tornadoes*



Watches from the SPC

- Specifically meant to provide 2 hours of lead time to the first report
- Smaller spatial coverage
- Counties added/removed by SPC forecasters at any time
- *In 2024: Added potential to color watch by probabilities associated with tornado / significant tornadoes*

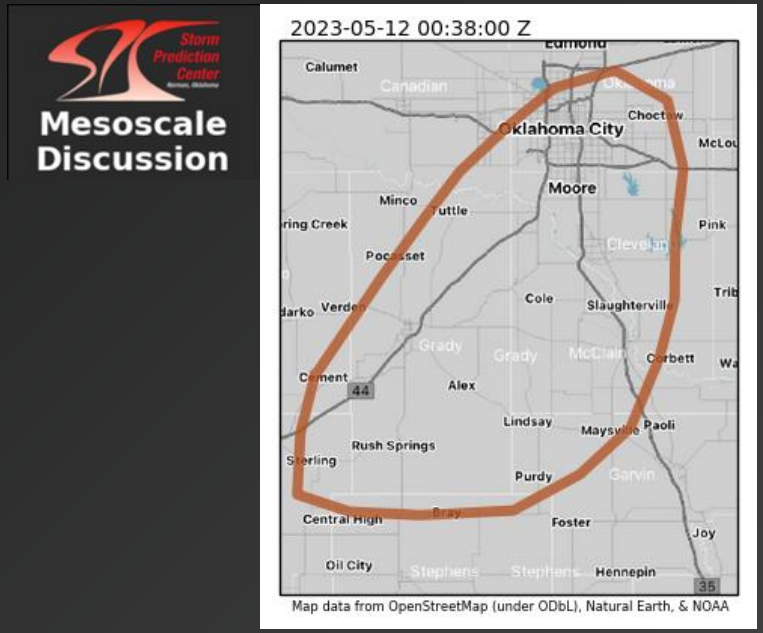
Regular Probs.	Sig. Probs.	Watch Color	Watch Text
20%	< 20%		A tornado or two possible
30-40%	< 20%		A couple tornadoes possible
30-40%	30-50%		A couple intense tornadoes possible
50%	< 20%		A few tornadoes possible
50%	30-50%		A few tornadoes and a couple intense tornadoes possible
60-70%	< 20%		A few tornadoes likely
60-70%	30-50%		A few tornadoes likely with a couple intense tornadoes possible
60-70%	60-70%		A few tornadoes and a couple intense tornadoes likely
80-90%	< 20%		Several tornadoes likely
80-90%	30-50%		Several tornadoes likely with a couple intense tornadoes possible
80-90%	60-70%		Several tornadoes and a couple intense tornadoes likely
95%	< 20%		Numerous tornadoes expected
95%	30-50%		Numerous tornadoes expected with a couple intense tornadoes possible
95%	60-70%		Numerous tornadoes expected with a couple intense tornadoes likely
80-90%	80-90%	PDS	Several tornadoes and a few intense tornadoes likely
95%	80-90%		Numerous tornadoes expected with a few intense tornadoes likely
95%	95%		Numerous tornadoes and a few intense tornadoes expected

Mesoscale Discussions

Mesoscale Discussion -

(similar to today)

- Precedes watches and updates
- Added probabilities of hazard over time
- Focused more often on meso-beta and meso-gamma discussions

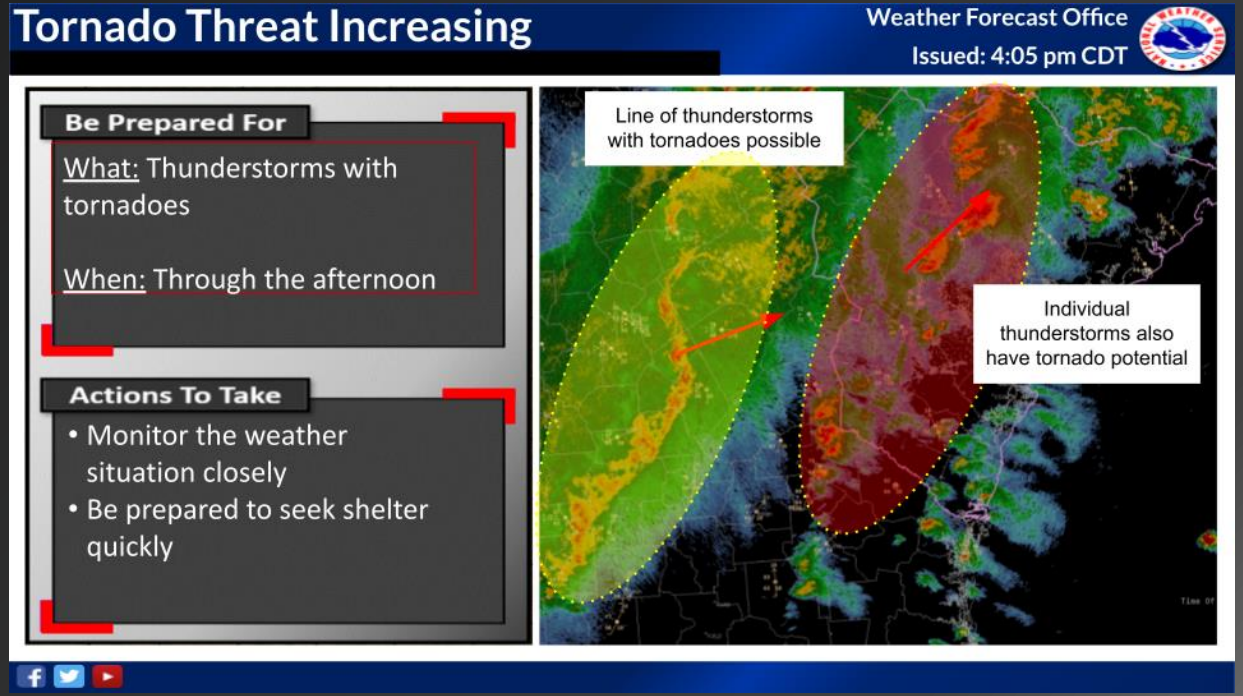


Thunderstorms within the cluster over Grady County OK have shown signs of better organization over the past hour or so. This trend will likely continue, with supercellular characteristics becoming prevalent. Strong buoyancy and moderate bulk shear will support the potential for very large hail up to 2.5. Storm proximity will result in interactions, some of which could disrupt the processes needed for tornadogenesis. However, low-level shear is still strong enough to support a tornado threat if storms can remain discrete.

Local Discussions (NWS Forecast Offices)

Local Discussion -

- issued by local forecast office
- Focus is timing, location, hazard
- Creates a well-defined geospatial domain (geojson – can move to other apps, systems)



Social media/NWS chat text: Two corridors of thunderstorms that will be capable of producing tornadoes continue across the area. Round one is ongoing now, and round two will arrive after 6pm and move west-to-east across the area into early evening.

