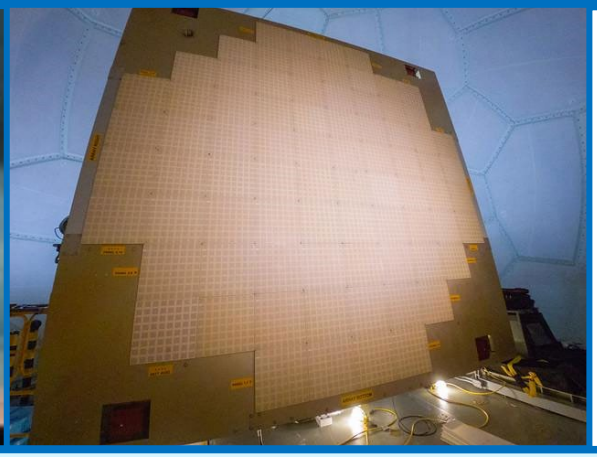
An Overview of Severe Weather Research at the National Severe Storms Laboratory

Alan Gerard
Chief, Warning R&D Division



NSSL's Mission Statement

- ***The National Severe Storms Laboratory serves to enhance NOAA's capabilities to provide accurate and timely forecasts and warnings of hazardous weather events.***
- ***NSSL accomplishes this mission through …***
  - ***research to advance the understanding of weather processes,***
  - ***research to improve forecasting and warning techniques,***
  - ***and development of operational applications.***
- ***NSSL transfers new scientific understanding, techniques, and applications to the National Weather Service (NWS).***

We don't make the forecasts & warnings, we make them better!

Forecast R&D Division

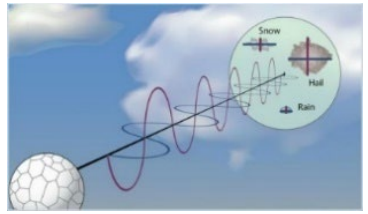
- **FRDD Activities**
  - **Hazardous Weather Testbed** (HWT)
    - Experimental Forecast Program (EFP)
  - Process studies of convective storms & environments
  - Ground-based instrument development and observational strategies
  - Severe weather climatology and long-term forecasting
  - **Warn-On-Forecast program**
    - Objective to increase tornado (and other severe weather) warning lead times based on numerical weather prediction forecasts
    - Goal to predict the probabilities of a specific hazard occurring and confidence in the location/path of the hazard with 30-60 minutes of lead time

Radar R&D Disivion


WSR-57


Doppler


NEXRAD
WSR-88D



Dual
Polarization


Phased Array
Weather Radar


Advanced
Technology
Demonstrator

- **RRDD Activities**
  - NOAA's primary weather radar laboratory with strong scientific and engineering leadership in dual polarization and phased array radar (PAR) for weather observations
  - Primary Research to Operations (R2O) entity for the Operational NEXRAD Radar Network
  - Leading NOAA’s R&D activities for a future operational radar network based on phased array technology

Warning R&D Division

- **WRDD Activities**
  - **Hazardous Weather Testbed** (HWT)
    - Experimental Warning Program (EWP)
  - **Multi-Radar Multi-Sensor** (MRMS) algorithm development
    - Severe weather applications
    - Quantitative Precipitation Estimation (QPE)
    - Flooded Locations and Simulated Hydrographs (FLASH)
    - Multi-Year Reanalysis of Remotely Sensed Storms (MYRORSS)
  - **Forecasting a Continuum of Environmental Threats** (FACETs)
    - Probabilistic Hazard Information (PHI)

Field Observing Facilities & Support

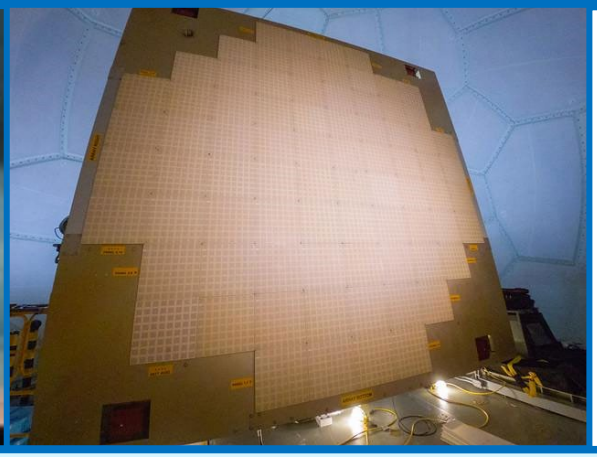
Social & Behavioral Science Studies

- ***Improve the effectiveness of forecasts and warnings of severe & hazardous weather***
  - Improve and evaluate forecaster decision tools
    - Better forecast models and observations
    - Probabilistic output
  - Improve communication of threats & impacts
    - Expressions of uncertainty
    - Messages understood by key partners (broadcasters and emergency managers)
  - Improve public understanding and reception of information
    - Understandable
    - Actionable for personal decision-making

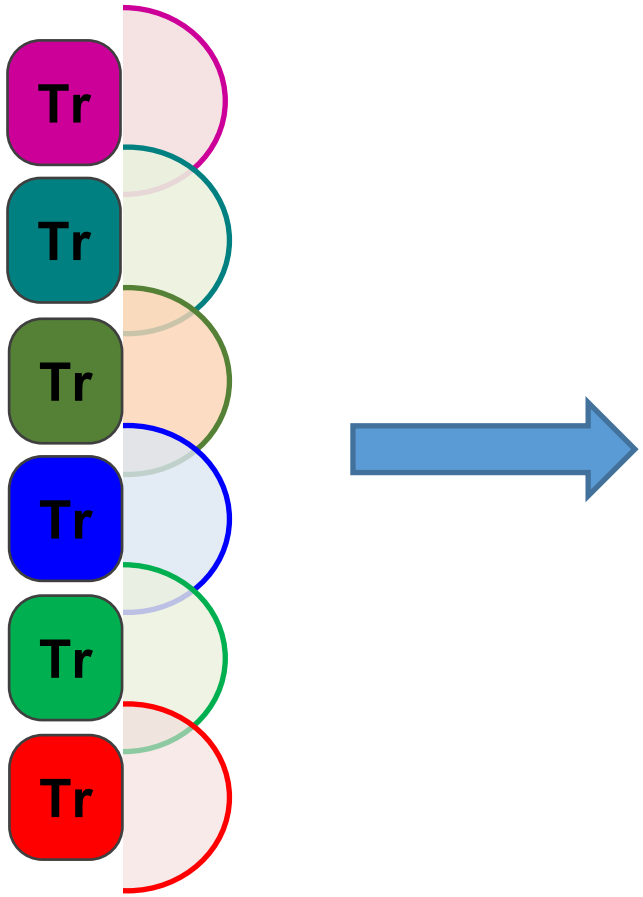
Recent NSSL Accomplishments

- **Warn-on-Forecast (WoF) Program**
  - Cloud-based Warn-on-Forecast System (CbWoFS) developed and used in real-time to support PERiLS field program
- **Phased Array Radar (PAR) R&D Program**
  - Phase 2 of ATD panel repair project in process and expected to be completed by end of CY22.
  - Market research for Rotating PAR Test Article acquisition nearly complete (sources sought posted)
- **VORTEX-SE Program**
  - Successful conduct of joint NOAA & NSF sponsored PERiLS field program
- **FACETs Program**
  - Threats-In-Motion (TIM) making progress; Tiny TIM development on track and will be tested in the NWS Operational Proving Ground later this year
- **Multi-Radar Multi-Sensor (MRMS) Program**
  - Completed MRMS Hurricane Supplemental project for NWS
    - MRMS V12.2 operational with Canadian radars; Demonstrated MRMS in the cloud; Evaluation of WCOSS operational transition

Phased Array Radar (PAR) Research and Development Overview

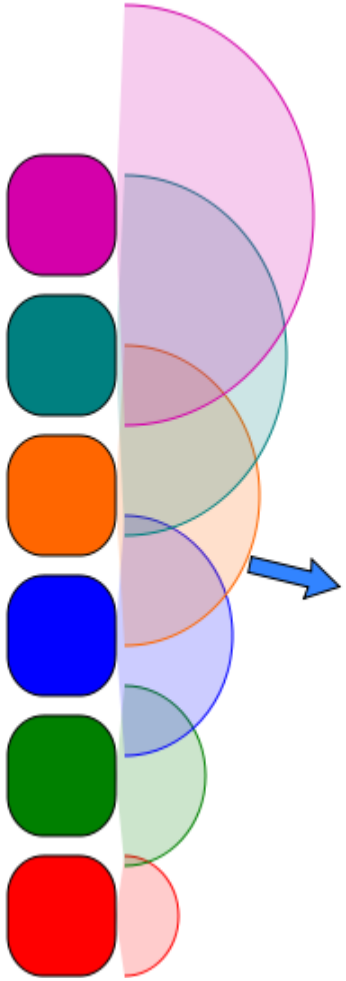


What is a Phased Array?

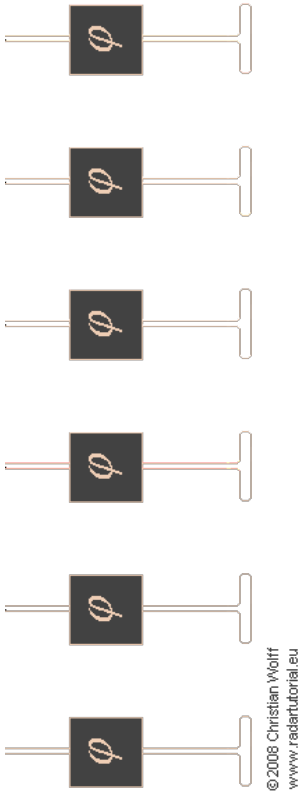


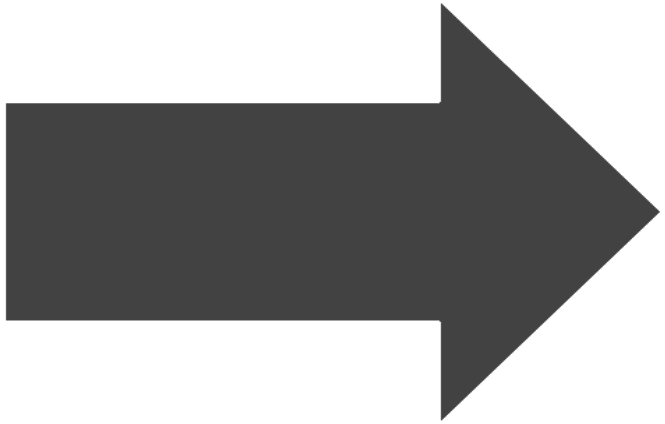
Instead of a single high-power transmitter, a phased array uses multiple transmitters that work collectively to steer the radar beam. If the transmitters all fire at the same time, the wave front is directed perpendicular to the array.

What is a Phased Array?



The timing (or phase) of the transmitters are synchronized to form a wave front in the desired direction. *(See animation)*





Rapid Update PAR Data

- **Demonstration of rapid update PAR SPY-1 data (1-min) vs WSR-88D update (5-min) from 24 May 2011**

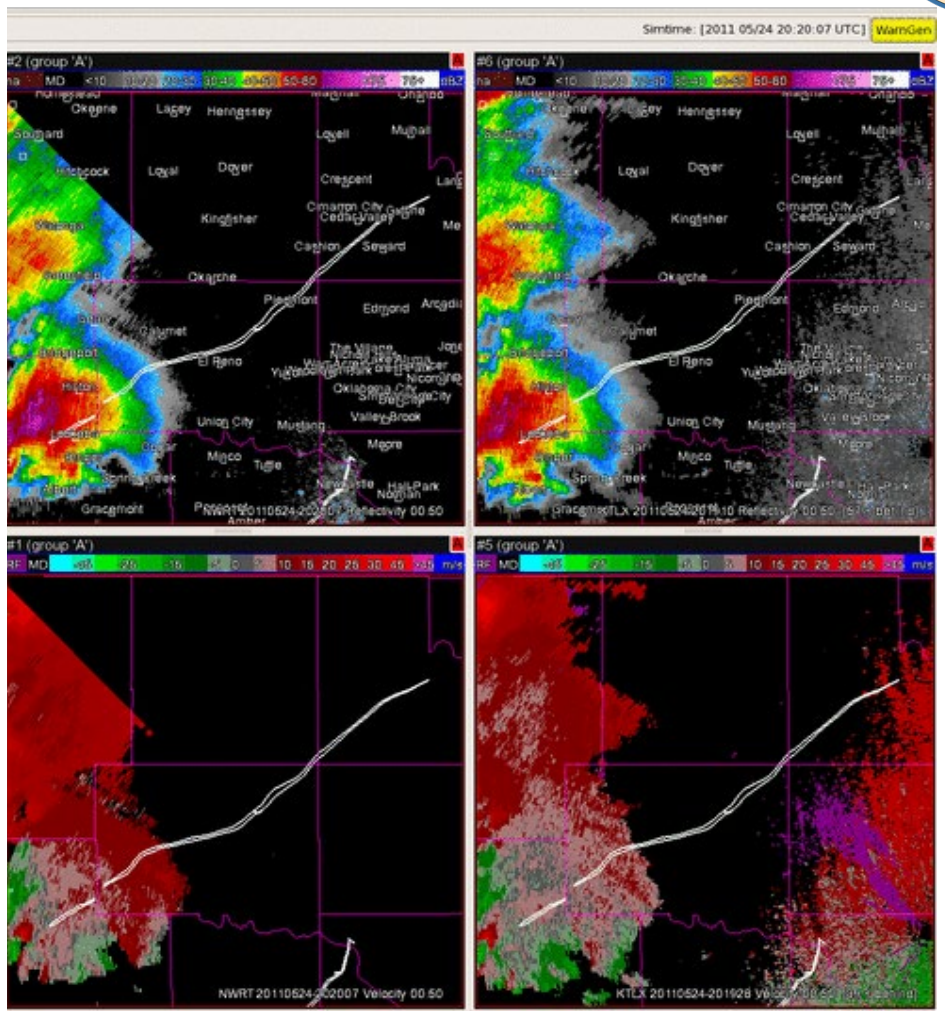
Navy SPY-1 system was installed in 2003

- ***Demonstrated the benefits of faster updates to warning performance***

NSSL's Advanced Technology Demonstrator (ATD) is the first dual polarization PAR and was installed in 2018 and fully tested in 2021

- ***Evaluation of dual polarization performance and calibration on PAR***

(1-min update) PAR SPY-1A | **(5-min update) WSR-88D KTLX**



https://wdssii.nssl.noaa.gov/web/wdss2/products/radar/rtmp/6xNWRT_24May11.gif

What we learned from the SPY-1 PAR

National Weather Radar Testbed (NWRT) SPY-1A (2003-2016) phased array radar system demonstrated ability to provide rapid volume updates.

