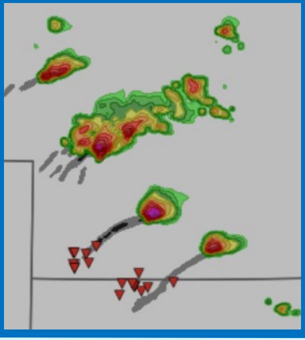
Forecast/Warning Tools and Techniques

Warn-on-Forecast System Overview

Patrick C. Burke MS, NSSL WoF Program Lead, FRDD



What is Warn-on-Forecast?

Problem Statement

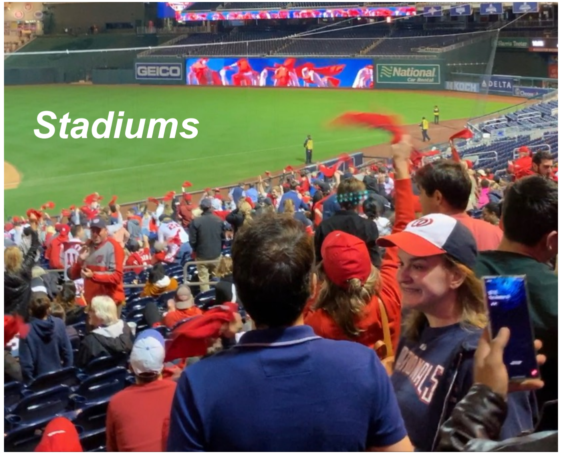
- Warnings for severe storms, tornadoes, and flash floods are based on radar- and spotter-based *detections*
- Numerical model guidance has not been geared toward “warning operations.”
- That guidance which does exist is not probabilistic.

Warning lead time shows no room for growth in a warn-on-detection paradigm

What is the Goal?

- Public venues likely need more time to take protective action

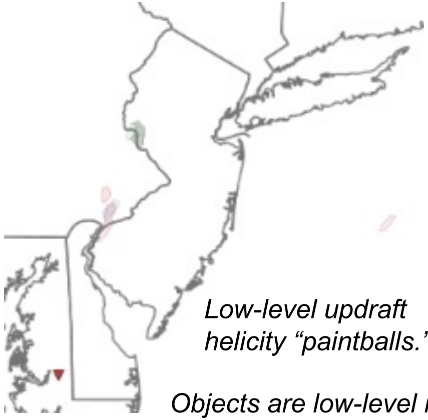
- A survey of about 500 firms in the Dallas-Fort Worth, Texas area conducted by Howard et al. (2021) found significant economic benefit in the use of probabilistic hazard information in the range of $2.3 to $7.6 billion in annual cost avoidance compared to the use of deterministic warnings



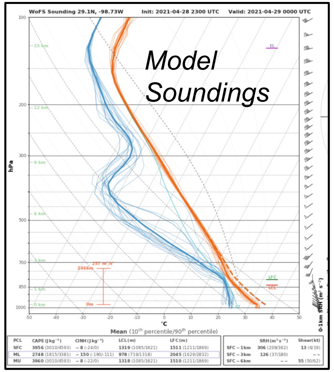
Goal: Develop and demonstrate with users an ensemble analysis and forecast system that makes probabilistic forecasts of individual thunderstorms and their hazards, 0-6 hours

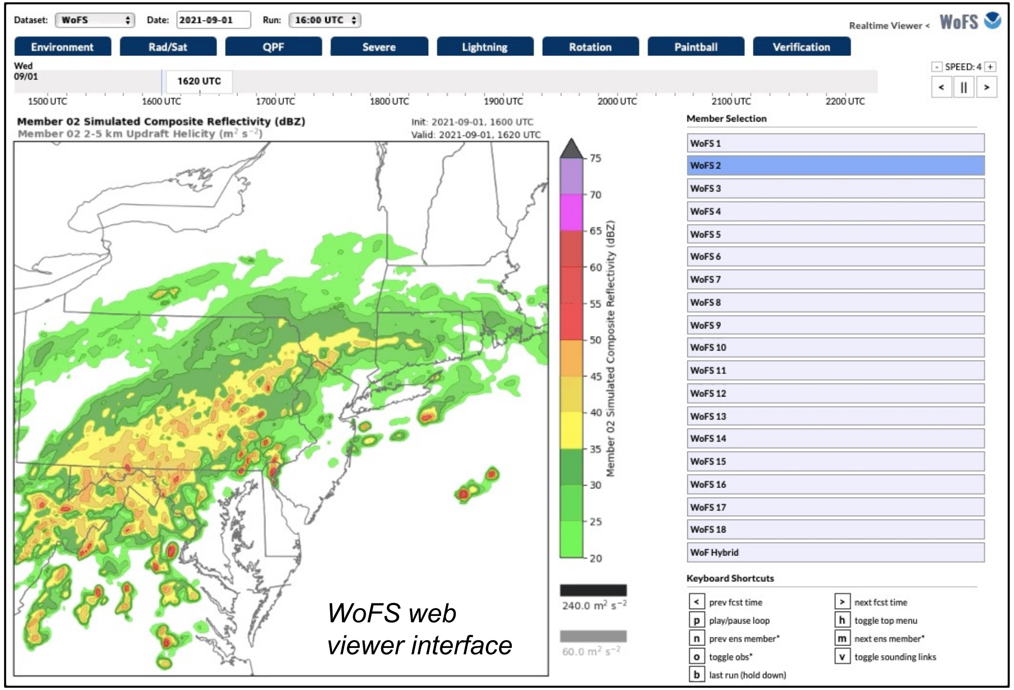
Real-time experiments

- Targeted regional domain, 3km grid
- 36 member analysis, 18 member forecast
- Assimilation every 15 min
- New forecast run launched every 30 min, projected 3-6 hours
- Movie-quality output at 5-min resolution
- Visualizations informed by users



Low-level updraft helicity “paintballs.”

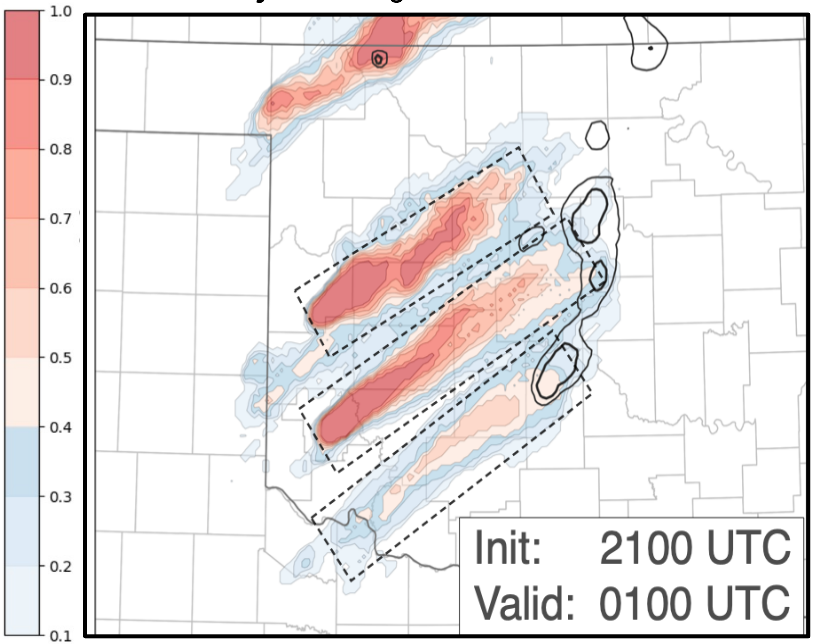




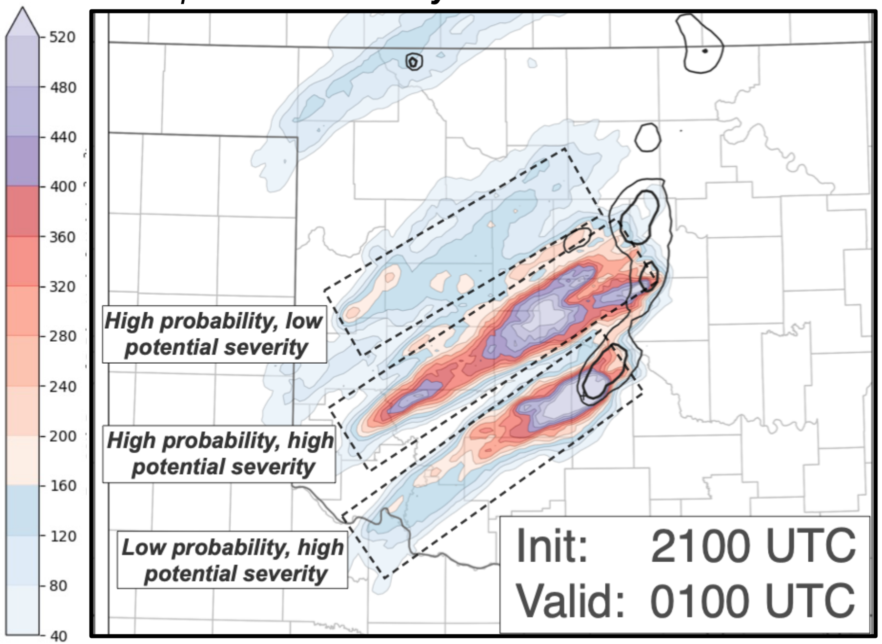
Objects are low-level mesocyclones from all members. Red triangles appear at times/locations of observed tornadoes.

