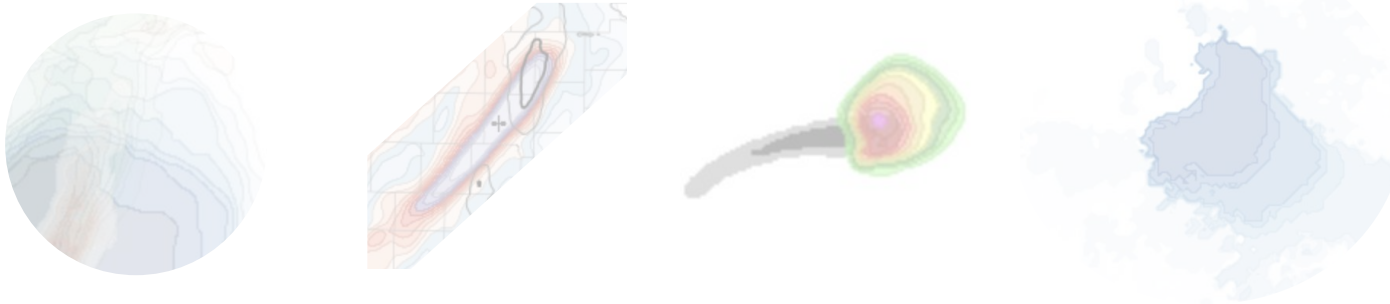
The Warn-on-Forecast System: Probabilistic Forecasts of Individual Thunderstorms

Patrick C. Burke

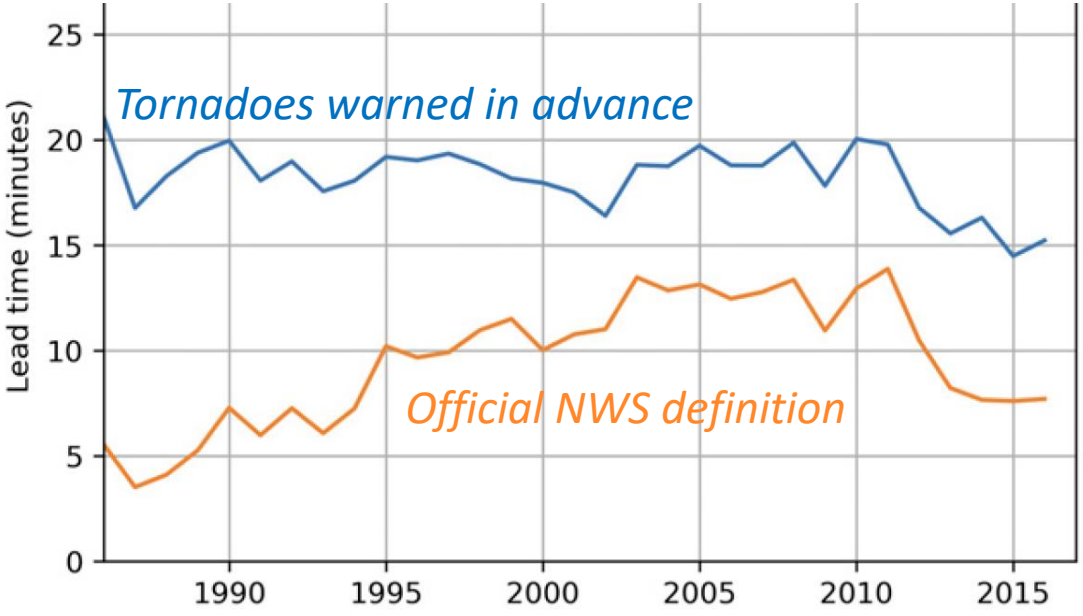
Warn-on-Forecast Program Lead

OAR / National Severe Storms Laboratory

Norman, OK



Tornado Warning lead time shows no significant trend; warnings based on radar, spotter reports (i.e., detection)



Brooks and Correia 2018

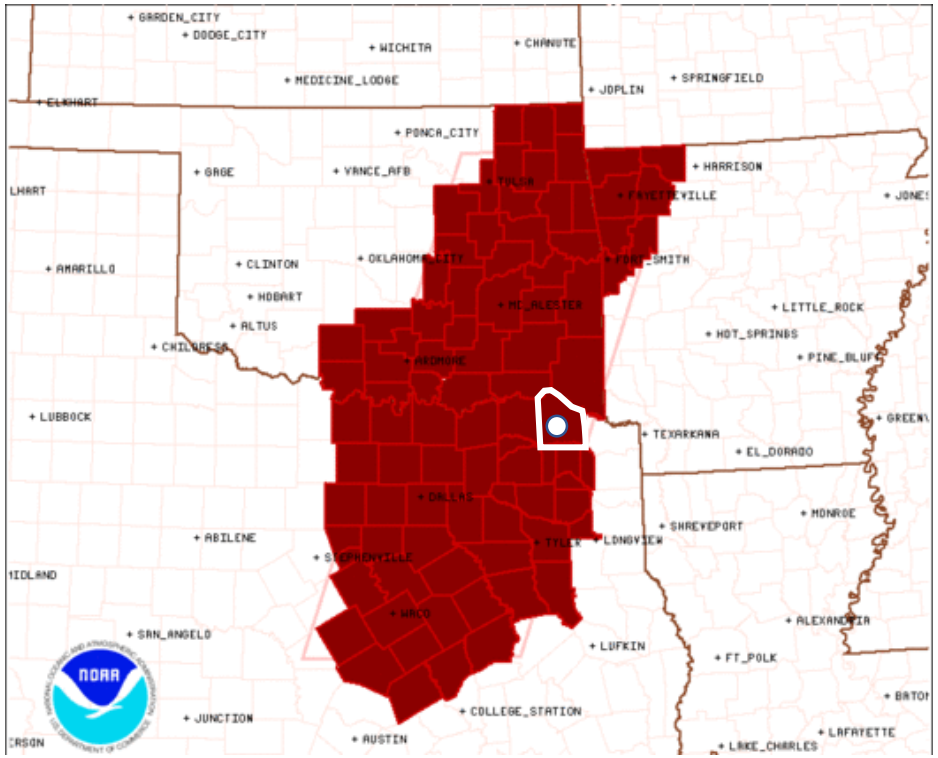
Many groups have fewer or more complex sheltering options, and could benefit from increased lead time

Maturing storm-scale models in the community

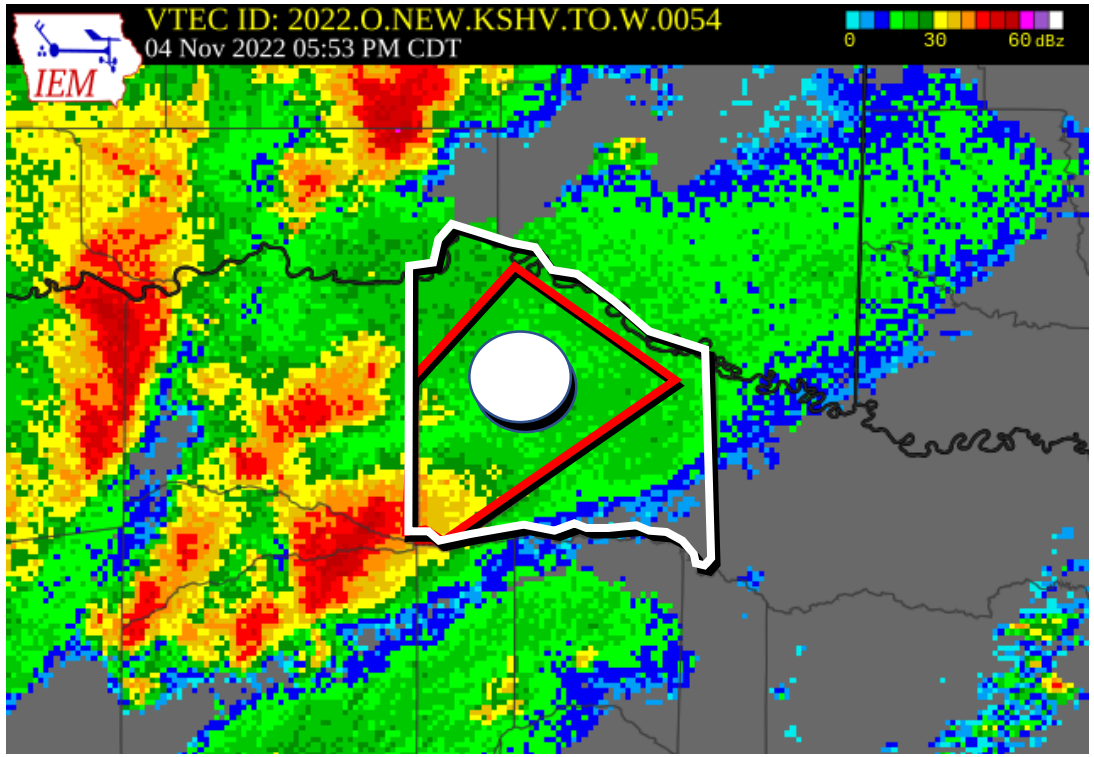
NSSL data assimilation and user-informed visualizations

In 2009, NSSL began a project to design a storm-scale NWP ensemble made specifically for “watch-to-warning” operations, 0-6 hours

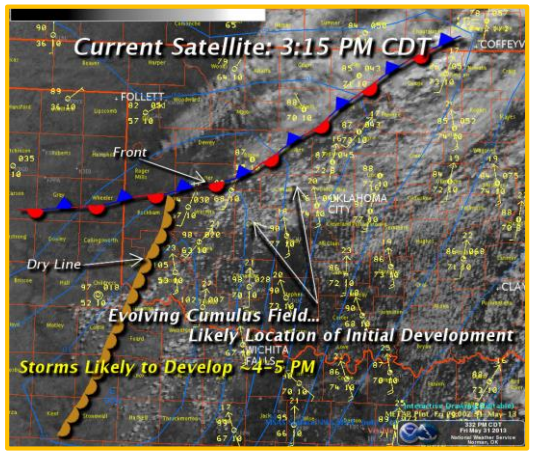
It often takes several hours for risk messaging to go from regional forecasts to local calls to action



Tornado Watch



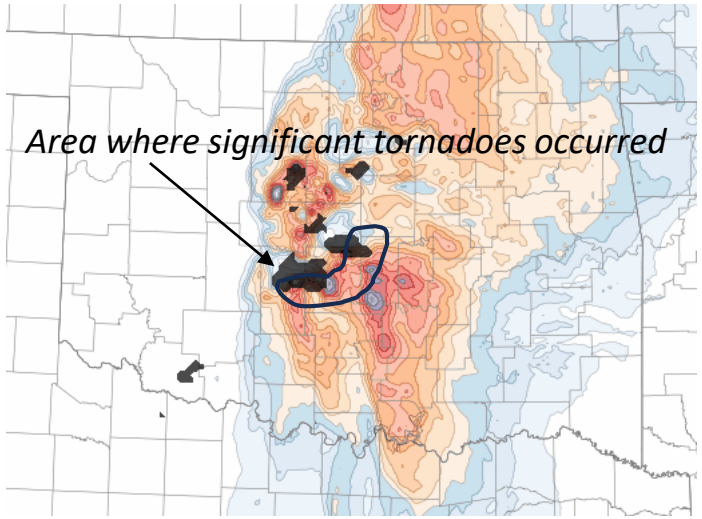
Tornado Warning



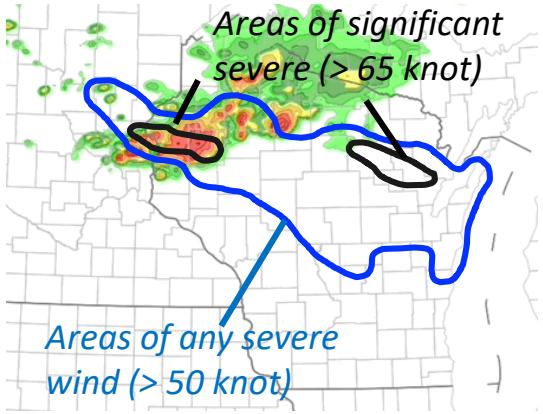
Everything leading up to the watch is informed by numerical guidance.

From Watch to Warning and Warning to Warning, observations dominate, and numerical guidance at the scale of city/county level decision-making has been lacking.

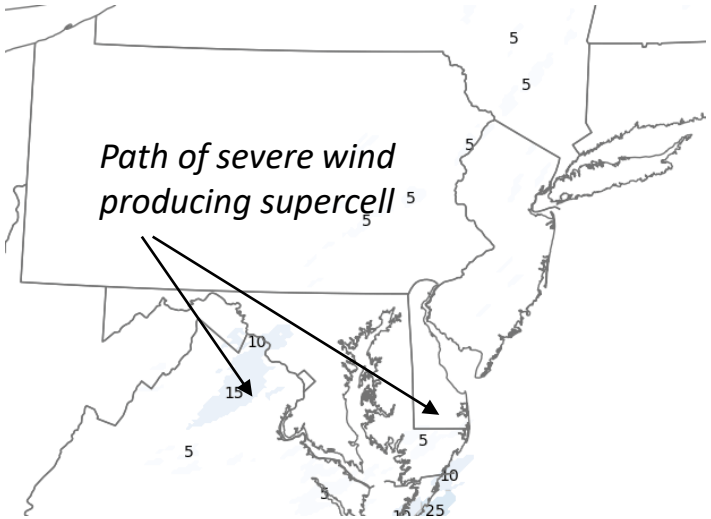
With the Warn-on-Forecast System



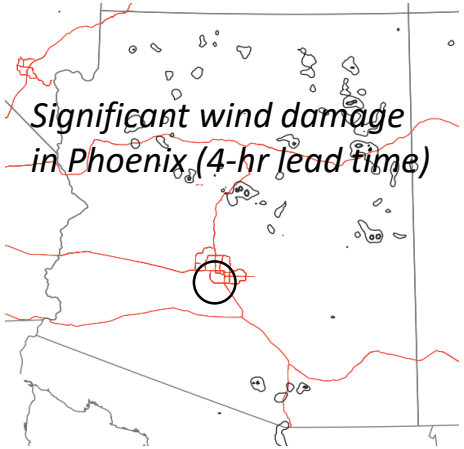
Significant Tornado Parameter (image) and observed storm objects (black fill)



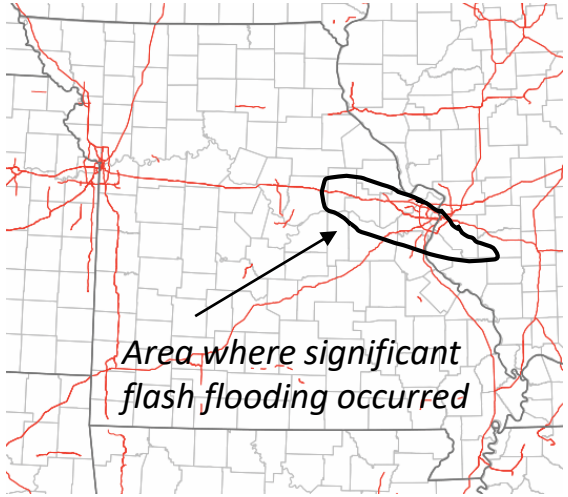
5-min simulated reflectivity and updraft helicity swaths



Machine-learning based storm-object, hazard-specific probabilities



90th percentile of maximum surface winds



WoFS single member 6-hr loop of 5-min rain rate

Tropical cyclone multi-hazard probabilistic plot (wind, rain, low-level rotation)