- ***With electronic scanning and adaptive scan strategies we were able to collect volumetric updates in 45-75 seconds within a 90-deg sector.***

What we learned with rapid update volume data from the SPY-1A …

- Improved scientific understanding of storm evolution process
- Demonstrated potential to increase tornado and severe weather warning lead times
- Demonstrated improved depiction of probabilistic threats via storm-scale numerical weather prediction models (i.e. Warn On Forecast studies)

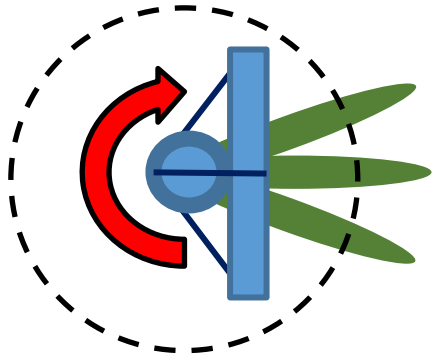
Possible PAR Configurations

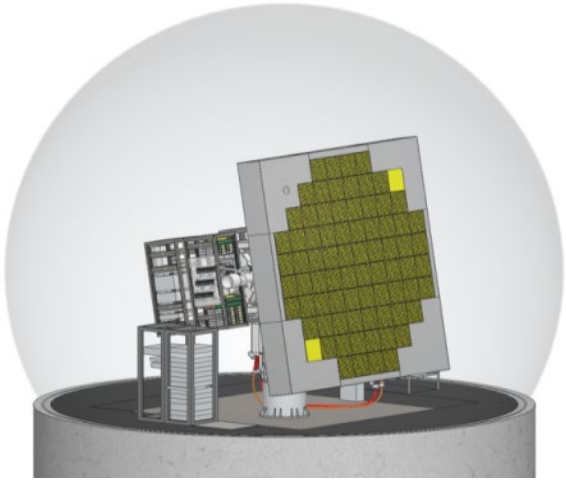
NOAA contemplating replacing the WSR-88D by 2040, requiring an Analysis of Alternatives by 2030. PAR is one of the alternatives being considered.

Rotating Planar Array

With Multiple Simultaneous Beams

- Less Costly to Procure
- More Technical Risk
- Less Costly to Operate

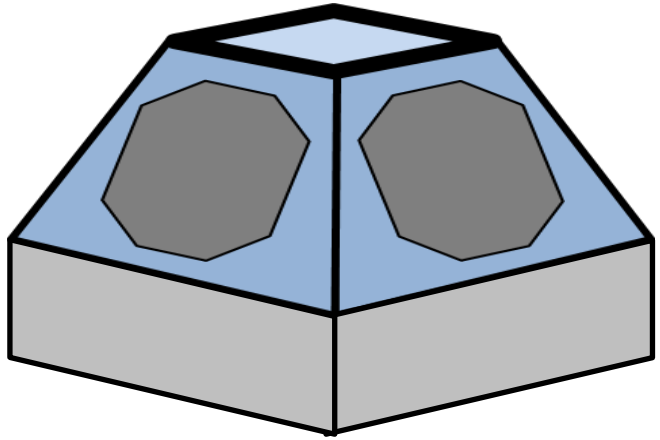


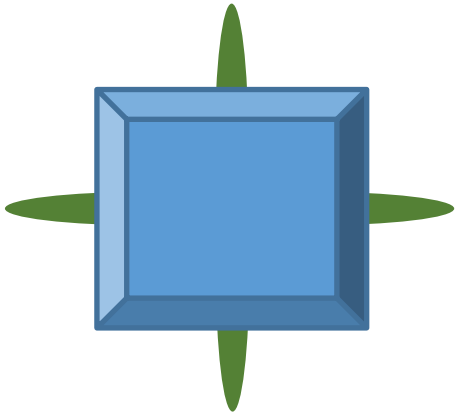


Multi-Face Planar Array

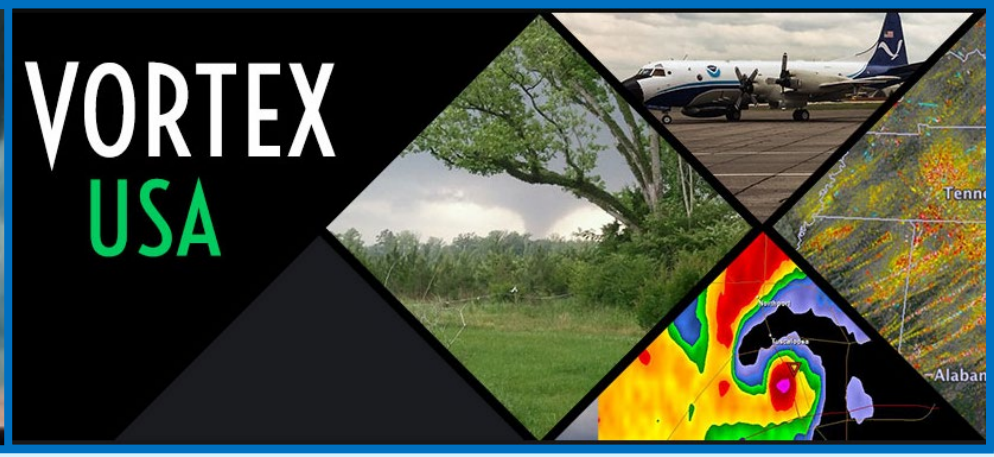
4 Independent Radars

- More Costly to Procure
- Less Technical Risk
- More Costly to Operate





VORTEX-SE / VORTEX-USA



VORTEX & TWIEP Overview

- **Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) in 1994-95 and 2009-10**
  - Joint NSF and NOAA field program to observe tornadoes and tornadic environments with up-close, high resolution mobile observation platforms
- **VORTEX-SE established by Congressional mandate in 2015**
  - To study storms in the southeastern US
- **Tornado Warning Improvement and Extension Program (TWIEP)**
  - Established in the Weather Research and Forecasting Innovation Act of 2017 to reduce loss of life via improved tornado forecasts and warnings
  - TWIEP Plan delivered to Congress in 2019
- **VORTEX-USA established by Congressional language in 2021**
  - Extend VORTEX-SE activities to the rest of the US
  - Result of funds requested for TWIEP

VORTEX-Southeast

- **In January 2015, Congress unexpectedly appropriated $5M money and directed NSSL to solve the Tornado problem in the Southeast**
- **From FY15 Omnibus Spending Bill:**

  "…establish why tornadic activity in the Southeast results in more deaths per capita than any other region of the country."
  "…to better understand how environmental factors that are characteristic of the southeastern United States affect the formation, intensity, and storm path of tornadoes for this region"

- **Rapid, effective, inclusive NSSL response**
  - Grants Program (over 50% of funds for competitive grants)
  - Community Engagement
  - Field Programs

VORTEX SOUTHEAST

VORTEX-Southeast

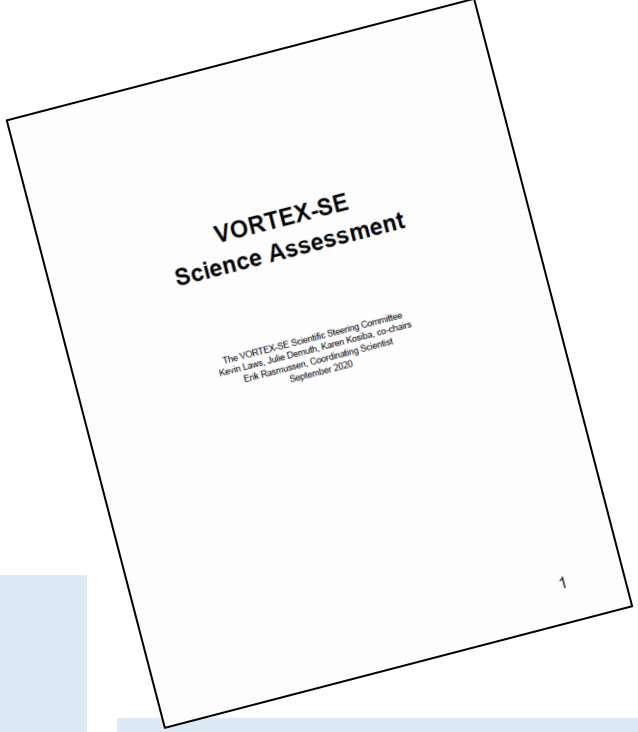
Physical Science Research

- Terrain and Roughness Influences
- Internal Storm Processes
- Storm Environment Influences
- Climatology
- Tornado Damage Assessment
- Landfalling Hurricane Tornadoes
- Prediction Models

VORTEX SOUTHEAST

Social, Behavioral, and Economic Sciences (SBES)

- Forecaster Decision-Making
- Risk Communication to Public
- Risk Assessment, Decision-Making, and Actions Taken by Public
- Assessing Tornado Impacts and Vulnerabilities

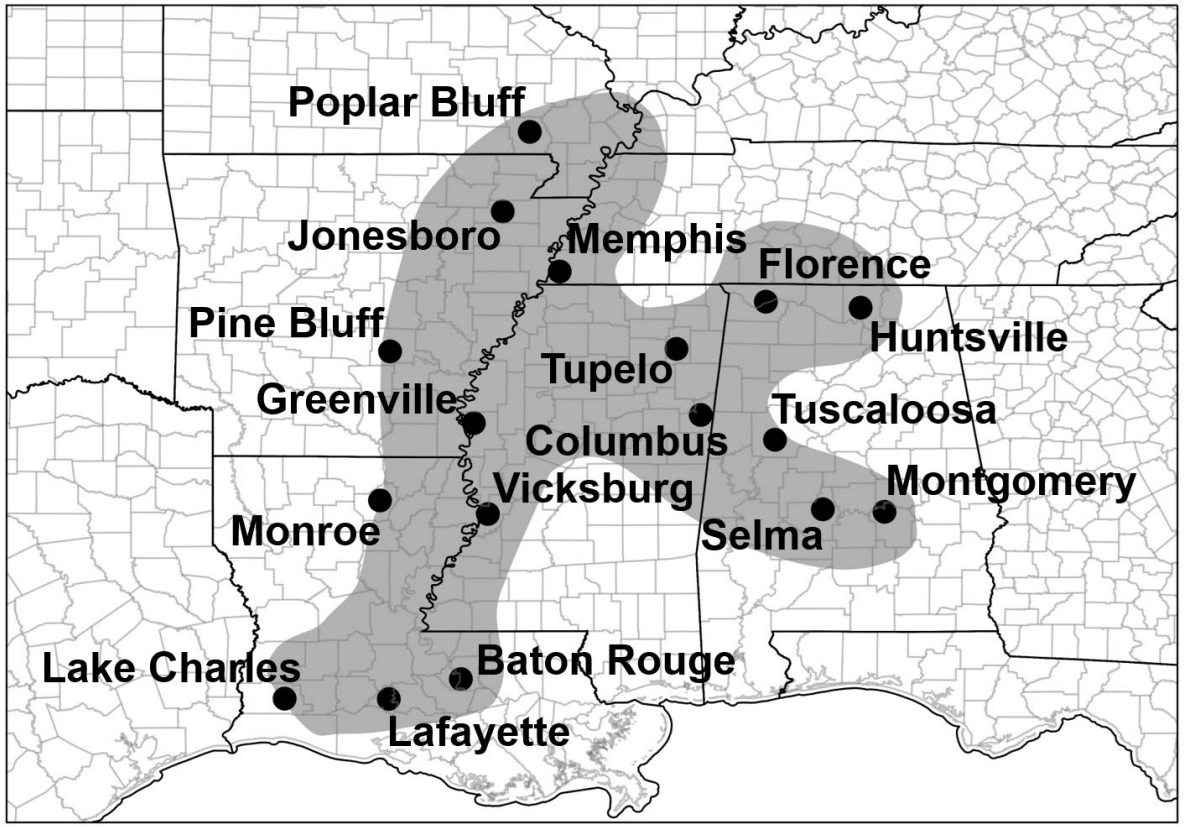


Field Campaigns

- Broad Meteorological Community Collaboration
- Procurement and Testing of New Instruments and Observation Strategies
- Impacts of New Observations on Analysis and Prediction
- Leverage other Funding Sources (e.g., NSF, NOAA)

PERiLS

- Propagation, Evolution, and Rotation in Linear Storms
- 1 March – 30 April 2022 and 8 February – 8 May 2023
- Joint NOAA (through VORTEX-USA) and NSF field campaign
- Operations across a large swath of the Southeast, including much of the mid-lower Mississippi Valley, Tennessee Valley, and Black Belt regions



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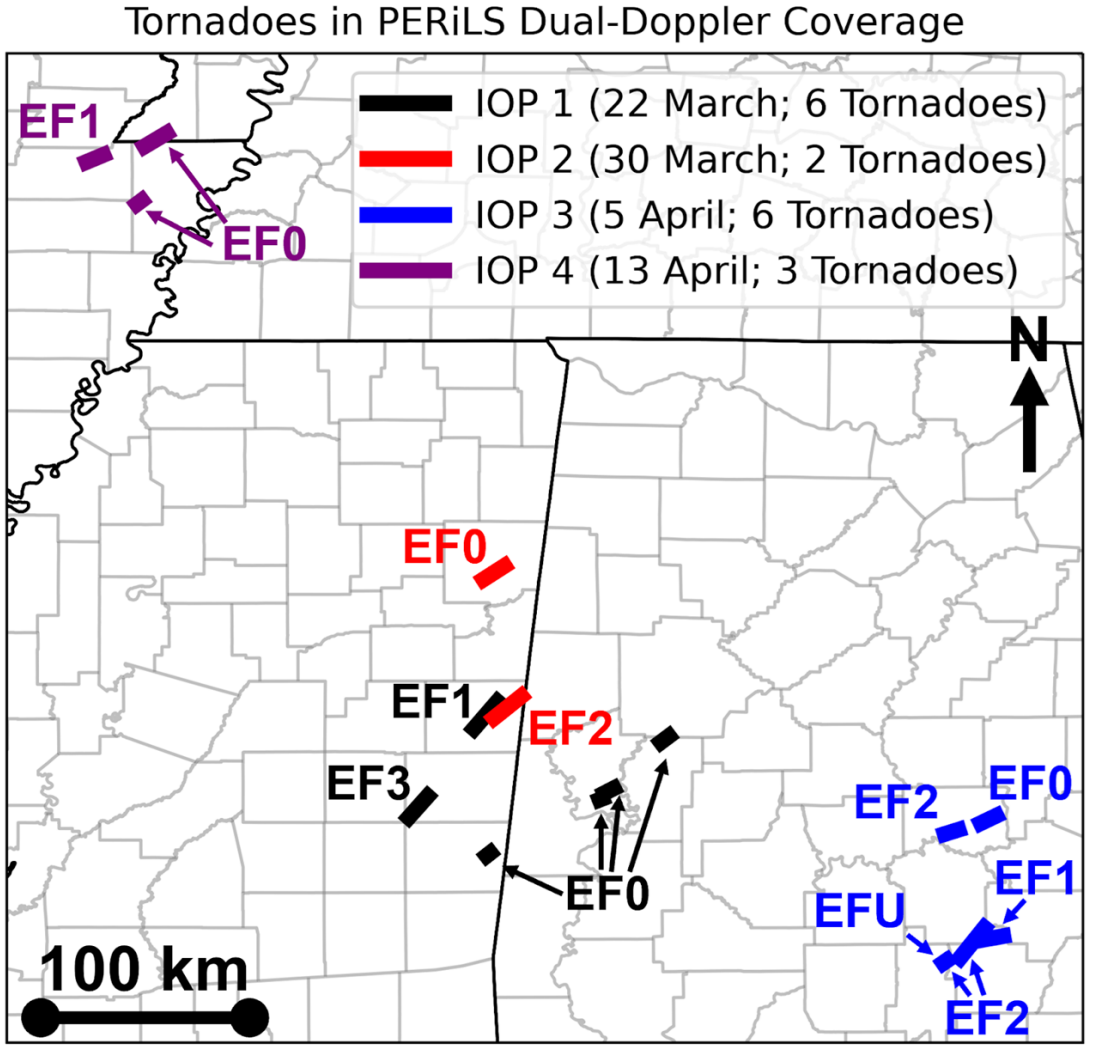
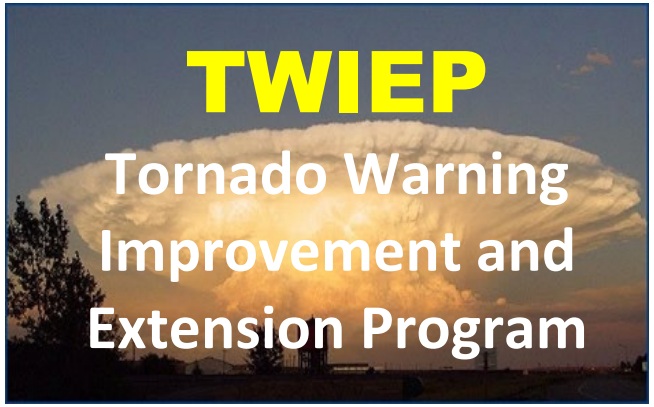


Courtesy Tony Lyza, NSSL/CIWRO



TWIEP

Tornado Warning Improvement and Extension Program

Tornado prediction beyond 1-hour, through improved observations, high-resolution prediction models, and an optimized approach to communicate risk informed by social sciences. *Established by P.L. 115-25 (Weather Act)*

1) Improve Observations

- Development of new observational capabilities, including rapid-deployment instruments and lowest 1-km measurements
- integration of the new GOES satellite series
- demonstration of phased array radar.