Local Discussion

NWS CHAT / SLACK:

Current Severe Probability: 60%

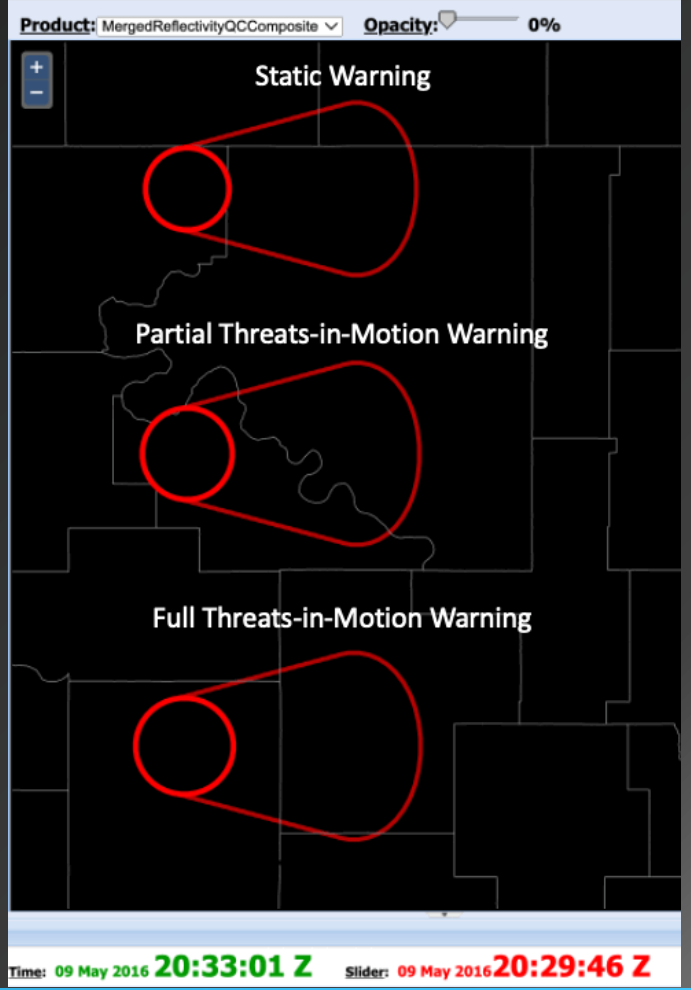
Discussion: Scattered strong to occasionally severe thunderstorms continue to affect areas of the OKC metro. **This activity will continue for the next few hours** within an environment conducive to hail and tornado development. Storms have struggled to distance themselves from one another, which has resulted in a lack of overall organization. Still, with favorable wind fields and remnant instability, these storms have produced **brief tornadoes along with hail and gusty winds.** These cells will continue to move east/northeast and pose a risk of severe weather. In addition, frequent lighting and torrential rainfall will be impactful to any outdoor events. The risk of severe weather looks to **gradually decrease after 9-10pm** as storms move east of I-35.

Threats-in-Motion Warnings:

1) Static Warnings (current paradigm).

2) Partial Threats-in-Motion (warning is tied to the object. Area behind storm removed each update).

3) Full Threats-in-Motion (warning is tied to the object. Both area behind removed and area ahead added to warning)



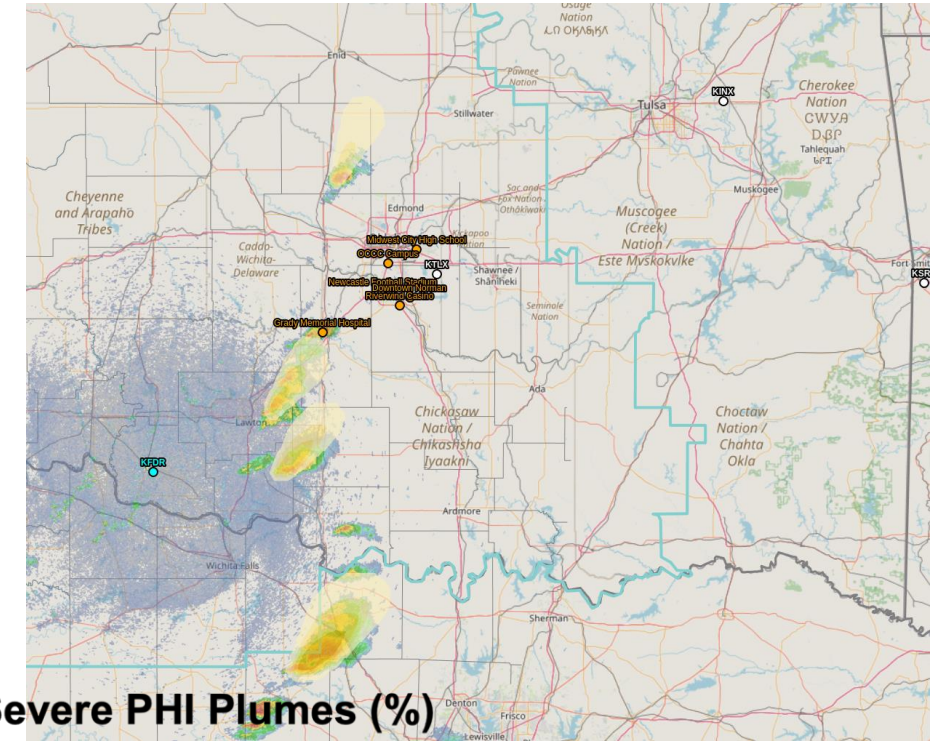
Severe Weather Threat Continues

Severe Weather Probabilities Pictured Valid Through 7 pm

Weather Forecast Office
Norman, OK
Issued: May 11, 2023 - 6:07 PM

Weather Details

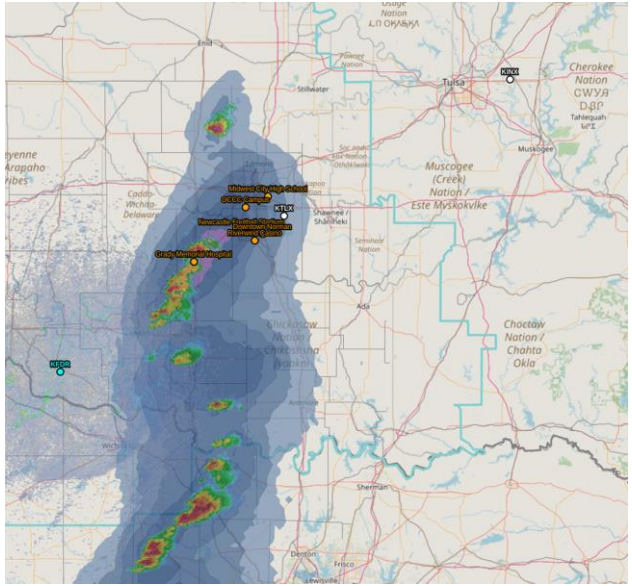
- Thunderstorm Coverage Increasing
- Medium to High Chance for Severe Weather
  - Very large hail the main concern
  - Damaging wind gusts up to 60 mph
  - Tornado threat expected to increase through the evening as the environment becomes more supportive.



Severe Weather Chance Through 8:15 PM

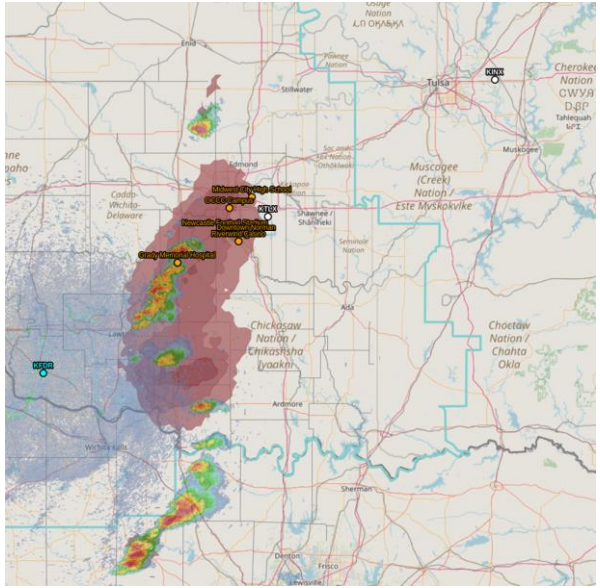
Weather Forecast Office
Norman, OK
Issued: May 11, 2023 - 6:20 PM

Through 8:15 pm - Severe Wind, Hail and Tornado Threats to Increase Along and West of I-35, Including the OKC Metro