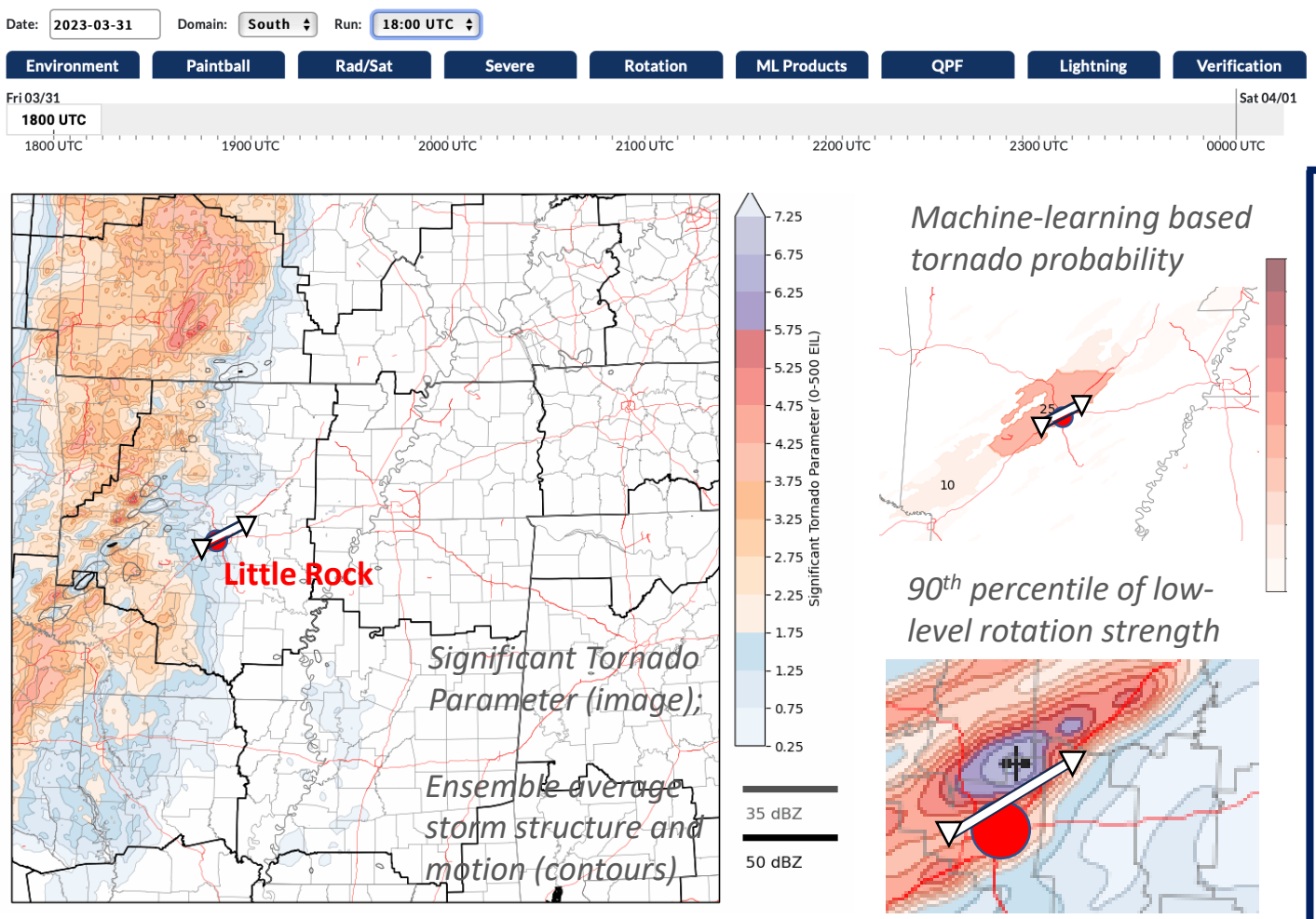
cloud-based

WoFS

Warn-on-Forecast System

Probabilistic forecasts of individual thunderstorms

wof.nssl.noaa.gov

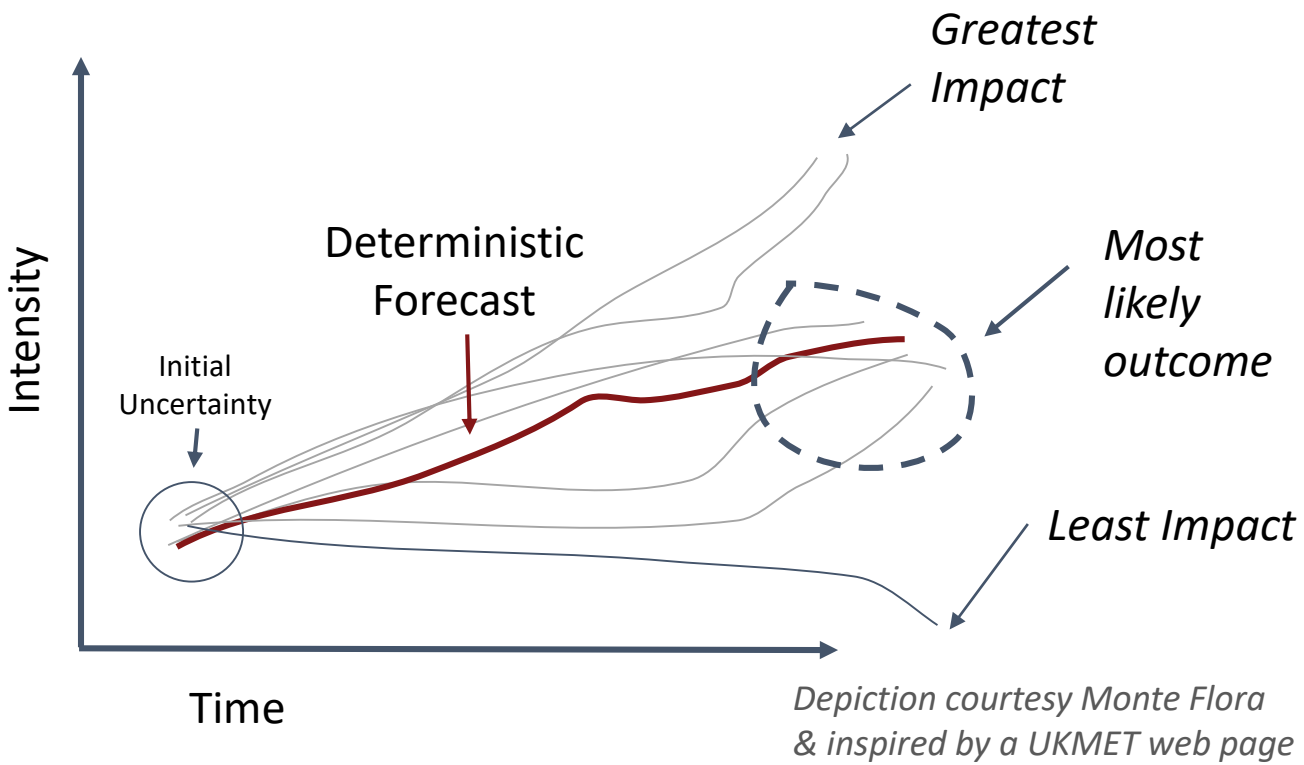


Snippets from the web-based viewer, WoFS products all corroborating the tornado potential at Little Rock with 82-minute lead time.

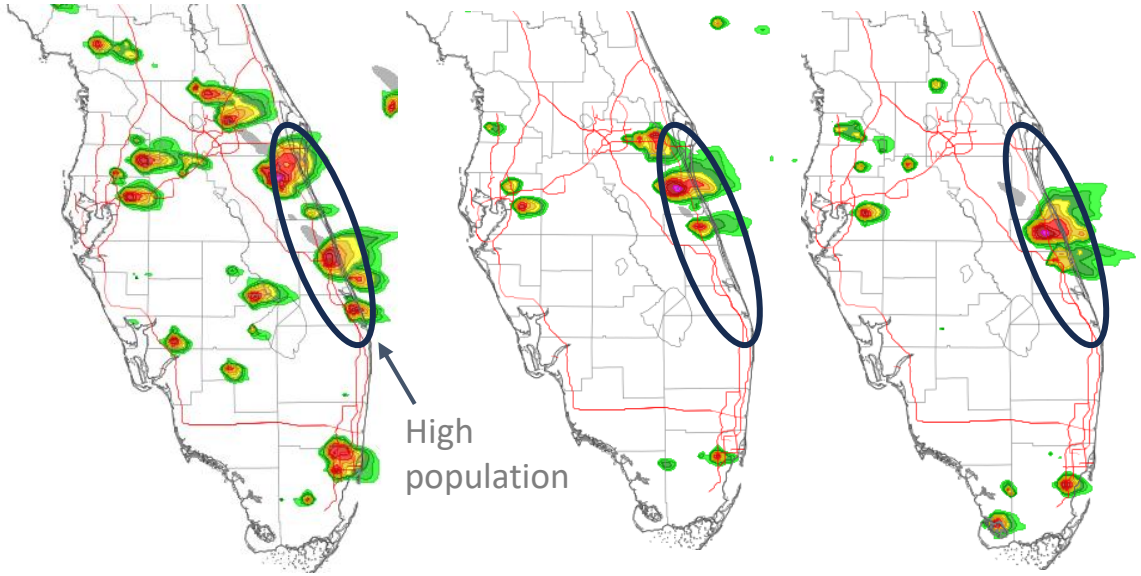
- *First-of-its-kind* storm-scale ensemble with rapid data assimilation (15-min) and rapid forecast relaunch (30-min)
- Output to 3–6 hours
- Members: 36 analysis, 18 forecast, 3-km
- Prototype 900-km squared domain; WoFS targets high-impact severe, flash flood events
- With containerized, cloud-based package multi-domains and/or larger domains possible

- System design emphasizes:
  - Probabilistic forecasts & IDSS
  - Machine learning
  - User-influenced visualization for easy, fast-paced use

	HRRR (state of the art single run)	WoFS (first of its kind ensemble)
WRF-based; RUC LSM; 36-member GSI-EnKF analysis; 3km grid spacing; 50 vertical levels	✓	✓
Designed as a forecast ensemble		✓
Radar reflectivity assimilated	✓	✓
Radar velocity assimilated		✓
GOES clear sky radiances	✓	✓
GOES CWP assimilated		✓
Multiple PBL Schemes (YSU, MYJ, MYNN)		✓
Microphysics	Thompson Aerosol Aware	NSSL Double Moment
Data assimilation cadence	60-min	15-min
Temporal resolution of output	15-min	5-min
Images per forecast run	~ 2,000	~ 20,000
Calibrated machine-learning based probabilities of individual hazards		✓



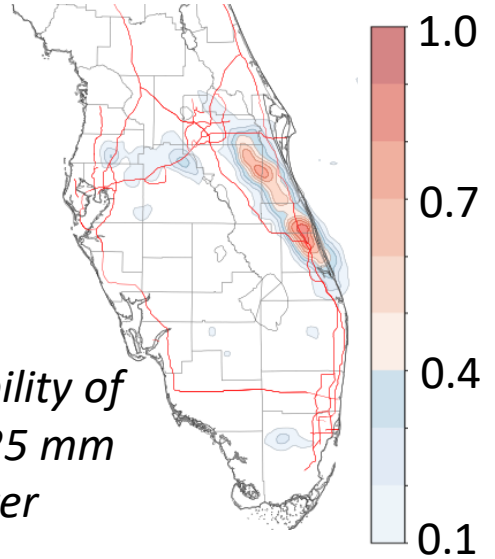
Depiction courtesy Monte Flora & inspired by a UKMET web page



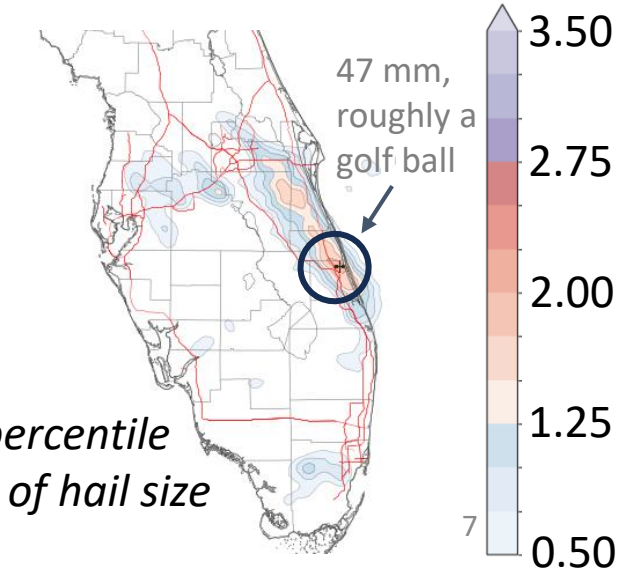
Greatest Impact | *Most likely outcome* | *Least Impact*

Probabilistic information is needed.

City-level details of convective forecasts show varying location, size, intensity, and motion.



Probability of hail > 25 mm diameter

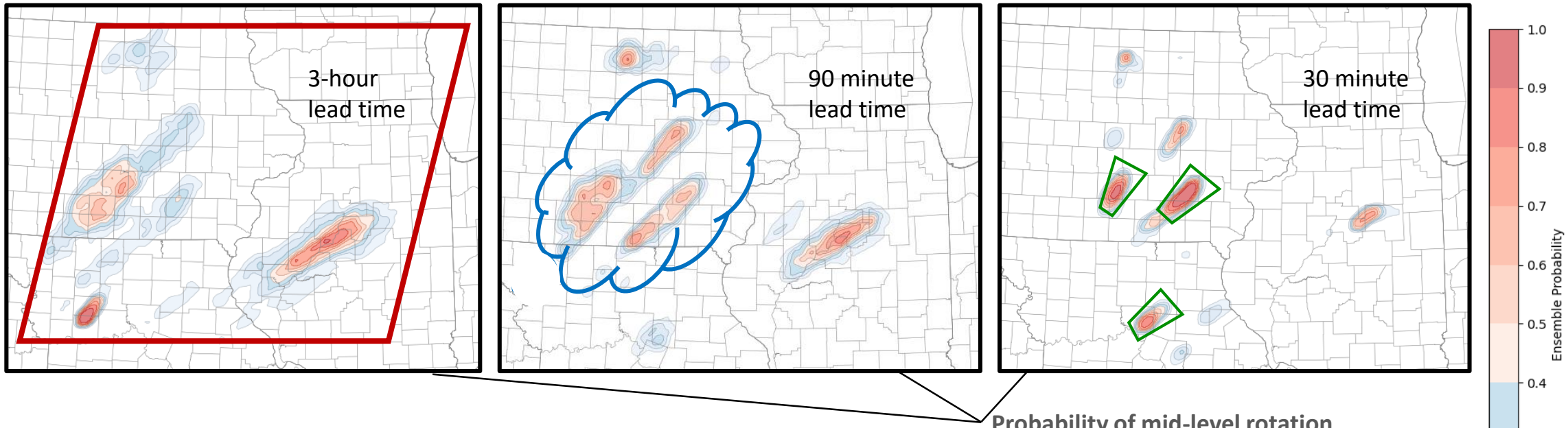


90th percentile value of hail size

WoFS Enables Probabilistic Severe Storms Communication

(i.e., Forecasting a Continuum of Environmental Threats, or Probabilistic Impact-Based Decision Support Services)

WATCH → WARNING



Probability of mid-level rotation from three different WoFS runs; these show the accumulated swath of probability of 2-5 km updraft helicity > 60 $m^2 s^{-2}$, all ending at the same time but of differing duration.

WoFS fills a critical gap in which newly arriving, probabilistic numerical model guidance has been lacking

3km Warn-on-Forecast System
Transition Plan

3km Warn-on-Forecast System

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Patrick Marsh[2], Chad Gravelle[3]
[1]OAR/NSSL, [2]NWS/SPC, [3]NWS/Southern Region

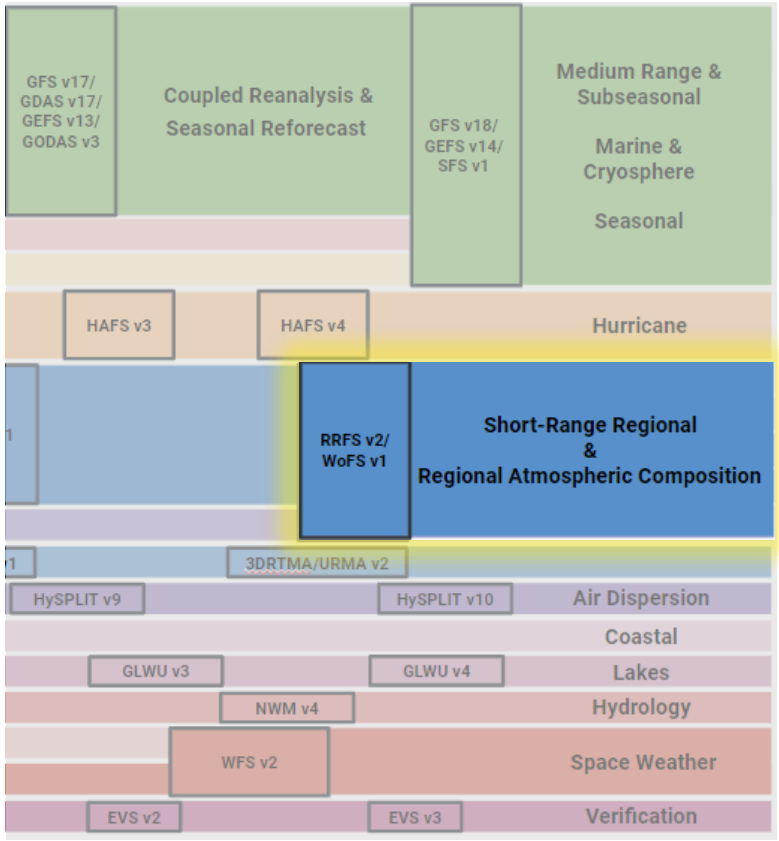
Research to Operations Transition Plan

Office of Oceanic and Atmospheric Research
and
National Weather Service

Date Submitted

Draft OAR/NWS transition plan.
Seeking approval later in 2023.

WoFS is anticipated around the same time as RRFS v2 on the Environmental Modeling Center's "rainbow chart." Or ~ 2 years after RRFS v1 implementation.



Collaborative Approach

NOAA Partners

University Partners

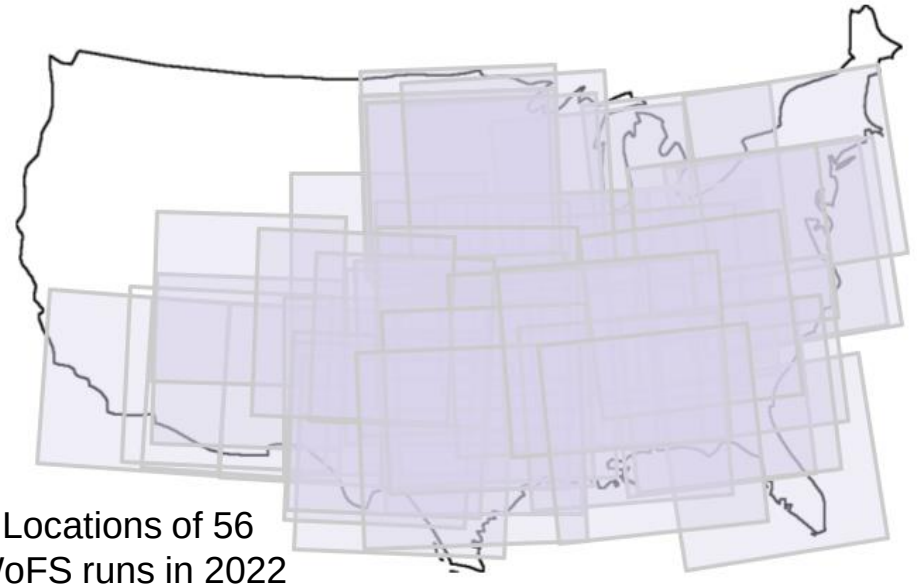
Norman Community

NOAA/NWS

Stakeholder Groups

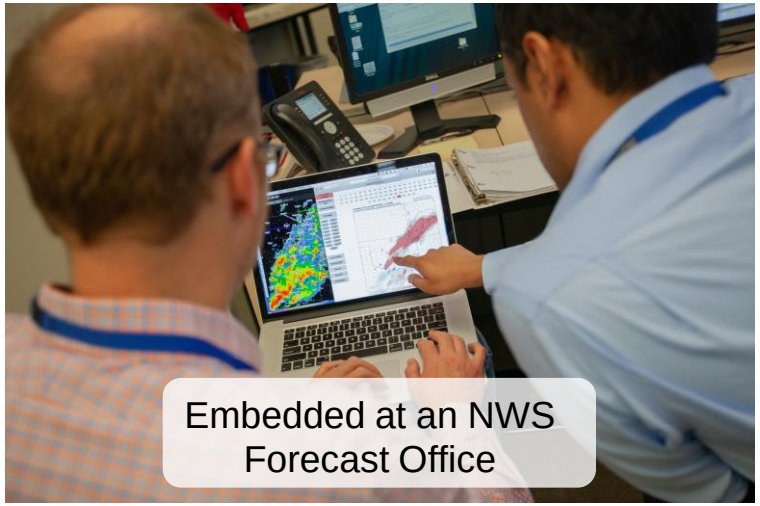
Emphasis on user engagement

Virtual Testbed Experiment



Locations of 56 WoFS runs in 2022

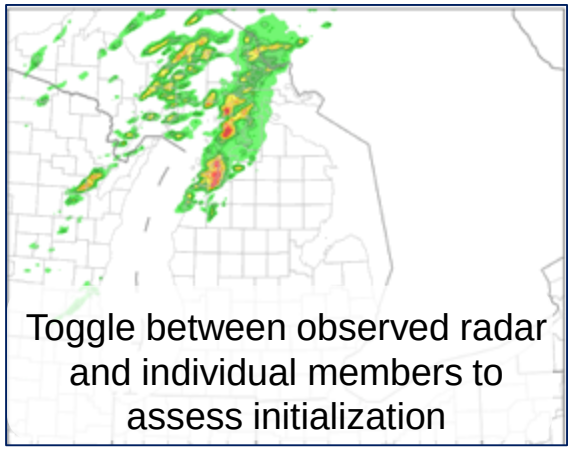
Oklahoma Emergency Managers Association Conference