2) Improve Tornado Forecasting Guidance (Models)

- Development of high resolution, convection-allowing (thunderstorm scale) computer prediction models, including the High Resolution Rapid Refresh (HRRR) and Warn-on-Forecast (WoF) ensemble systems.

3) Use Social, Behavioral and Economic Sciences (SBES) to improve Tornado-Forecast Efficacy

- Optimize the ability of forecasters to fully utilize the numerical guidance they receive for issuing tornado warnings
- Improve delivery and info content of tornado warnings to empower all members of society to make optimal protective-action decisions

4) Development of the Next-Generation Warning System (FACETs)

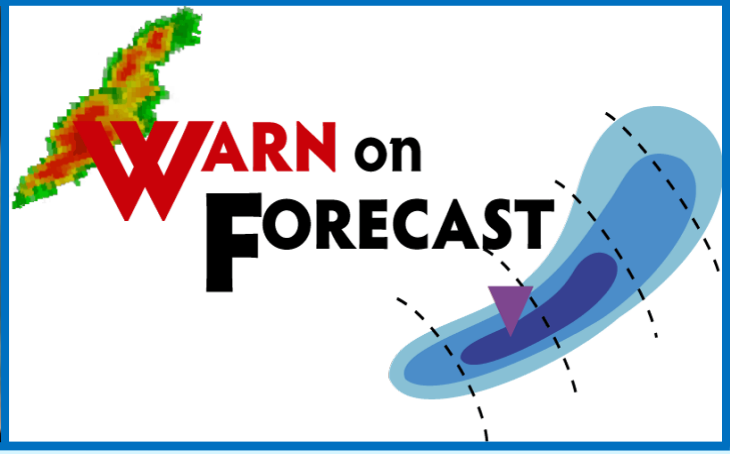
- Modernize NOAA's approach to risk communication, informed by social sciences, and delivered to decision makers, the public, and weather enterprise stakeholders before, during, and after tornado events.

4 Major Components of TWIEP

TWIEP Plan – Goals

- **Short Term (5 years)**
  - Conduct research aimed at developing streamlined national observational database suitable for advanced data assimilation and reducing model error.
  - Further develop, test, and implement a Warn-on-Forecast prototype system.
  - Implement next generation NWS warning paradigm with extended lead times that empower effective decision-making.
  - Implement a prototype Convection Allowing Model ensemble system.
  - Define and implement optimal predictive information content and lead time for decision makers.
  - Establish physical and societal performance metrics to accurately assess effectiveness of current and future forecasts.
- **Long Term (10 years)**
  - Develop and test optimal approaches for enhancing observations (including beyond radar) to substantively improve short-range forecast of thunderstorm initiation and evolution.
  - Define, develop and implement more effective dissemination strategies.
  - Triple the current skill and effectiveness of tornado forecasts and warnings.

Warn-on-Forecast R&D

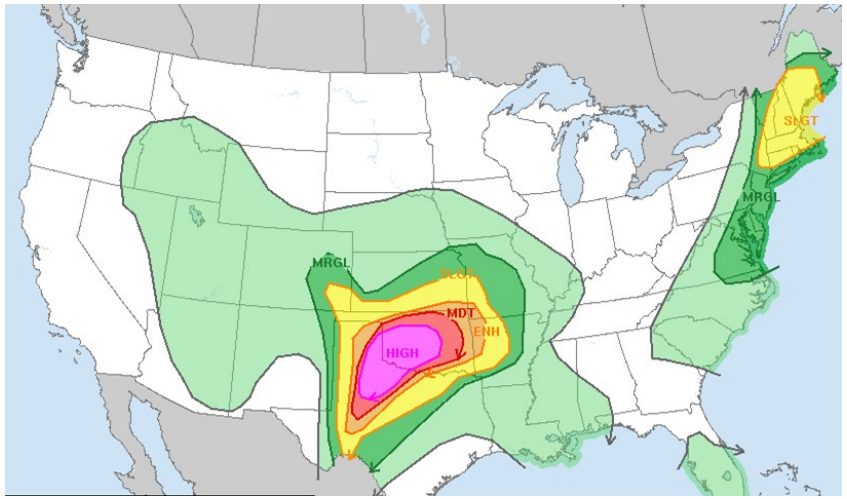


The Warn on Forecast Goal

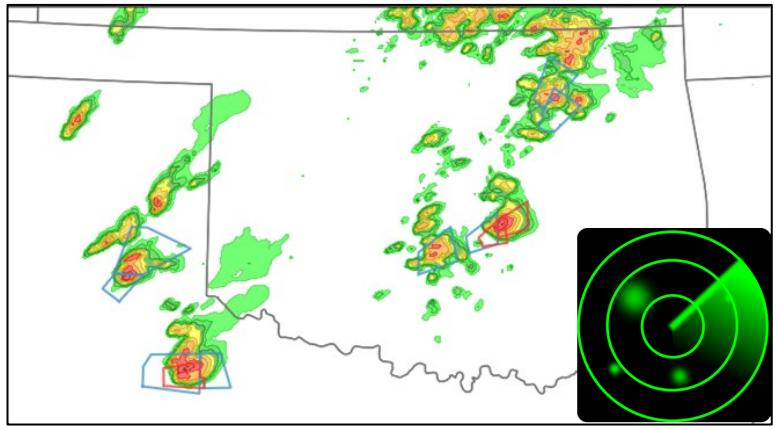
Revolutionize the predictive tools available to warning operations to bring about increased lead time for severe weather warnings

Why Warn on Forecast?

Traditionally:



Weather models help predict thunderstorm areas



Forecasters rely on radar and spotters to make severe storm warnings

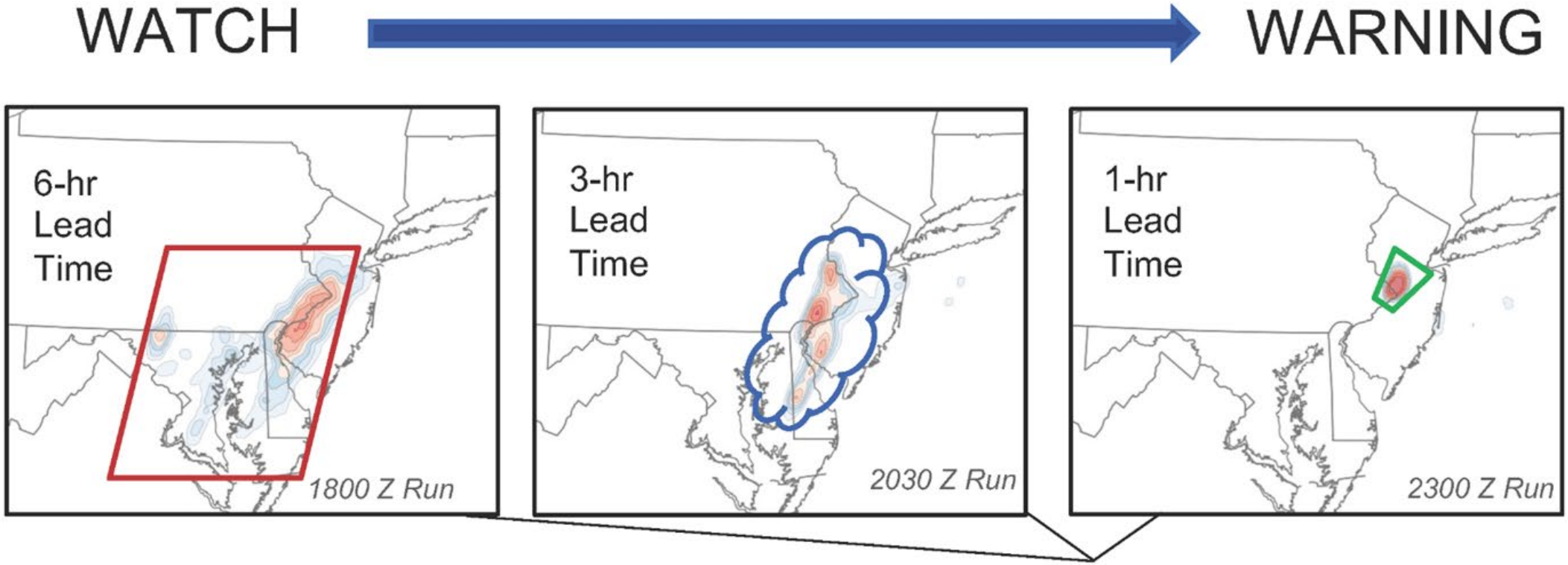
WoF asks:

Can we now model individual storm threats quickly enough to double or triple the warning lead time?

WoF answers:

WoFS is a rapidly updating, storm-scale ensemble predicting individual thunderstorms

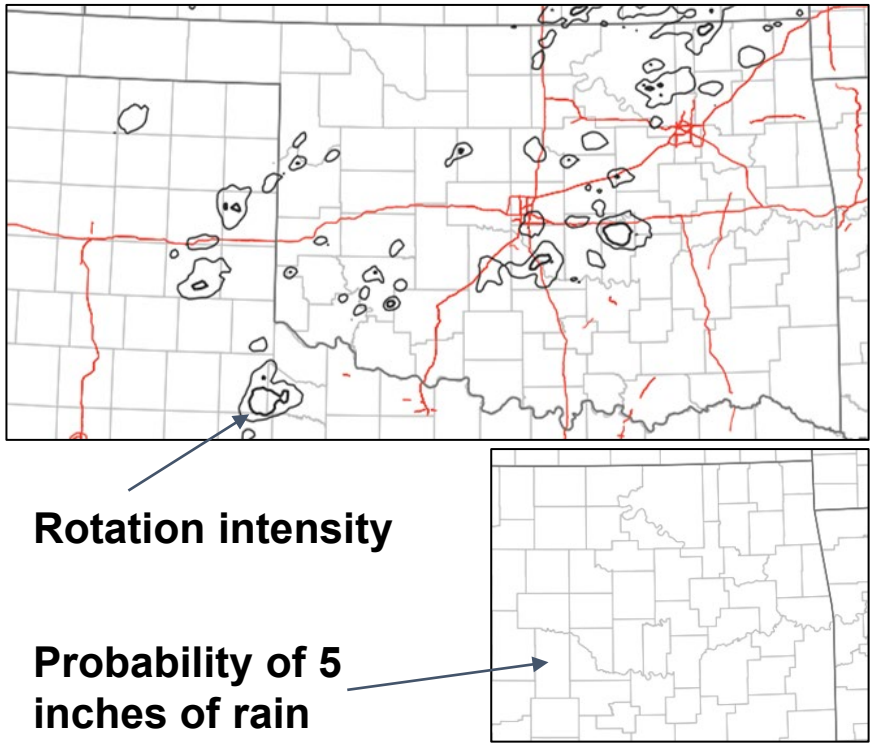
The Watch to Warning Gap



Running at 0-6 hours, WoFS fills a critical gap in which newly arriving, probabilistic numerical model guidance has been absent

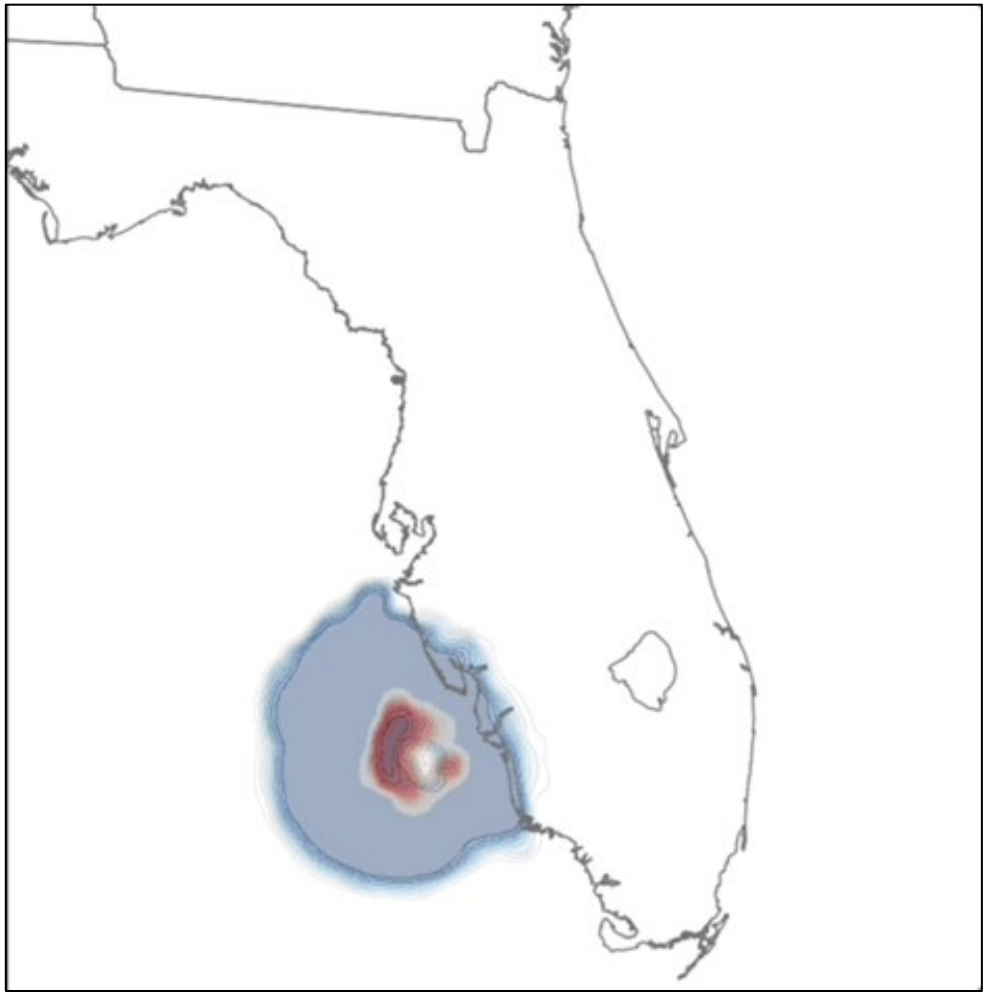
Probability of low-level rotation
from three different WoFS runs; these show the accumulated swath of probability of 0-2km updraft helicity > 20 $m^2 s^{-2}$, all ending at the same time but of differing duration.