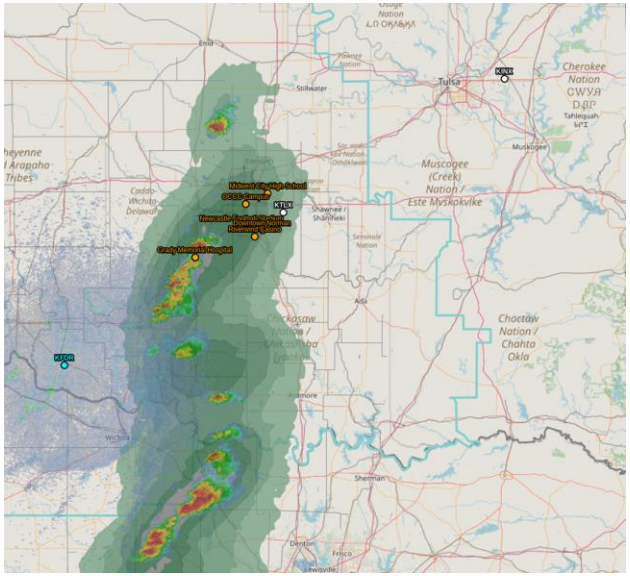
WoFS-PHI (Blended) Severe Wind (%)

10 30 50 70 90



WoFS-PHI (Blended) Tornado (%)

1 5 10 20 30 40 50 60



WoFS-PHI (Blended) Severe Hail (%)

10 30 50 70 90

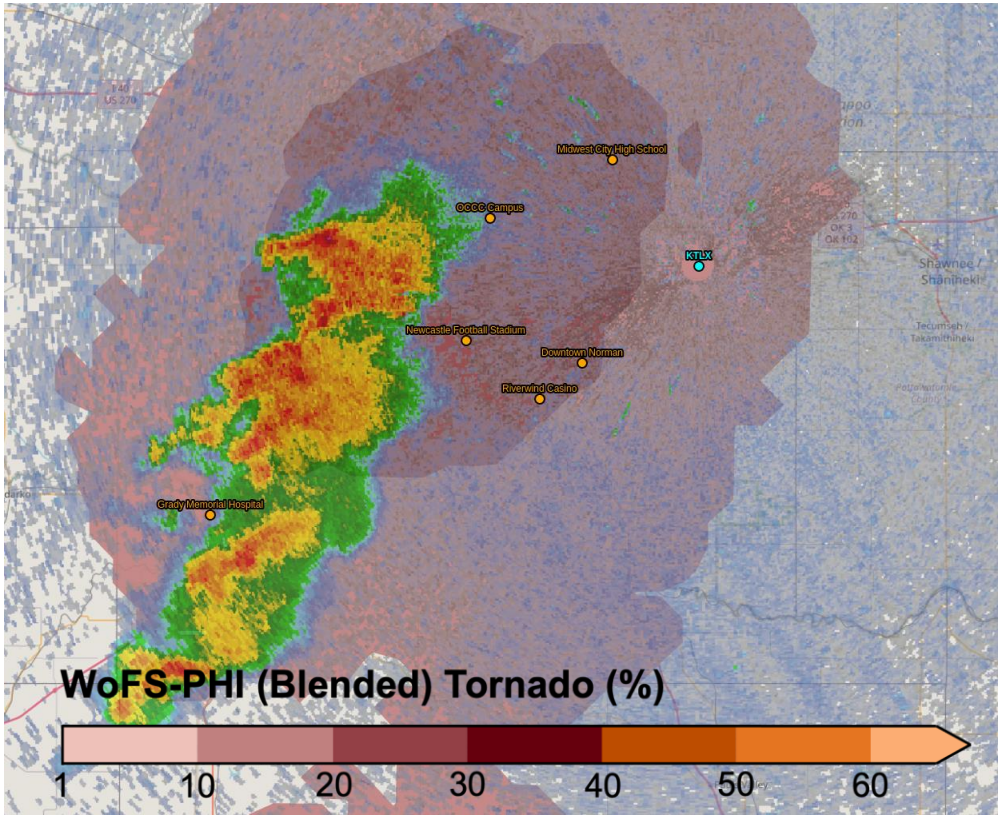
Low Tornado Threat Into OKC Metro

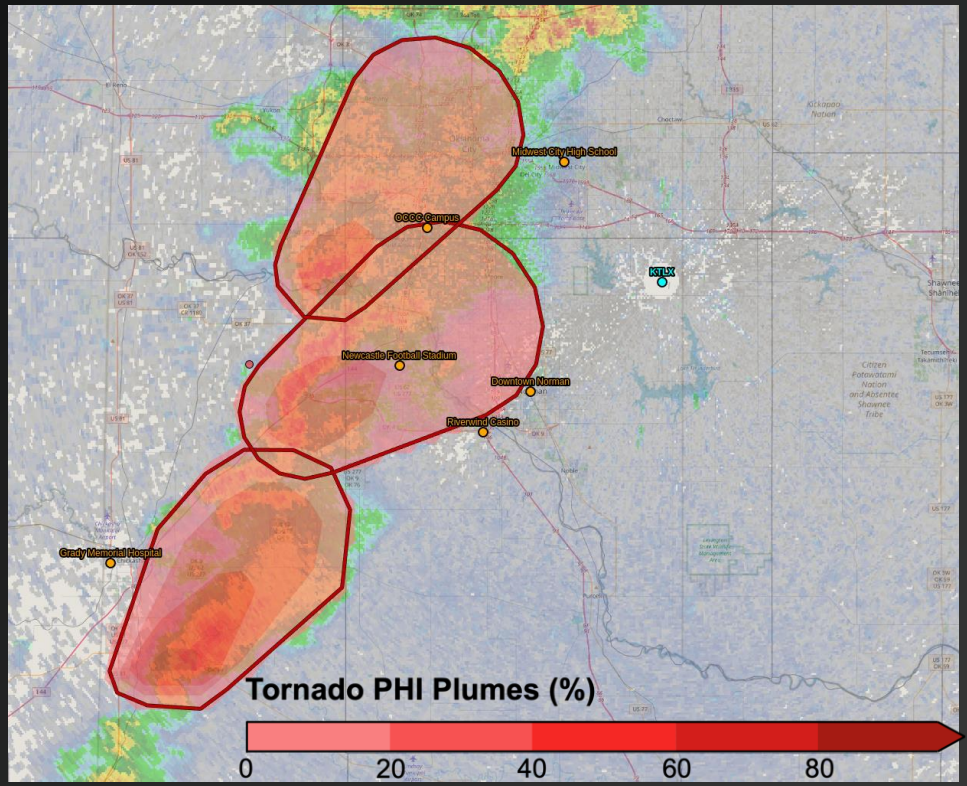
NO Tornado Warning in Effect At This Time

Weather Forecast Office
Norman, OK
Issued: May 11, 2023 - 6:53 PM

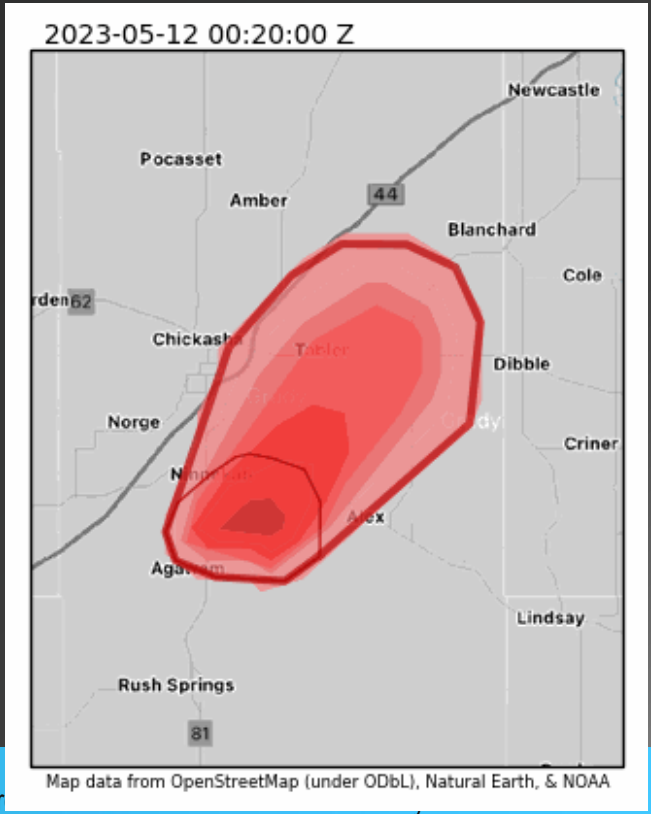
Hazard Information

- 10-20% chance of tornadoes in the next 30 minutes into most of the OKC metro
- Storms have exhibited weak low level rotation at times





[NWSChat] Update: *this is in a difficult spot to interrogate radar-wise but the environment and history support at least hanging on to the tornado warning a bit longer until the threat has decreased significantly (Updated: 00:34 UTC)*



Emergency managers were particularly interested in seeing storms in motion with trends associated with hazards and likelihood.