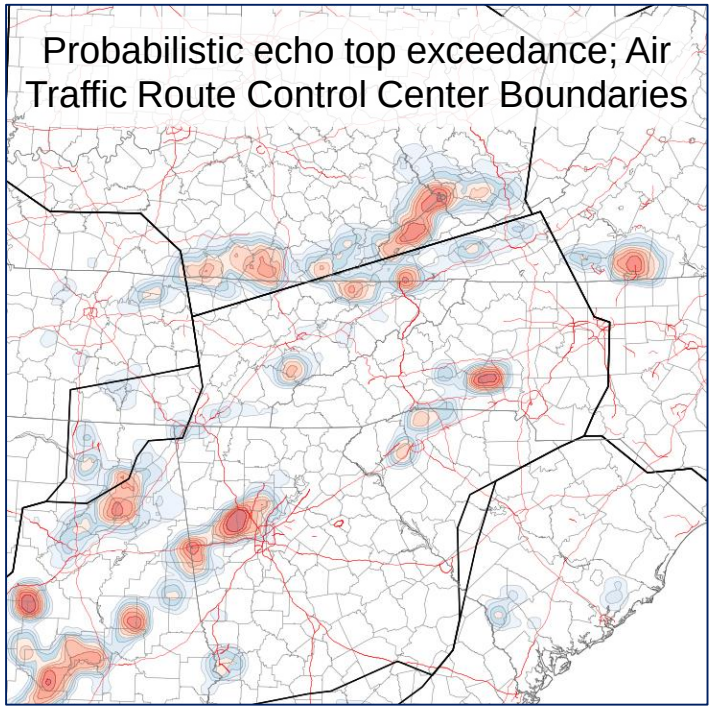
Embedded at an NWS Forecast Office

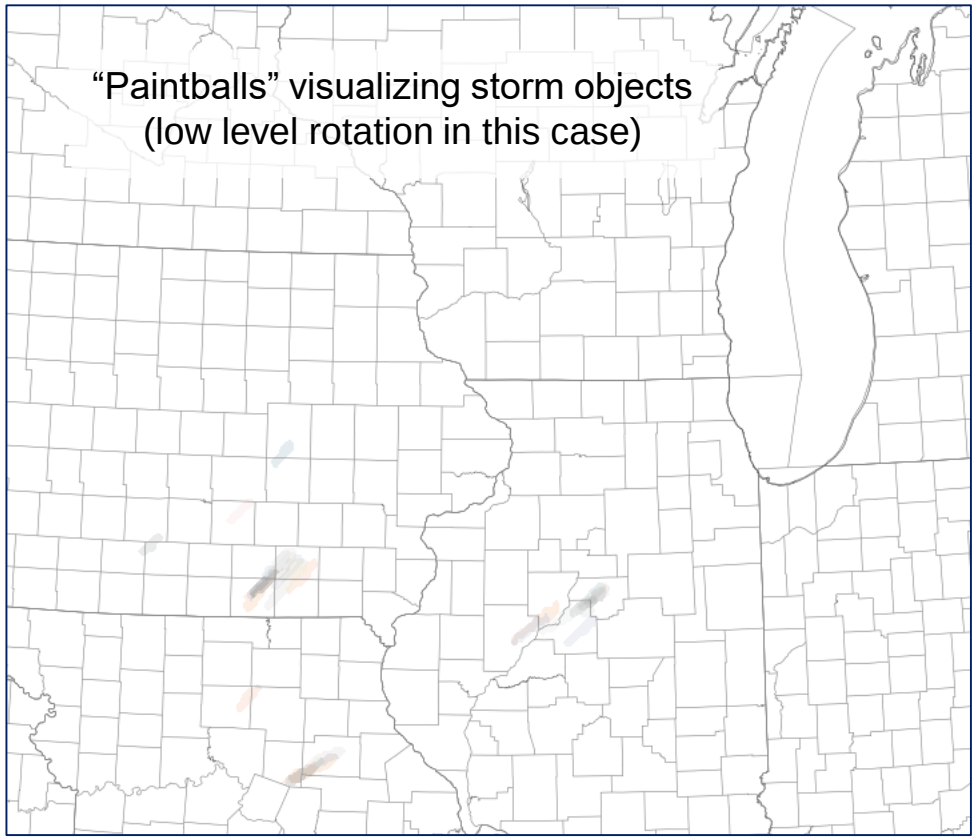
Invited to the Aviation Weather Testbed

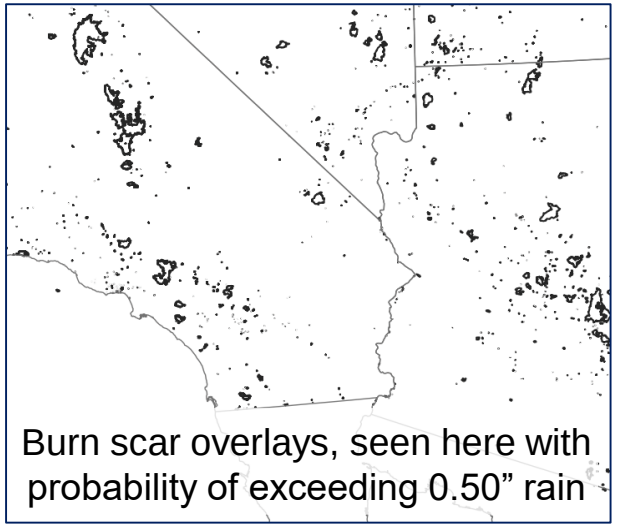
Resulting Design Gains



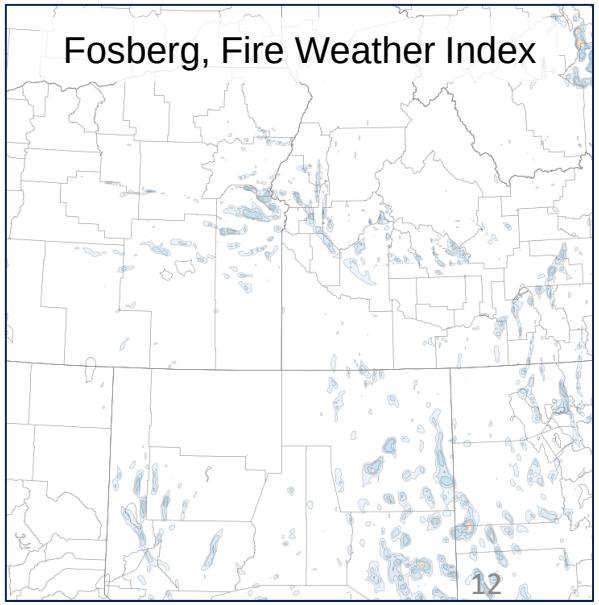
Toggle between observed radar and individual members to assess initialization







Burn scar overlays, seen here with probability of exceeding 0.50” rain

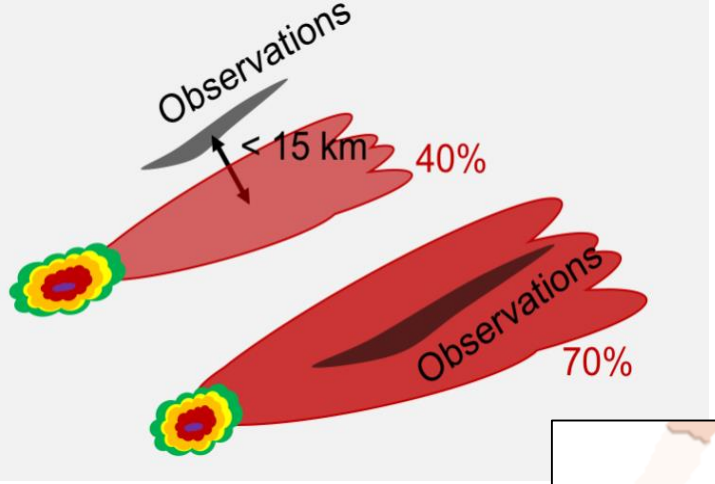


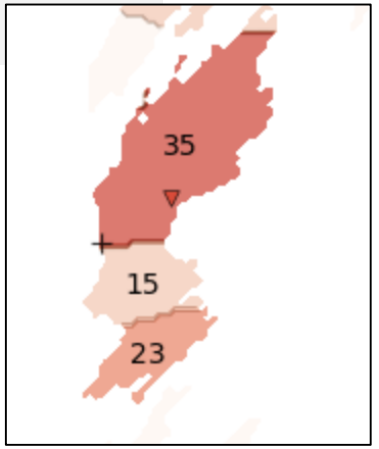
Machine Learning-based Probabilities

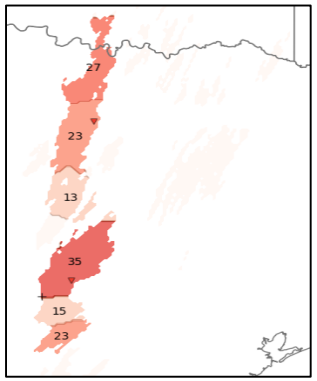
Event probability – what is the probability that X hazard will be reported in the event space during the specified time frame?

Event space – the space carved out by the identified storm or storm cluster across the 18 WoFS forecast members

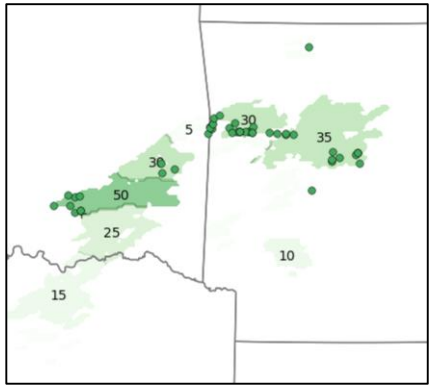
In principle – On time scale of WoFS we should have enough confidence in storm location and track to break away from spatial probabilities (circular neighborhood around a point)



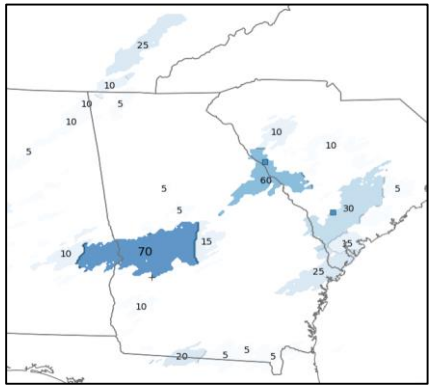




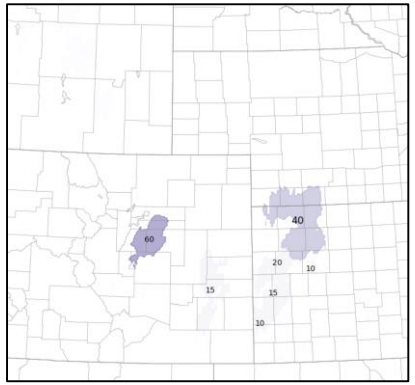
Tornado



Hail



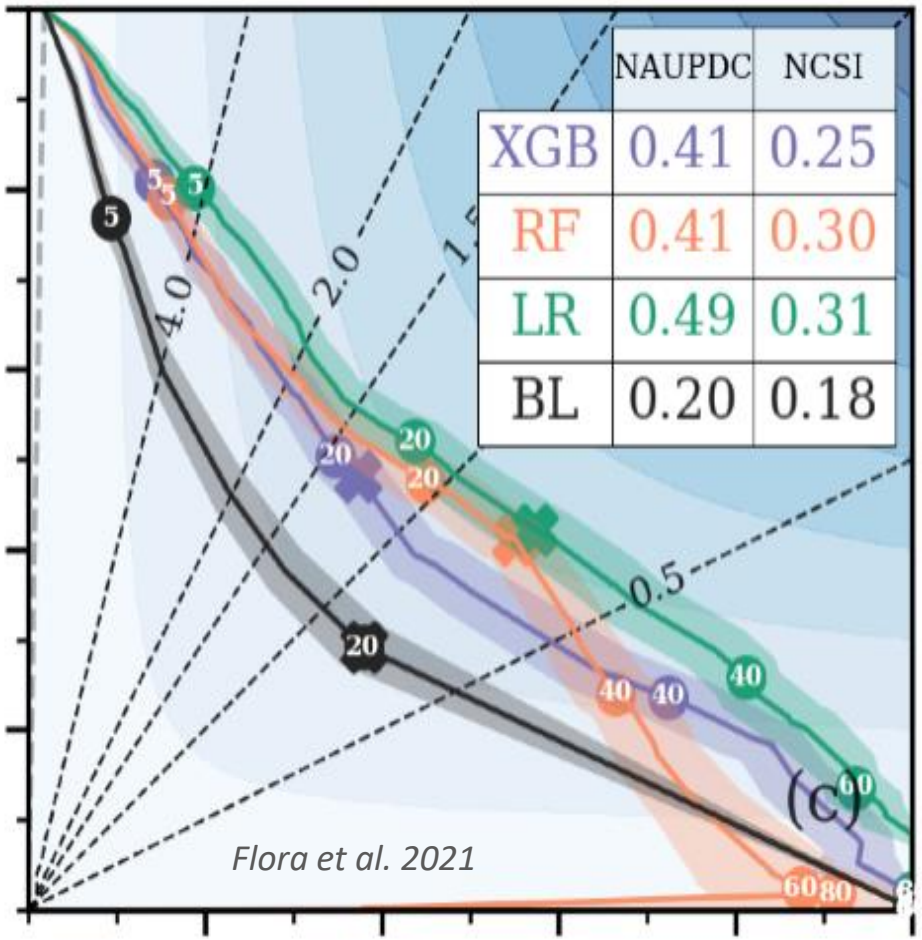
Wind



Any Severe

Significant Severe

ML products are more reliable

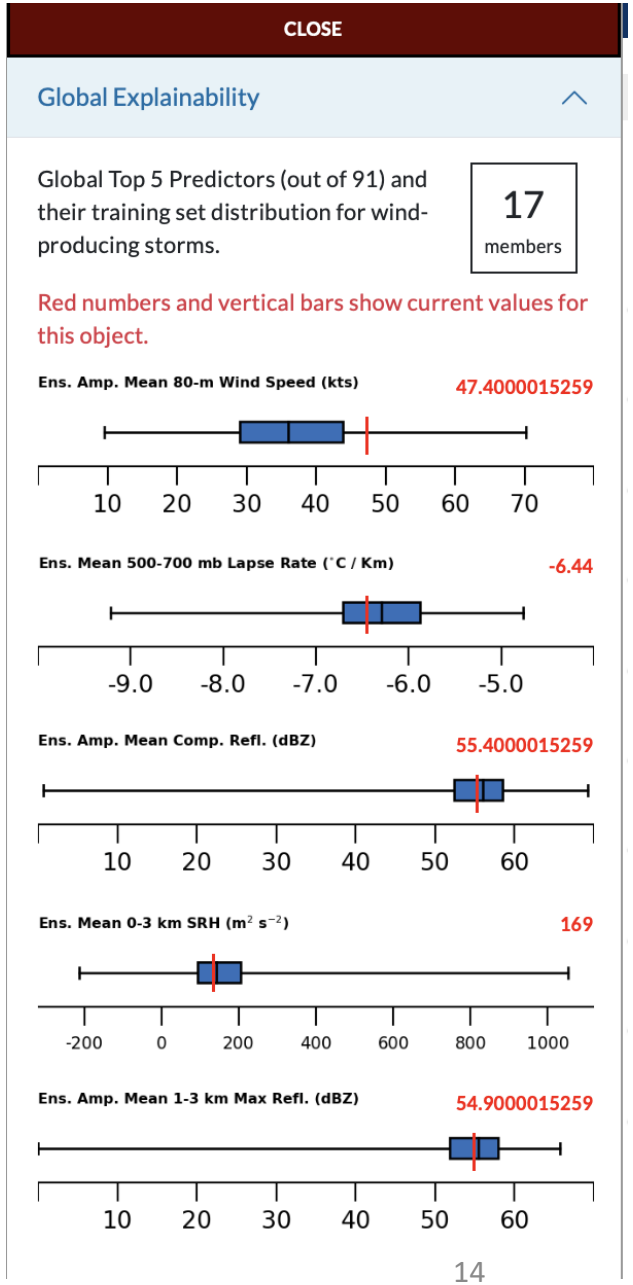


BL = Baseline (calibrated WoFS output)

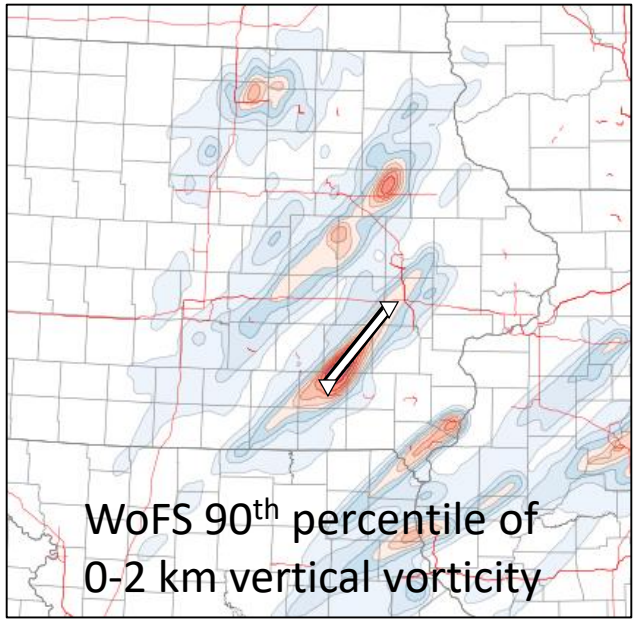
LR = Logistic Regression (the model we've chosen to carry forward)

Explainability graphics help create trustworthy AI

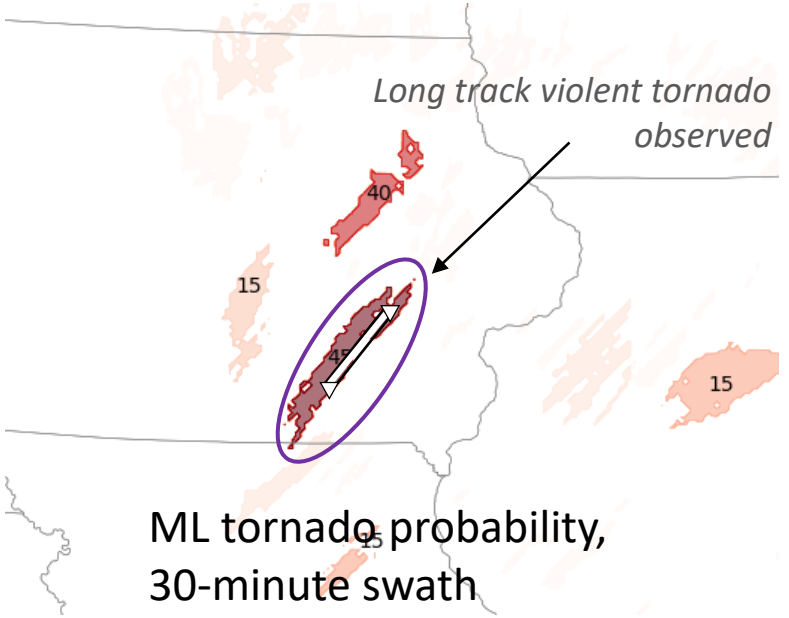
Red ticks and readouts indicate where the current object falls on the respective distributions for the top 5 predictors of this hazard in the training dataset.