May 4, 2022 in Oklahoma



Hurricane Ian

Combined Wind, Tornado, and Rainfall Threat Graphic



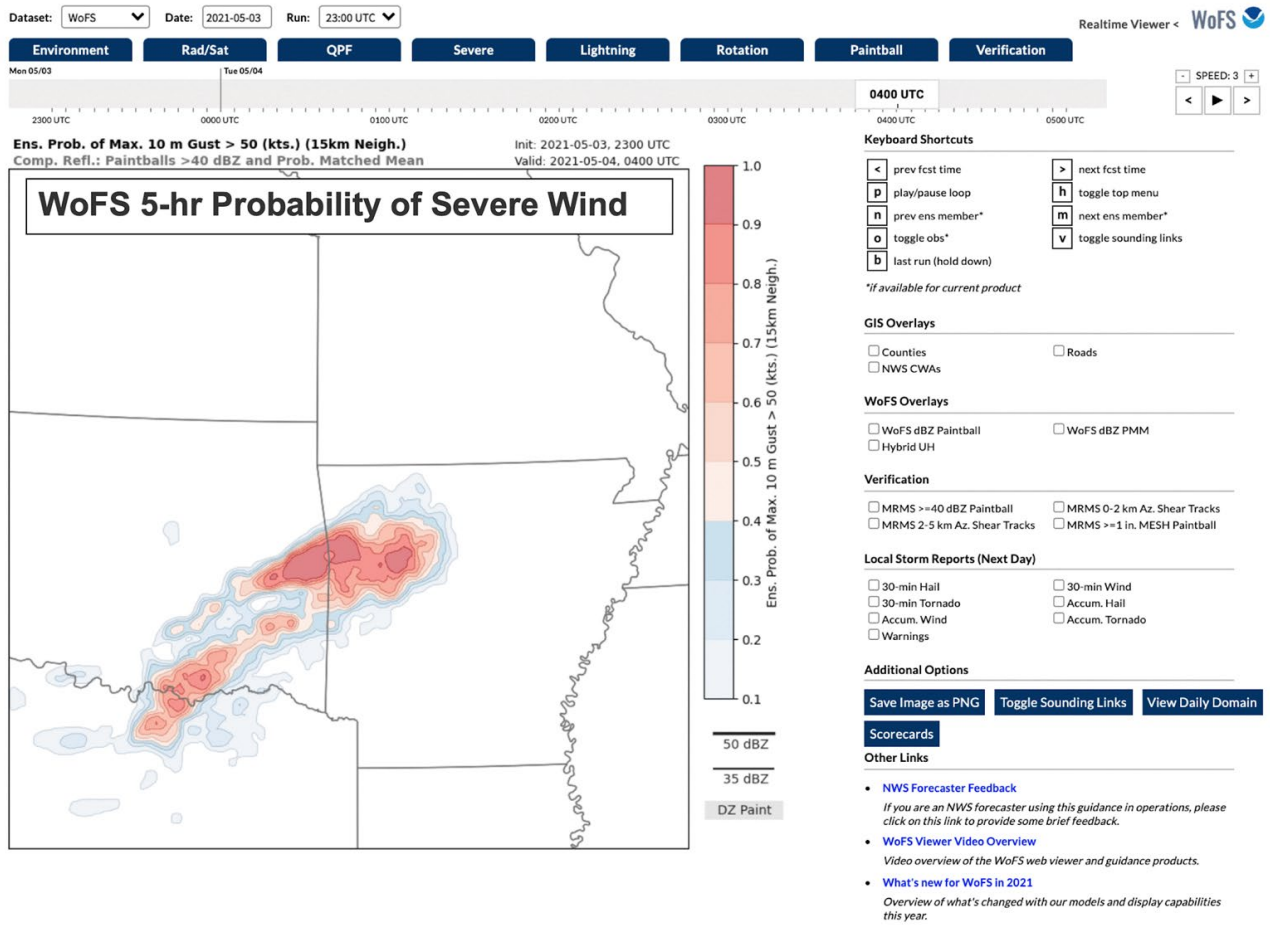
WoFS Strengths

- First of its kind, rapid update, storm-scale ensemble
- Exceptional forecasts of severe winds, flash floods
- A “watch-to-warning” tool for FACETs
- Forecasters involved in WoFS development

Real-Time Guidance Dissemination

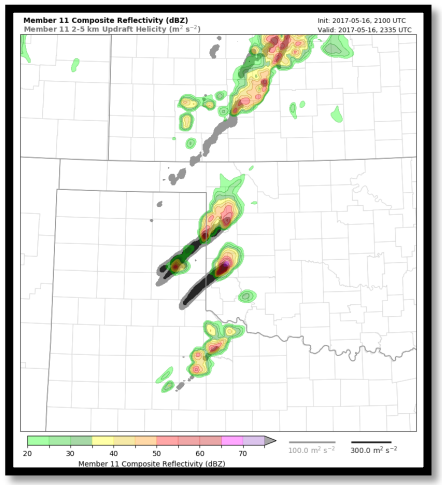
WoFS Web Viewer: https://wof.nssl.noaa.gov/realtime

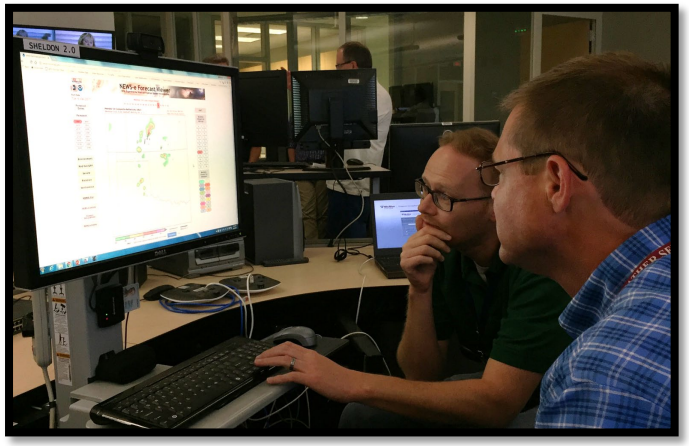
- **Complete 6-hr forecasts available ~45 min after initialization**
- **>125 different forecast products (>20,000 images) each forecast run**
- **Forecasts available from 205 WoFS cases from 2017–2021**



Warn-on-Forecast in Operations

- Co-location of NSSL/OU CIWRO with the Norman Forecast Office and Gchat room for other WFOs
- Warn-on-Forecast guidance is available during the real-time run season
- Impromptu science support during weather events
- Learning *together* about the real-time applications of Warn-on-Forecast guidance



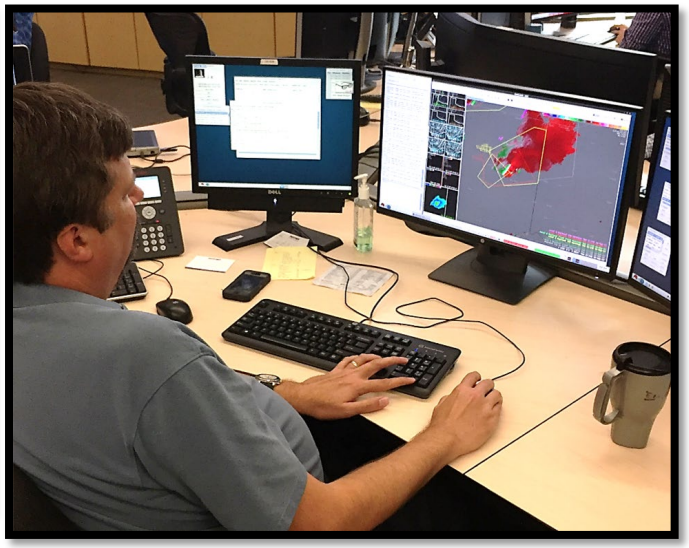


...SIGNIFICANT WEATHER ADVISORY FOR northwestern Harmon... southwestern Roger Mills...western Beckham and northwestern Greer Counties Until 545 PM CDT...

Storms capable of producing tornadoes were located in the Texas panhandle. One storm was located southwest of Wheeler and the other located northwest of Wellington at 515 pm. The storms were moving northeast at 35 MPH. These storms will move into western Oklahoma before 6 PM. Severe weather is likely with these storms as they move into Oklahoma and there is a high probability that tornado warnings will be issued.

PRECAUTIONARY/PREPAREDNESS ACTIONS...

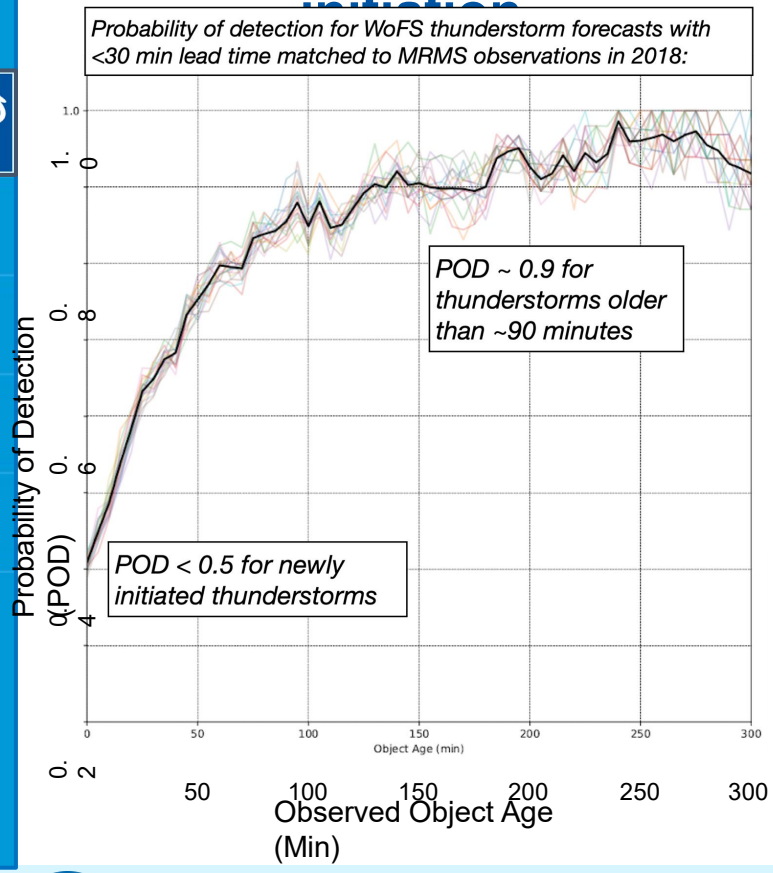
Monitor the situation closely. Be ready to act quickly if a warning is issued or if storms threaten you.

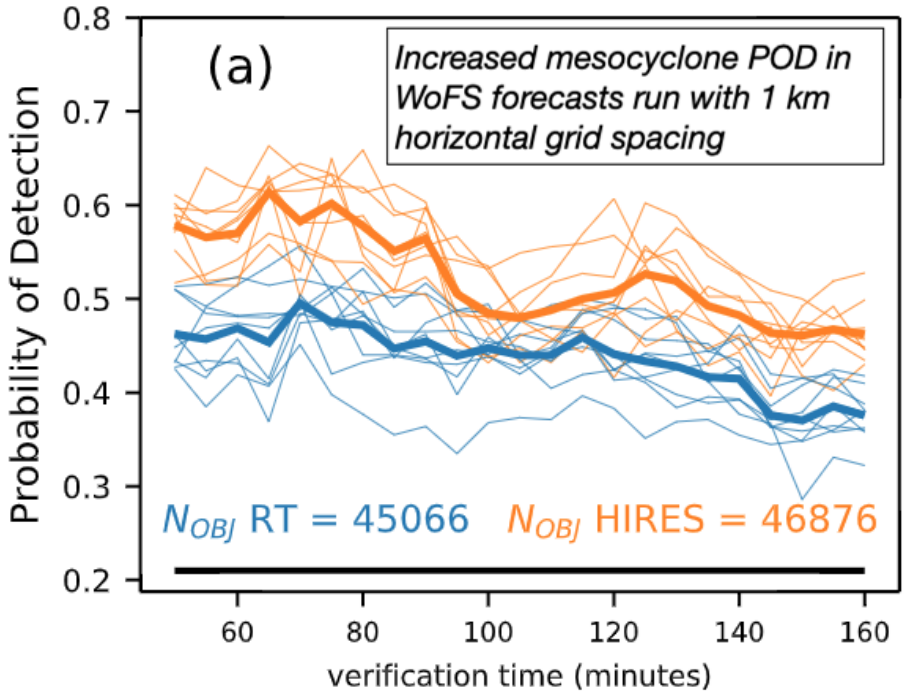


Images courtesy of WFO Norman

Object-based Verification of WoFS Guidance

Characterize changes in WoFS accuracy before and after convection initiation

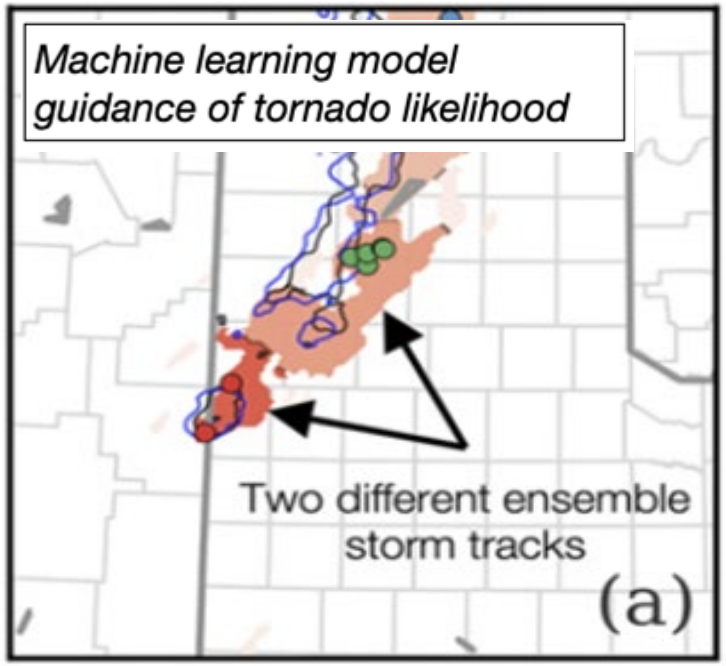




Miller et al. 2021

Quantify improvements in WoFS mesocyclone prediction with increased horizontal resolution

Create probabilistic forecast objects to input into machine learning models

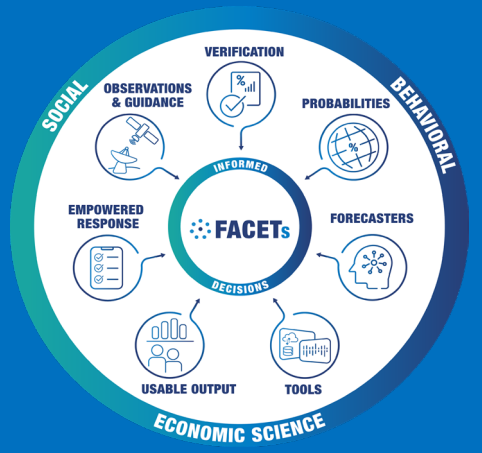


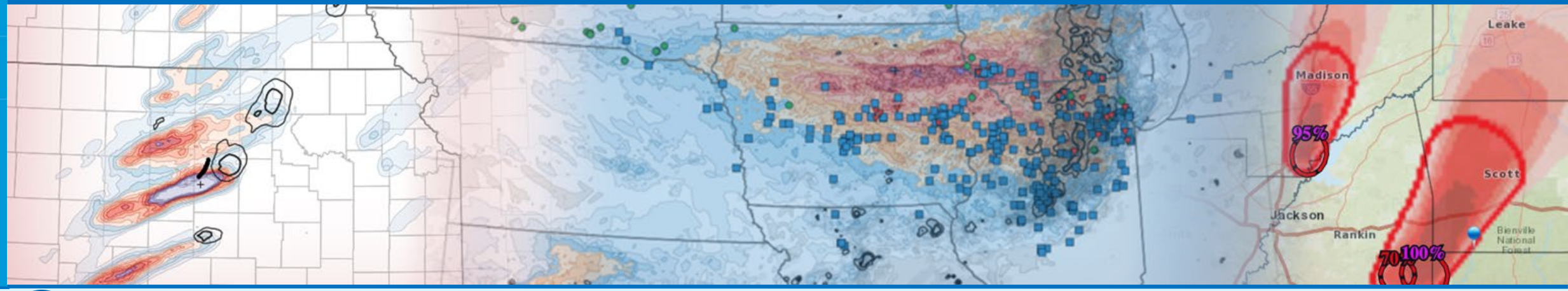
Flora et al. 2021

What's Next?