EM Scenario Introduction (Example)

Chickasaw Nation

The Chickasaw Nation Riverwind Casino in Goldsby (I-35 and Hwy. 9) is hosting a summer kickoff concert and food truck festival. The headlining act is Journey, which will likely skew the attendee crowd to be slightly older. The concert organizers are anticipating between 7,500 and 10,000 attendees for this outdoor concert. The event is scheduled to start at 7 pm, with the headliners coming onstage sometime around 9 pm.

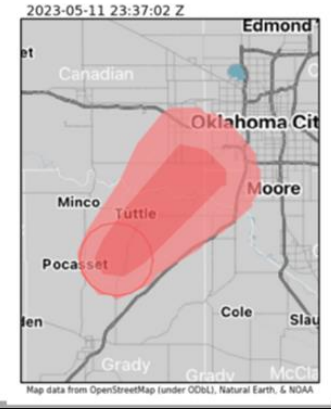
Chickasaw Nation Emergency Management has been asked to support on-site operations, acting as a liaison for weather communication for the event. Due to the economic impact of the event, and the fear of reputational damage, organizers are loathe to cancel or postpone unless absolutely necessary. That said, festival organizers will suspend activities due to lightning within an 8-mile radius of Goldsby for 30 minutes after the last strike. Non-severe wind gusts over 40 mph are also a concern, particularly due to tents and stage construction.

There is an option to to move the entire event indoors into the casino's permanent concert venue. This decision would need to be made no later than 5:30 pm, but is not considered ideal due to the food truck portion of the event. Organizers have requested frequent updates, with briefings being expected at a minimum of every 30 minutes if inclement weather is a possibility. It should be noted that traffic flow is a significant concern due to ongoing construction at the I-35/Hwy. 9 interchange, thus impacting egress for folks trying to drive north toward Norman/OKC.

EM Scenario

NCAA and Thunder Update

The storms are intensifying and one of the cells is producing a more favorable environment for tornado development. This image is not a tornado warning just an illustration of the areas that have the greatest probability of tornado development at this moment. All indications show the storms are tracking towards both of your facilities.



David Hogg - NO...
1:59 PM Aug 29

From NCAA - The first game is running ahead of schedule and should be ending in the next 15

Show more

david
2:04 PM Aug 29

Ill answer in slide 19

1

David Hogg - NO...
2:07 PM Aug 29

From Downtown area - doors to the Paycom Center have been opened, so crowd pressure is

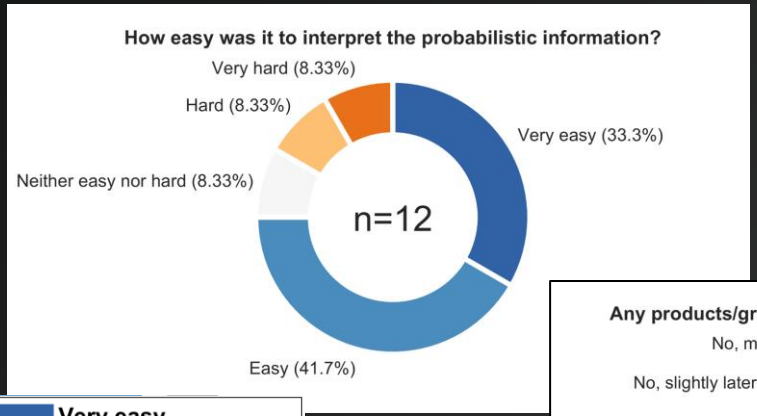
Show more

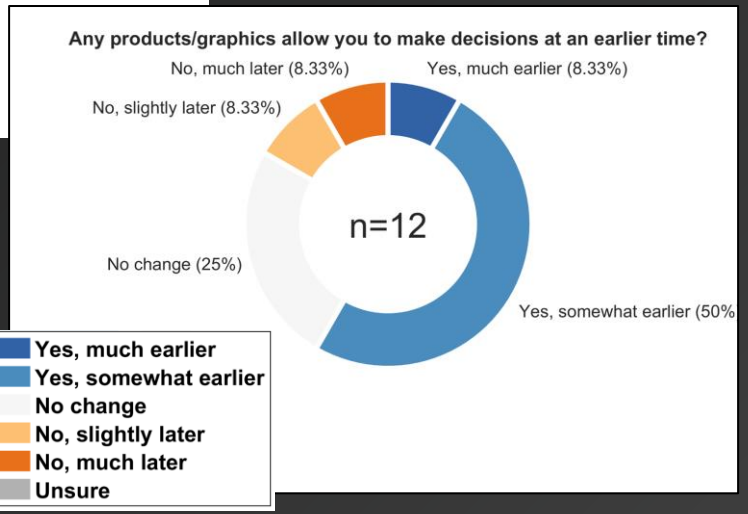
david
2:15 PM Aug 29

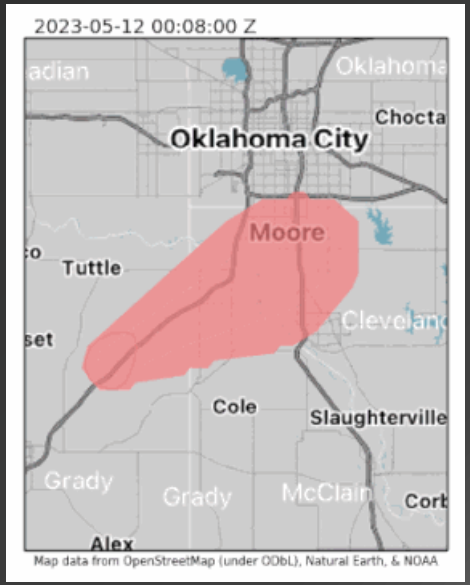
Main threat continues to be hail. The severe thunder storm warning is currently tracking to the NW of

Show more

EMs: Probabilistic products were easy to interpret and helped with decision making