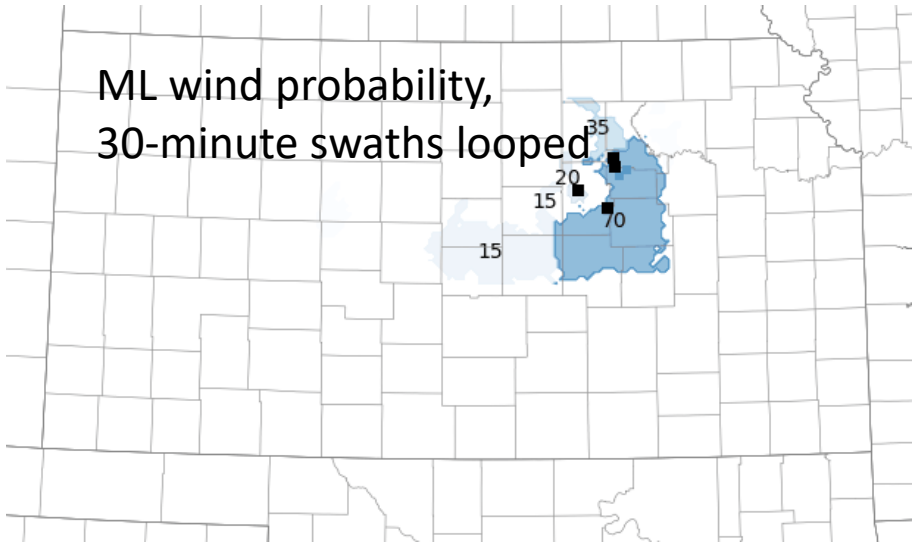
Pair with other fields to gain confidence



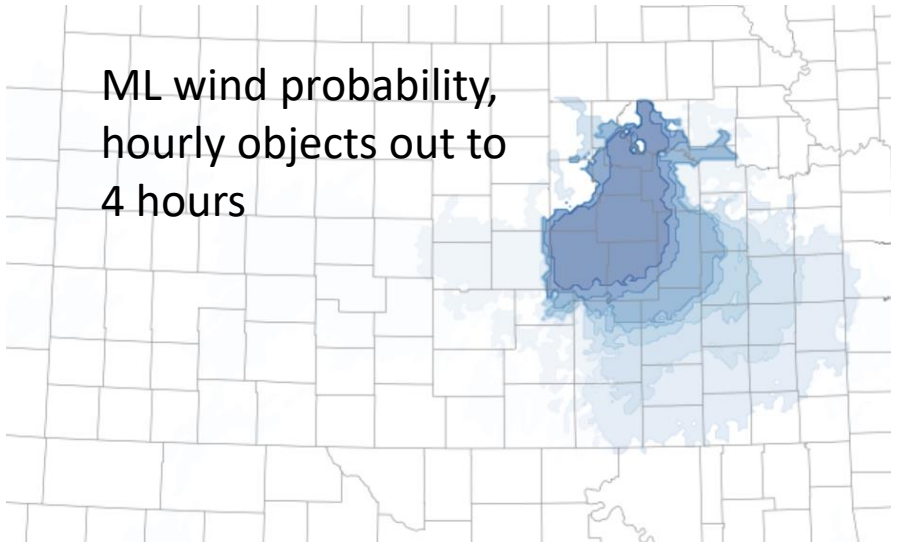
WoFS 90th percentile of 0-2 km vertical vorticity



ML tornado probability, 30-minute swath



ML wind probability, 30-minute swaths looped



ML wind probability, hourly objects out to 4 hours

Different means for visualizing severity trends

Cloud-based WoFS (cb-WoFS)

Experimental real-time runs are executed on the Microsoft Azure cloud since 2022

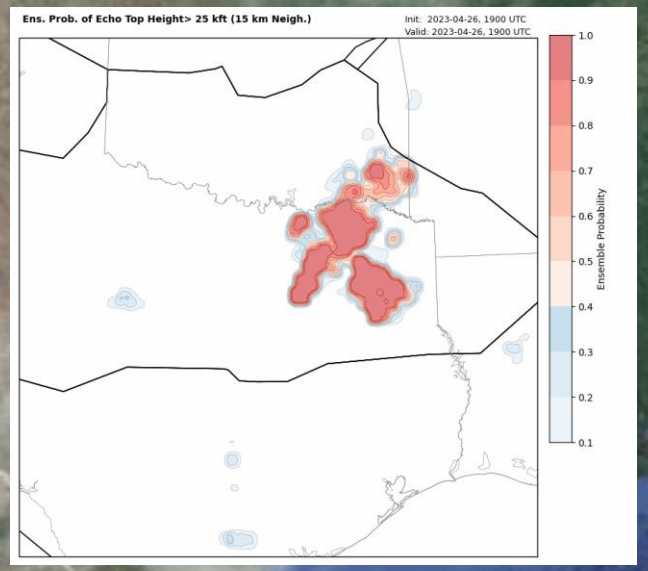
- Removes dependency on in-house research HPC
- cb-WoFS is containerized, drop it on any nodes and start running (no need to compile)
- Automatically see the benefits of Microsoft upgrades to their machines
- Ability to throttle resources on-demand so WoFS will catch up to real time in the event of any data delays or hiccups
- Helping the field explore this space, learning ins and outs of running a model on the cloud
- Cheap ! ~ $1,000 per run (i.e., day). Other costs associated with data storage / egress

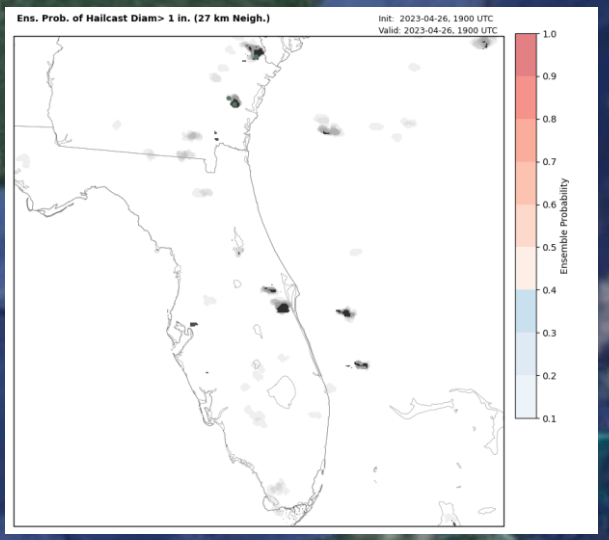
Using the intuitive interface, one could set a domain and start a run using their smart phone.

Dual domain demonstration

"Watching the WoFS solution…we've already messaged that our southwest and southeast posts will be shut off..."
- NWS Fort Worth aviation meteorologist

"Thanks WoFS team for spinning up the [Florida] domain yesterday!"
- NWS Jacksonville Science Officer

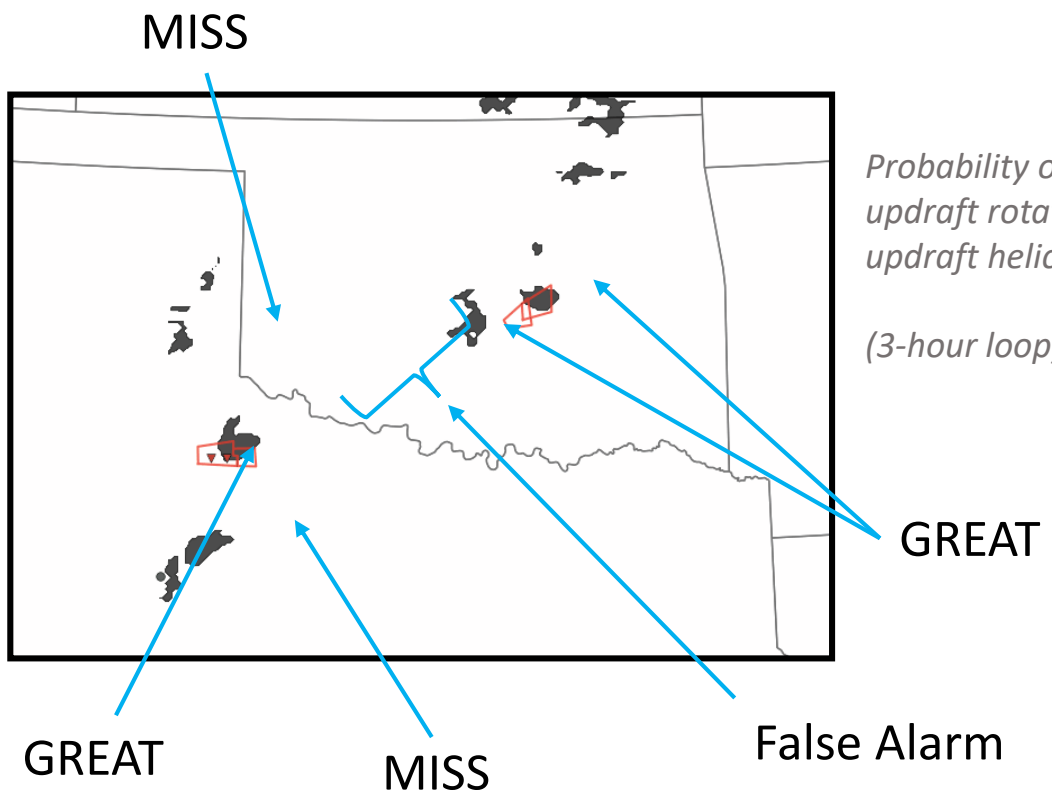




26 April 2023

Use of Experimental WoFS in Operations

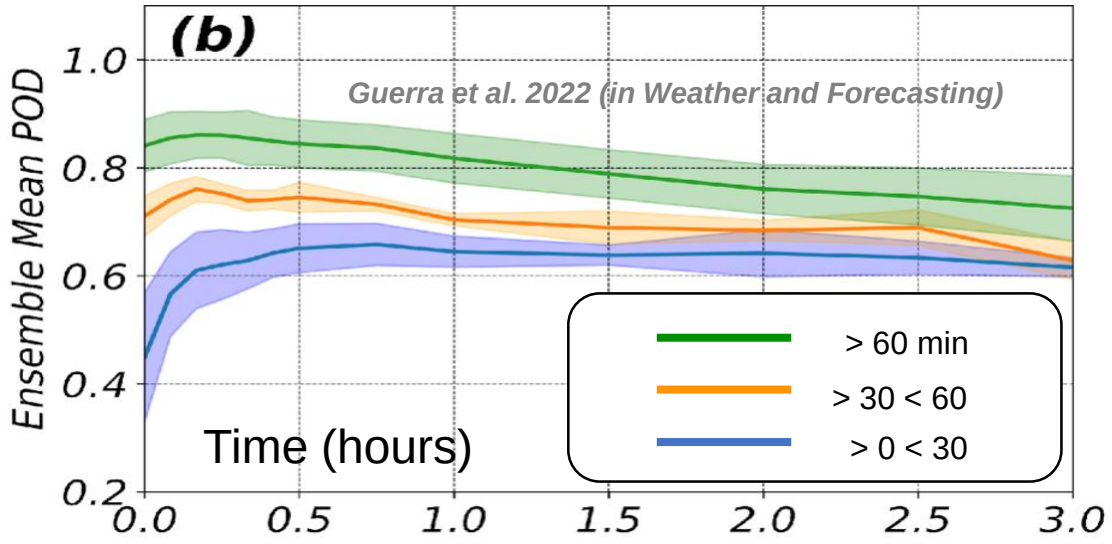
- Assess how well an individual storm is assimilated. WoFS is a collection of forecasts of individual storms.
- Don't give up. WoFS' rapid assimilation allows it to catch up after an initially poor forecast.



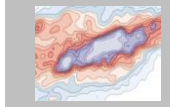
Probability of mid-level updraft rotation (2–5 km updraft helicity)

(3-hour loop)

More than 60 minutes worth? Best !
More than 30 minutes worth? Great !
Assimilated some obs of storm? Good !

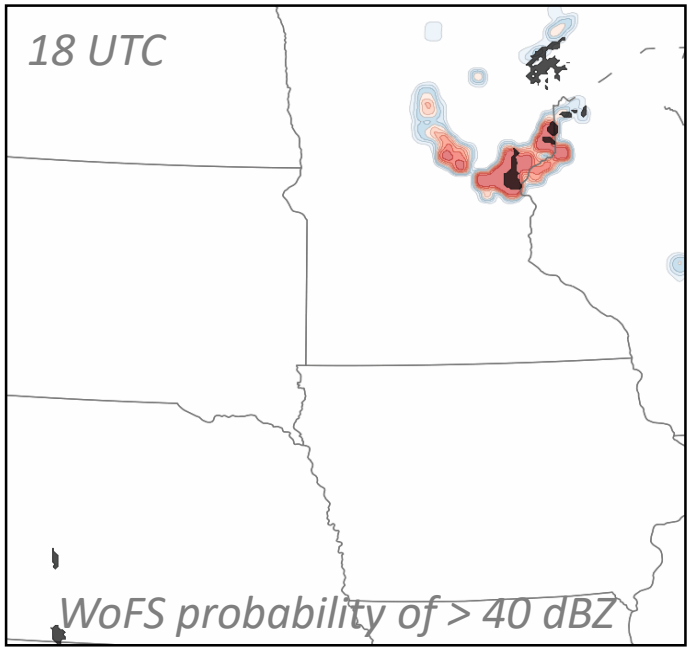


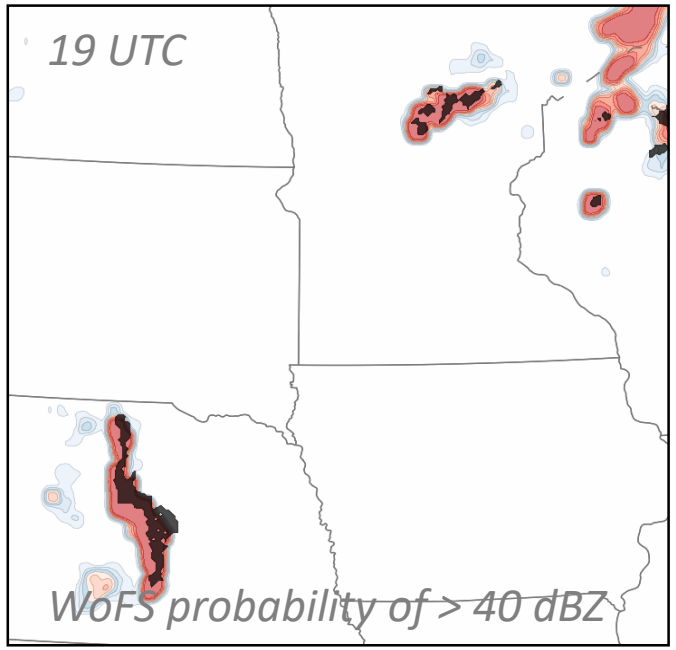
Dark blobs are the observed storms, from radar (NSSL MRMS)

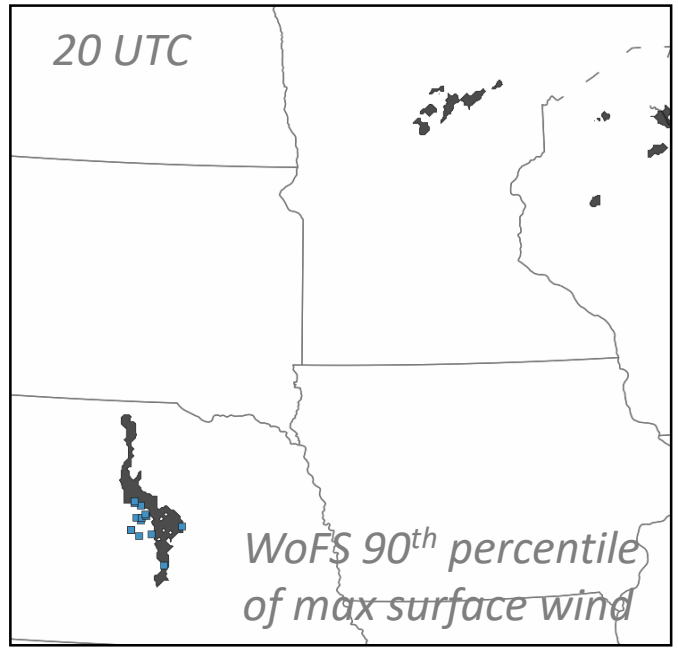


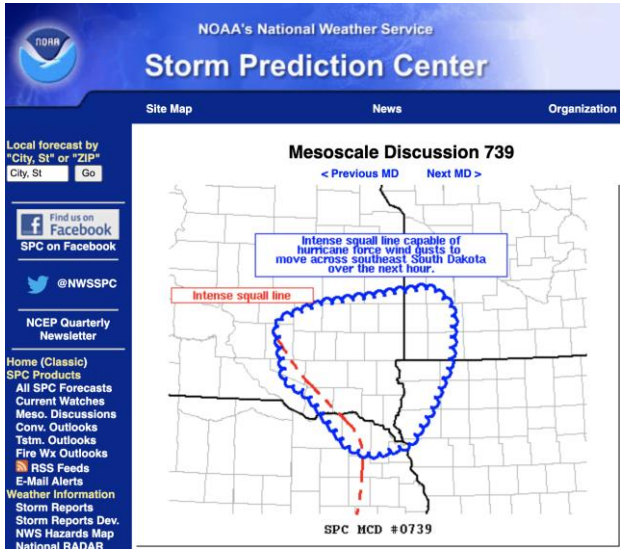
Color-filled streaks are where some of the 18 WoFS members are placing storms with intense rotation