Power of WoFS Probabilistic Forecasts

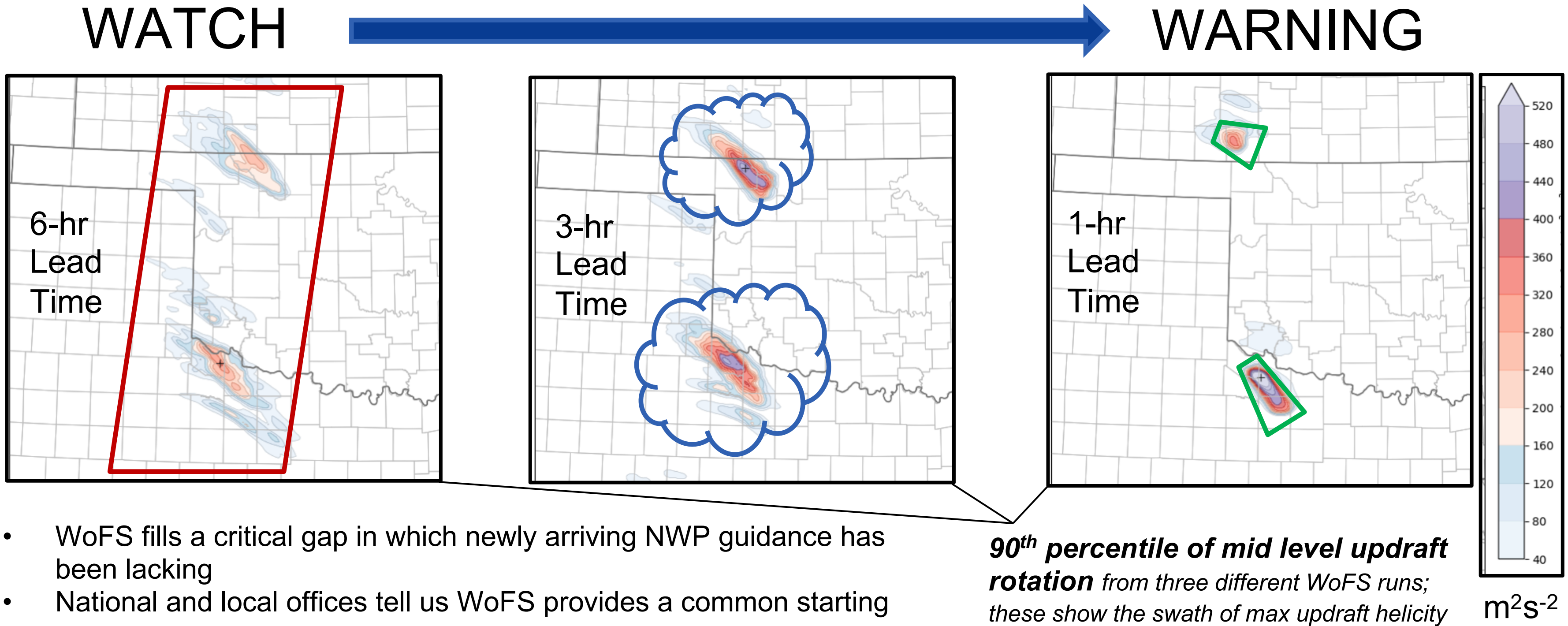
***Probability** of strong mid-level storm rotation*



*90th percentile **severity** of mid-level storm rotation*



Filling the Watch-to-Warning Gap



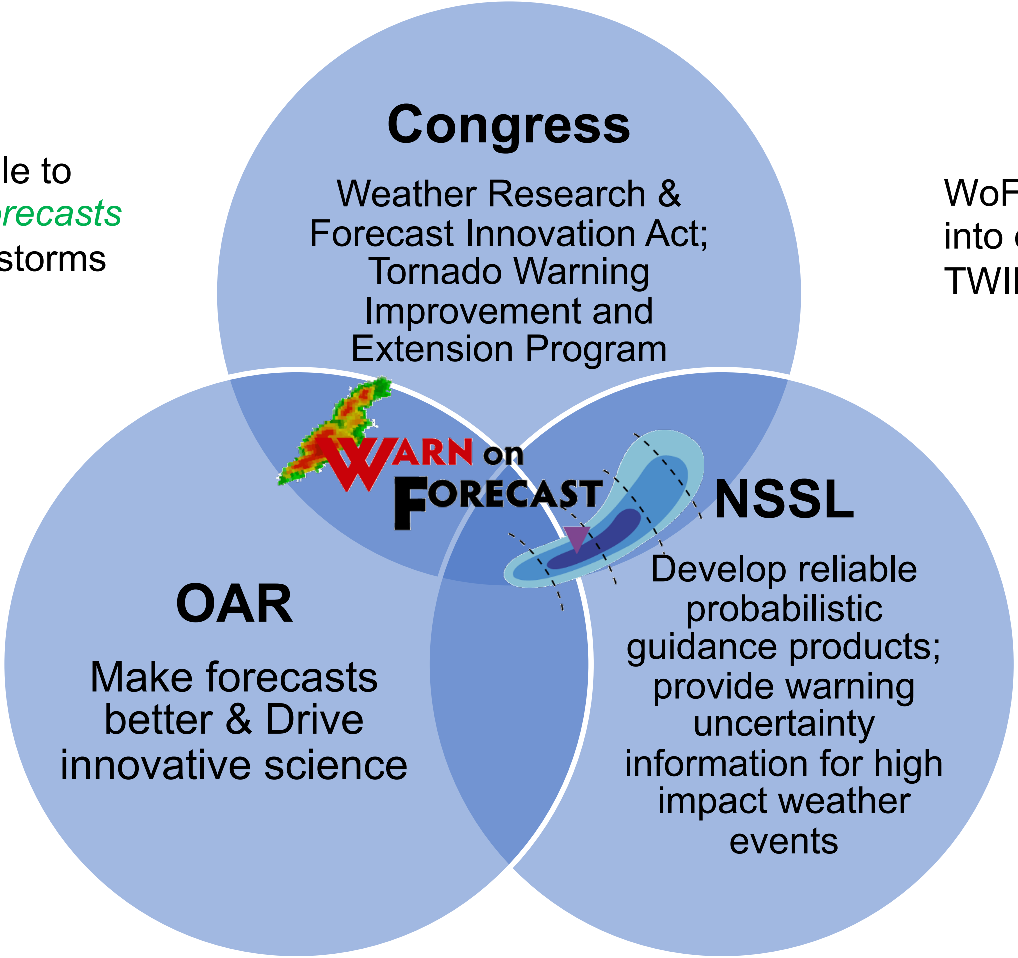
- WoFS fills a critical gap in which newly arriving NWP guidance has been lacking
- National and local offices tell us WoFS provides a common starting point for collaboration in the Watch to Warning time/space

(2021 WoFS Virtual HWT Experiment)

90th percentile of mid level updraft rotation *from three different WoFS runs; these show the swath of max updraft helicity at each grid point ending at the same time (0100 UTC), but of differing duration.*

Relevance

WoFS: First ensemble to make *probabilistic forecasts* of individual thunderstorms and their hazards



WoFS integration into operations is a TWIEP goal

Quality & Performance

- Dr. Pam Heinselman

NWA Dr. Ted Fujita Research Achievement Award

“outstanding leadership of… NOAA/NSSL Warn-on-Forecast…particularly…in developing collaborations with the operational community…” (2021)

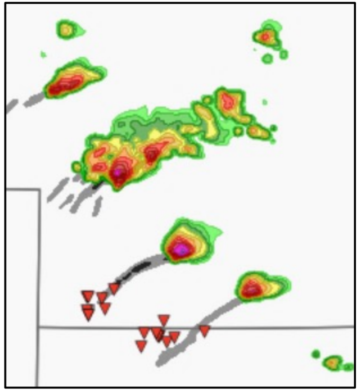
- Dr. Corey Potvin

White House Presidential Early Career Award for Scientists and Engineers (PECASE, 2017)

"significant and innovative contributions to observational analysis of thunderstorms, assimilation… into numerical prediction models, and groundbreaking research to predict thunderstorm-related threats such as tornadoes."

Quality & Performance

- 80+ publications since 2016 (including a recent invited submission to an AGU Monograph on predicting weather and climate extremes)
- Formal R2O2R projects completed with the NCEP Weather Prediction Center, and separately with NWS Southern Region



"We used this model guidance to forecast with greater lead time and greater confidence." – Todd Lindley, NWS Norman

"…we were able to activate outdoor warning sirens about 30 minutes ahead of the tornado." – Lonnie Risenhoover, Elk City Emergency Manager

Collaborators

NOAA Partners

University Partners

Norman Community

NOAA/NWS

Stakeholder Groups

Coming Up

2. Scientific R&D for WoFS

Dr. Lou Wicker

3. Computing Infrastructure & Cloud-Based WoFS

Dr. Lou Wicker & Joshua Martin

4. Post Processing & Verification

Dr. Patrick Skinner

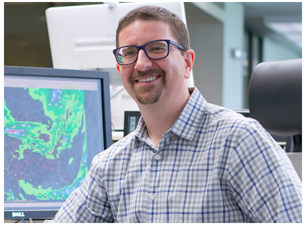
4. User Engagement & Case Examples

Dr. Katie Wilson

5. Flash Flood Applications

Dr. Nusrat Yussouf

5. Future Directions



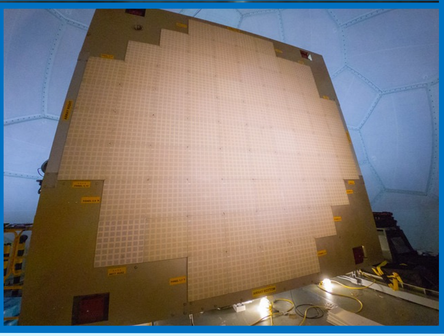
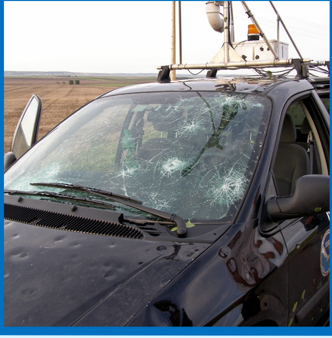
Patrick Burke