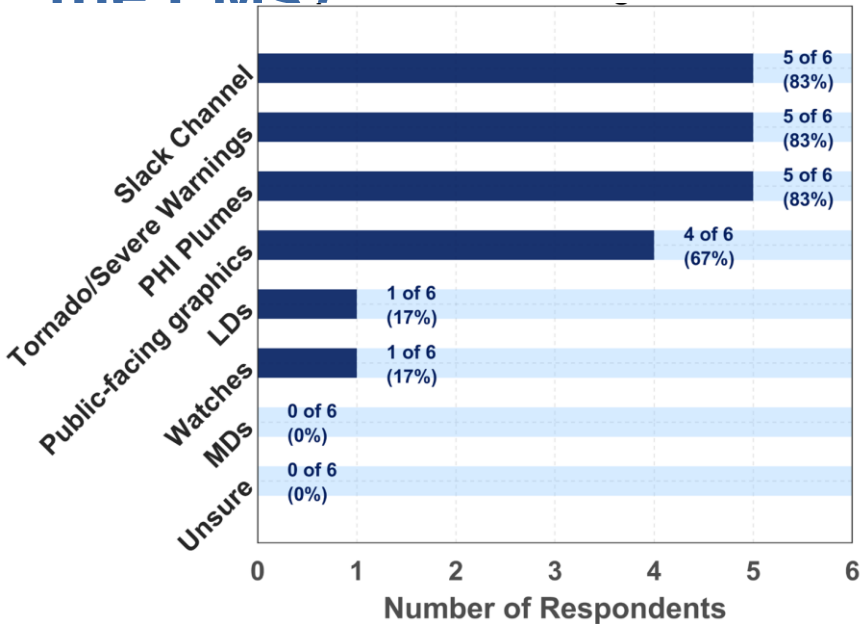




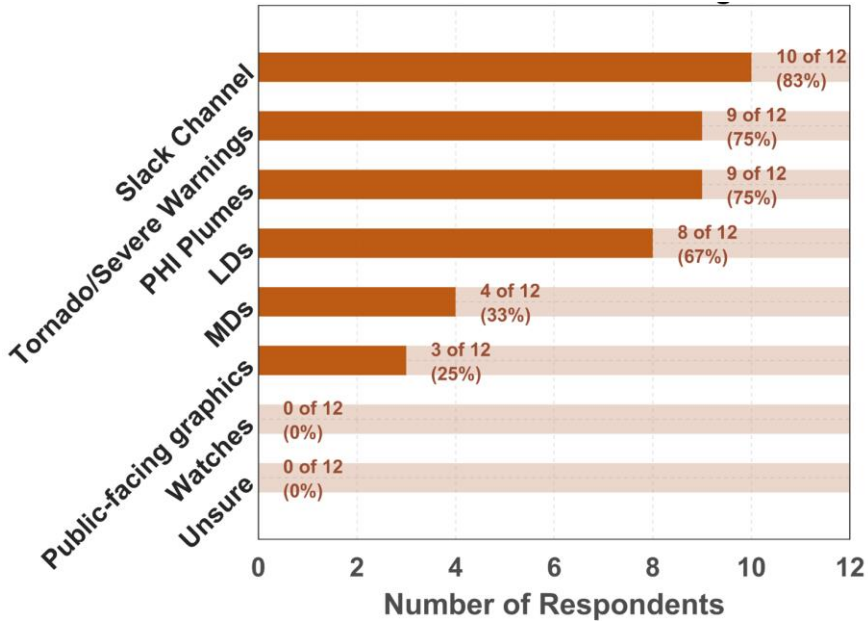


PHI plumes show storm motion, threat location

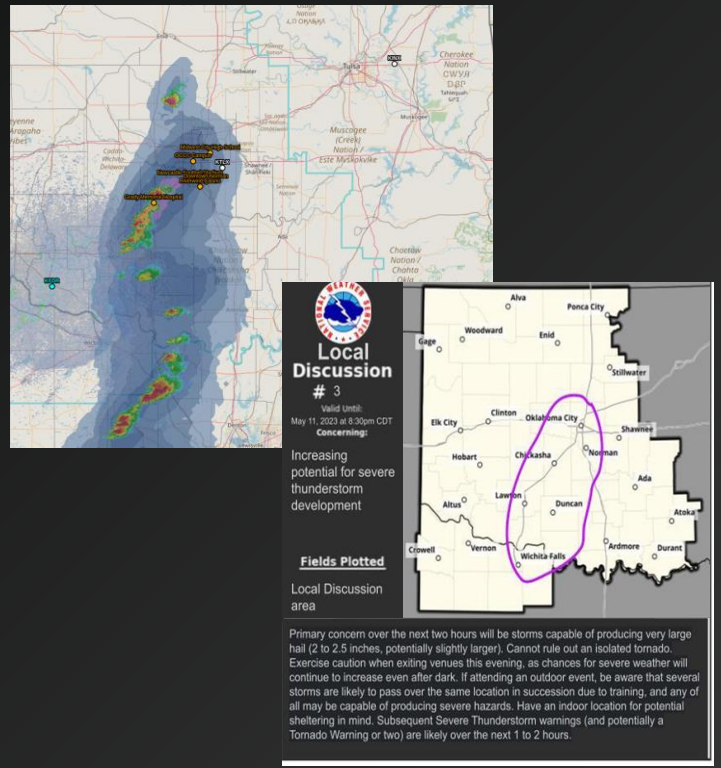
Forecasters: Which service did you prioritize/find most useful for communication with the EMs?

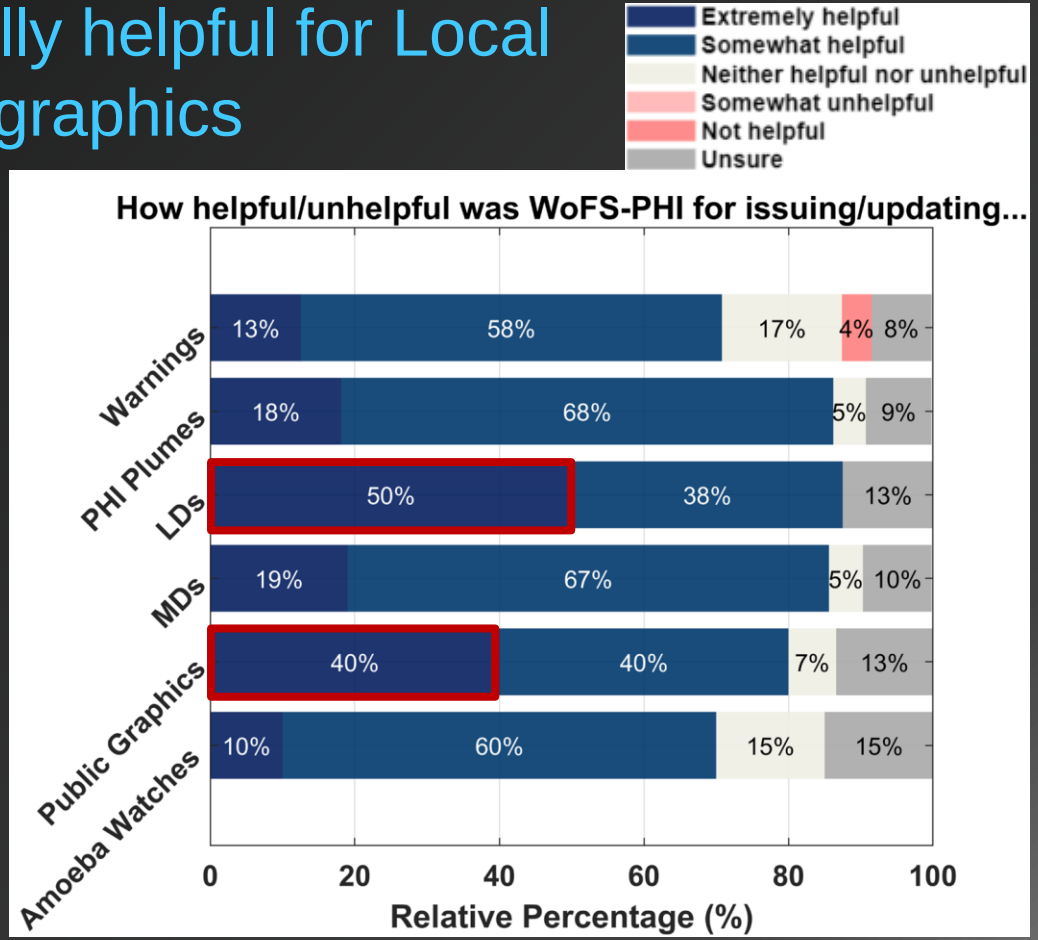


EMs: Which service did you find the most useful for decision making?