Observed storms are dark patches



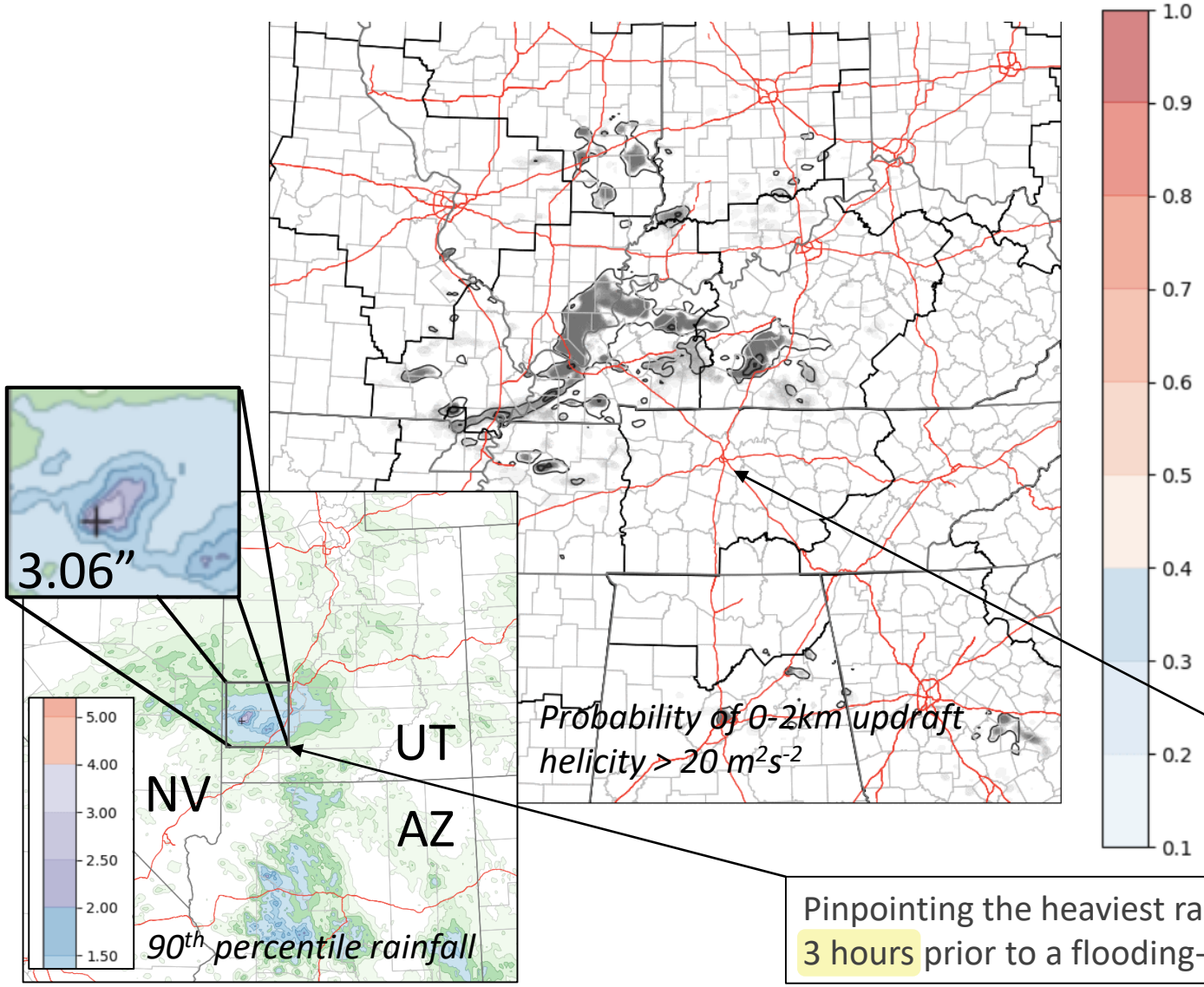






- New WoFS runs every half hour between 1900 and 2100 UTC consistently forecast a high probability of high-end winds
- NWS-NSSL WoFS Google Chat room discussions boosted WFO North Platte's confidence to issue severe thunderstorm warnings with Wireless Emergency Alert tags
- An SPC mesoscale discussion at 2130 UTC cited radar and "...several consecutive runs of the WoFS…" to support "...widespread 75+mph winds likely with some gusts approaching 100mph possible."

Groundbreaking Accuracy at Greater Lead Time



Increased lead time means earlier and more accurate communication of:

1) probabilities
2) uncertainties
3) near certainties

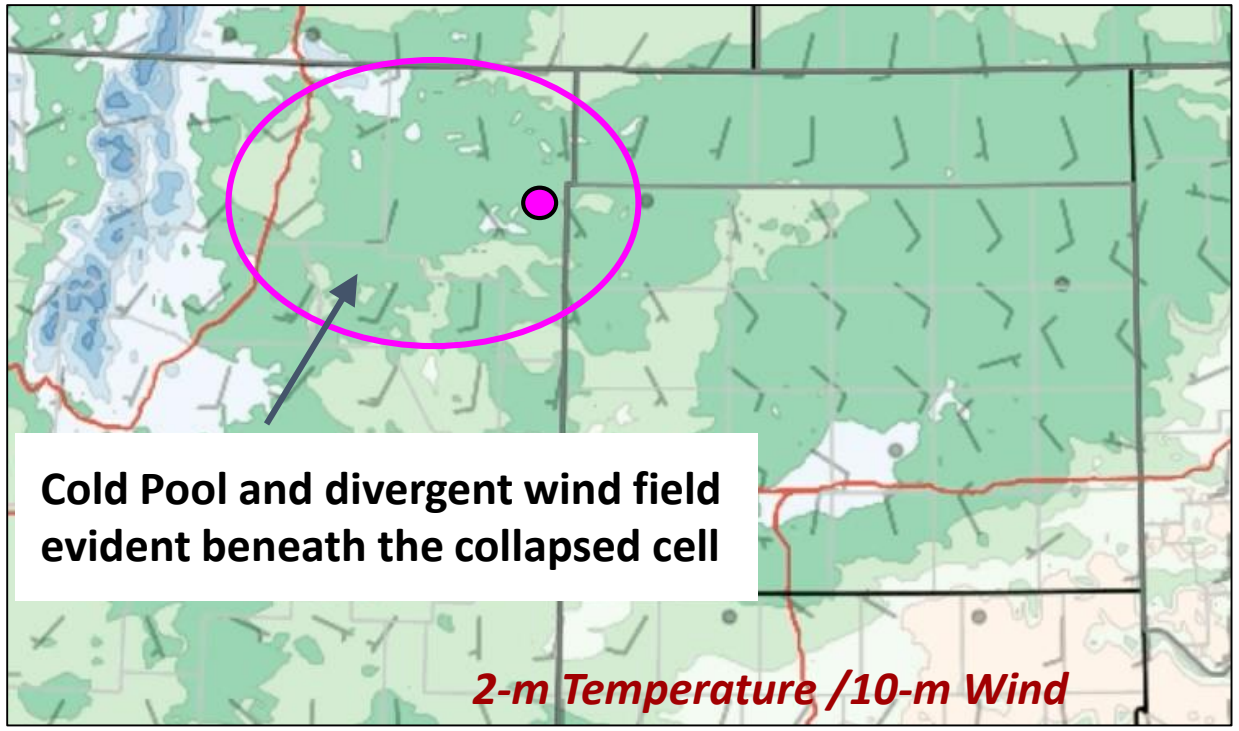
2 to 3 hour lead time on strongly rotating storms coming into Nashville (March 2020)

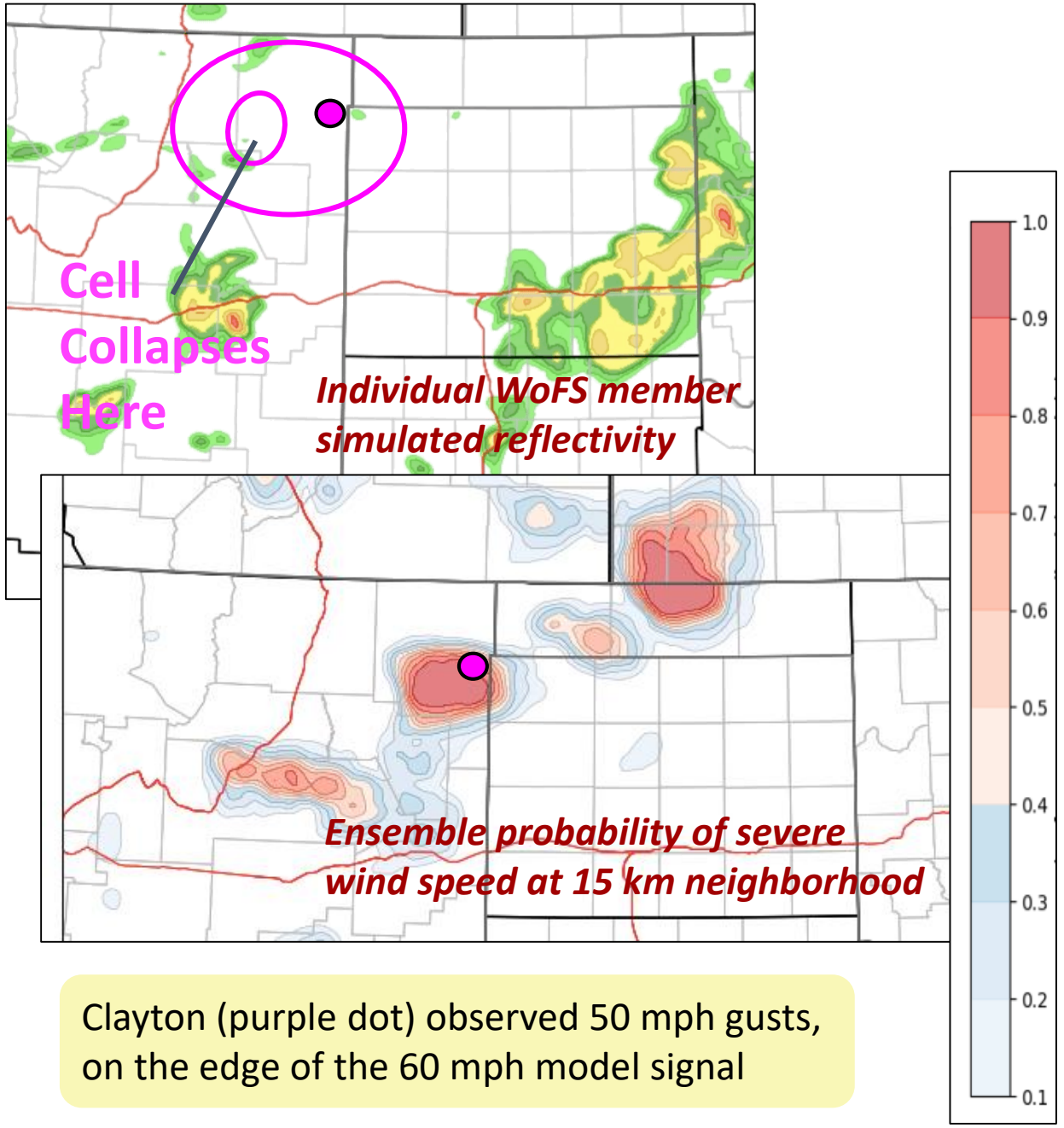
Pinpointing the heaviest rain that will occur in the 900km x 900km domain 3 hours prior to a flooding-induced train derailment (July 2021)

Individual Cell Collapse

7 May 2021
National Weather Service Albuquerque

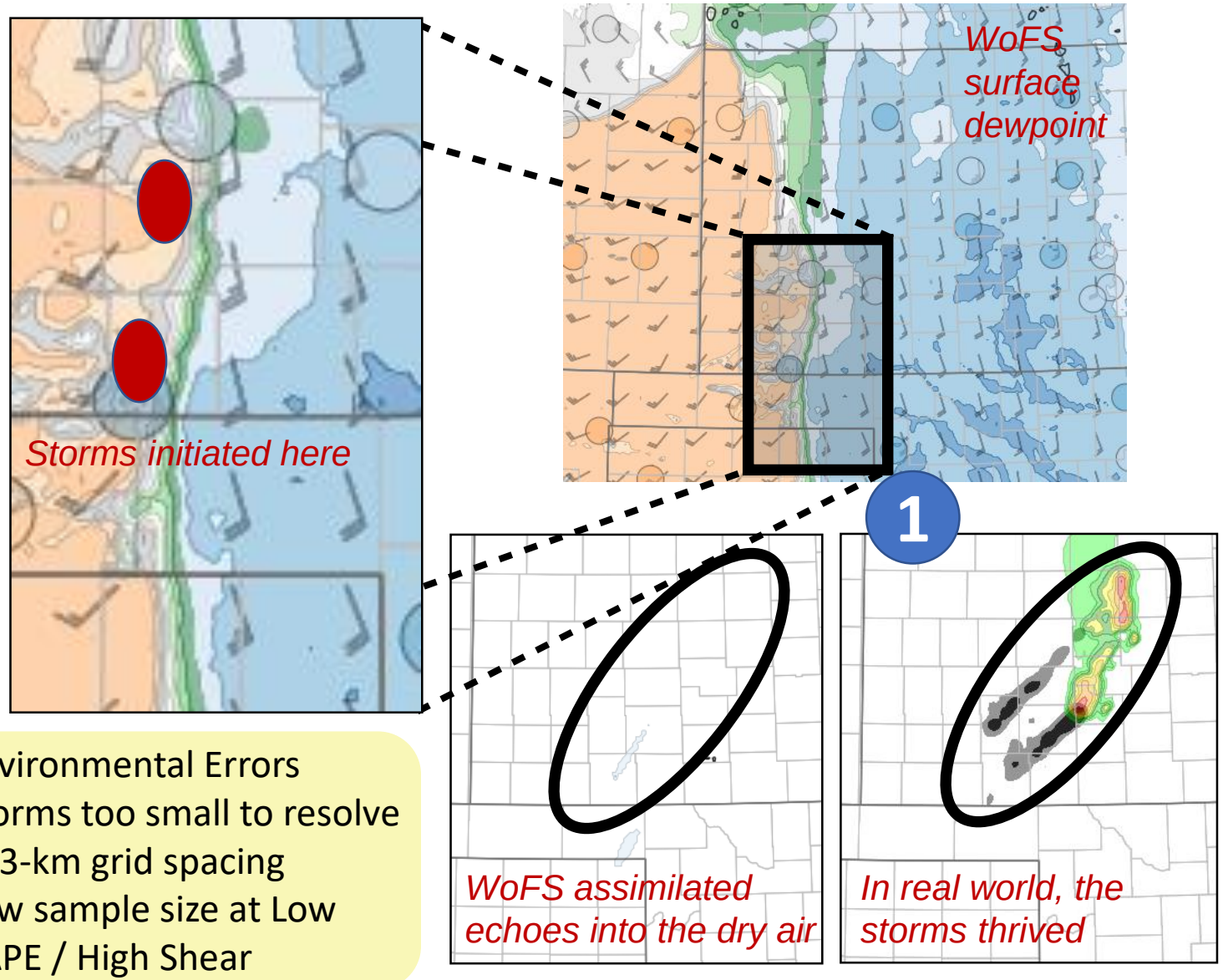
Forecasters latched onto the cohesive swath of high probability severe winds where reflectivity was fractured or had fallen apart.



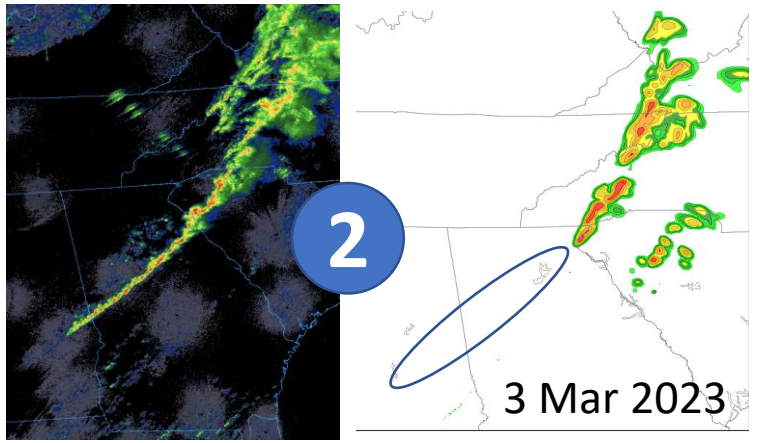


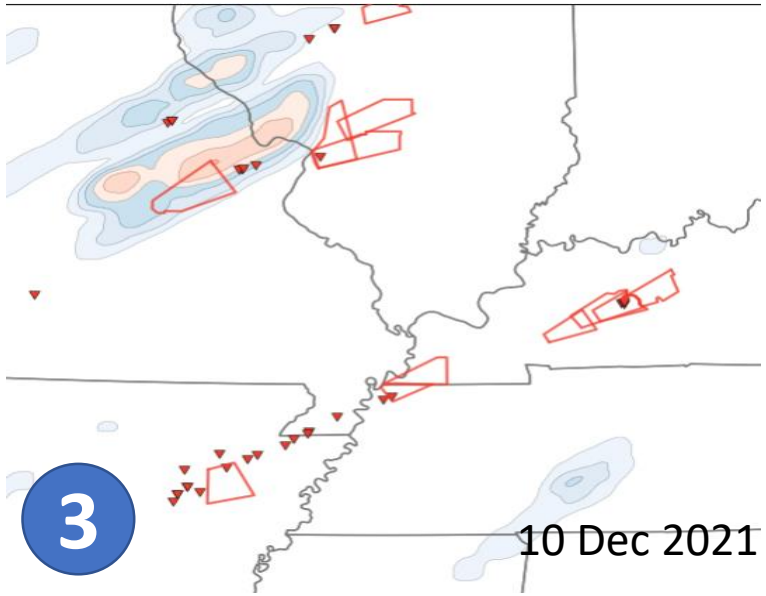
Clayton (purple dot) observed 50 mph gusts, on the edge of the 60 mph model signal