Forecast/Warning Tools and Techniques

WoFS: High Performance Computing

Lou Wicker PhD, NSSL Chief Scientist for WoF, FRDD
Joshua Martin MS, CIWRO Research Associate, FRDD



Some History

- NSSL has had in-house high-performance computing (HPC) for experiment NWP for last two decades.
- Available research computing from NOAA could not accommodate the computational requirements of a real-time rapidly-updating CAM ensemble
- Informed by our experience with forecasters in the Hazardous Weather Testbed during the 2000s:
  - WoFS needed strong O2R cycle to produce a storm-scale NWP system <u>useful to forecasters</u>
  - WoFS required 3000+ computer cores, 12 hr/day, 1-2 months per year
  - WoFS development required **dedicated research computing!**

Finding Dedicated Computing

- NSSL was able to purchase a “used” Cray XT4 in 2015
  - This system was originally used by the UK Met Office in Reading, England
  - Real time: 36 member ensemble with 750 km^2 domain

- Upgraded to Cray XE30 system in 2018
  - Configuration: 5500 Ivy Bridge cores with 2 PB of Cray Lustre file storage
  - System provides 4 million core hours each month for WoF and FRDD
  - Real time: 36 member ensemble with 900 km^2 domain + concurrent EnVar high-res member

Looking Forward

Reaching end-of-life for Cray in 2022!

How to replace 4 million core hours of dedicated computing per month?

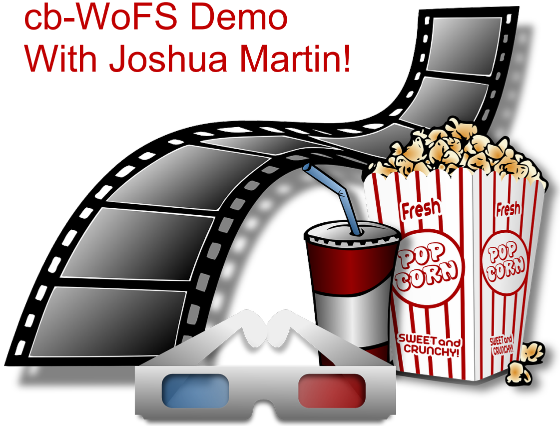
FY22-26: WoF program is pursuing a three-pronged HPC strategy

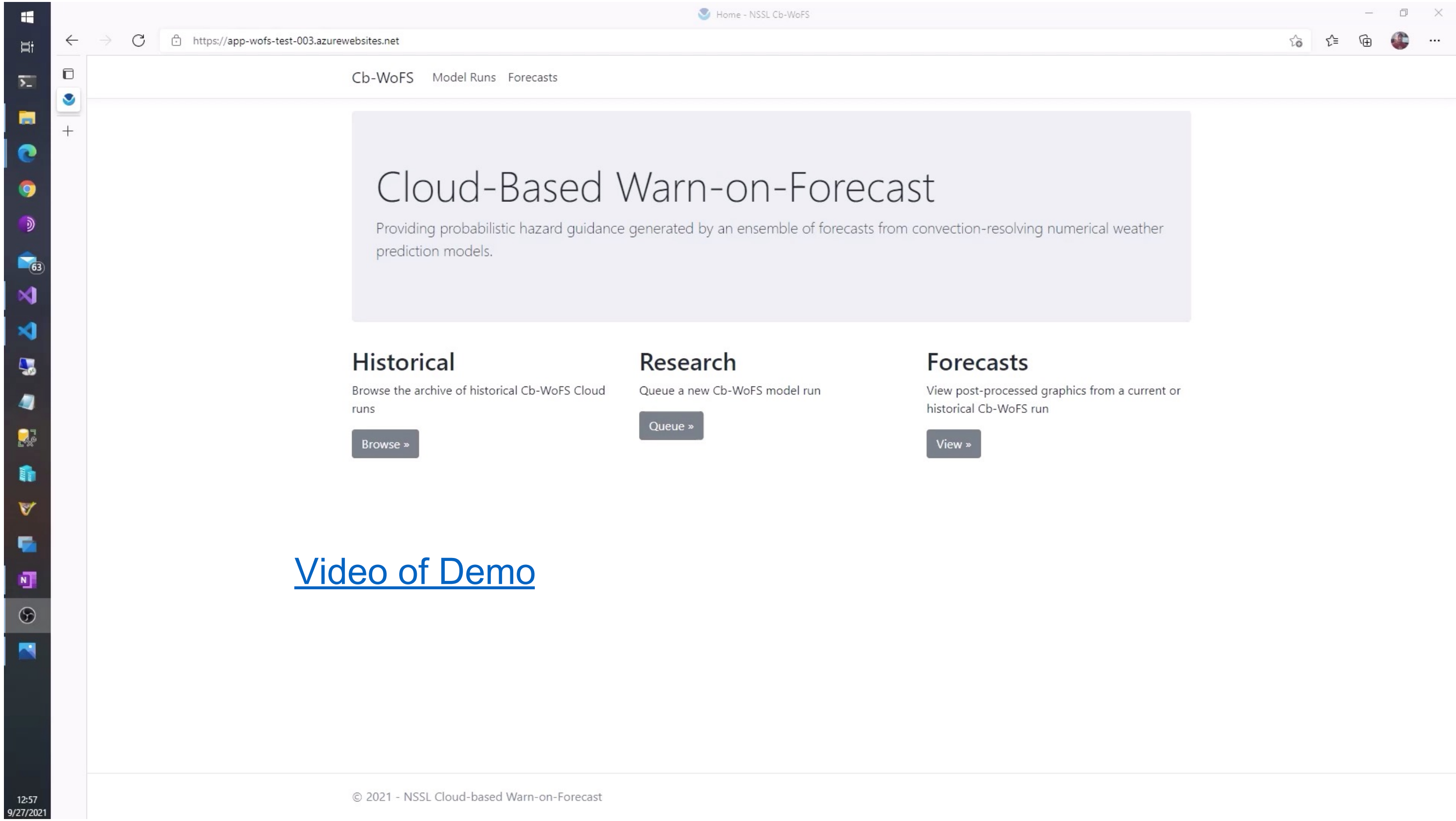
- Request increased allocations for research computing on NOAA HPC, e.g., ESRL Jet facility
- Possibly acquire new in-house HPC
  Need ability to "fail quickly" in research mode
- Use cloud-based computing where cost effective

Cloud-Based WoFS

- Cloud computing: cloud-based WoFS ➔ cb-WoFS
  - Joshua Martin: Development on Azure began in early 2020.
  - Research system is 99% complete. Real-time system 90% complete
  - Plan is to run real-time on Azure cloud for 2022 activities
- Cb-WoFS: a new web application
  - Uses Azure's Infrastructure as a System (IaaS)
  - Web interface for the entire workflow (GitHub ➔ compiling ➔ configuring ➔ running)
  - Able to scale-up & out: Multiple WoFS domains can be run simultaneously!

cb-WoFS Demo
With Joshua Martin!



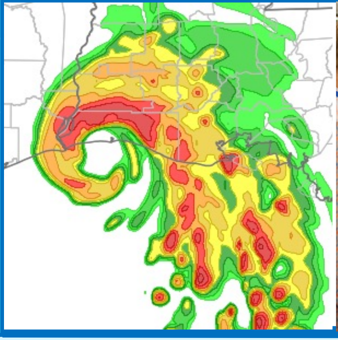


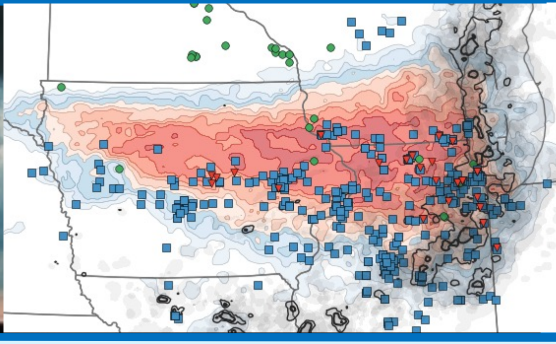
[Video of Demo]

Forecast/Warning Tools and Techniques

WoFS: Post-Processing and Verification

Patrick Skinner PhD, CIWRO Research Scientist, FRDD

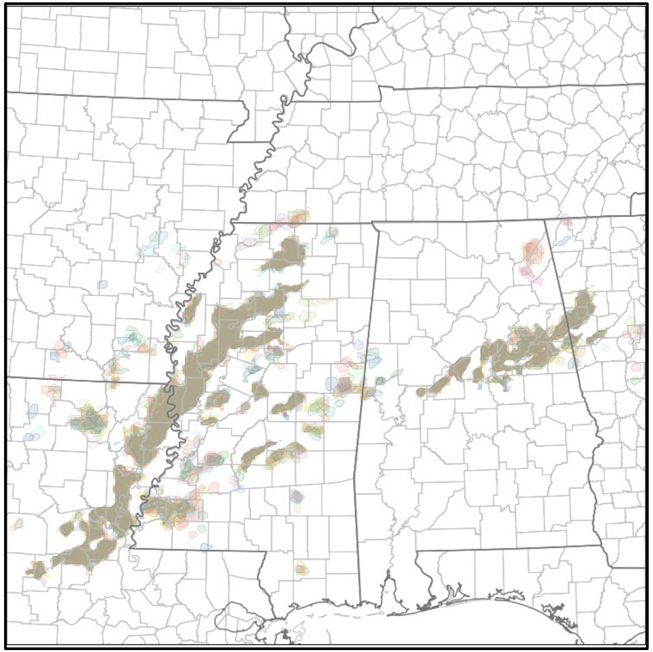




Post-Processing Provides Real-Time WoFS Guidance

- Real-time use requires:
  - Rapid transmission
  - Efficient visual communication