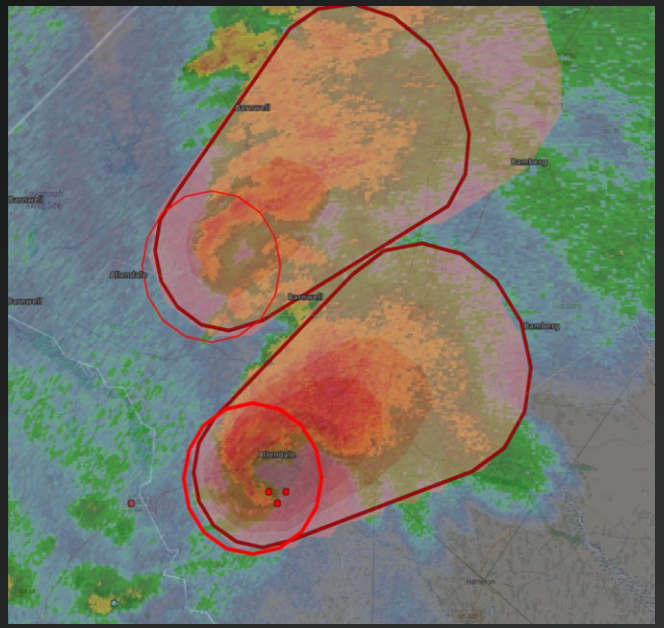


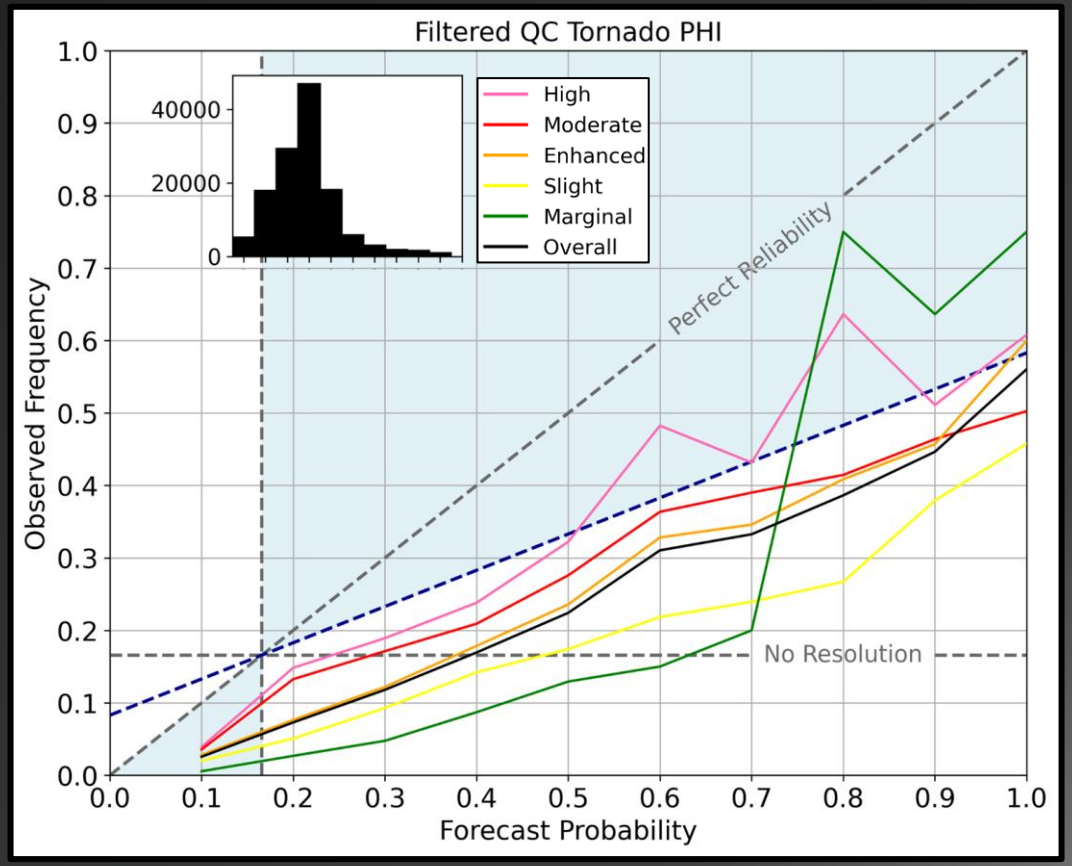
WoFS-PHI was especially helpful for Local Discussions and public graphics