Common Failure Modes



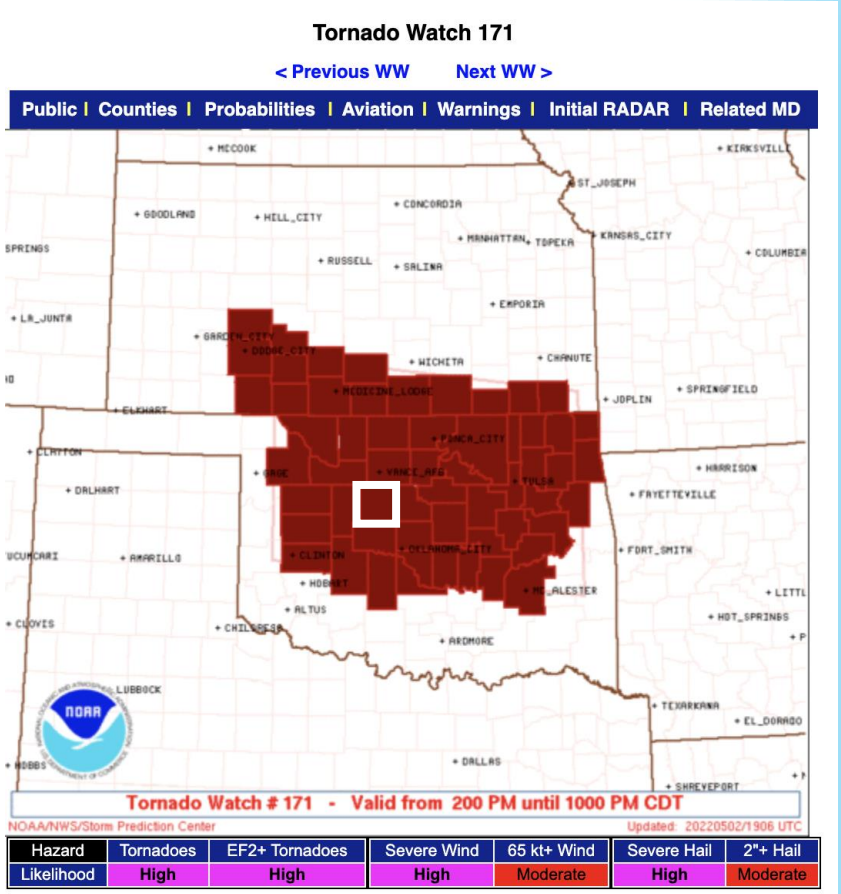
1. Environmental Errors
2. Storms too small to resolve at 3-km grid spacing
3. Low sample size at Low CAPE / High Shear



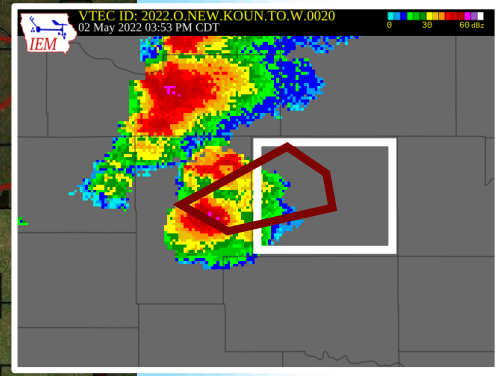


Caution: WoFS is beguiling!

Watch-to-Warning Graphic



SPC Watch
2:00pm

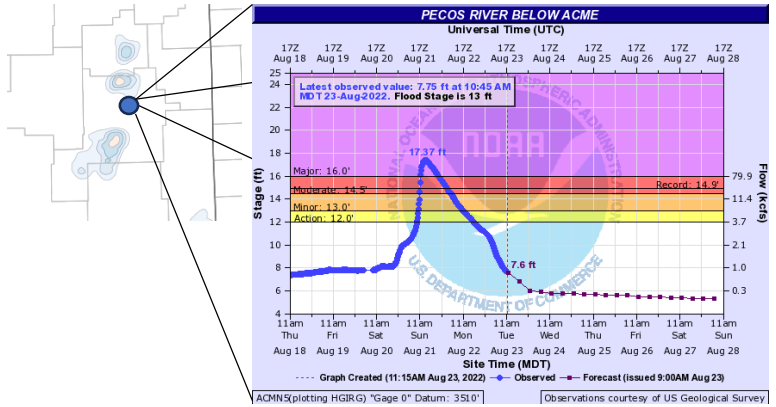


May 2, 2022
WFO Norman, OK

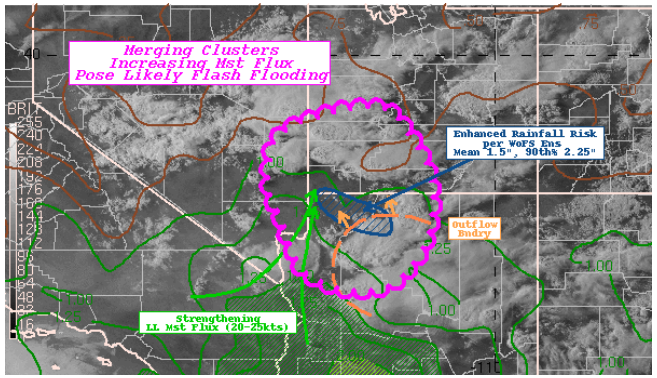
Tornado Warning
3:53pm

Public graphic from WFO, informed by WoFS, depicting currently the greatest threat within the watch, 2:27pm

NWS Chat Message to partners

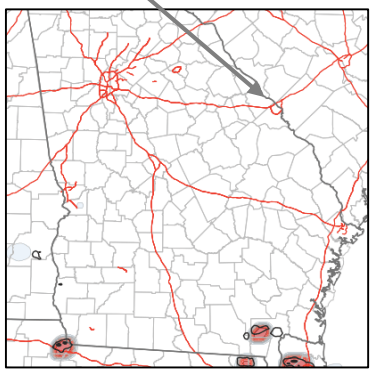


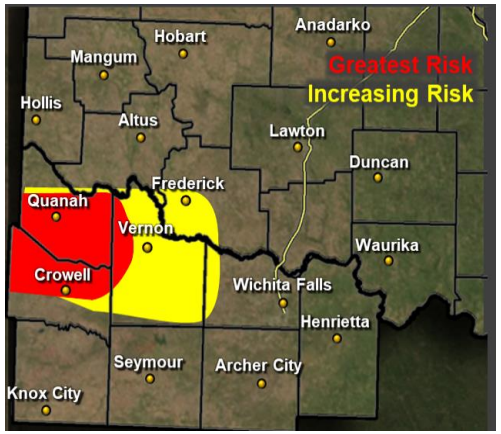
National Center mesoscale discussions (SPC and WPC)



Promoting ideas from the Local Forecast Office to an Emergency Manager or River Forecast Center

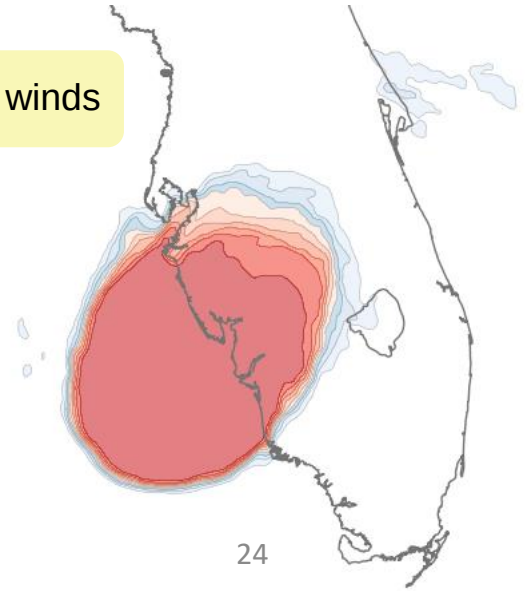
Masters Golf Tournament
Augusta, Georgia





Impact-based decision support

Inland decay of hurricane winds



9 documented cases of increased “effective lead time” for Tornado Warnings since 2017

"We used this model guidance to forecast with greater lead time and greater confidence".

"It helped me make the decision of when to issue a Severe Thunderstorm Warning versus a Tornado Warning, providing better service to the public. I don't think I would have had that confidence without WoFS."

"…this forecast proved to be very useful in providing early warning to the Chaves County Emergency Manager…"

"(WoFS) knocked the forecast out of the park."

WoFS is giving forecasters the confidence to communicate specific scenarios at greater lead time.

"I used the lightning density forecasts from WoFs to estimate when lightning would become a threat to the (golf tournament)"

"…close evaluation of the output can lead to meaningful warning decisions and anticipation of extremes…"

"Forecast provided confidence for anticipated air traffic holding for after 21 UTC at Houston International Airport."

"…WoFs very quickly picked up a signal for a wind threat about 4 hours out and grew steadily more confident on approach."

"Once you start using WoFS, on the days when you don't have (the domain over your area), you're kind of mad."

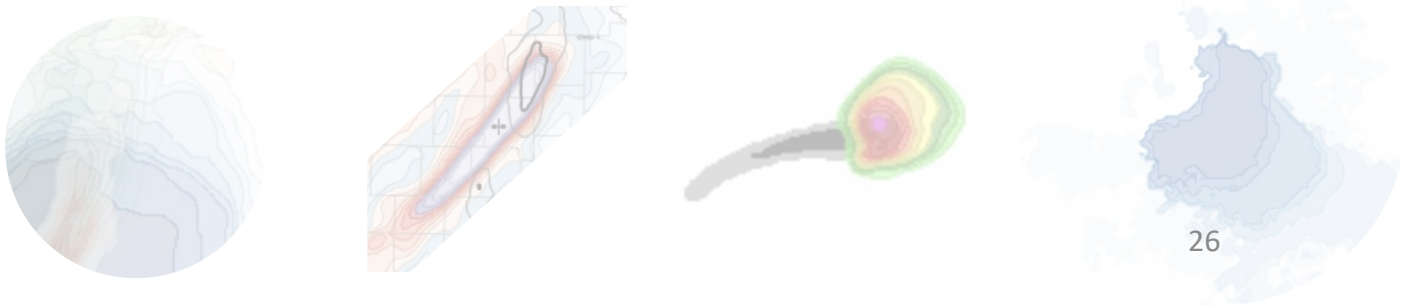
WoFS and UFS

- Close relationship with Global Systems Lab / RRFS developers
- NSSL Microphysics now available in the Common Collaborative Physics Package (CCPP)
- NSSL participation on UFS land surface team (Larissa Reames)
- WoF group performed development / vetting of FV3 for rapid-DA convective ensemble forecasting (2020-2023)

	q	N	Z	Volume
CCN		X		
droplets	X	X		
rain	X	X	X	
cloud ice	X	X		
snow	X	X		
graupel	X	X	X	X
hail	X	X	X	X

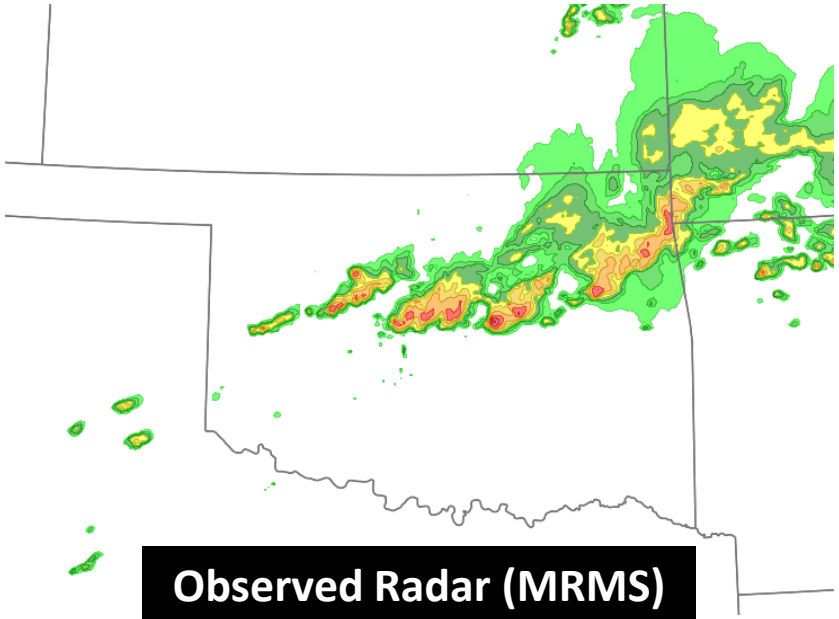
Many items are toggle on/off options

NSSL Microphysics is fully double moment.
3-moment scheme soon to arrive in CCPP (3-moment for fast-falling species).
Hail species is intended as "true" hail (only initiated from large, wet-growth graupel.



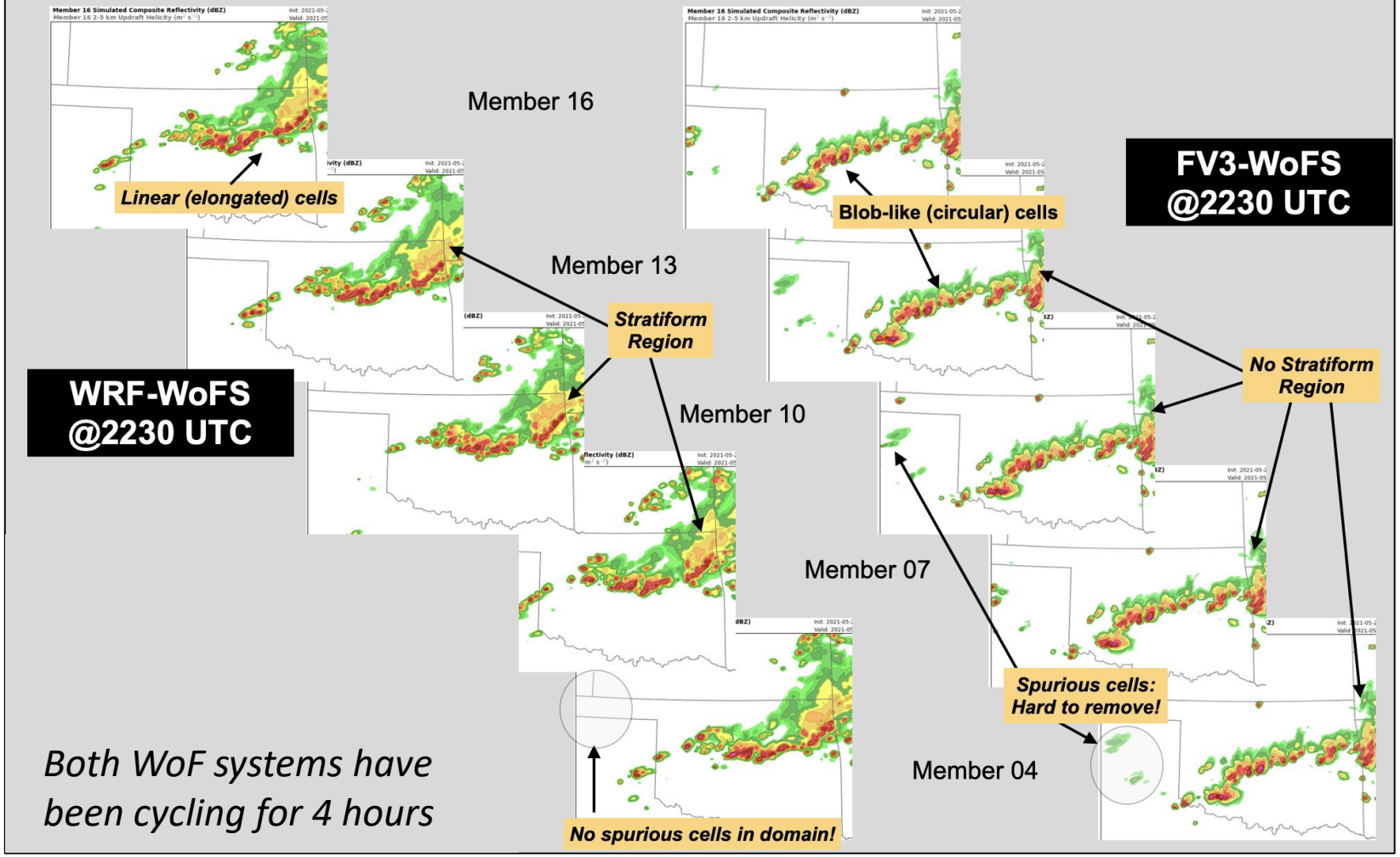
What about an FV3-based WoFS?

First, FV3 must be able to represent the structure of individual convective storms to the satisfaction of forecasters.



Observed Radar (MRMS) at 2230 UTC, 27 May 2021

Comparing WRF vs FV3-WoFS Cell Structure 2200 UTC Forecasts at T+30 min for Individual Members

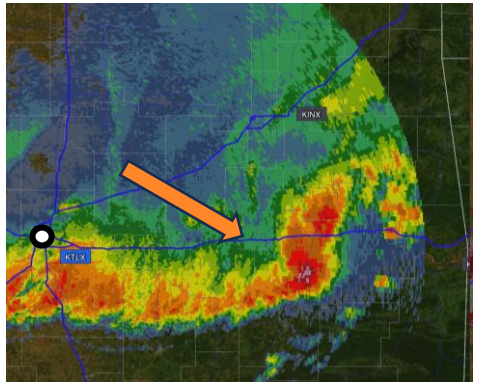


Both WoF systems have been cycling for 4 hours

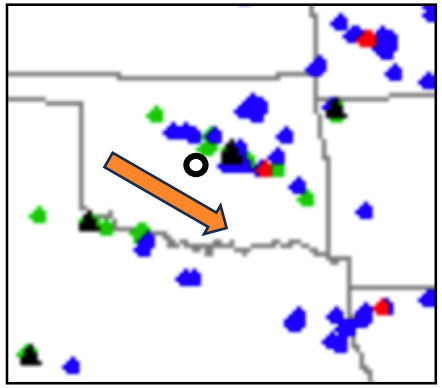
What about an FV3-based WoFS?

Second, FV3 must be able to assimilate radar and satellite observations using rapid data assimilation cycling on a targeted domain.