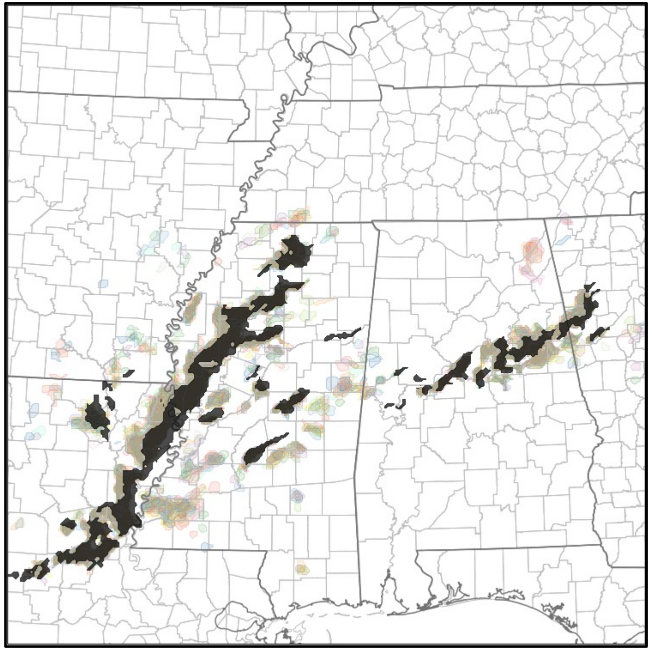
- Real-time WoFS guidance facilitates communication of warning uncertainty information for high-impact weather events (NSSL GSC 6)



WoFS 6-hr Forecast of reflectivity "paintballs" > 40 dBZ

Verification Quantifies Value of WoFS Guidance

- Verification enables:
  - Evaluation of WoFS forecast quality relative to alternative forecast systems
  - Evidence-based decisions on system development
- Necessary to develop reliable probabilistic guidance products (NSSL GSC 1)



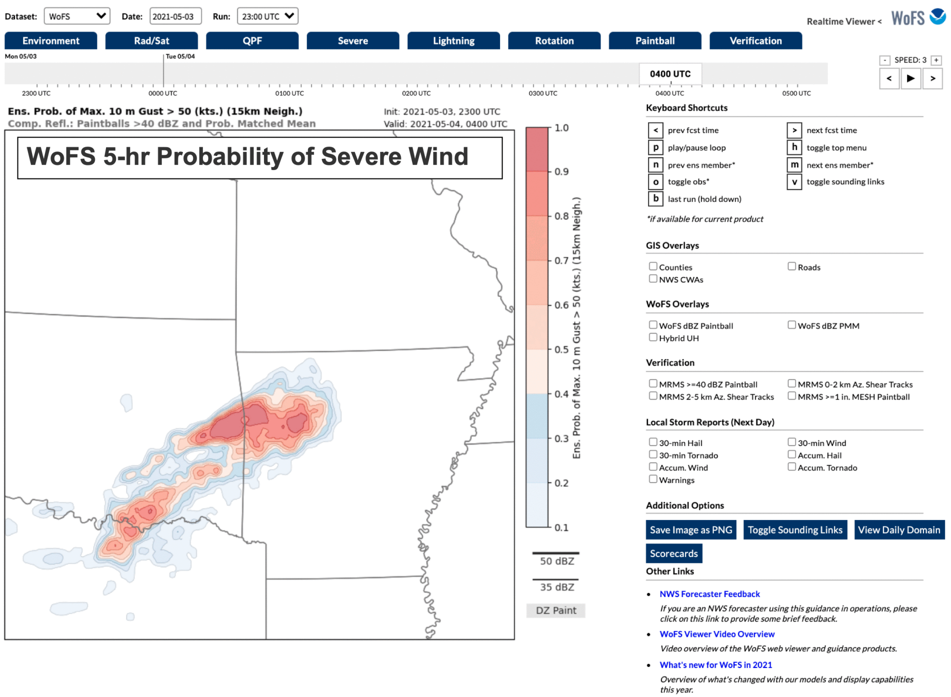
WoFS 6-hr Forecast of reflectivity “paintballs” > 40 dBZ

MRMS Observed reflectivity “paintballs” > 40 dBZ

Real-Time Guidance Dissemination

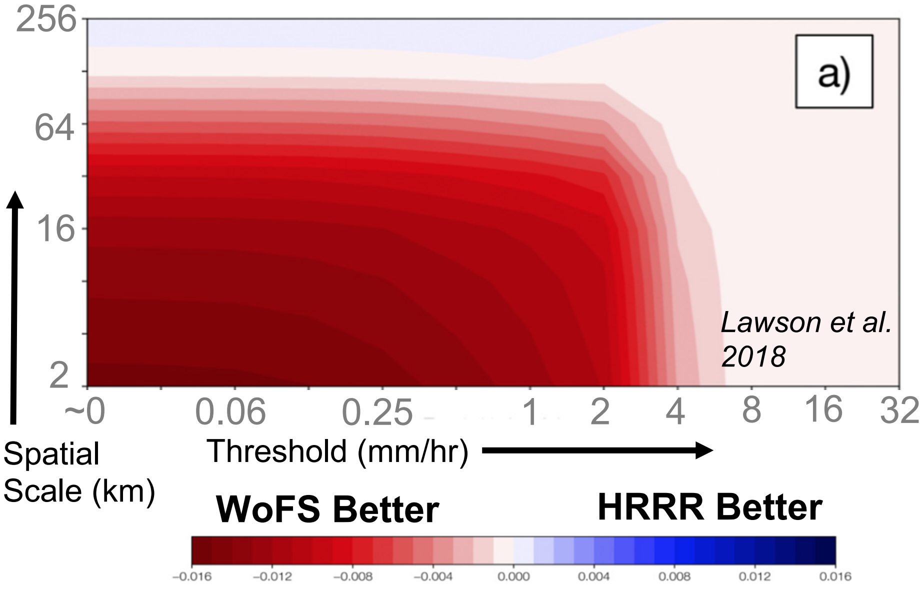
WoFS Web Viewer: https://wof.nssl.noaa.gov/realtime

- Complete 6-hr forecasts available ~45 min after initialization
- >125 different forecast products (>20,000 images) each forecast run
- Forecasts available from 205 WoFS cases from 2017–2021

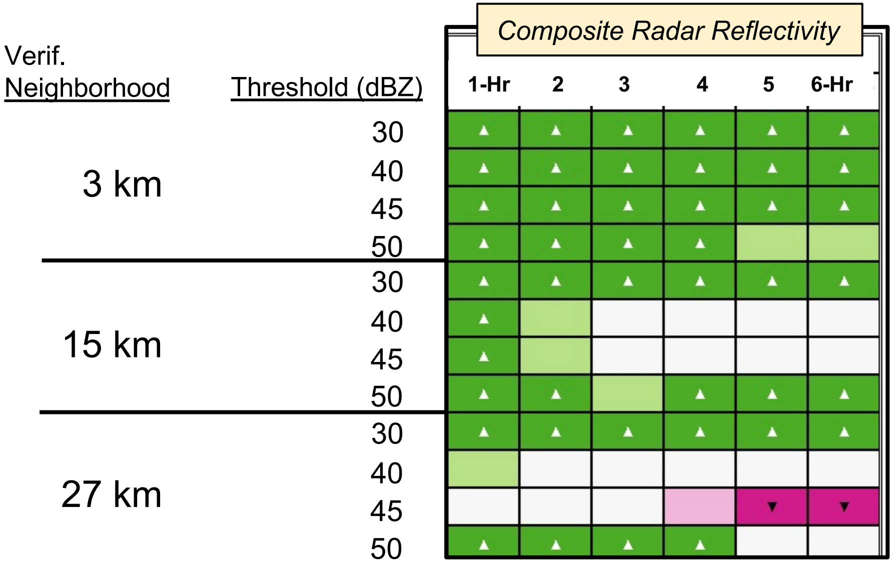


WoFS Skill Relative to Alternative Systems

WoFS rainfall forecasts have higher Fractions Skill Scores than HRRR at finer spatial scales

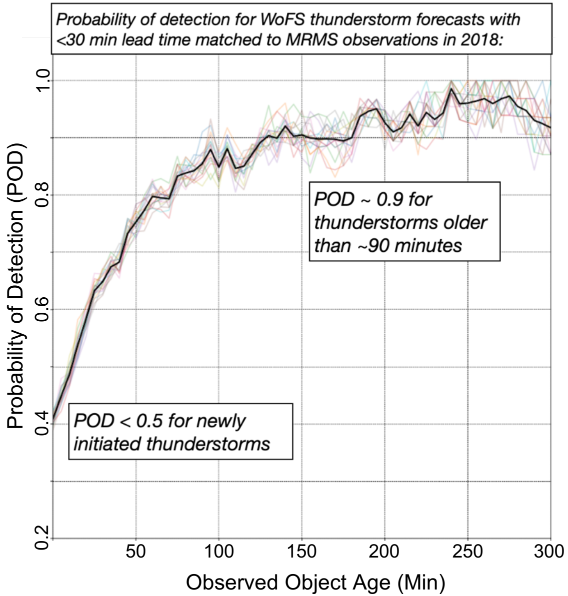


Verification scorecards show WoFS produces significant improvements over HREF (green boxes) at multiple scales and lead times