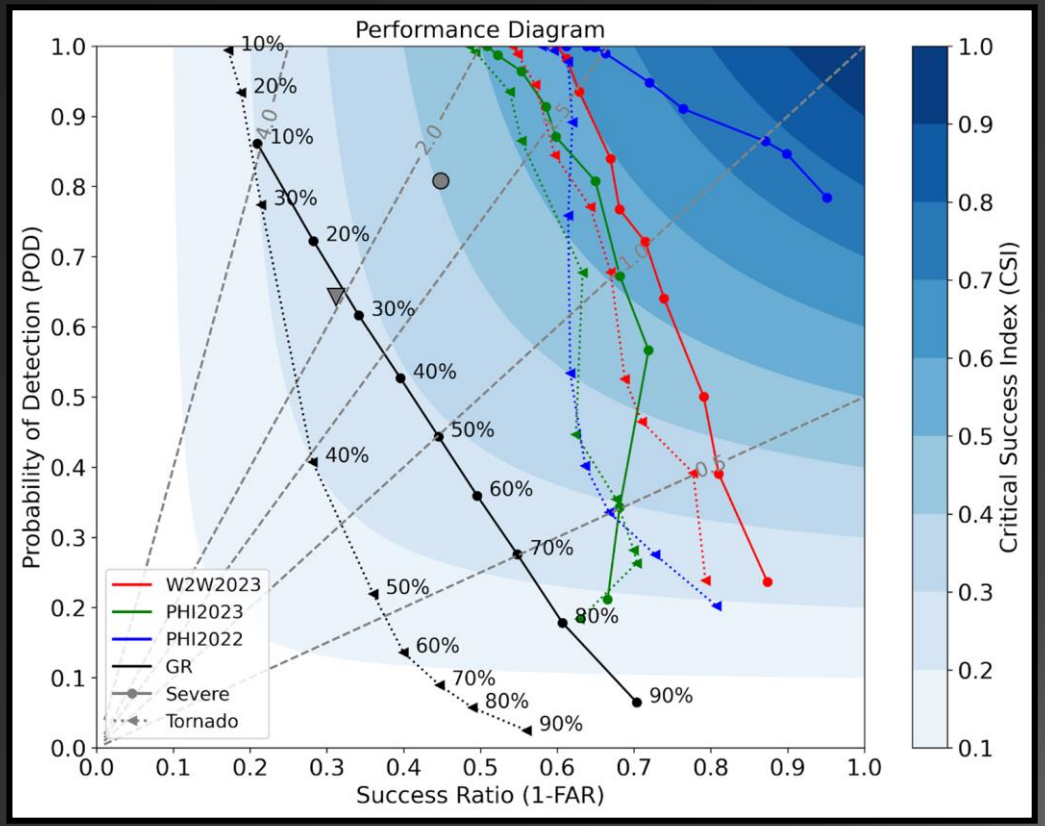
PHI Verification



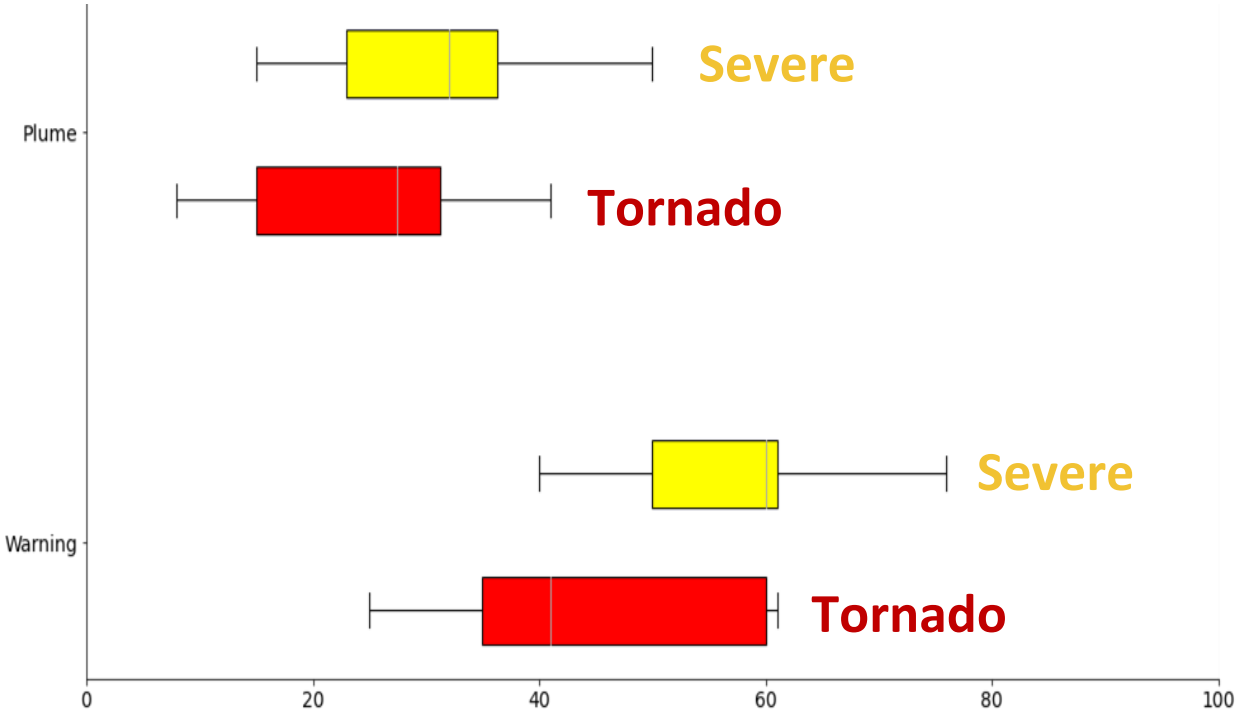


Forecaster changes to machine learning guidance

Blue/red/green lines represent forecaster added value to automation during HWT experiments.



Choosing a probability to issue first PHI vs Warning for a storm:

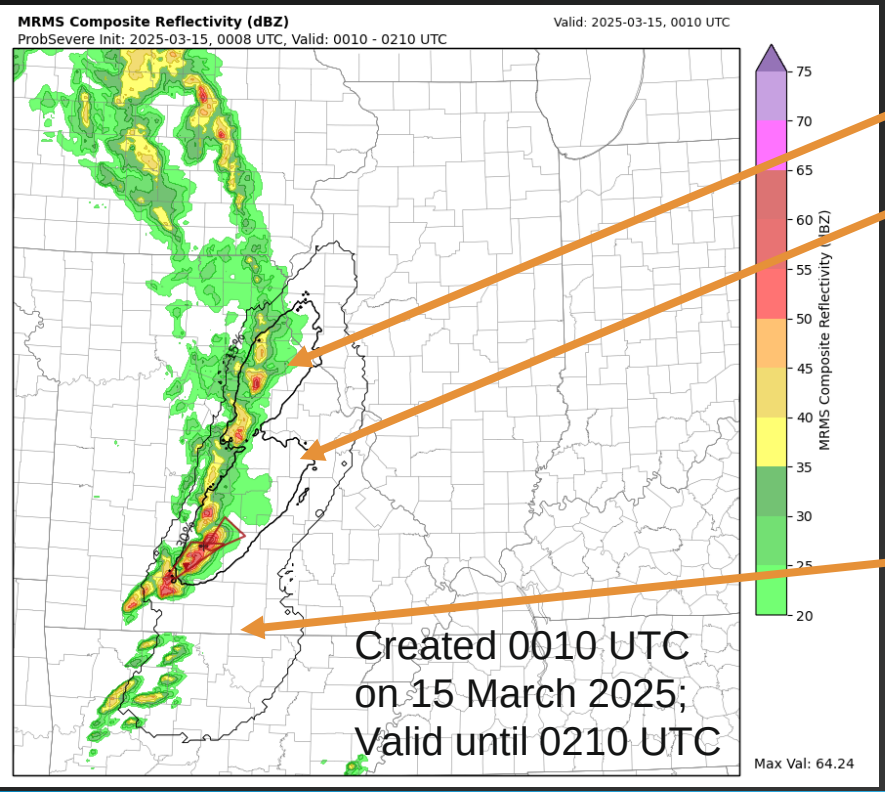


How can forecasters apply this information?

- Use PHI and WoFS-PHI for messaging/situational awareness
  - Will highlight corridors of greatest risk before warnings

- Create “Local Discussion” graphics for EMs/public
  - Highlight an area and discuss in lay terms

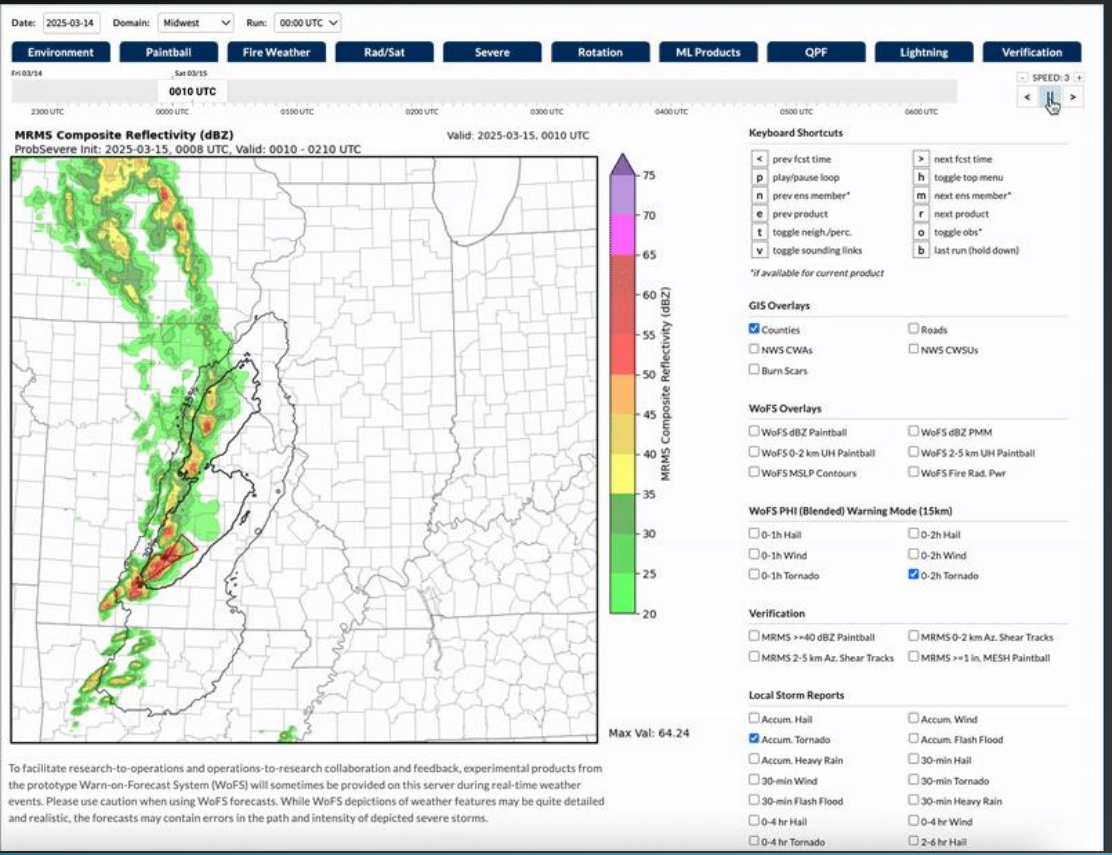
Example: WoFS-PHI Warning Mode for situational awareness/messaging