- Transition our cloud-based WoFS to operations
- Expand engagement to other users (aviation, emergency management, media)
- Long term development of higher resolution WoFS, getting closer to the scale of individual tornadoes

Forecasting a Continuum of Environmental Threats (FACETs)

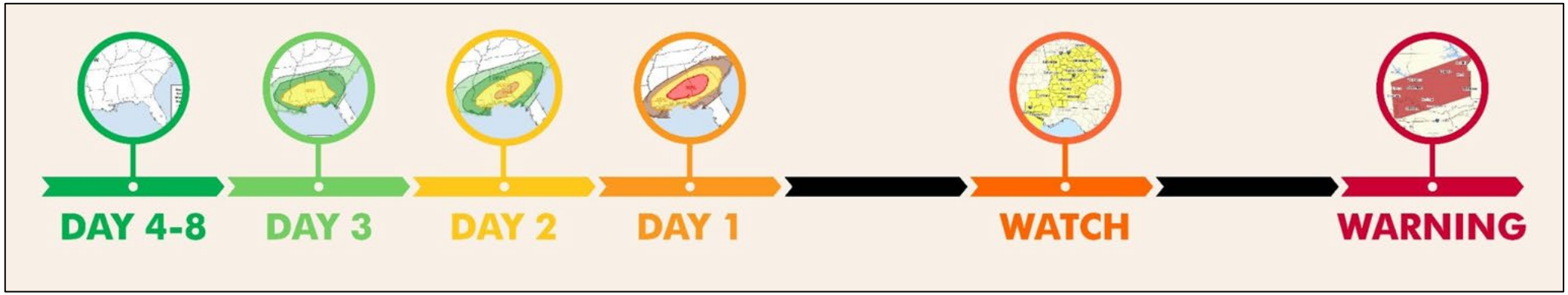




What is FACETs?

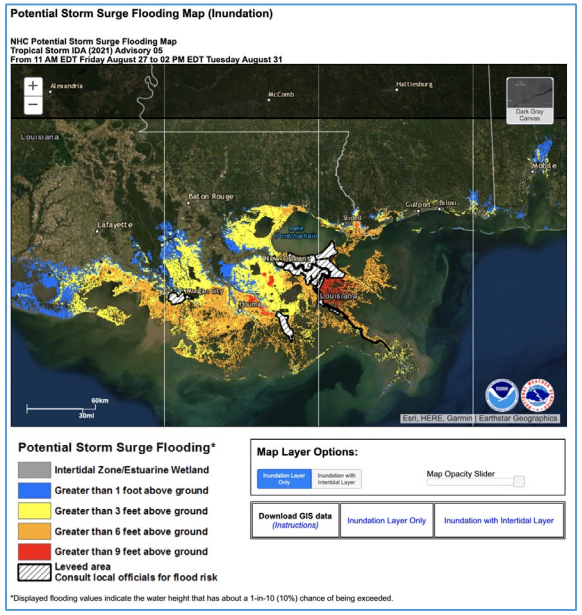
Framework to modernize the forecast & warning system to provide more actionable information when it's available for:

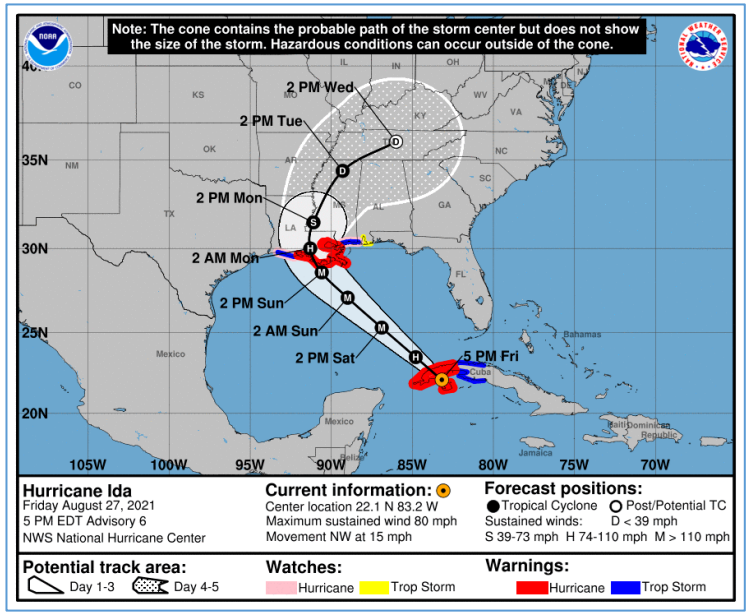
- **Better individual decision making**
- **More consistent communication & impact-based decision support services**
- **Meaningful quantification of hazard probabilities**
- **To produce a continuous stream of high-resolution probabilistic hazard information extending from days to within minutes of an event – for *all environmental hazards***

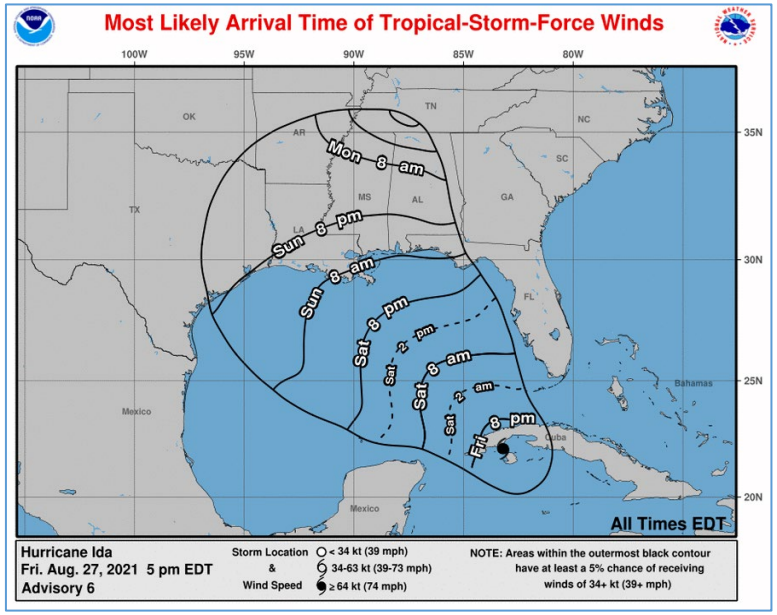


Facet 1: Probabilities

- Grid-based probabilities
- Already exist in some of the NWS product suites
- Serve as the foundation for impact-based decision support services

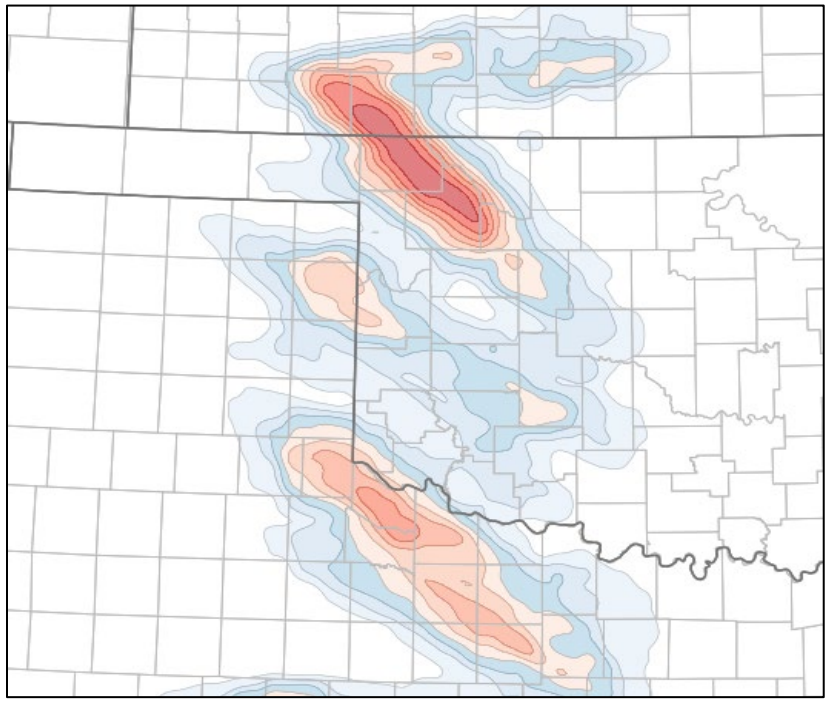




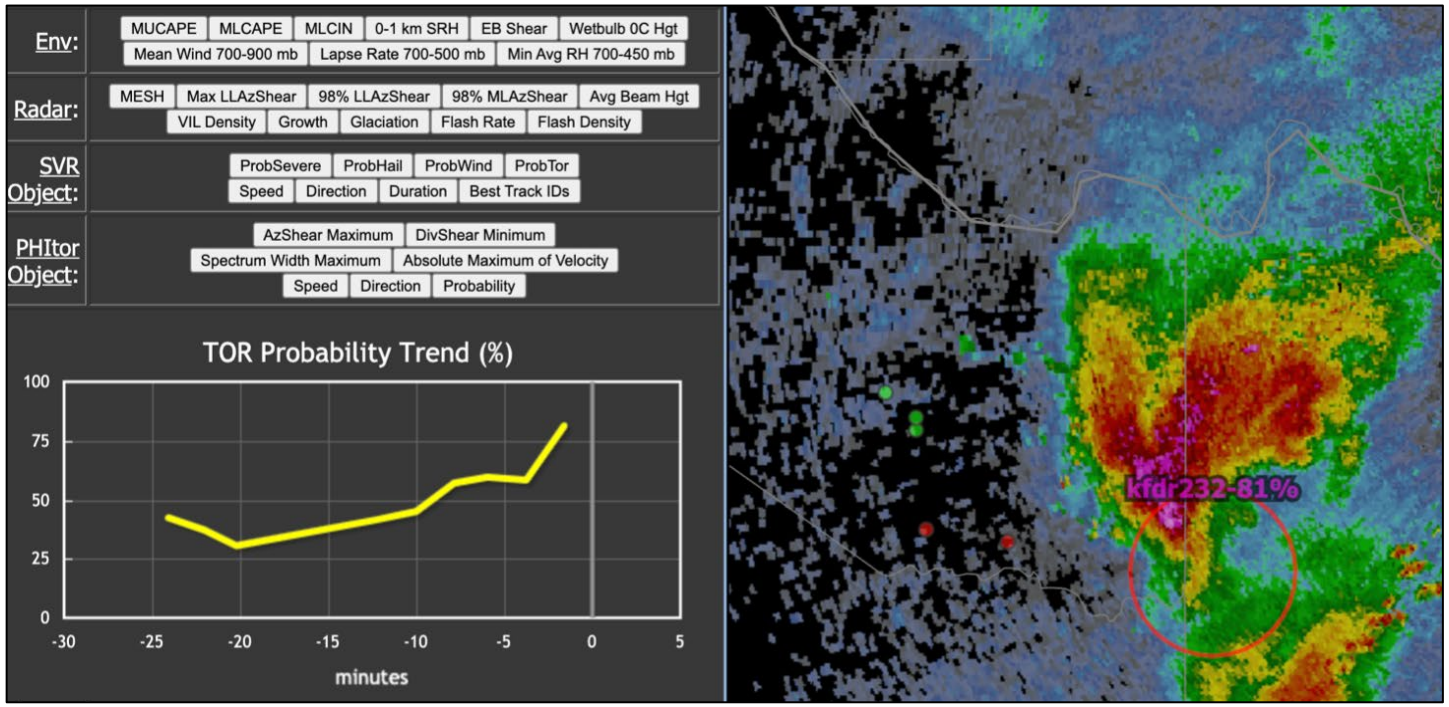


Facet 2: Observations & Guidance

- **What forecasters use to make decisions**



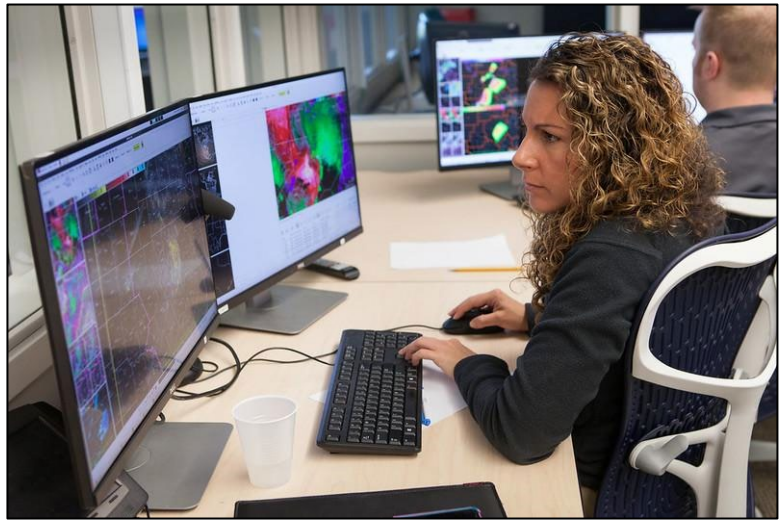
Probability of severe hail from the Warn-on-Forecast System.