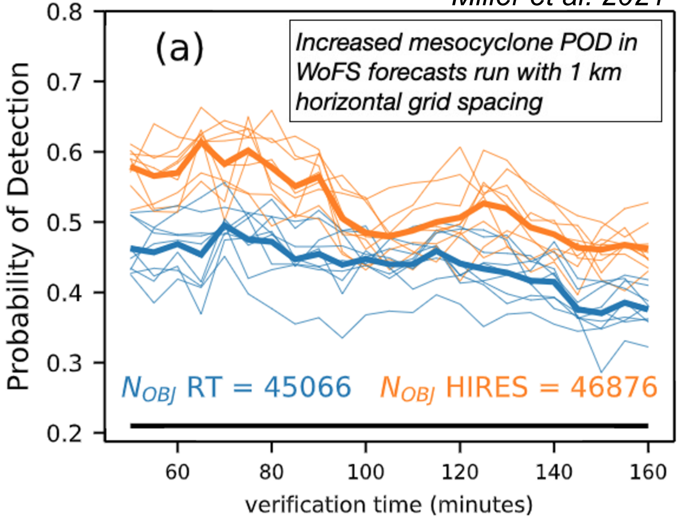


Object-based Verification of WoFS Guidance

Characterize changes in WoFS accuracy before and after convection initiation

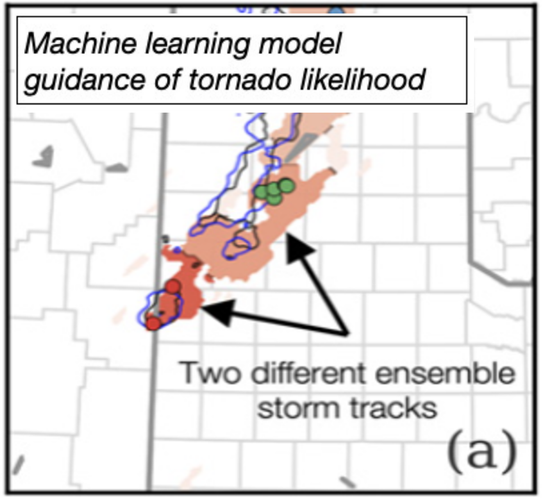


Miller et al. 2021



Quantify improvements in WoFS mesocyclone prediction with increased horizontal resolution

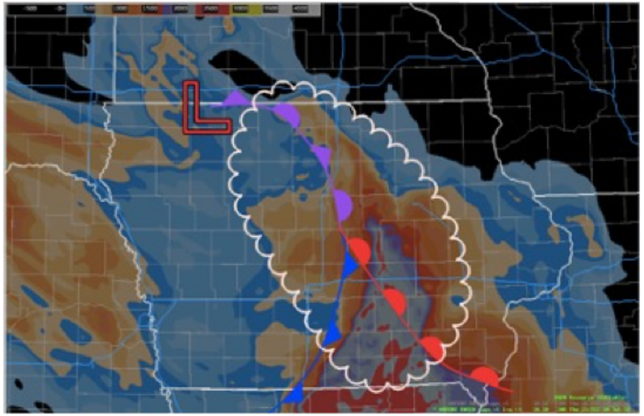
Create probabilistic forecast objects to input into machine learning models

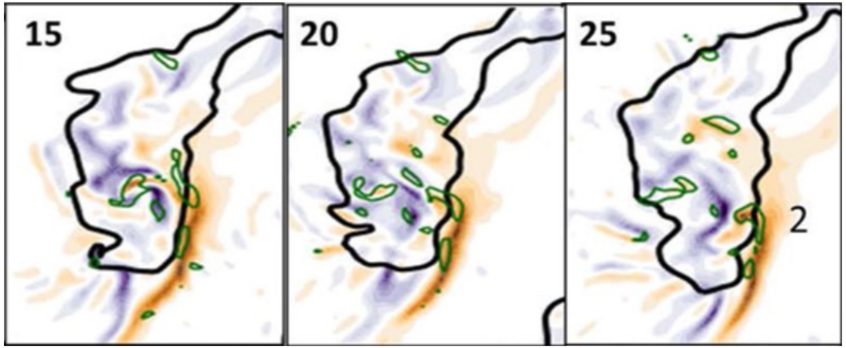


Flora et al. 2021

Future Post-Processing and Verification Work

- Integration of WoFS with the Advanced Weather Interactive Processing System (AWIPS2)
- Evaluate quality of FV-3 based WoFS relative to current system
- Quantify impacts of increased resolution on forecast skill and identify novel uses of higher resolution forecasts





Britt et al. 2020

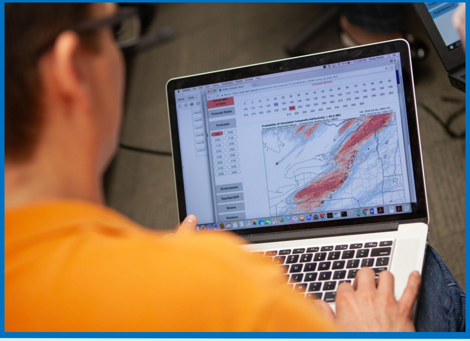
DOC / NOAA / OAR
National Severe Storms Laboratory

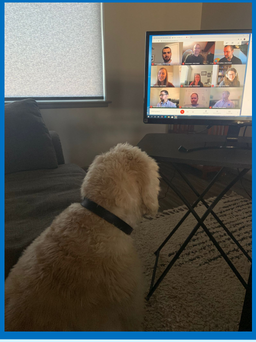
2021 NSSL Science Review

Warn-on-Forecast System

User Engagement and Case Examples

Presented by Dr. Katie Wilson, FRDD, Research Scientist



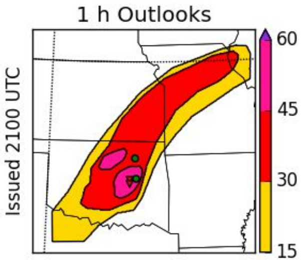



History of User Engagement

First real-time demonstration of WoFS use in NWS operations.

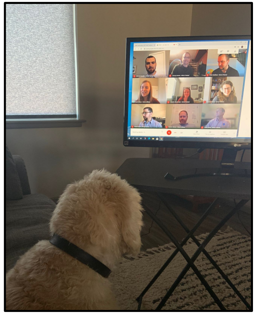
2017

NOAA Hazardous Weather Testbed experiments for 1) severe and tornadic events and 2) flash flood events.

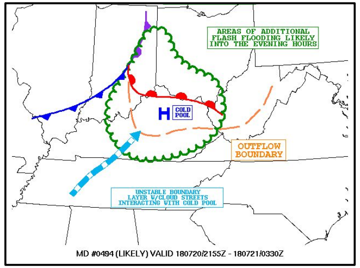


2019

First WoF testbed experiment conducted involving <u>both</u> national centers and local forecast offices.



2021



2018

Began real-time WoFS evaluations with WPC Metwatch Desk for flash flood forecasting.

2020

Established a working group with NWS southern region. Provided WoFS training, real time scientist-forecaster interaction, and event reviews.

Why is User Engagement Important?

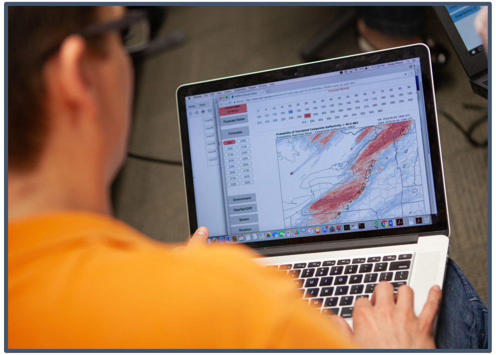
Establish baseline knowledge of meteorologists' understanding of storm-scale probabilistic guidance.

Develop and improve training resources.

Enhance the user web interface.

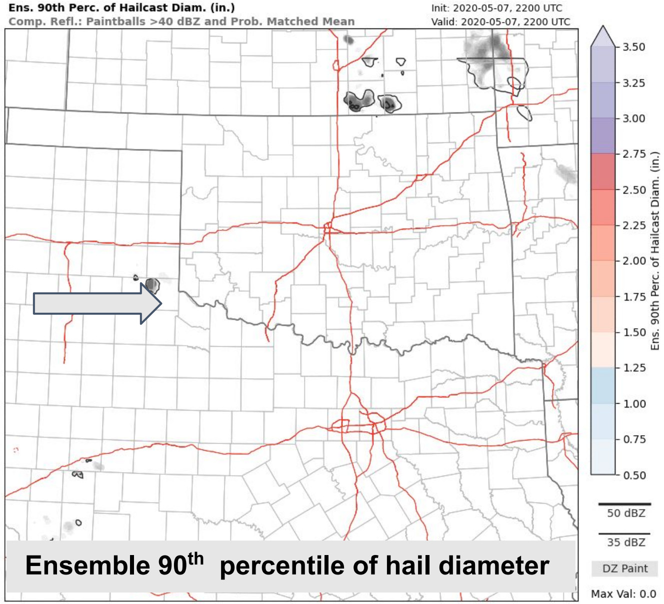
Hone expectations for how WoFS guidance best fits into the forecast process.

Build lasting collaborations that will support future operational implementation.



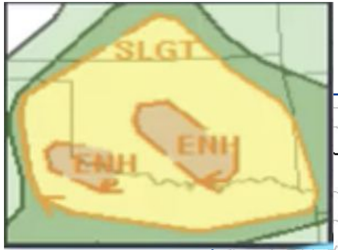
Operational Example 1: Texas Hailstorm on May 7, 2020

SPC: WoFS accurately forecast the initiation, location, storm split, rightward motion, and end point of the supercell, supporting pre-, post-, and downstream watch decision making.