30% areas without a warning might deserve a 2nd look for warning or messaging

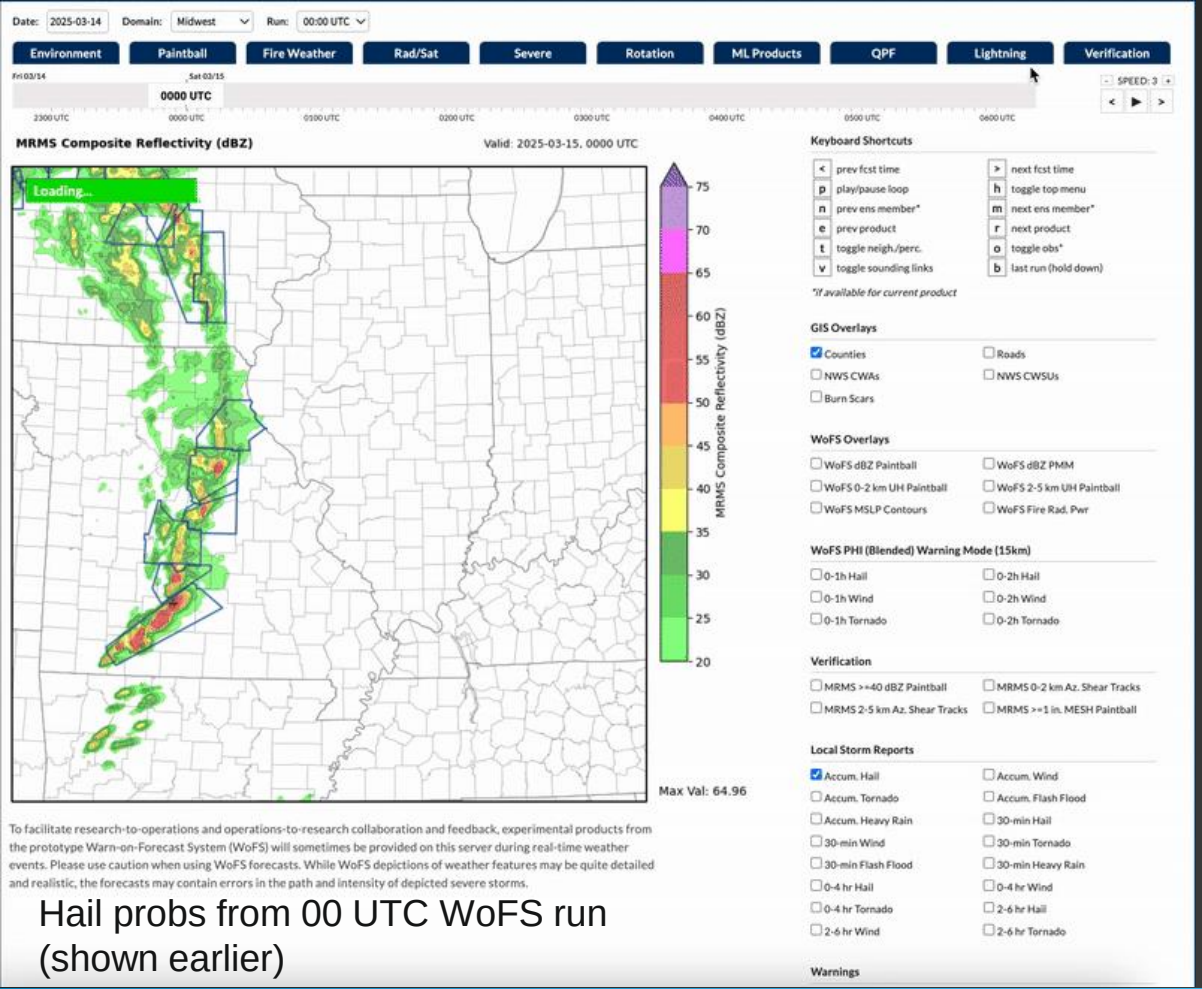
<30% areas might warrant extra attention/messaging as storms develop

How does this play out?



2h WoFS-PHI Tornado Probabilities (Warning Mode)

00-06 UTC
15 March 2025

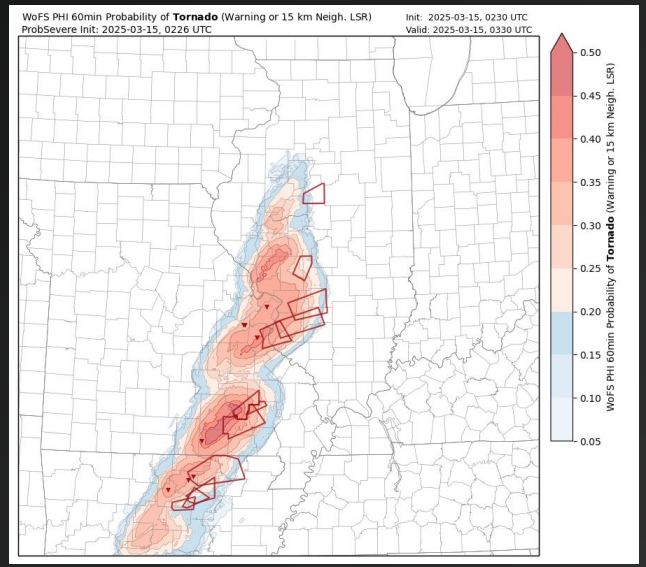


Hail probs from 00 UTC WoFS run (shown earlier)

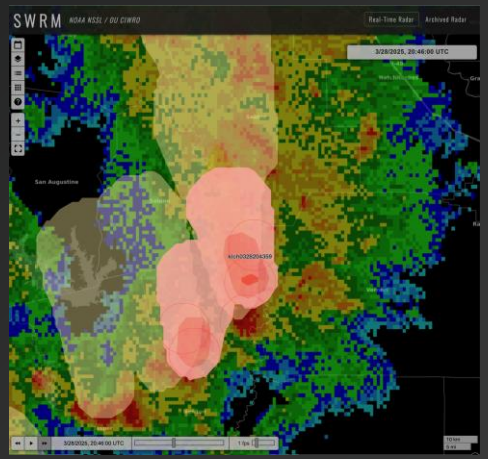
Use bigger radii/time windows at longer lead times

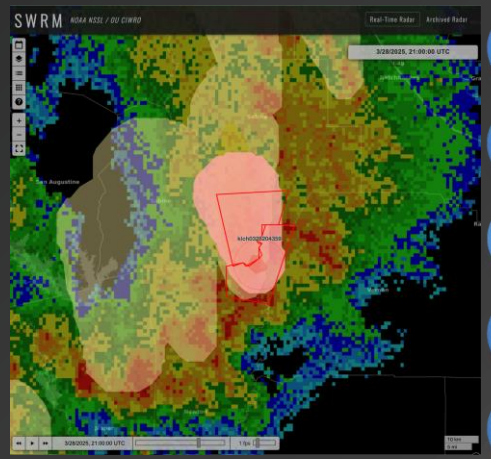
WoFS-PHI spatial probabilities will naturally decrease with lead time (as uncertainty increases)

We can take advantage of these tools and messaging strategies now!



1h, 15km WoFS-PHI tornado probs, valid 0230-0330 on 15 March 2025. Tornado LSRs (red dots) and warnings (red polygons) at 0330 UTC are shown.





Fully automated PHI plumes on 28 March 2025. Tornado PHI derived from TORP and warnings (red polygons) at 2046 and 2100 UTC are shown.