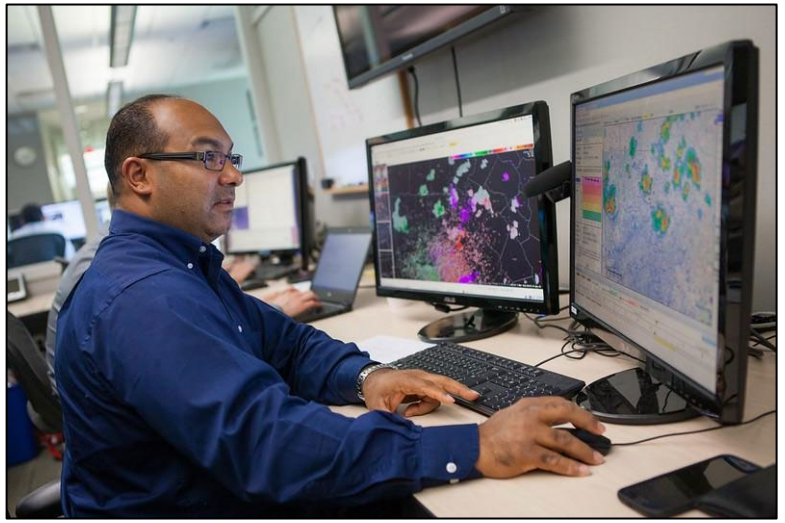


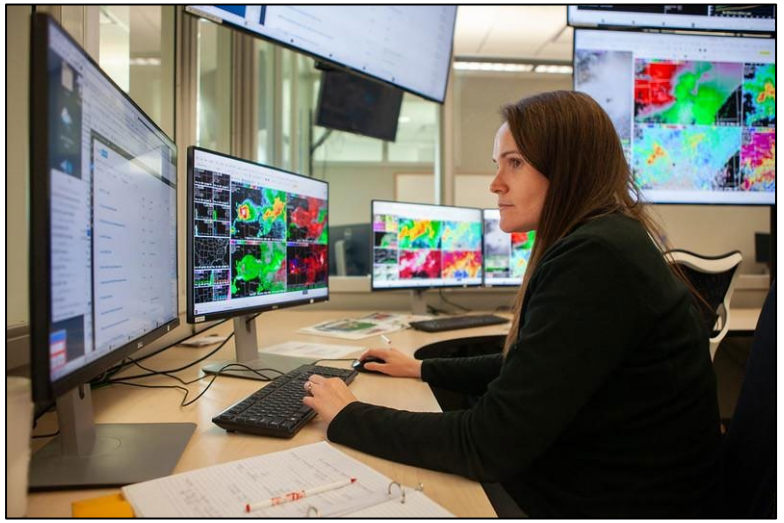
Probability of tornado from random forest algorithm.

Facet 3: Forecasters

- **The people (meteorologist, hydrologist) making the forecast & warning decisions**
  - As essential as ever to the entire forecast & warning process
  - Knowledge, skills, abilities
- **New tools/products = new training**



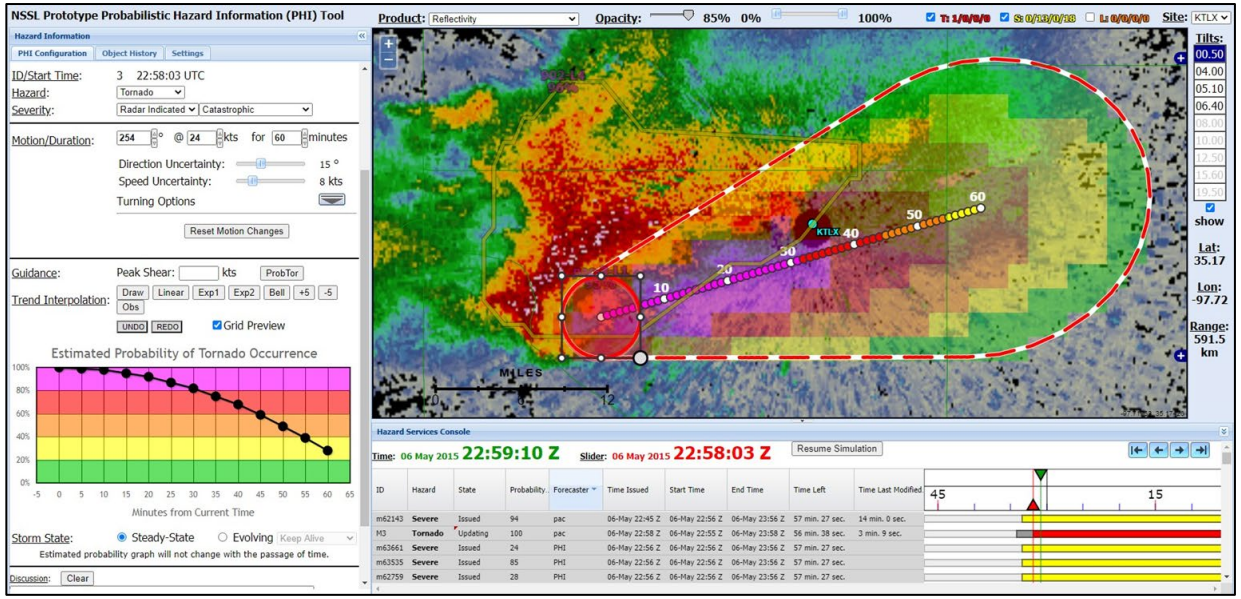


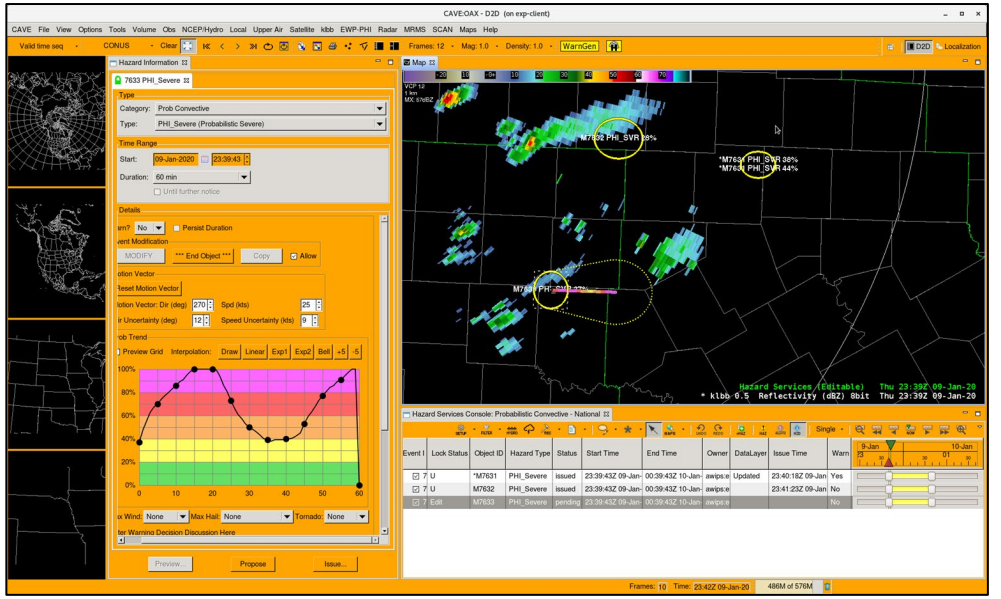


Facet 4: Tools

- **What forecasters use to create forecast and warning information**

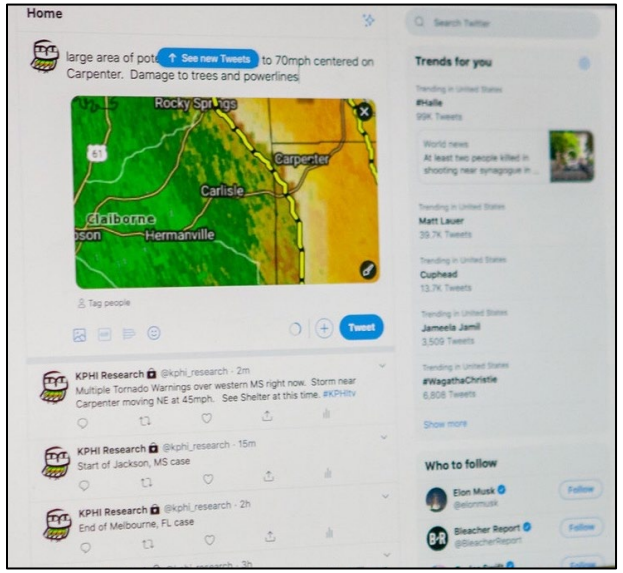
Nimble web tool for rapid prototyping → Software the forecasters use

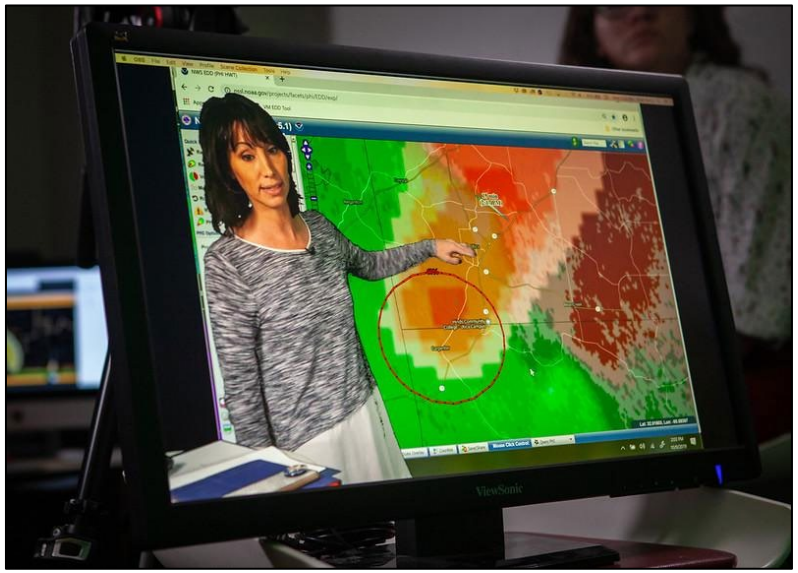




Facet 5: Usable Output

- **What the end users see & hear**
  - Graphical, textual, auditory, etc.
- **Social/behavioral sciences are key**





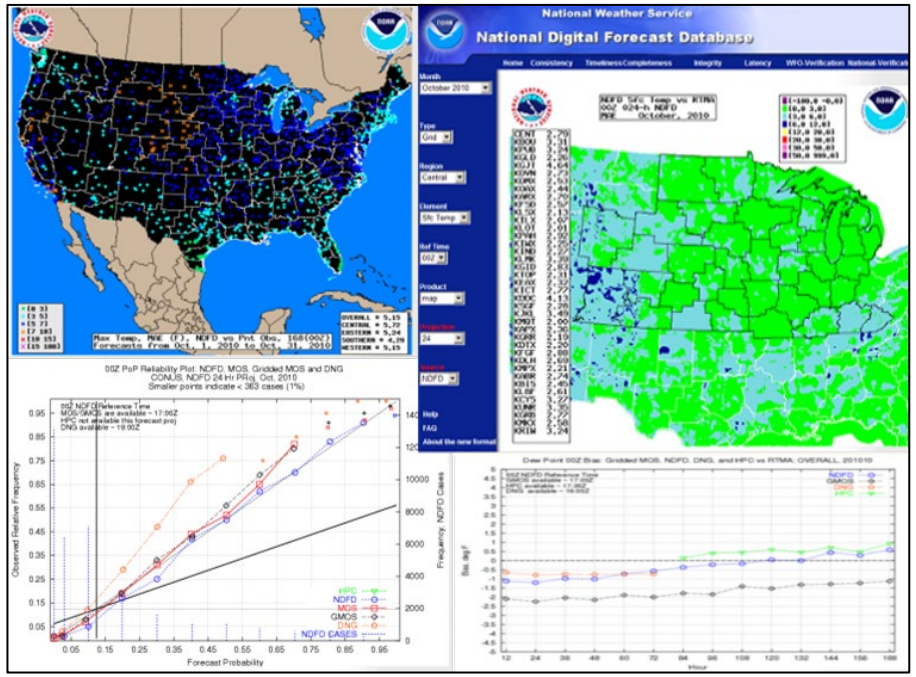
Facet 6: Empowered Response

- **What the end users do with the usable output**
  - The physical/social interface
  - The most important facet
- **Where social & behavioral science research pays off**