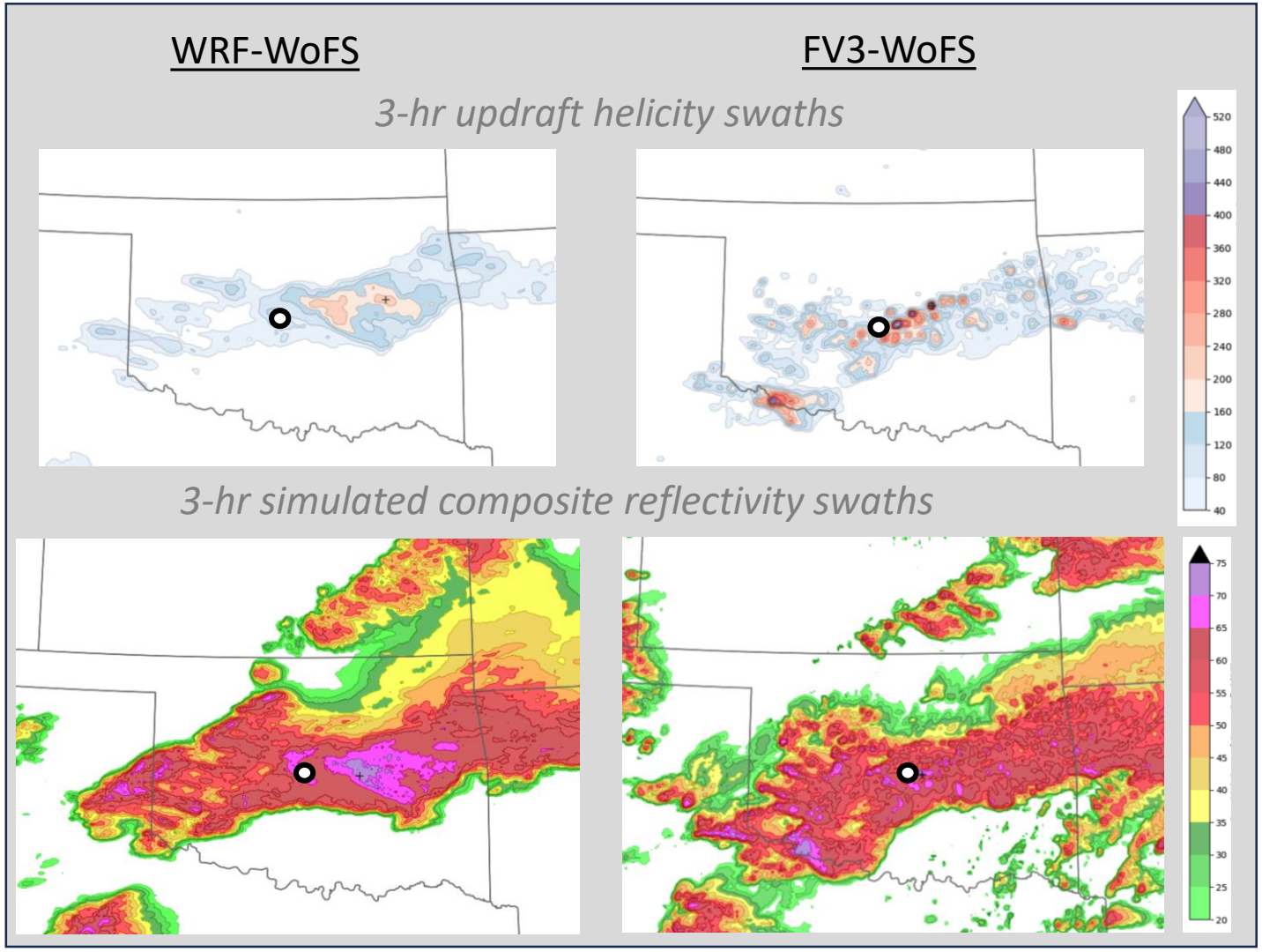
Observed radar, mid event



Severe weather reports



Distinct southeastward storm motion, with severity emphasized at bow echo apex



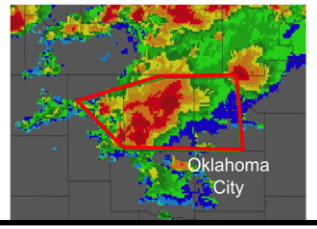
Note the relative coherence of individual storm tracks (or swaths)

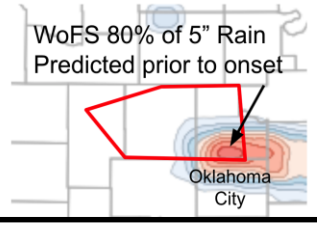
After 4+ hours of cycling, FV3 at this scale has yet to "settle down" and produce coherent structures

3

Can FV3 provide similar gains in lead time and description of high-impact events at this scale?

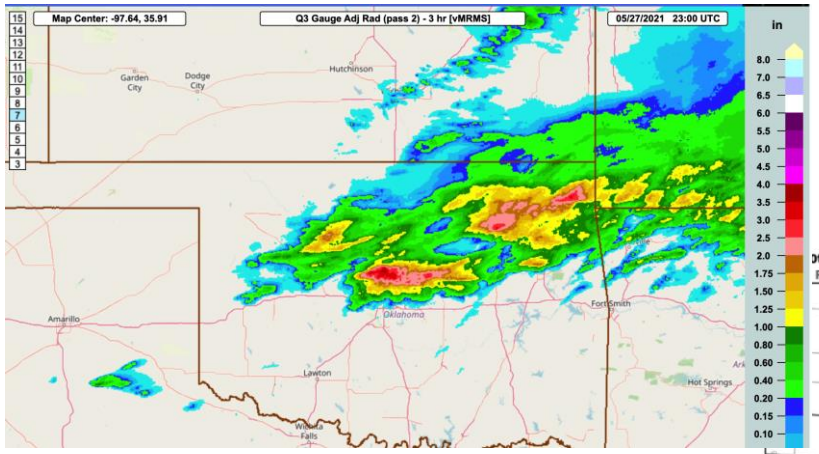
Demonstrated Real-World Lead Time for Flash Flooding



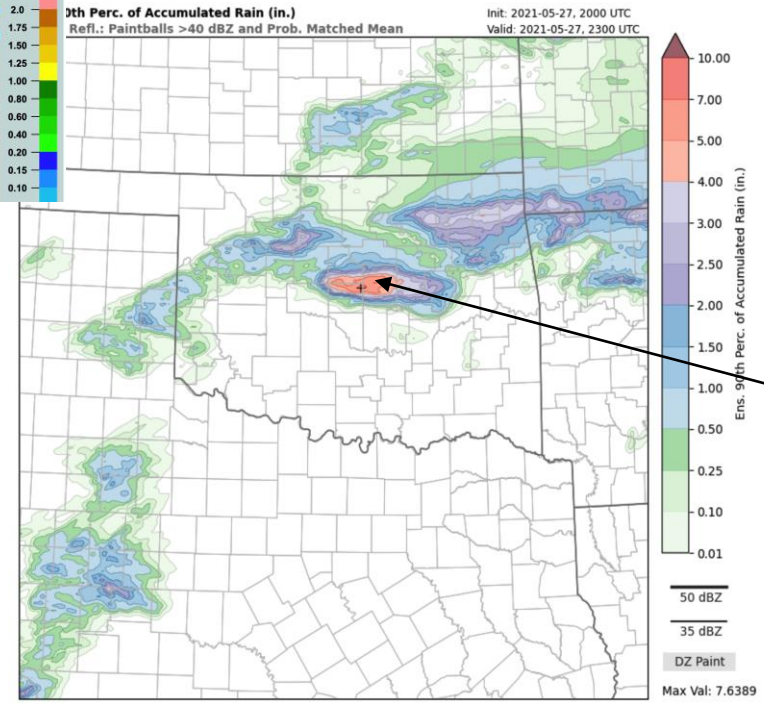


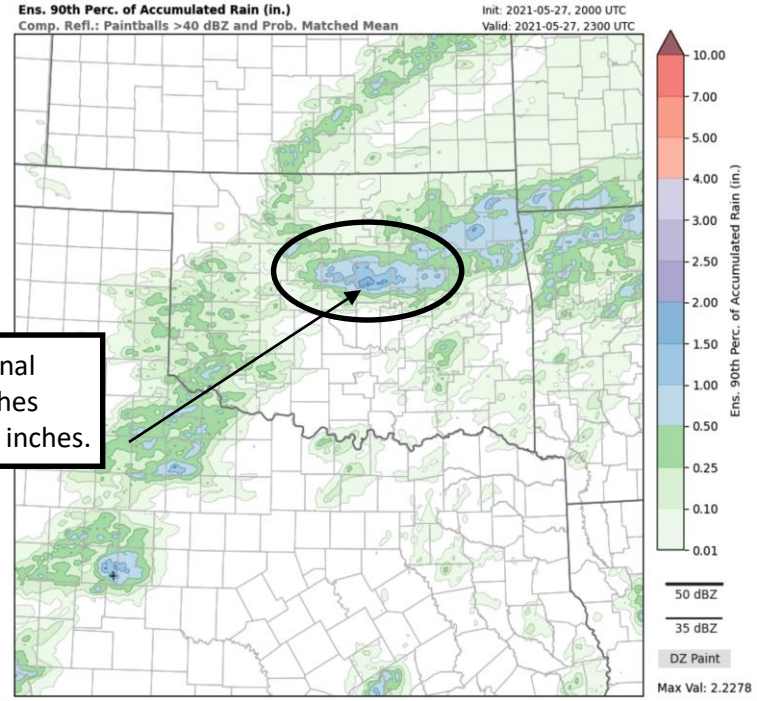
May 27, 2021
Norman, OK Forecast Office:
Average warning lead time 53 minutes
"1-3 hour rain forecasts from WoFS increased confidence for high-end rainfall of 4 to 5 inches, *directly influenced warning decisions.*"

from Burke et al. 2022



Observed Rainfall. Red is > 3 inches; locally 5+ inches was measured





Flash flooding signal
- WoFS: 7+ inches
- FV3-WoFS: 2+ inches.

In the real world the WoFS signal directly contributed to a literal use of the Warn-on-Forecast concept for flash flooding. The FV3 precipitation forecast would not have supported this.

Expanding UFS for small-scale applications

1. WoFS makes probabilistic forecasts of individual thunderstorms at the city and county level
   - FV3 individual thunderstorms lack important characteristics at this scale
2. WoFS runs on a focused domain and its primary advantage is rapid (15-min) data assimilation
   - FV3 at these scales in WoFS generates noise which masks storm-scale signals and causes negative feedback with continued cycling
   - Future applications for severe storms and fire weather will use even finer grid spacing and more rapid data assimilation (1-km and 5-minute DA version of WoFS already in development)

After 3 years work and considerable tuning, the conclusion is FV3 will not work for WoFS

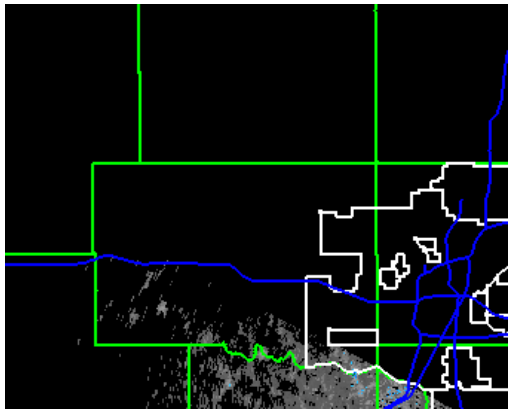
NSSL is offering WRF-based WoFS for the first operational version. And exploring the model for prediction across scales (MPAS) for potential WRF replacement in the next generation of WoFS

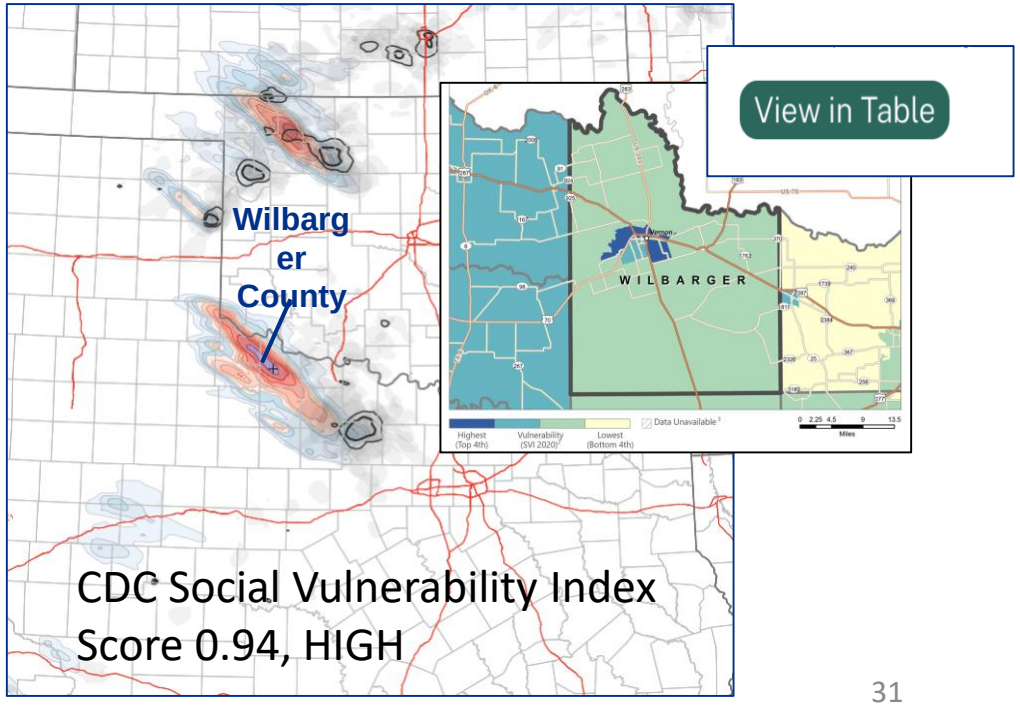
For more information on FV3 testing in WoFS, please contact louis.wicker@noaa.gov

The Future… MPAS, 1 km, Dual-Pol, Phased Array

- Exploring the Model for Prediction Across Scales (MPAS) to possibly drive 2nd generation WoFS
- Developing 1-km grid spacing WoFS
- Data assimilation for new datasets, dual-pol, phased array, uncrewed aerial systems
- Connecting forecasts to social vulnerability; working with integrated warning team partners

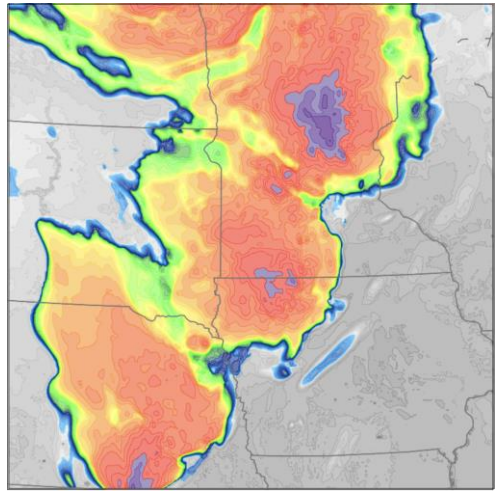
NSSL process studies inform data assimilation and physical parameterizations



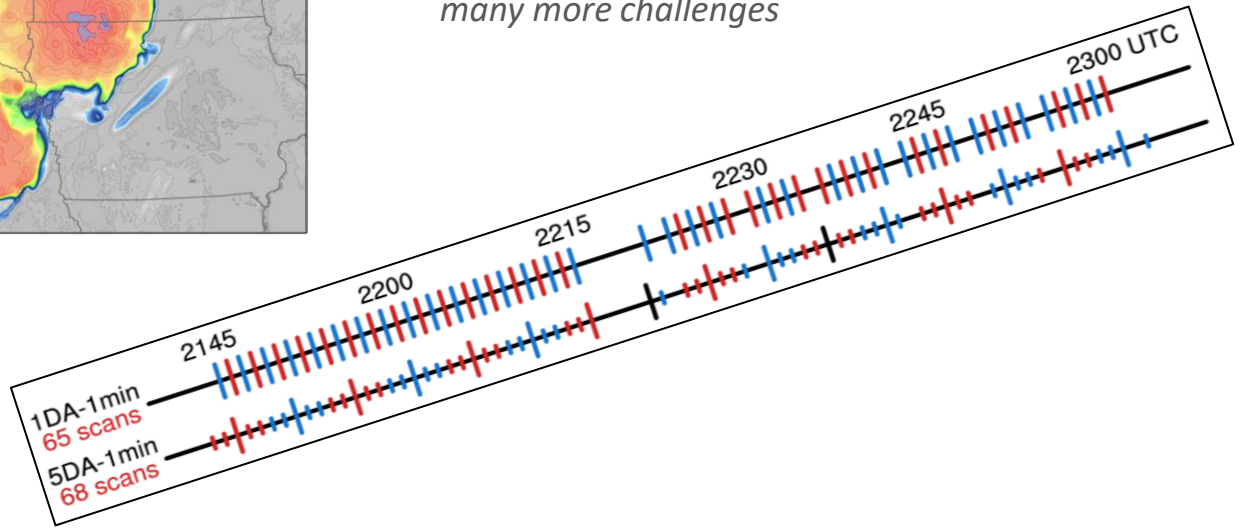


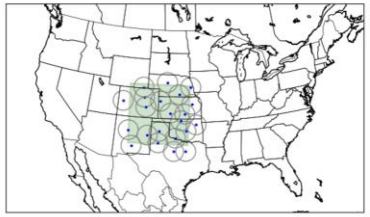
There has never been an ensemble like this.

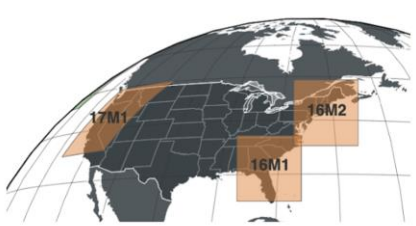
There has never been a transition to operations like this.

