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

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

<table>
<thead>
<tr>
<th>Probability of strong mid-level storm rotation</th>
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<tr>
<td>Init: 2100 UTC</td>
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<tr>
<td>Valid: 0100 UTC</td>
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**90th percentile severity** of mid-level storm rotation

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Filling the Watch-to-Warning Gap

**WATCH**

- 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)

**WARNING**

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.

**Legend:**
- m$^2$s$^{-2}$
Relevance

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

Congress

Weather Research & Forecast Innovation Act; Tornado Warning Improvement and Extension Program

WoFS integration into operations is a TWIEP goal

OAR

Make forecasts better & Drive innovative science

Develop reliable probabilistic guidance products; provide warning uncertainty information for high impact weather events
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

University Partners

NOAA/CIWRO

NOAA/NWS

NOAA Partners

GFDL

NOAA/NWS

Developmental Testbed Center

University of Oklahoma

NCEP

MRMS

University of Maryland

WPC

NOAA/NWS

Purdue University

Stakeholder Groups

University of Maryland

University of Oklahoma

Norman Community

University of Maryland

University of Oklahoma

University of Maryland

University of Oklahoma

University of Maryland

University of Oklahoma
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 useful to forecasters
  • 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 km² 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 km² 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!
Cloud-Based Warn-on-Forecast
Providing probabilistic hazard guidance generated by an ensemble of forecasts from convection-resolving numerical weather prediction models.

Historical
Browse the archive of historical Cb-WoFS Cloud runs

Research
Queue a new Cb-WoFS model run

Forecasts
View post-processed graphics from a current or historical Cb-WoFS run

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](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.

<table>
<thead>
<tr>
<th>Neighborhood</th>
<th>Threshold (dBZ)</th>
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<tr>
<td></td>
<td>1-Hr</td>
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<tr>
<td>3 km</td>
<td>30</td>
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<td>40</td>
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<td>27 km</td>
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<td>45</td>
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<tr>
<td></td>
<td>50</td>
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Lawson et al. 2018

Composite Radar Reflectivity

Spatial Scale (km) | Threshold (mm/hr) |
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<tr>
<td>WoFS Better</td>
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<tr>
<td>HRRR Better</td>
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</table>
Object-based Verification of WoFS Guidance

Characterize changes in WoFS accuracy before and after convection initiation

Quantify improvements in WoFS mesocyclone prediction with increased horizontal resolution

Create probabilistic forecast objects to input into machine learning models

- Miller et al. 2021
- Flora et al. 2021

![Graph showing probability of detection over observed object age](image)

- POD = 0.9 for thunderstorms older than ~90 minutes
- POD < 0.5 for newly initiated thunderstorms

![Line graph with improved POD](image)

- Increased mesocyclone POD in WoFS forecasts run with 1 km horizontal grid spacing
- \( N_{\text{OBJ RT}} = 45066 \quad N_{\text{OBJ HIRES}} = 46876 \)

![Map showing storm tracks](image)
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

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

2018

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

2019

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

2020

First WoF testbed experiment conducted involving both national centers and local forecast offices.

2021

1 h Outlooks

Issued 2100 UTC
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.

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

- **2016**: Proof-of-concept demonstration of WoFS for heavy rainfall prediction (Yussouf et al. 2016)
- **2017**: Concept-of-Operation evaluations, WPC MetWatch Desk and WFOs
- **2018**: First evaluation at NOAA-HMT Flash Flood and Intense Rainfall & HMT-Hydro experiments
- **2019**: WPC Meso Discussion
- **2020**: WoFS Domain Day 1 WPC Outlook
- **2021**: WoFS Output

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.

NSSSL 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

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

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
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

- Excellent
- Good
- Acceptable
- Poor
- Very Poor

Effect on Confidence?

- Increased Greatly n=20
- Increased Slightly n=44
- Stayed the Same n=16
- Decreased Slightly n=5
- Decreased Greatly n=0

Forecaster Ratings Per Storm Attributes

- Location
- Timing
- Coverage
- Intensity
- Convective Mode

How did WoFS Perform?

- n=0
- Decreased
- n=5
- Decreased Slightly
- n=44
- Increased Slightly
- n=20
- Increased Greatly
- n=0
- Stayed the Same
Forcing to Hydrologic Ensemble

Probability of Receiving Flash Flood Reports

## Forcing to Hydrologic Ensemble

**2018-2019 HMT-Hydro Experiment**

Displaced Real-time Evaluation

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

<table>
<thead>
<tr>
<th>CWA Location</th>
<th>Operational FFW Date/Time</th>
<th>Operational FFW Lead Time (min)</th>
<th>WoFS-FLASH Experimental Average FFW Lead Time (min)</th>
<th>Increase in FFW Lead Time with WoFS-FLAS H</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWX Ellicott City</td>
<td>2026 UTC</td>
<td>8</td>
<td>38.38</td>
<td>+30.38</td>
</tr>
<tr>
<td>Baltimore</td>
<td>2050 UTC</td>
<td>5</td>
<td>71.60</td>
<td>+66.60</td>
</tr>
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</table>
Future Work (1-3 years)

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

Machine learning and artificial intelligence techniques to improve WoFS rainfall prediction

Hydrologic WoFS: Use WoFS as a forcing to the National Water Model for explicit probabilistic flash flood prediction
Forecast/Warning Tools and Techniques

Future Directions for WoFS

Patrick C. Burke MS, WoF Program Lead, FRDD
WoFS Advances Convection Allowing Models

- **1980s**: First 3D models for convective research
- **1990s**: Experimental CAM real-time forecasts, First large-domain CAM forecasts
- **2005**: Ensemble data assimilation at convective scales, 3D variational techniques for convective storms analysis and forecasting at U. of Okla.
- **2005**: Lilly: Numerical Prediction of Thunderstorms, Has it’s time come?
- **2010**: WoF Project Begins
- **2015**: First real-time testing
- **2018**: 3km WoFS matures
- **2021**: User engagement expands

Ready
Groundbreaking Accuracy at Greater Lead Time

Increased lead time means earlier and more accurate communication of:

1) probabilities
2) uncertainties
3) near certainties

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

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

3.06” 90th percentile rainfall

Probability of 0-2km updraft helicity > 20 m²s⁻²
Research Priorities through 2025

- **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

*Example comparing 1km- to 3km- WoFS*
Transition WoFS to NWS Operations

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

Options for targeted model domains could take many forms.

SPC Mesoanalysis sectors

GOES mesoscale domain scheduler

A WoFS scientist sits with a forecaster during warning operations
We believe WoF’s time has come

TEAM LEADS

Pam Heinselman (pam.heinselman@noaa.gov)
Lou Wicker (louis.wicker@noaa.gov)
Patrick Burke (patrick.burke@noaa.gov)

REST OF THE NSSL WoF TEAM

Jack Kain, Adam Clark, Nusrat Yussouf, Patrick Skinner, Corey Potvin, Jidong Gao, Thomas Jones, Katie Wilson, Burkely Gallo, Montgomery Flora, Gerry Creager, Kent Knopfmeier, Yunheng Wang, Brian Matilla, David Dowell (GSL), Ted Mansell, Brett Roberts, Larissa Reames, Anthony Reinhart, Kimberly Hoogewind, Derek Stratman, Jorge Guerra, Christopher Kerr, Eric Loken, our in-house WRDD and radar partners, and many more past contributors.