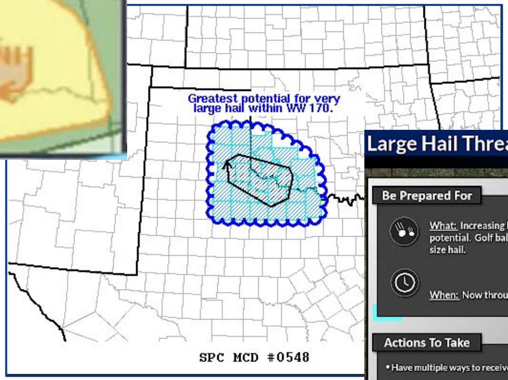


Ensemble 90th percentile of hail diameter

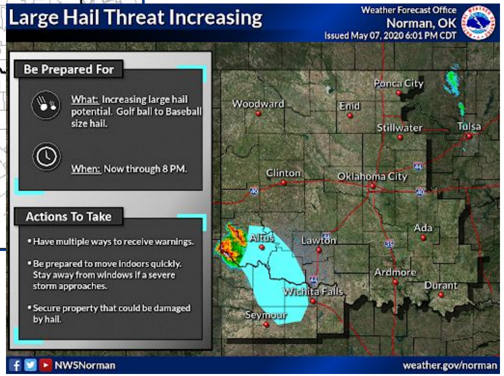
Convective Outlook



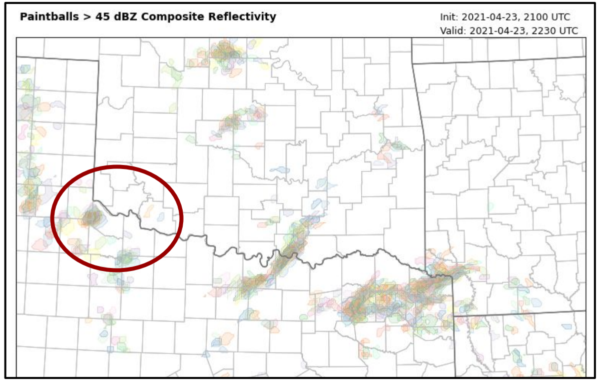
Mesoscale Discussion



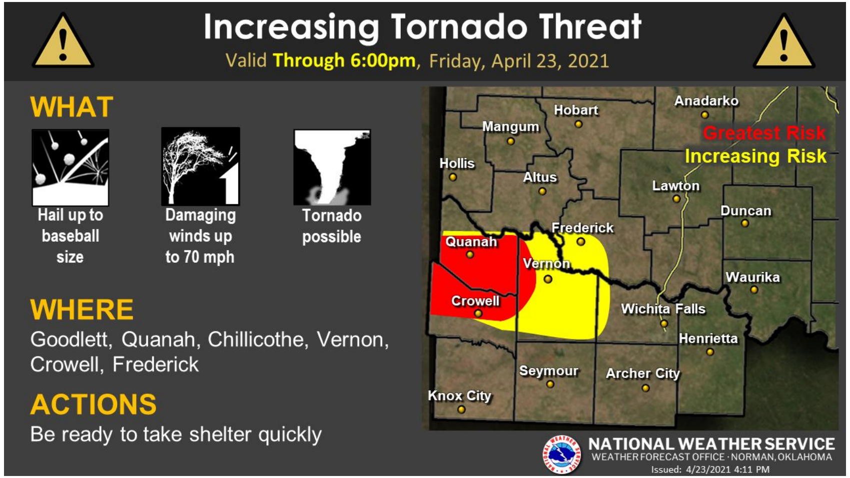
WFO Hail Threat Graphic



Operational Example 2: Texas Tornado on April 23, 2021



"Mesoscale analysis supported a narrow zone of tornado potential. WoFS resolved a right moving supercell within that zone."

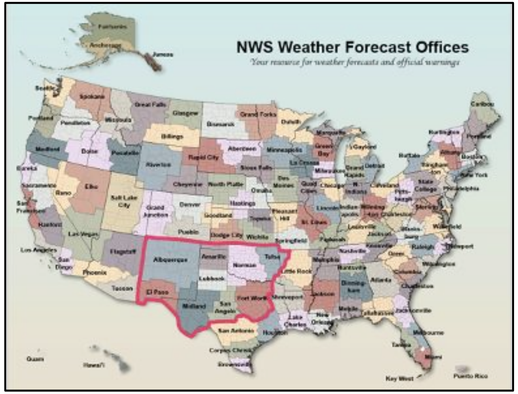


Decision support service graphic issued 92 min prior to the first tornado.

Future Work

1. Analyze and report findings from the **2021 WoF testbed experiment**. Use findings to further develop training.

2. Expand **collaborations** and real-time WoFS use across the NWS.



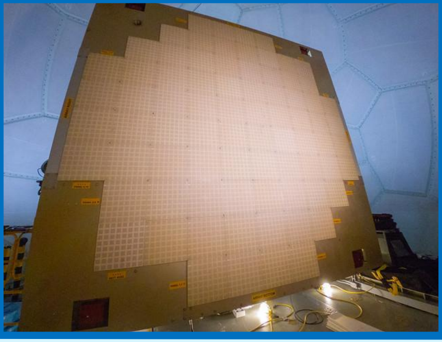
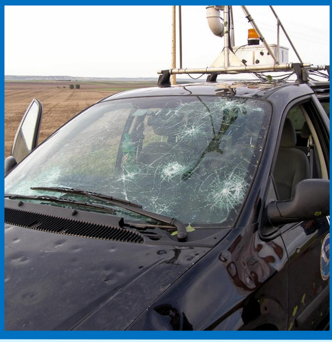
3. Examine the **blending** of probabilistic hazard information across the watch-to-warning period

Forecast/Warning Tools and Techniques

WoFS: Heavy Rainfall and Flash Flooding

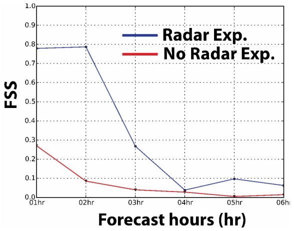
Nusrat Yussouf PhD, CIWRO Research Scientist, FRDD



History of WoFS for Flash Flooding

Proof-of-concept demonstration of WoFS for heavy rainfall prediction (Yussouf et al. 2016)



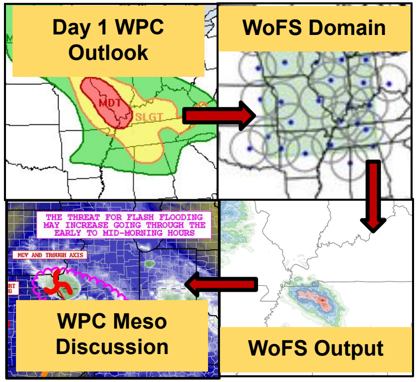
2016

2018

First evaluation at NOAA-HMT Flash Flood and Intense Rainfall & HMT-Hydro experiments

2019

Concept-of-Operation evaluations, WPC MetWatch Desk and WFOs



2020

2021

Real-time experiment with NWS WFOs for Southwest Monsoon flash flood events

Relevance

Flash flooding is the deadliest form of hazardous weather in the United States

A strategic mission goal for NSSL and NOAA is improved water warnings and forecasts to reduce loss of life, injury, and damage to the economy

NSSL Grand Scientific Challenges (GSC)

- GSC 3: Reliably predict flash flooding
- GSC 1: Develop reliable probabilistic guidance products

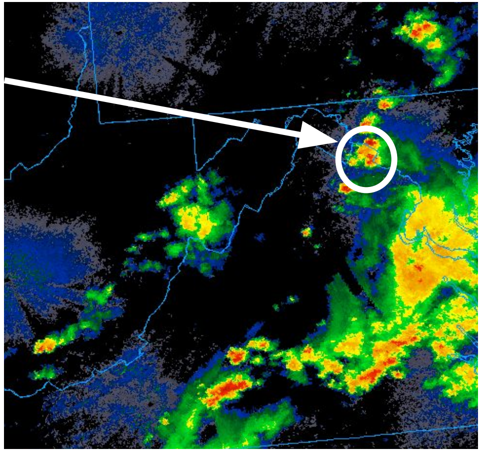
Flash flood impacts at Waverly, Tennessee, in August 2021. Photo courtesy @DicksonSevereWx via NWS Nashville

Prediction During a Flash Flood Emergency Leesburg, Virginia, 6 Aug 2020

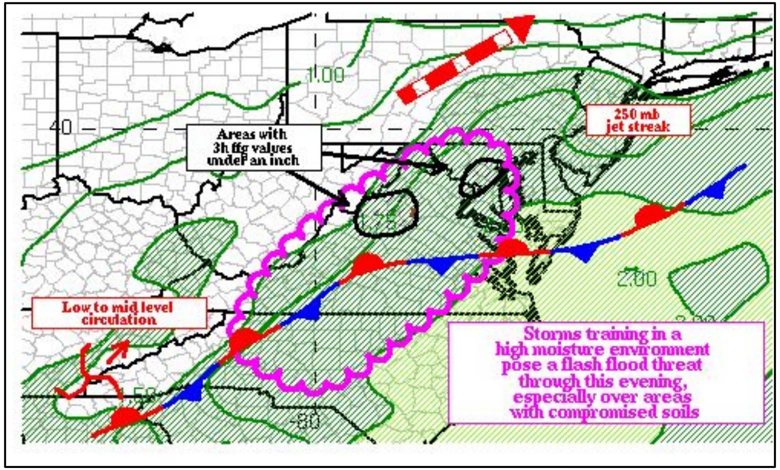
Small storm cluster persisted in place for 4.5 hours