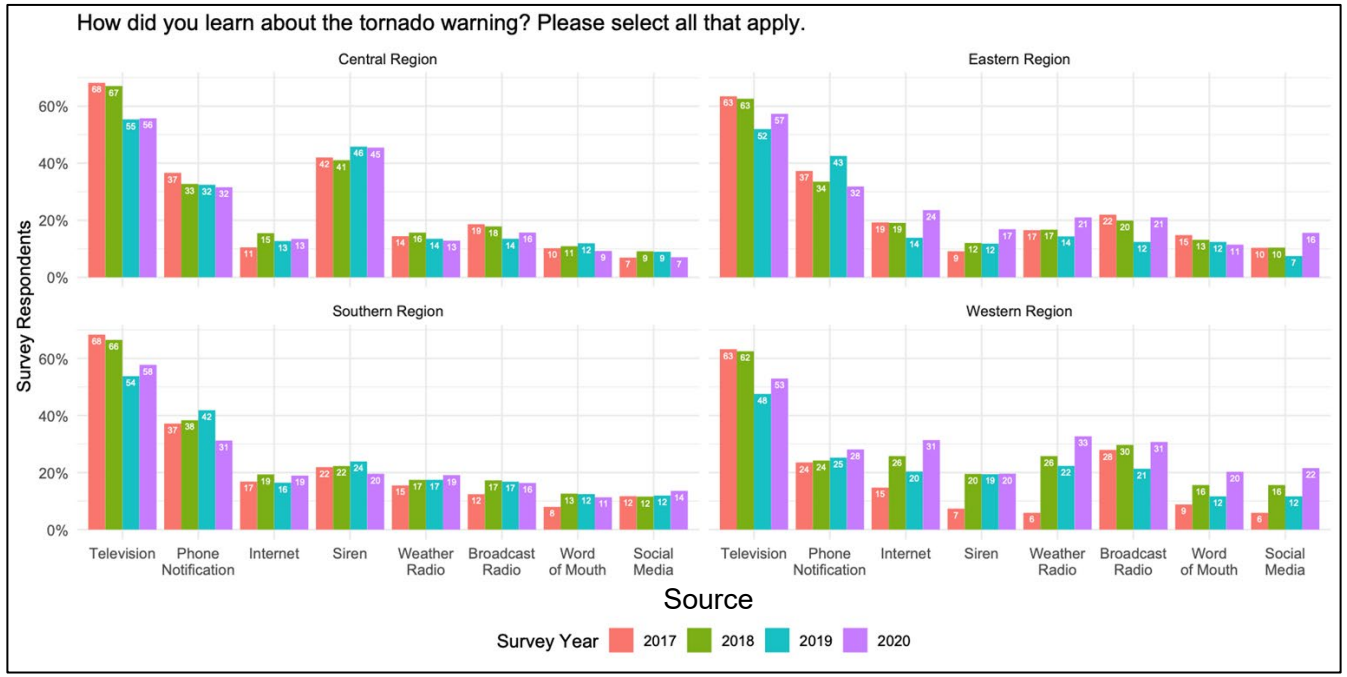
Facet 7: Verification

Evaluating system effectiveness

Verifying forecasts & warnings

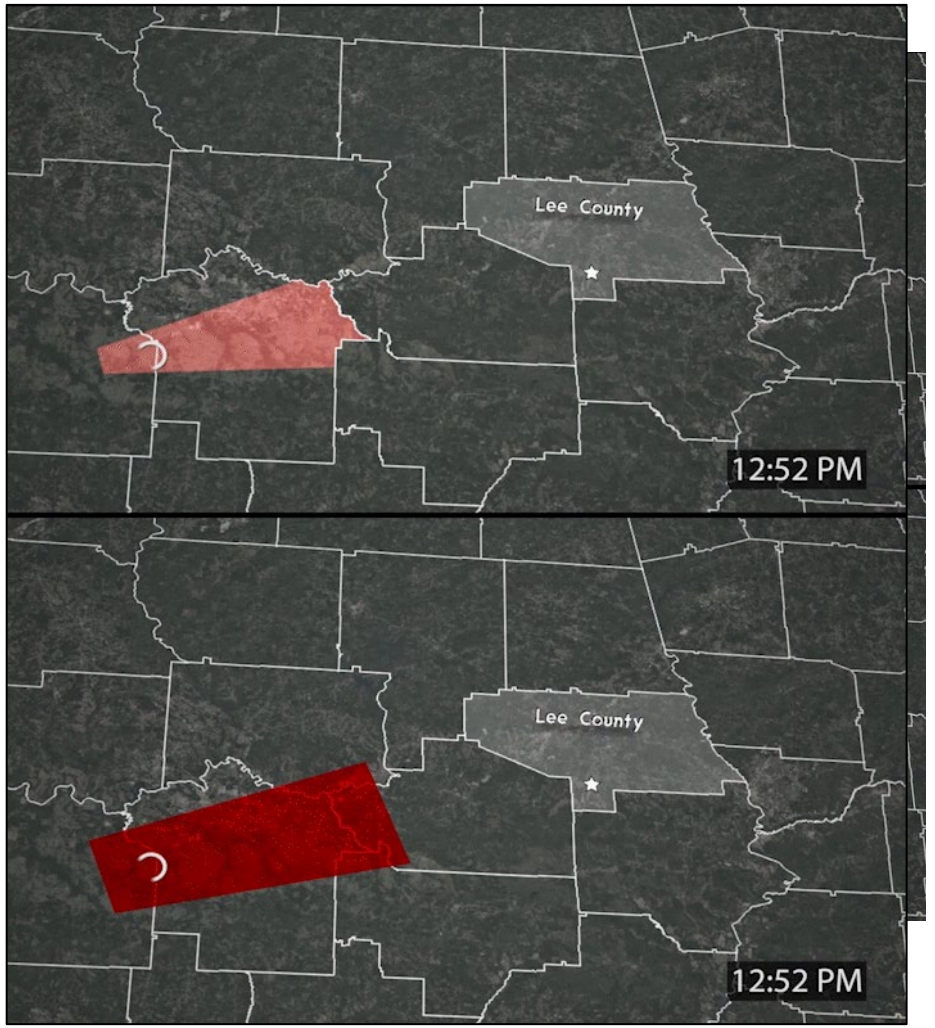


Verifying public response & understanding



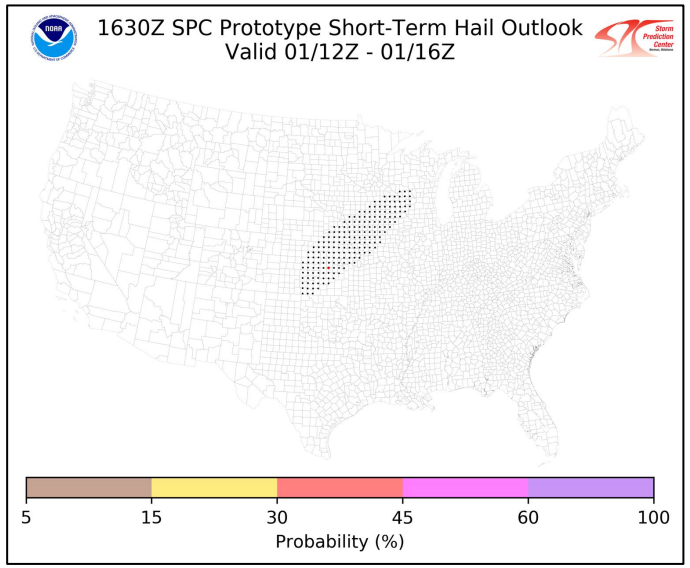
Threats-in-Motion (TIM)

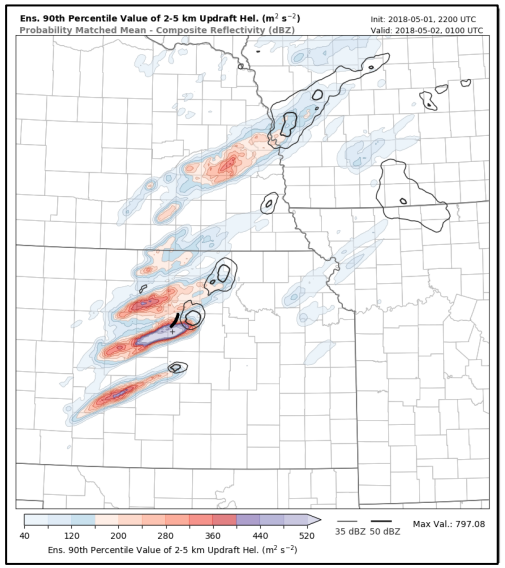
- **Severe thunderstorm and tornado warnings that move with the storm**
- **Initial step to shift the current NWS convective watch and warning paradigm toward a more *continuous flow of information***

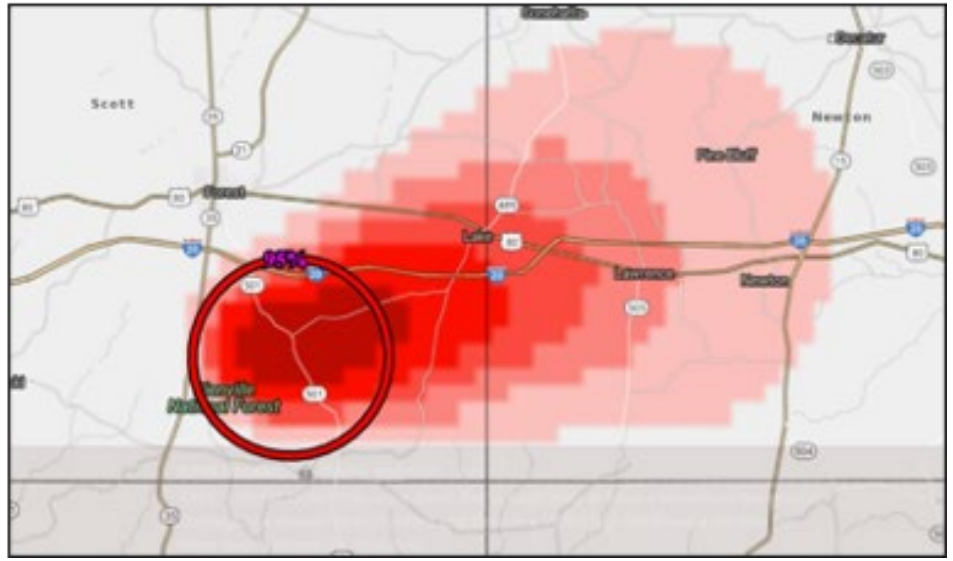


Future FACETs Work

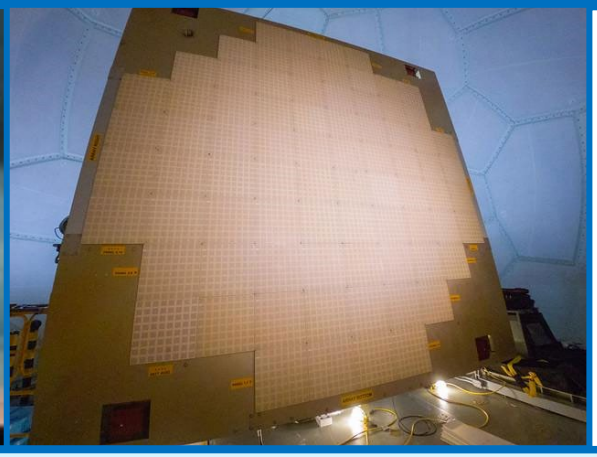
Cross-division effort to ensure FACETs-related research and products tell a cohesive story across time and space scales





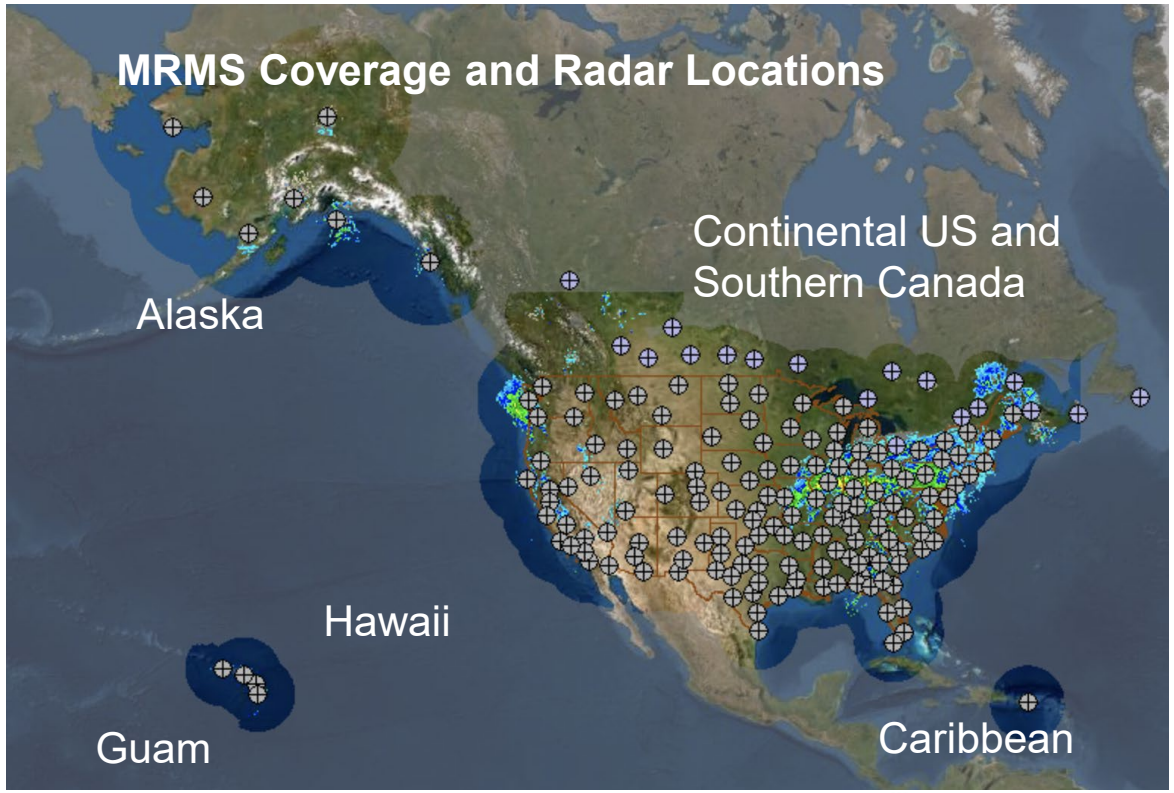


Multi-Radar Multi-Sensor (MRMS)

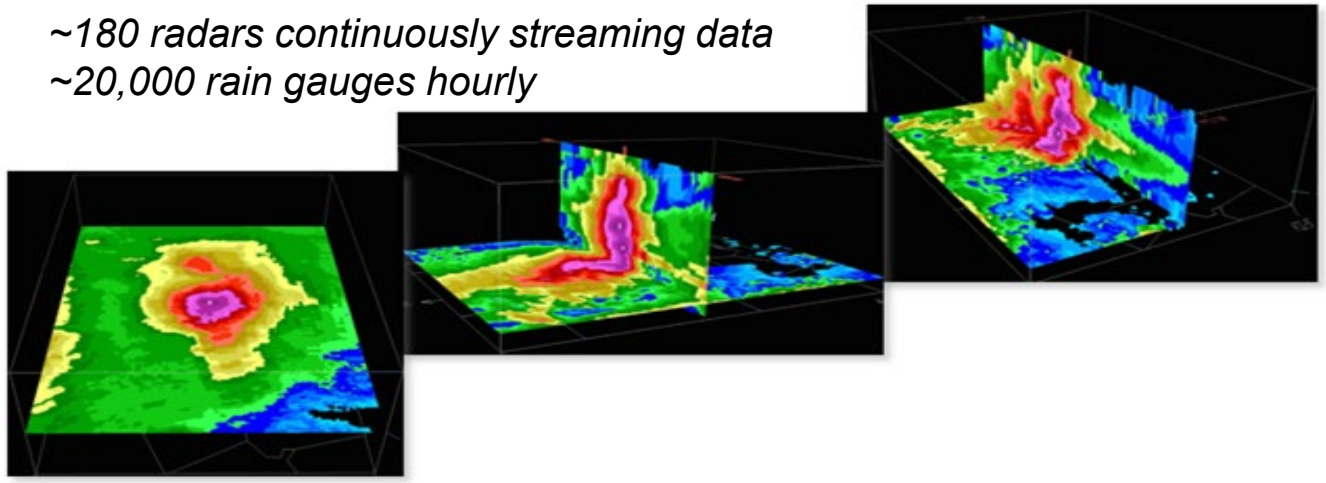


Multi-Radar Multi-Sensor (MRMS) is an advanced remote sensing processing system that:

- Integrates radar, surface observations, satellite, lightning, and numerical weather prediction data into common reference grid
- Automatically generates complete seamless national 3D radar mosaic, storm attributes and multi-sensor quantitative precipitation estimates at high temporal and spatial resolution



~180 radars continuously streaming data
~20,000 rain gauges hourly



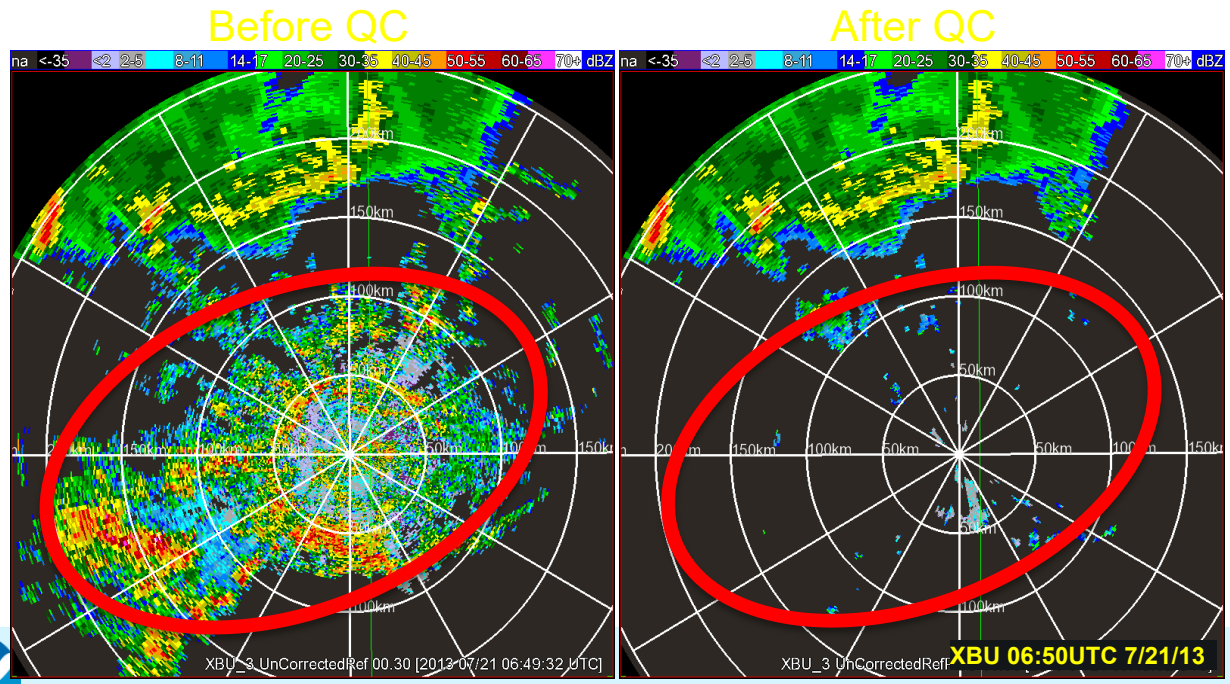
Running operationally at NOAA/NCEP since 2014