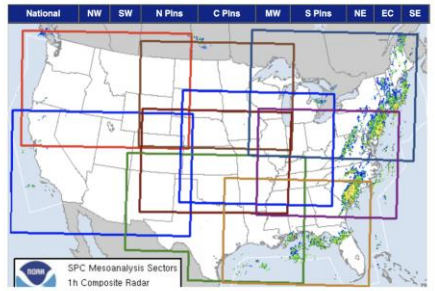


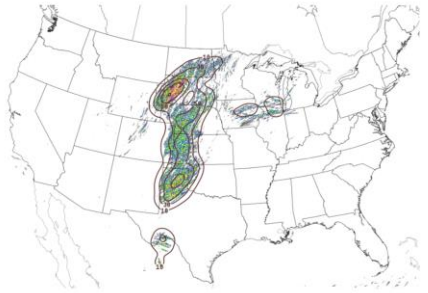
Creating infrastructure for rapid data assimilation, building cloud expertise, determining a domain strategy, and many more challenges











Thank you! From the whole NSSL-WoF team in NSSL's Forecast R&D Division

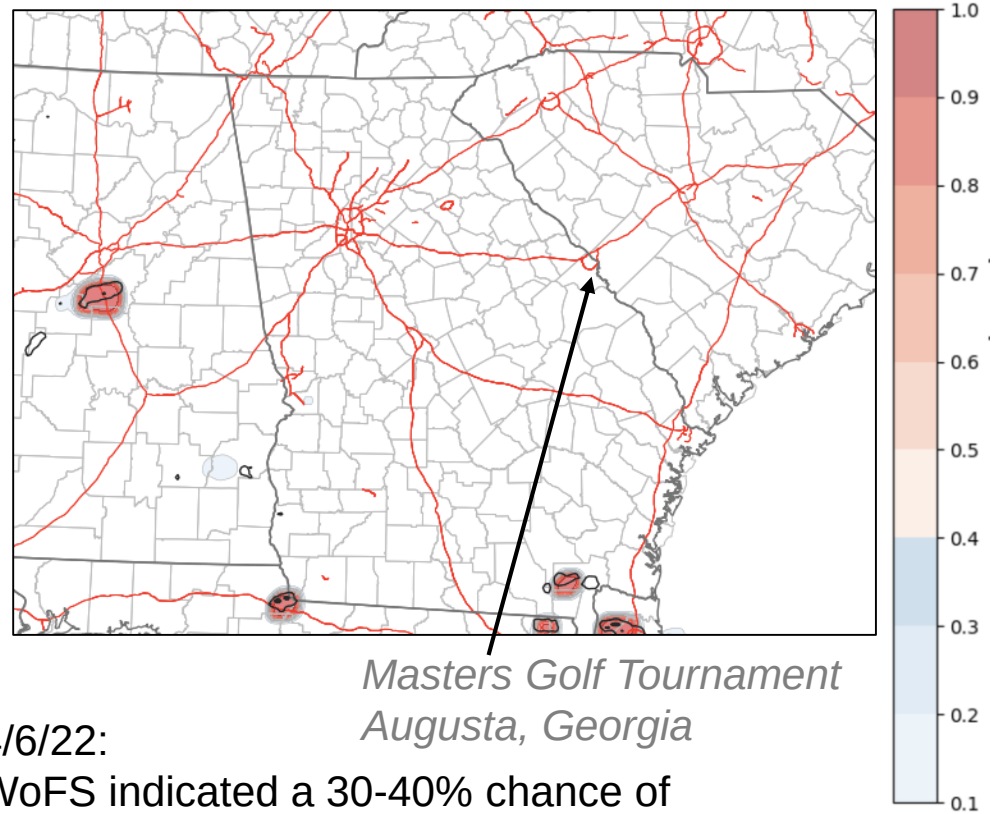
Patrick C. Burke

patrick.burke@noaa.gov

EXTRAS

Lightning

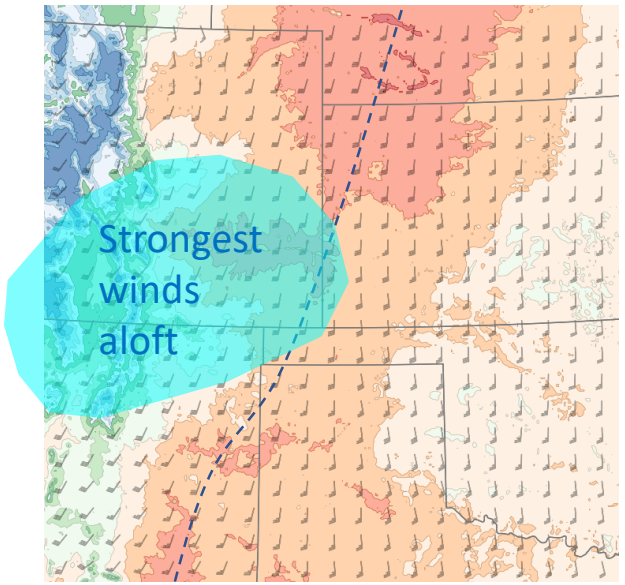
Probability of 10 lightning flashes per 5 minutes per grid box



Masters Golf Tournament
Augusta, Georgia

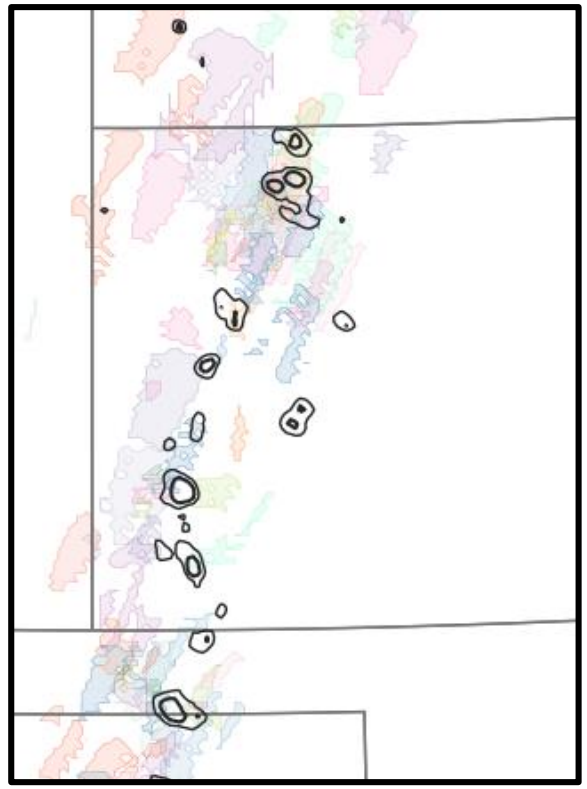
4/6/22:
WoFS indicated a 30-40% chance of thunderstorms arriving hours ahead of the main line. NWS called county EMs. Subsequently play was suspended and spectators told to disperse.

Fire



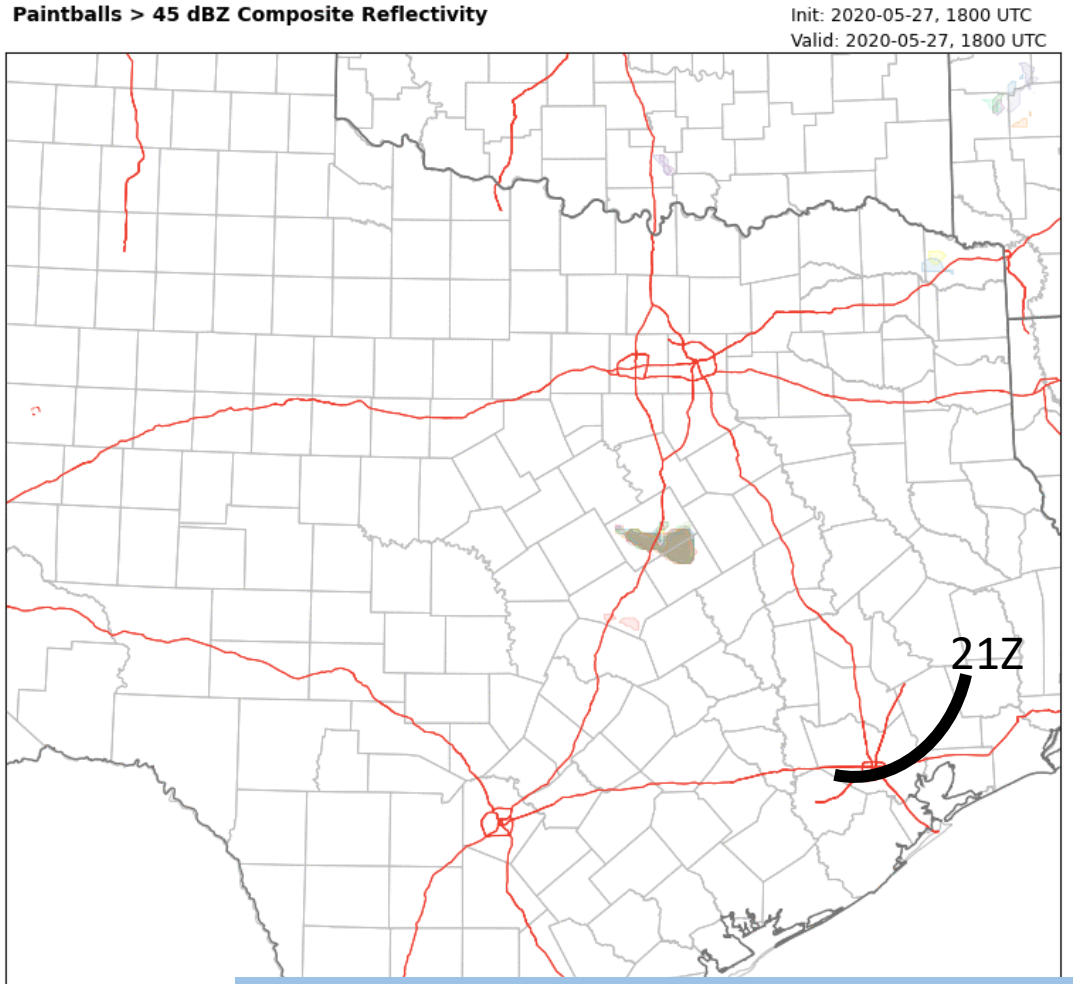
Warmest surface weather

4/22/22:
An incident meteorologist used WoFS in real time to brief NWS forecasters and state agency fire behavior analysts.

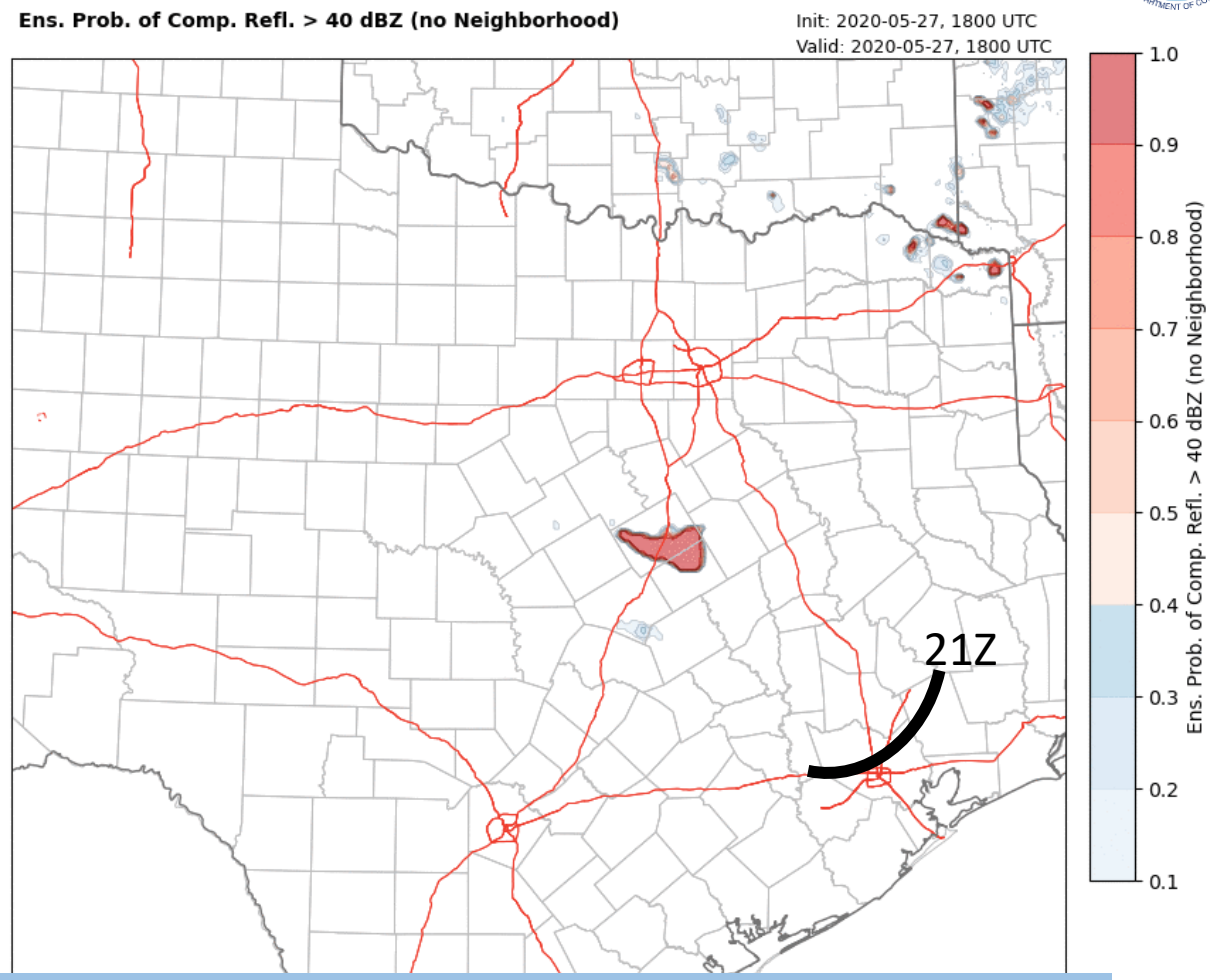


Paintballs of predicted severe wind swaths with thunderstorms

Paintballs > 45 dBZ Composite Reflectivity



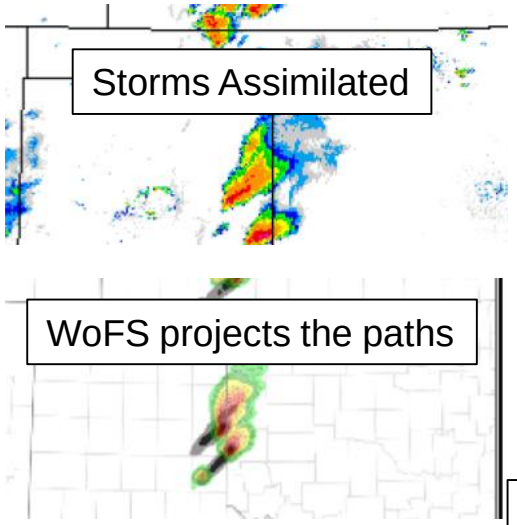
Ensemble Prob Reflectivity > 40 dBZ



Roland Nunez (CWSU):

"I just briefed the outgoing and incoming Supervisor Traffic Management Coordinators (STMC)
the 1730Z and 18Z Paintball >45 dBZ Comp Ref and the Ens. Prob of Comp Ref >40dBZ.
Forecast provided confidence for anticipated air traffic holding for after 21Z at IAH."

May 16, 2017
First use of Experimental WoFS in Watch-to-Warning Products
WFO Norman, OK



WOFS scientist embedded at WFO

WFO Norman issues a Special Weather Statement:

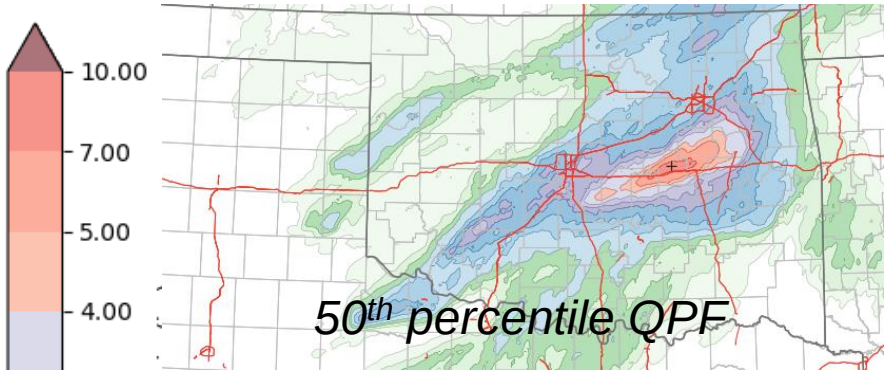
"…there is a high probability that Tornado Warnings will be issued."

60 minutes prior to first warning, 80 minutes from Elk City impacts

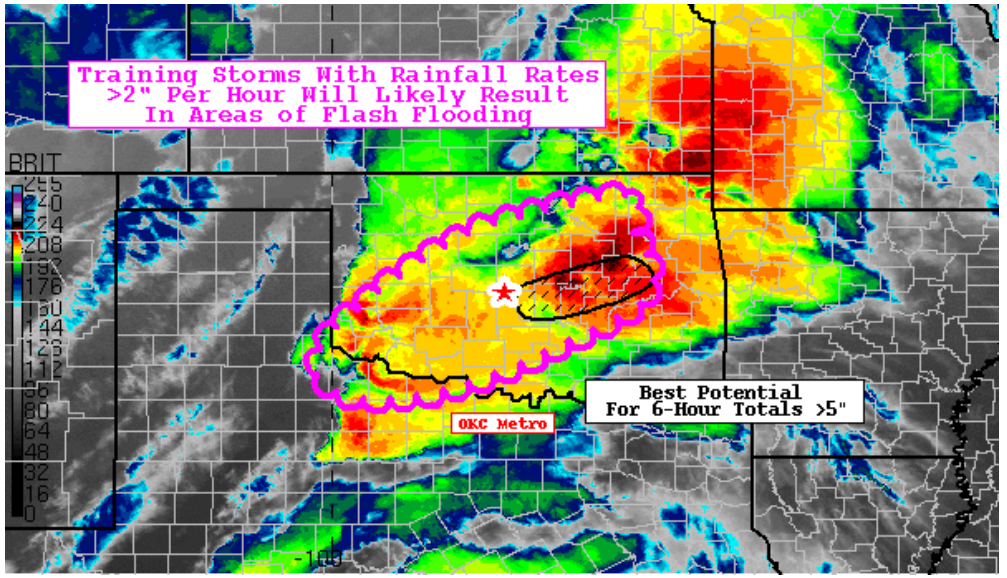
5/16/17: "We used this model guidance to forecast with greater lead time and greater confidence". - Todd Lindley

"Based on the information from the NWS, we were able to activate outdoor warning sirens about 30 minutes ahead of the tornado" – Lonnie Risenhoover, Elk City EM

May 4, 2022,
Expert Use of Probabilistic Concepts
Weather Prediction Center
Mesoscale Precipitation Discussion



50th percentile QPF



WPC MPD Graphic Highlighting a Hatched Corridor

"…it is here where the combination of merging cells and adjacent mean flow to the warm front will cause a swath of intense convection that generates excessive rainfall rates. The experimental **(1) *00Z WoFS showed a series of training 40 dBZ paintballs*** across the mid-section of Oklahoma with the area seeing the longest residency time being east of OKC. ***(2) Remarkably, the QPF 50th percentile of the 00Z WoFS between 00-06Z included a maximum of 8"*** east of OKC with the ***(3) 90th percentile even higher***. ***(4) It also identified a >60% chance for WoFS ensemble probabilities of rainfall rates >2"/hr*** east of OKC this evening ***(5) between 02-05Z***.