Streams rose 7 feet

Water entered buildings, several water rescues needed



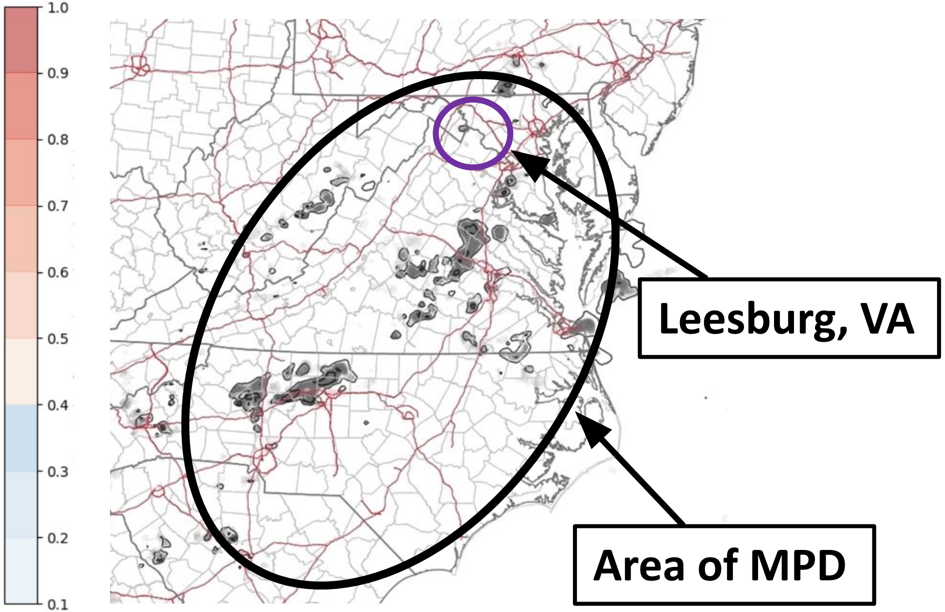
Observed radar during height of the event



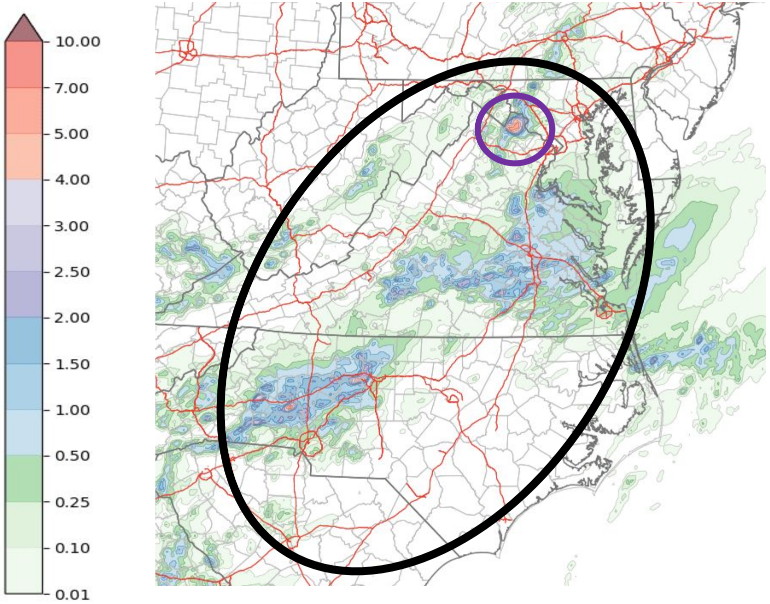
Weather Prediction Center Mesoscale Precipitation Discussion (MPD) graphic issued during the event; the associated text discussion mentioned WoFS forecast signals

Flash Flood Warnings were upgraded to a Flash Flood Emergency about halfway through the event

Highly Accurate WoFS Run Launched at 2300Z, 90-min Lead Time to First Flash Flood Report



6-hour Loop, WoFS Probability of > 3" Rainfall, 27km Neighborhood

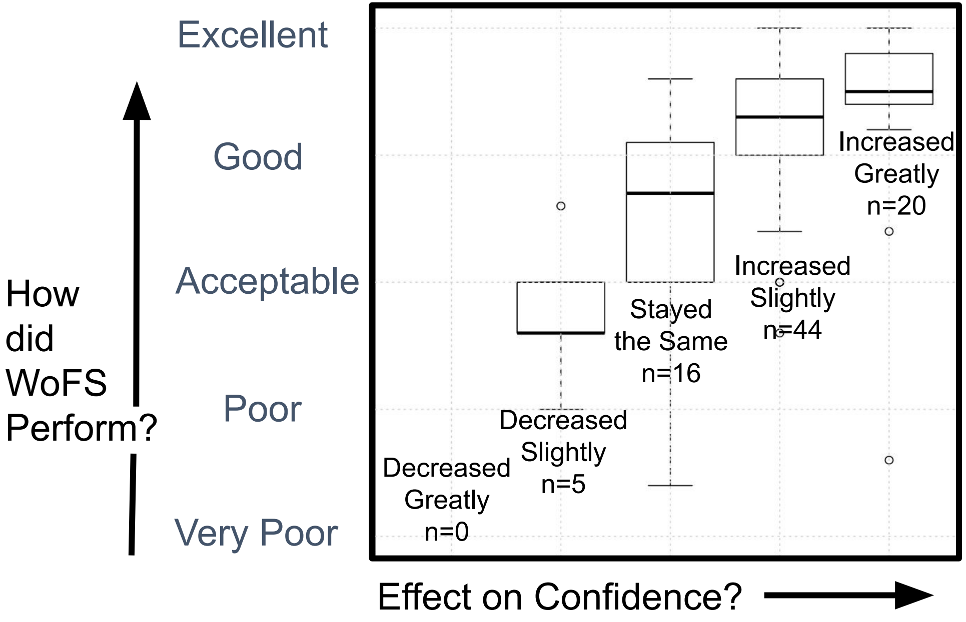


Multi-Radar Multi-Sensor Observed Rainfall, ~ 5" at Leesburg, VA

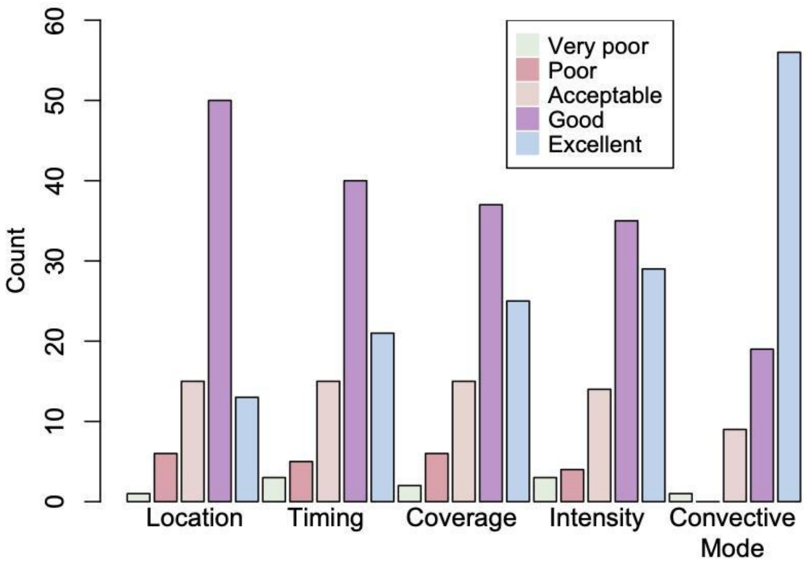
From WPC MPD #0606: **"…HRRR…as well as the 05/21z run of the…WoFS...showed pockets of hourly rainfall rates of 2.00 inches continuing…"**

MetWatch Desk Evaluation, Summers 2019 & 2020

WoFS Influence on Forecaster Confidence

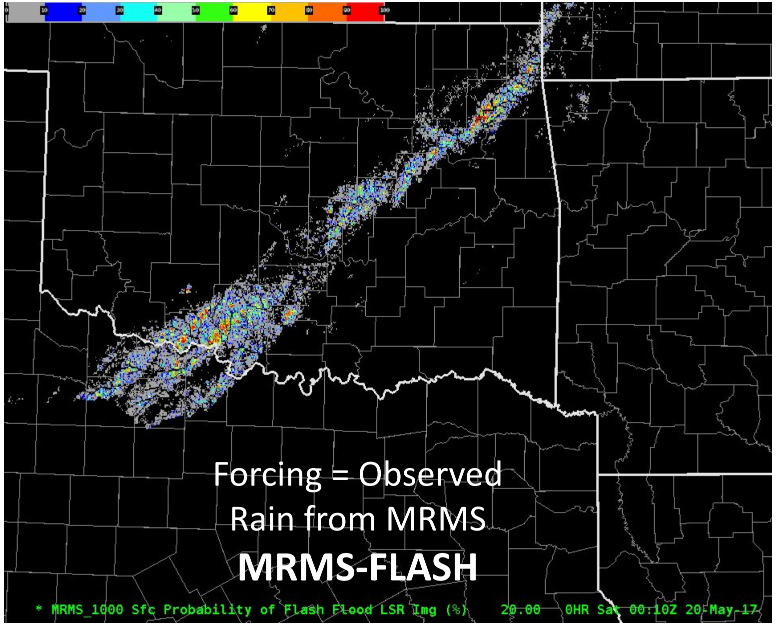


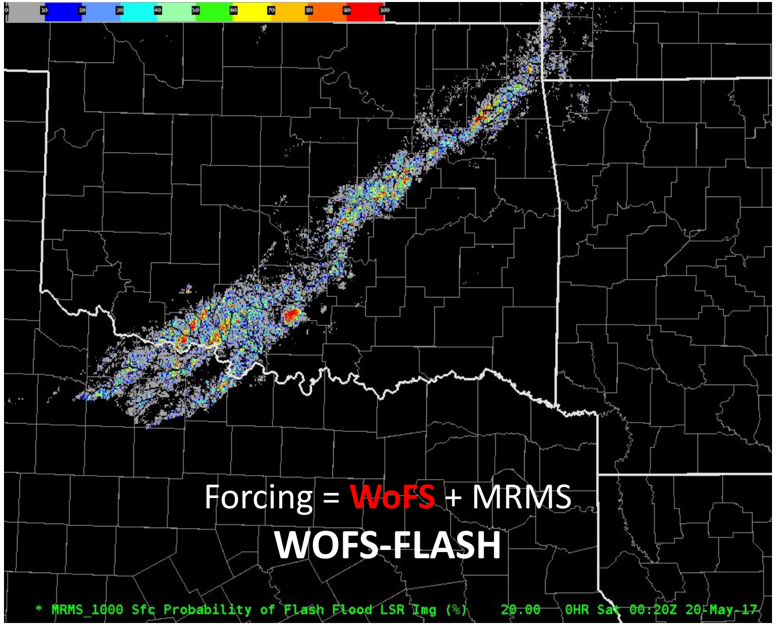
Forecaster Ratings Per Storm Attributes



Forcing to Hydrologic Ensemble

Probability of Receiving Flash Flood Reports





Yussouf, N., K. Wilson, H. Arrieta-Vergera, S. M. Martinaitis, P. L. Heinselman, and J. J. Gourley, 2020: The Coupling of NSSL Warn-on-Forecast and FLASH Systems for Probabilistic Flash Flood Prediction, *Journal of Hydrometeorology, 21, 123-141*