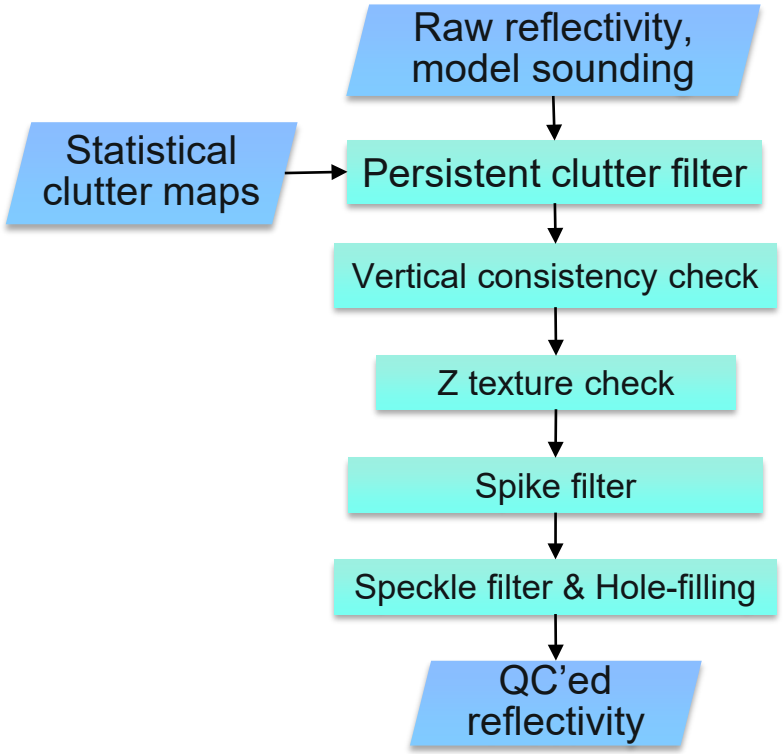
Operational Product Viewer:
https://mrms.nssl.noaa.gov/qvs/product_viewer/

Canadian Radar Data QC: Single-Pol

Objective: to remove non-hydrometeor echoes.

Methodology: persistent clutter filter; anonymous propagation clutter mitigation via 3D reflectivity structure, texture and environmental data.

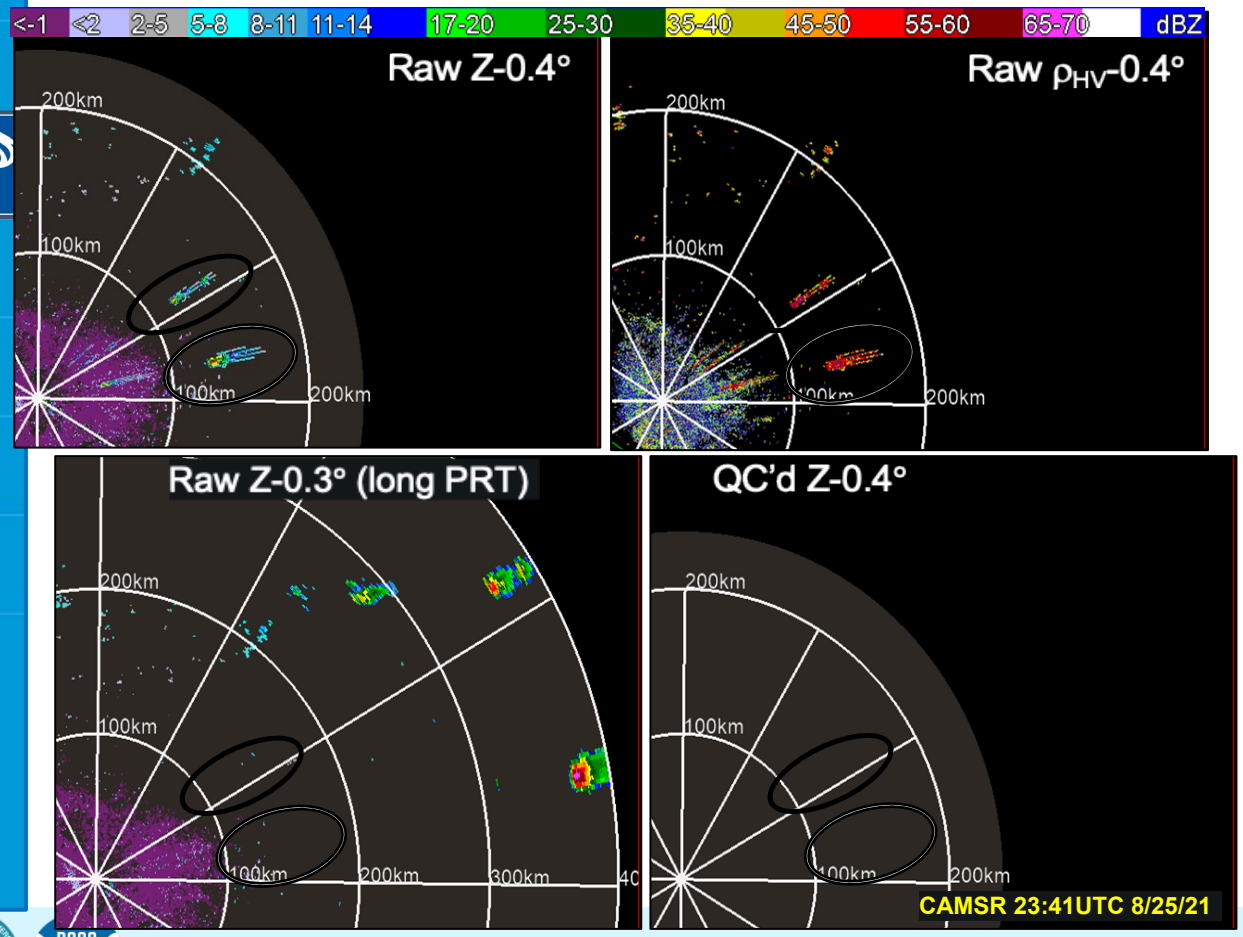


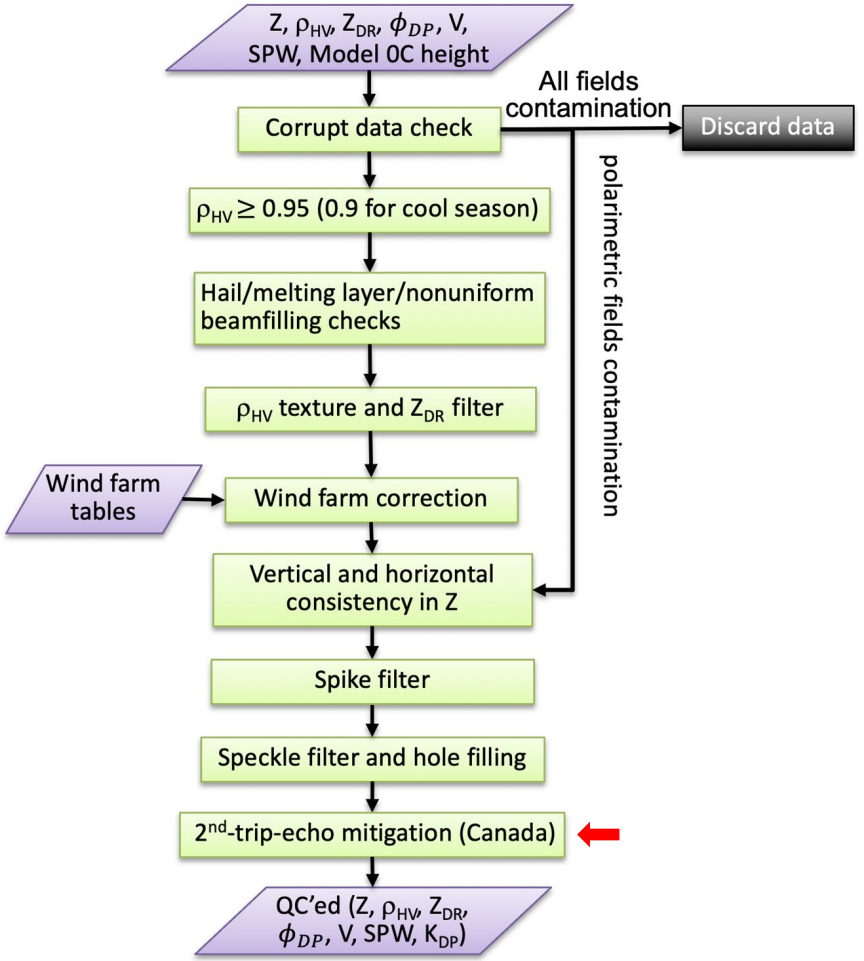


Tang et al. 2014: A physically based precipitation–nonprecipitation radar echo classifier using polarimetric and environmental data in a real-time national system. *Wea. Forecasting*, 29, 1106-1119.

Canadian Radar Data QC: Dual-Pol

Methodology: a decision tree based on polarimetric radar variables and 0°C height. A 2nd trip echo removal process is added for Canadian radars.



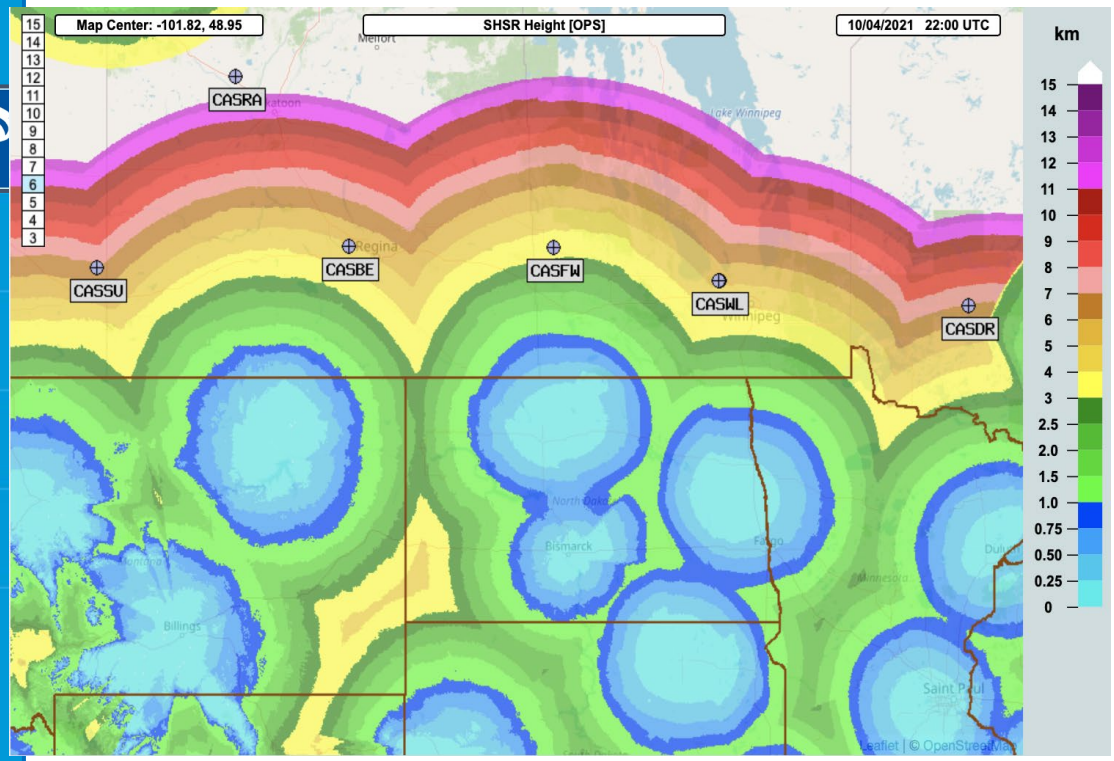


Z: reflectivity; Z_{DR}: differential reflectivity; ρ_{HV}: correlation Coefficient; φ_{DP}: differential phase; K_{DP}: specific differential phase; *V*: radial velocity *SPW*: spectrum width

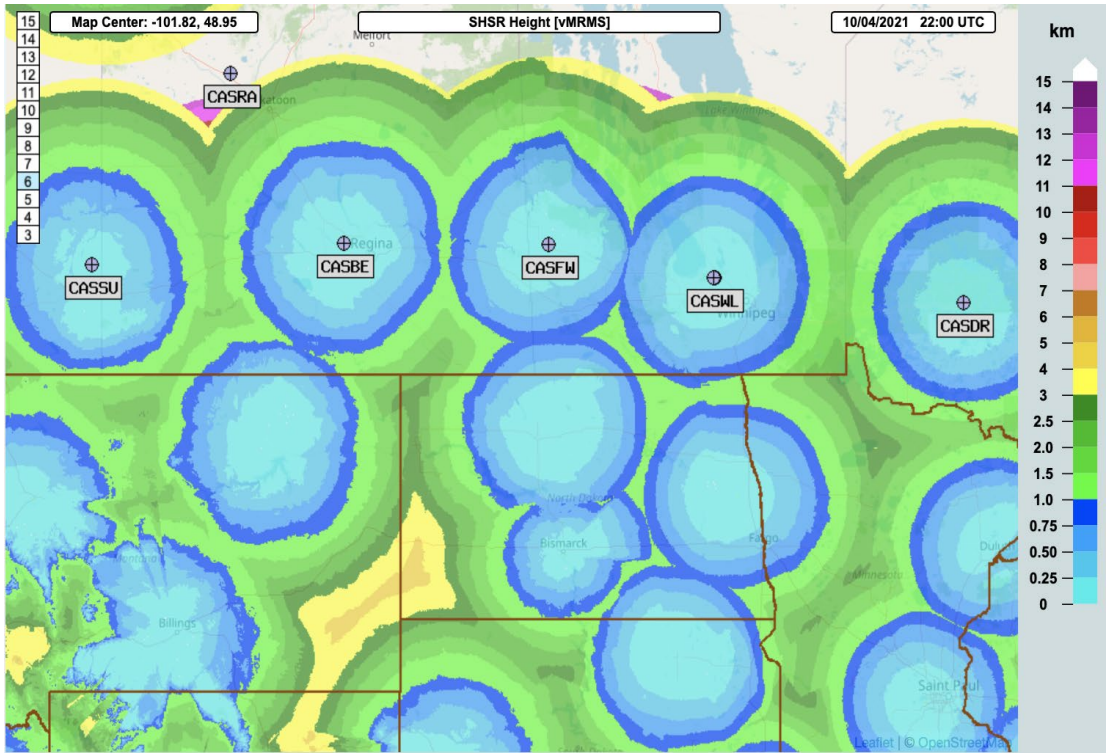
Tang et al. 2020: Updates on the radar data quality control in the MRMS quantitative precipitation estimation system. *J. Atmos. Oceanic Technol.*, 37, 1521–1537.

MRMS Radar Coverage

Lowest radar beam (bottom) height (AGL)



No Canadian radars



With Canadian radars