Forcing to Hydrologic Ensemble

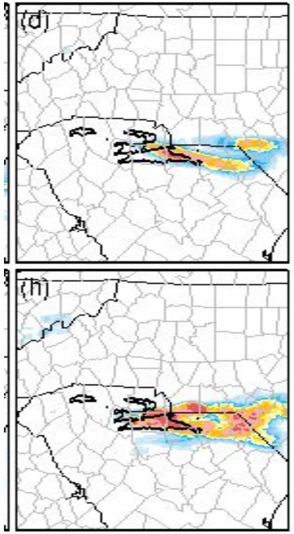
2018-2019 HMT-Hydro Experiment
Displaced Real-time Evaluation

Ellicott City and Baltimore, MD Flash Flood, 27-28 May 2018

CWA	Location	Operational FFW Date/Time	**Operational** FFW Lead Time (min)	**WoFS-FLASH Experimental** Average FFW Lead Time (min)	Increase in FFW Lead Time with WoFS-FLASH
LWX	Ellicott City	2026 UTC	8	38.38	+30.38
	Baltimore	2050 UTC	5	71.60	+66.60

Future Work (1-3 years)

1-km WoFS for improved heavy rainfall prediction
(i.e. amount, location, and timing)



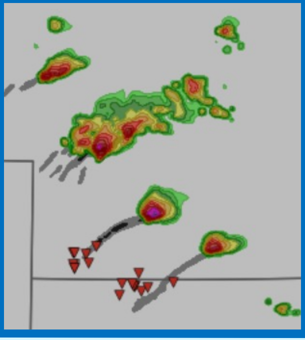
Hydrologic WoFS: Use WoFS as a forcing to the National Water Model for explicit probabilistic flash flood prediction

Machine learning and artificial intelligence techniques to improve WoFS rainfall prediction

Forecast/Warning Tools and Techniques

Future Directions for WoFS

Patrick C. Burke MS, WoF Program Lead, FRDD

WoFS Advances Convection Allowing Models

CAMs

1980s First 3D models for convective research

1990s Experimental CAM real-time forecasts

2005 First large-domain CAM forecasts

NSSL real-time modeling begins

WoFS

2005 Ensemble data assimilation at convective scales

1990s 3D variational techniques for convective storms analysis and forecasting at U. of Okla.

1980s **Lilly: Numerical Prediction of Thunderstorms, Has it's time come?**

WARN on FORECAST

2010 **WoF Project Begins**

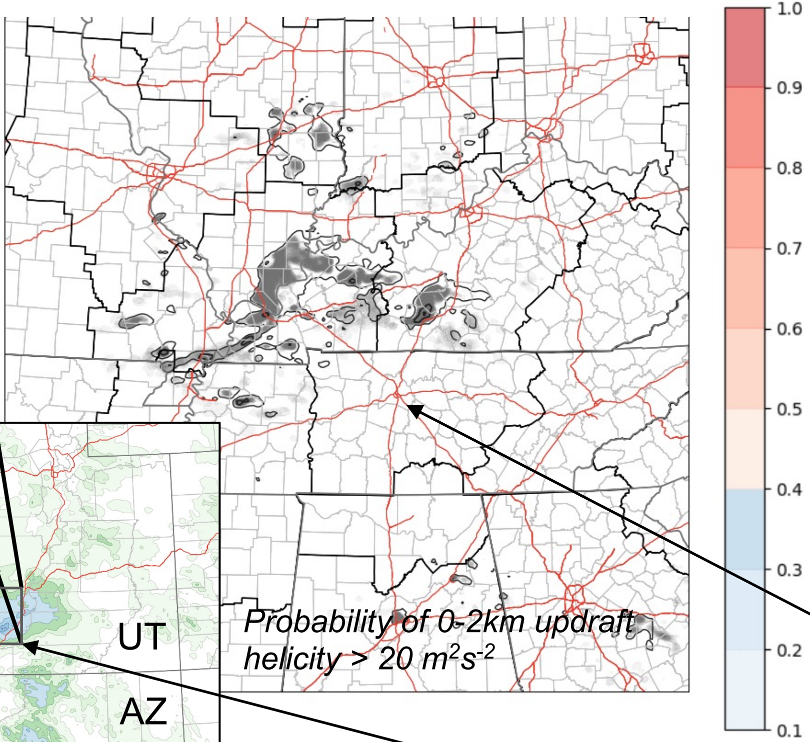
2015 **First real-time testing**

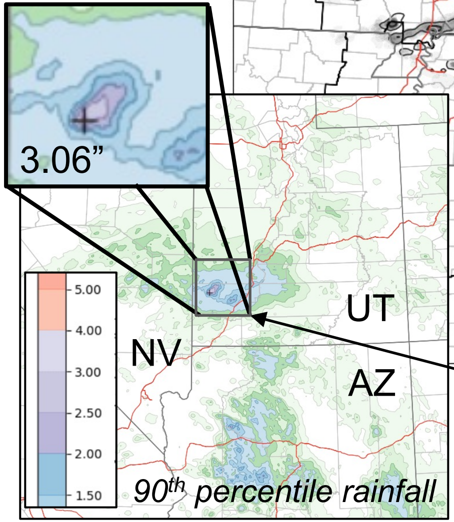
2018 **3km WoFS matures.** **User engagement expands**

2021

Ready

Groundbreaking Accuracy at Greater Lead Time





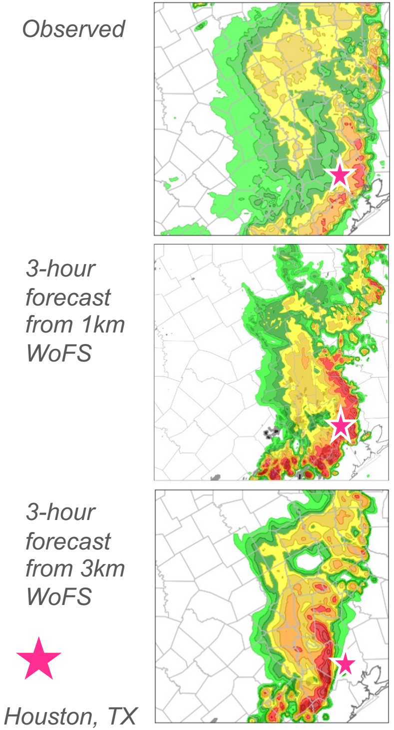
Increased lead time means earlier and more accurate communication of:

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)

Research Priorities through 2025



Example comparing 1km- to 3km- WoFS

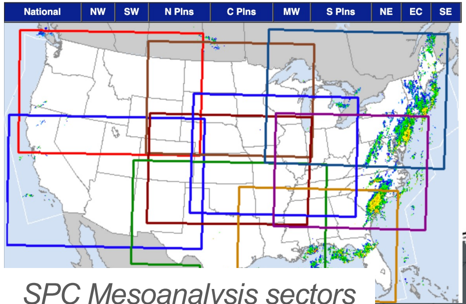
- Unified Forecast System
  - First project to attempt rapid data assimilation using FV3
  - Exploring ensemble data assimilation using Joint Effort for Data assimilation Integration (JEDI) community structure
- Calibrated Probabilistic Output
  - Based on machine learning
  - Bridging across scales to develop verification for multi-hazard probabilistic hazard information in the watch-to-warning time frame
- Begin Next Generation WoFS
  - Real-time runs on the cloud
  - Exploring 1km (or less) grid resolution

Set

Transition WoFS to NWS Operations

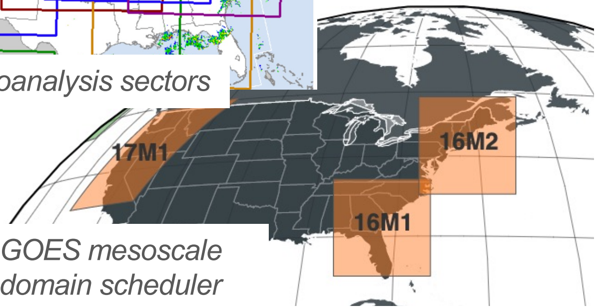
- Documenting operational strategies
- Training users on probabilistic watch-to-warning strategies
- Multiple domains
- Coordinated OAR/NWS Transition plan

A WoFS scientist sits with a forecaster during warning operations



SPC Mesoanalysis sectors

Options for targeted model domains could take many forms.



GOES mesoscale domain scheduler

We believe WoF's time has come

<u>TEAM LEADS</u>

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WARN on FORECAST

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